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A Factor Analysis of the Dimensions of Economic Damages from Tropical Storms and Hurricanes in Louisiana

James Luke Boutwell
Louisiana State University and Agricultural and Mechanical College

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A FACTOR ANALYSIS OF THE DIMENSIONS OF ECONOMIC DAMAGES FROM TROPICAL STORMS AND HURRICANES IN LOUISIANA

A Thesis

Submitted to the Graduate Faculty of
Louisiana State University and
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James Luke Boutwell
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Abstract

Coastal communities are highly sensitive to disturbances from tropical storms and hurricanes. This is particularly true in Louisiana and along the U.S. Gulf Coast where economies are largely dependent on tourism and natural resource based industry. Since Hurricane Katrina and, more recently, Hurricane Sandy, there has been an increase in concern for how coastal communities will mitigate and respond to the impacts of coastal storms. These concerns are made more acute by the increasing population concentrated along the coast and the risk of more frequent and more severe coastal storms in the future.

A commonly advocated-for method of storm damage mitigation is wetland preservation and restoration. This research explores the extent to which wetlands attenuate damages from coastal storms in Louisiana from 1997-2008. Using factor analysis, the relationships between wetlands, storm events and coastal populations are explored. The factor analysis suggests that wetland presence is associated with a reduction in economic damages from coastal storms. The results also demonstrate a distinct negative association between the degree of relative estuarine wetland coverage and the degree of economic risk present, illustrating the trade-off between development and conservation. Additionally, factor scores are computed to examine the extent to which wetlands reduce damages according to storm intensity. Representative storms are presented as case-studies to illustrate the result that wetlands may not be a suitable measure of protection against stronger storms. The value of the storm protection provided by wetlands is discussed in monetary terms and economic considerations are highlighted. Finally, limitations and consideration regarding the specifications of the model are discussed and future research areas are highlighted.

1. Introduction

The vulnerability of coastal communities to storm damage is highlighted annually as the U.S. coastline is impacted by hurricanes and tropical storms. Most recently, Hurricane/Superstorm Sandy devastated populated regions along the Atlantic coast, causing billions of dollars in damages (NCDC, 2012), and even relatively weak storms like Hurricane Isaac demonstrate the susceptibility of coastal communities in the northern Gulf of Mexico, and especially Louisiana, to the disruption of economic activity, structural damage, and loss of life that can result from tropical storms (NCDC, 2012). Coastal wetlands are thought to play an important role in the mitigation of damages from such storms. In Louisiana, as populations suffer wetland loss, and in the face of a changing climate that is expected to increase the severity and frequency of climatic disturbances, coastal communities are increasingly at-risk of damage, making the management of the resources involved in storm events evermore necessary.

1.1 Background

The coast of the Gulf of Mexico is seeing a population increase that is expected to continue. In the period 1995-2025, the U.S. Gulf Coast is expected to see 40% population growth, from 44.2 million in 1995, to an expected 61.4 million in 2025 (EPA, 2013). Despite this population growth, much of the Gulf Coast, which includes the western coast of Florida, Alabama, Mississippi, Louisiana, Texas and Mexico, is relatively rural. In fact, nearly half of the population of the Gulf Coast lives in counties or parishes with a population of less than 200,000 people (ONE, 2012). This distribution makes protecting populations from coastal hazards such as tropical storms and hurricanes more challenging because of the geographic extent of protection that is necessary and issues with the equity with which that protection is provided.

The Economy of the Gulf Coast is highly dependent on the use and extraction of natural resources. In 2011, the Gulf of Mexico region accounted for 54% of U.S. oil production and 47% of U.S. natural gas production. The majority of the oil and gas activities are concentrated off the coast of Louisiana (EIA, 2013). Fisheries also play an important role in the economy of the Gulf Coast. In 2010, Louisiana alone landed over 456,000 tons at a value of nearly $250 million (NMFS, 2012). A related industry – tourism – is also highly dependent on the natural resource base upon which it thrives. At over $45 billion annually, tourism constitutes the second largest economic sector in the Gulf of Mexico behind oil and gas exploration and production (CTO, 2010). Visitors to the region enjoy recreational fishing and hunting, nature viewing and cultural opportunities provided by the gulf region's natural assets. Both the fisheries and tourism industries can be highly seasonal because of the preference for activities that are dependent on environmental conditions (meteorological conditions, ecological dynamics). Additionally, because of this dependence, the industry is inherently sensitive to environmental change (such as coastal storms, etc.), making the effective management of these natural resources particularly important.

Despite widespread acknowledgement of these notions, the systematic relationship between coastal storms, the natural environment and impacted populations are not well understood. Among other reasons, this is because the degree to which wetlands and other natural features mitigate storm damages is challenging to assess due to the complex nature of coastal storm events (Barbier et al. 2008). The economic damage resulting from storm surge varies according to storm track, forward speed, local topographic and bathymetric conditions and available structural protection (Koch et al. 2009). While modeling of the mechanical and physical processes by which storm surge is attenuated by wetlands and other features are being achieved with some success (Gedan et al. 2011), economic analysis suffers from a lack of data regarding observed damages that result from storm events, particularly at scales that are inferentially useful, This lack of data and its associated resolution makes assessing components of storm events challenging in economic contexts.

Economic modeling of coastal hazards has the potential to increase the efficiency of coastal management. Understanding the relationships between coastal human and natural systems during storm events will be important in managing resources so that coastal communities are more economically and ecologically resilient. Much of this management occurs at local scales where management entities lack resources. For this reason, protection-, conservation- and resiliency-promoting initiatives to be least-cost and multi-benefit. Toward that end, wetlands conservation or construction has long been suggested as such a measure.

1.2 Research Objectives

The Louisiana Coastal Master Plan designates $50 billion to protection and restoration projects through the year 2061. However, the document states that “An in depth evaluation of ecosystem services would include a dollars and cents component that captures how much these services are worth monetarily. 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.” Assigning monetary values to wetland ecosystem services will allow resource managers to evaluate policy and allocate resources using comparable measures of economic change between development and conservation, extraction and preservation. This analysis explores the relationship between human populations, wetland features and storm events in order to identify how economic shocks from storm events are associated with these hazard components. The following research is meant to characterize the nature of the tradeoff between wetland conservation and coastal development along the Louisiana gulf coast in order to contribute to the development of tools available for coastal planning and to lay the groundwork for more comprehensive analysis of the monetary value of wetlands and their features.

2. Context and Considerations

As coastal management entities attempt to minimize damage from future storm events, it will be critical to weigh the benefits of the different options that are available to achieve such a goal. By most accounts, it is desirable to promote response preparedness, structural (natural and artificial) protection, and reduce economic risk in order to effectively avoid damages (Van Koningsveld, 2004). However, there is no consensus as to how resources should be allocated between mitigation initiatives. The efficient allocation of those resources will depend on the spatial distribution of in situ resources (that is, the resource that are exposed to loss from coastal storms and the resources which may reduce exposure to those storms) that are important with regard to influencing economic damages.

2.1 Wetlands as Buffers

Understanding the value of all ecosystem services provided by wetlands will be vital to understanding the full cost of wetland loss and degradation and the benefits of protection and restoration. Because conservation initiatives are often far less expensive than structurally engineered protection, wetlands should be considered first, and in conjunction with other measures (Halpern *et al.* 2007; Costanza *et al.* 2008). Additionally, wetlands provide several other economically beneficial services such as the provision of recreational opportunities, fisheries habitat, water quality regulation, etc. This multi-functionality makes wetlands a potentially attractive option for coastal protection against storm damage.

Wetlands reduce wave energy by several processes that can be categorized as direct mechanisms or indirect mechanisms. Direct mechanisms are those in which wetland vegetation physically interacts with waves and dampens their effect (Gedan, 2011). As water flows through the vegetated structure of wetlands, drag and friction cause wave energy and turbulence to decrease (Nepf *et al.* 2007). The most effective wetlands at attenuating wave energy and turbulence are partially submerged and emergent wetlands (Neumeier and Ciavola, 2004). In coastal Louisiana, these wetlands are salt marshes, intertidal bottomland forests and oyster reefs (Cowerdin *et al.* 1979).

There are other manners in which wetland ecosystems attenuate surge and wave energy. Indirect mechanisms are those that propagate changes in the underlying bathymetric conditions and coastal morphology (Gedan et al. 2011). As wetland ecosystems develop, decaying plant matter and living root structures fortify the underlying sediment. This is because organic soils generally resist erosion resulting from wave energy more effectively than less organic soils in wetlands (Feagin *et al*. 2009). Because wave height and velocity are largely determined by subsurface terrain, the development of a coastal bathymetry that reduces the destructive energy in waves and storm surges is a valuable function of wetlands. Bed friction from marsh-edge wetland soils is thought to be an important aspect of a wetland ecosystems capacity to reduce wave energy.

Similarly, fully submerged vegetation has been shown to be at least as important at reducing wave energy as partially submerged vegetation (Neumeier and Ciavola, 2004). This notion was supported by a meta-analysis performed by Gedan et al. (2011) which reported estimates of high wave attenuation values for wetland vegetation even at depths greater than one meter. Additionally, wave height is proportional to water depth, making substrate accumulation even more important for the attenuation of wave energy (Le Hir *et al.* 2000).

Recent research, however, has questioned the degree to which certain wetlands can mitigate damages resulting from tropical storms, particularly during larger storm events (Feagin, 2010; Resio and Westerlink, 2008). It was been noted in the literature that coastal wetlands are likely most protective against the wave and storm surge energy that is associated with shorter, less intense storms (Day, 2007; Gedan et al. 2011). This could be a result of the reduction of the attenuating properties of wetlands due to the depth of their submergence as storm surge levels increase. In other words, larger storms overwhelm the attenuating capacity of wetlands. Small-scale physical science experiments and models have recently supported this argument (Resio and Westerlink, 2008; Feagin et al. 2009; Wamsley et al. 2009).

Evaluating the monetary value of the storm protection services provided by wetlands is a relatively recent endeavor. This review of some valuations should be preceded by cautioning that values are often reported (and most easily compared) on a per unit basis. These values are not 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.

Early 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. For this study and other studies (Barbier, 2007; Costanza et al. 2008), storm frequency is used to estimate the value of wetlands and these studies reach comparable conclusions. However, because of the limited number of observations for each storm category to estimate an accurate frequency, and because this approach does not account for the potential of wetlands for reducing the number of economically impactful events, these values may be more appropriately studied on a case-by-case basis (Georgiou, 2011). The practice of valuing wetlands as storm damage mitigation providers has seen increased attention, particularly since Hurricane Katrina in 2005, and turned toward valuing wetlands for their storm surge and wave attenuating properties.

The values are often calculated according to the degree to which wetlands presence resulted in a reduction of damages (damage cost avoided, or DCA; synonymous with expected damage function, or EDF) 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 greater than seven times those estimates for 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.

When evaluating the degree to which wetlands attenuate economic damages, economists must rely on observed damages, or use data based on physical science models of coastal processes. 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. 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.

Alternatively, economists use computer models or simulations to derive a value estimate for storm surge reduction. Georgiou et al. (2012) used 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. 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. Although causal links are more easily inferred using fine scale computer models, broad scale damages are not well understood or predicted by models (HAZUS; Longnecker, 2011).

2.2 Coastal Community Risk

It has been suggested that initiatives to allay economic damages are most impactful when focused on managing the risk associated with coastal storm events (Pielke et al. 2000). Over one third of the world's population lives in coastal areas (UNEP 2006). This presents a significant risk, especially as sea levels are projected to rise and tropical storms to become more frequent and severe (IPCC, 2007). Yet, the risk from an increase in frequency and severity of storms are small compared to risks posed by the demographic changes occurring along coastlines. In fact, it has been estimated that, by 2050, for every dollar increase in storm damages expected to be attributable to climate change, up to $60 will be attributable to increased concentration of wealth along the coast (Pielke et al. 2005). Because population is becoming increasingly concentrated along the coast (Donnor and Rodriguez, 2008), the management of coastal economic growth will be critical for mitigating storm damages.

The decisions that are made regarding the protective and at-risk resources that are involved in storm events can influence the resulting economic damages. Perhaps nowhere are those decisions more economically impactful than when managing actual economic risk that is exposed to coastal storms. Intuitively, if there is no significant improvement in the storm-readiness of newly built buildings and if greater amounts of built capital are concentrated in areas that are vulnerable to storm damage, storm damage will increase. Regardless of changes in storm patterns or natural protection, storm damages will increase as more wealth is accumulated near the coast in areas that are known to have the potential to be inundated by storm surge (IPCC, 2007). If per capita wealth and population grow at 5% annually along the coast (which is not unreasonable in many quickly developing locales), even if hurricane frequency and severity do not increase (which is contrary to scientific consensus), coastal communities will experience a doubling of the real cost of hurricanes every 15 years (Pielke et al. 2000). Such a notion highlights the importance of managing the growth of coastal communities in a way that is sensitive to the consequences of mismanaging economic capital at risk of coastal hazards.

3. Methodology

In order to explore an underlying relationships regarding the components of storm events that are known to influence economic damages, a factor analysis is performed. For this analysis, data are collected across four dimensions of interest: storm intensity, wetland protection, economic risk and economic damage. Applying factor analysis to this set of data will allow for the examination of the interrelations between human and natural systems and how these systems interact during storm events. Most importantly, the analysis will deliver a measure of the degree to which storm damages are explained by each of the other three factors.

3.1 Factor Analysis

Factor analysis is a term used to refer to a class of multivariate techniques that address the interrelationships of variables that represent a smaller number of explanatory components. In this research, variables are chosen to represent specific components of storm events. These components are summarized by indicative variables and their relationships are considered simultaneously. In this manner, the analysis will be able to describe general relationships between wetlands and socio-economic risk, storm damages and socio-economic risk, and wetlands and storm damages based on data from several storm events.

Representative factors are established for components of storm events that are related to economic damages. These components are represented by eigenvectors (factors) emitting from an origin. The rotated and unrotated eigenvectors are analyzed in this research. The unrotated factor solution extracts the factors according to their importance for explaining the maximum amount of variance for the entire dataset. The initial factor exhibits high factor loadings (the correlation between the eigenvector and the variable) for most variables, and subsequent factors are indicative of the residuals.

Rotating the factors can allow for a more meaningful representation of the latent components involved in the dataset by redistributing the variance explained in the initial factor to the latter factors. A factor rotation is the pivot of the reference axes about the origin. Such an adjustment can allow the delimiters of factor space to be moved in a manner that allows for the simplification of the variables for each sample. Generally, unrotated solutions are insufficient for practical interpretation, and a rotated solution necessary to reduce any structural ambiguities manifest in the initial unrotated factors. For the purpose of this analysis, an orthogonal rotation, where the factor axes are held perpendicular to one another, is used. Plotting factors in orthogonal factor space, as opposed to oblique factor space (where the axes are not held perpendicular) generally allows for the derived factors to display greater correlation (Hair, 1959).

This factor analysis uses an orthogonal varimax rotation. A varimax rotation is achieved by simplifying the specification of each factor (the maximum simplification for a factor would leave only 1s and 0s as variable loadings), thereby making each factor more suitable for practical analysis. Verimax rotation allows poorly understood variables (in this case, economic damages) to be explained by latter factors by assuring the structure of the initial factors are highly simplified and allowing variance to be explained in subsequent factors (if that variance is not well explained by initial factors). This is contrary to alternative orthagonal rotations that seek, in varying degrees, to maximize the number of variables loaded onto each factor and ensure that all variables are represented well be at least one factor (Hair, 1959).

Additionally, analysts often employ oblique rotation techniques, which do not constrain the factor axes to a perpendicular structure. This method of rotation allows factors to be correlated with one another. This research seeks to explore unique variance and the relationship between distinct factors. Because correlation between factors inherently means that the variance is less unique between factors, no oblique rotational methods were used for this analysis.

3.2 Data

The data used in this factor analysis are composed of seven variables. Because the objective of this analysis is to identify ways in which economic damages are associated with populations and their environment, a single variable for economic damage is included among six other variables. These variables represent the three factors of interest: storm intensity, economic risk and wetland protection. Each of these factors will be composed of two variables as described below. Two variables were chosen to describe each factor to ensure that a similar amount of variance in the dataset was explained by each factor, and that the relationship of these factors to the damage variable could be interpreted more simply. A more detailed discussion of the reasoning behind using two variables and the limitations and implications of that decision are described in Chapter 5, Section 3.

3.2.1 Storm Data

Data used to represent storm intensity were obtained from the National Oceanic and Atmospheric Administration’s (NOAA) National Climatic Data Center (NCDC). These data include details regarding the maximum sustained winds and minimum barometric pressure at the time of landfall (NCDC). Collectively, these two variables compose the factor describing storm intensity and are highly negatively correlated (-0.950), which is desirable for a representative reduction of the data. The magnitude of economic damage during the storm is, at least to some degree, dependent on the intensity of the storm. Therefore, these variables are included so that the relationship of the factors – economic risk and wetland protection – to storm damages are not obscured by the omission of a presumably highly explanatory factor. Of course, the intensity of an individual storm is not expected to have any statistical relationship to the presence of wetlands or economic risk. There are no evident correlations between variables describing these components.

Table 3.1.

Storm Date	Storm Name	Storm Category	Minimum Pressure at Landfall	Maximum Sustained Winds at Landfall	Damage in Louisiana (year of storm, USD)
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

Table 3.1 describes each storm in chronological order. Included in the table are the variables that are used in the model to represent the storm intensity factor, minimum barometric pressure and maximum 60-second sustained wind speed at landfall. Also included in the table is the date of the storm, the category of storm (from tropical storm to 1-5 on the Saffir-Simpson hurricane scale, or SSHS), and the damage that was reported for all parishes in Louisiana (not just those parishes used in the analysis) from that storm.

3.2.2 Economic Risk Data

The economic risk of a parcel of coast is represented by two variables: population and the value of housing exposed to storm surge risk. Population data was retrieved from the U.S. Census Bureau parish estimates for the year of each storm event. So, the population value for Orleans Parish, Louisiana is 301,842 for the sample describing hurricane Ike (2008) and 489,722 for the sample describing hurricane Lili (2002) (U.S. Census Bureau). Population is a generally applicable indicator of vulnerability to damages, under the assumption, which the data validates, that the value of surge-vulnerable built capital exhibits high correlation with the size of a population.

The value of housing exposed to storm surge hazard is acquired from the FEMA Region IV Flood Loss Atlas, and is reported and used in this analysis in thousands of dollars. The data are based on a combination of two simulation models. First, the Hazards U.S (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. The HAZUS model is the model used in the delineation of federal flood insurance program zones. This model 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 and social impact of a particular storm on a community (HAZUS).

The extent of the storm surge for a given category of storm is assigned according to National Hurricane Center (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. The maximum surge level is calculated for hundreds and 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 (Conver, et al. 2008).

The FEMA Coastal Flood Loss Atlas (CFLA) 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 a designated area for each level of storm (Longenecker, 2011). The value used to describe the economic risk of parishes in the factor analytic model is the value of all structures that have the potential for damage in any storm scenario, sometimes referred to as the maximum envelope of water (MEOW). This variable, combined with the population data, represents the economic risk component of the model. The CLFA has based the estimates on data from the year 2002, near the median year for the storms in this analysis. Ideally, the population data will describe any year-to-year variance in risk that occurs in parishes between storms. These variables are highly correlated (0.981) and provide an indication of the vulnerability of a community to economic damage from coastal storms. The damage vulnerability estimates for each parish are listed in Table 3.2.

3.2.3 Wetland Protection Data

The data used to characterize the degree of protection provided by wetlands were collected using a geographic information system (GIS), ArcGIS. Data describing wetland type, as classified by Cowerdin, et al (1979), were downloaded and projected with Louisiana parish maps from the U.S. Fish and Wildlife Service. These data files were developed between 2002

Table 3.2. Potential Risk

Parish	HAZUS MEOW Damage Potential (Thousands of Dollars, 2002)
Cameron	$ 604,134.00
Iberia	$ 3,248,273.00
Jefferson	$ 28,274,132.00
Lafourche	$ 4,610,986.00
Orleans	$ 27,252,820.00
Plaquemines	$ 1,273,600.00
St. Bernard	$ 3,822,364.00
St. Charles	$ 2,841,415.00
St. John the Baptist	$ 2,312,986.00
St. Mary	$ 2,349,263.00
St. Tammany	$ 11,026,825.00
Terrebonne	$ 5,323,060.00
Vermilion	$ 2,612,099.00

and 2007 (Stout et al. 2007). Consistent land cover data are not available for each of the years necessary to provide each sample with the data from the year of the respective storm. The median year for storms in this analysis is 2003. Raw area estimates were obtained by manually delineating boundaries for each parish using U.S. Census Bureau parish shapefiles and extracting all data features that are identified by FWS code for either “Marine Wetland” or “Estuarine Wetland.” The acre values for these features were then independently summed to yield an estimate for each wetland classification within each parish (including marine wetlands immediately seaward of a respective political boundary). An example of how the data are provided by the USFWS is displayed in Figure 3.1, which shows a representative portion of the coastline in Terrebonne Parish, just south of the coastal city of Houma, Louisiana.

The marine deepwater and estuarine marine wetland classifications are the wetlands that possess the properties that are thought to attenuate surge and wave energy. Estuarine wetlands, for example, include intertidal forested wetlands, scrub-shrub wetlands, emergent vegetation, and other rooted and floating vascular plants. These are thought to be the *direct mechanisms* by which wetlands reduce wave energy. Marine deepwater wetlands include aquatic beds and reefs, unconsolidated sea bottom and shallow near-shore habitats, and they are wetlands that control wave and surge energy via *indirect mechanisms*. These wetland types dominate the land cover along the Louisiana coast and are the wetlands that serve as buffers between the open gulf and coastal communities (Cowerdin et al. 1979; Gedan et al. 2011).

Because these wetlands occur exclusively along the coast, parishes with longer coastlines are expected to have a larger area of coastal wetlands. It can also be expected that parishes with longer coastlines have greater geographic exposure to waves and storm surge. This transitively implies that areas with larger areas of coastal wetlands should experience more exposure to waves and storm surge and, therefore, more storm damage. Such an implication is an artifact of the nature of the political boundaries used in this analysis.

The relationship between coastal wetlands and storm damages will be confounded if length of coastline is not taken into account. In order to control for the effects of coastline length, the wetland values used for each sample are equal to the area of each wetland in a parish divided by the length of shoreline exposed to the Gulf of Mexico or open bay or estuary (such as Lake Pontchartrain) in that parish. The adjusted wetland protection values that were used in the analysis are shown in Table 3.3. Also provided are the raw acre estimates for each wetland type in each parish and the corresponding coastal length.

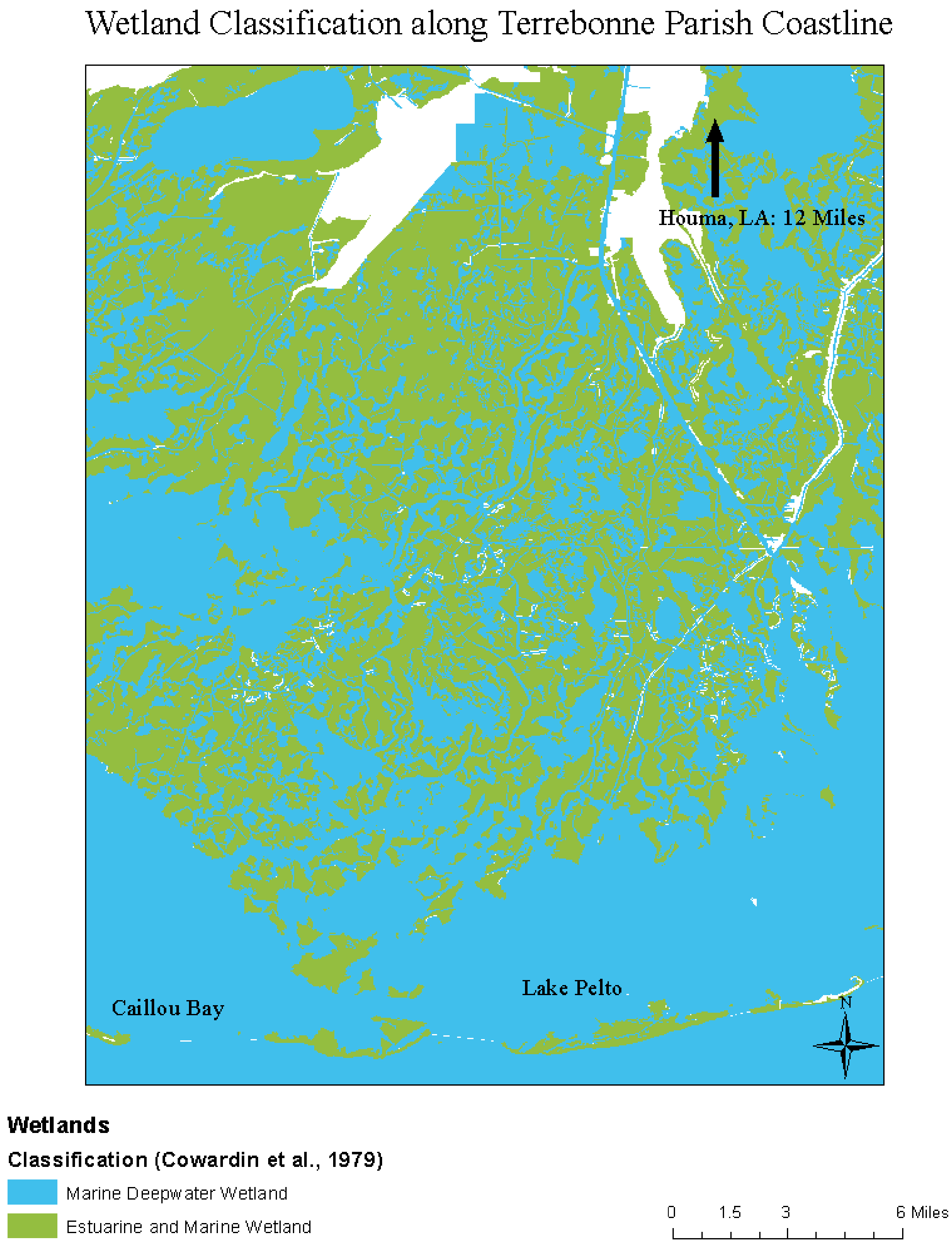

Figure 3.1. Example of Coastal Wetland Classification

Table 3.3. Wetland Area Data

Parish	Acres-Marine Deepwater Wetlands	Acres-Estuarine Marine Wetlands	Miles of Direct Surge Exposure	Marine Index Value*	Estuarine Index Value*
Cameron	548628	371223	96	5706	3861
Iberia	285574	45896	30	9651	1551
Jefferson	674744	71104	41	16574	1747
Lafourche	1246251	224063	68	18379	3304
Orleans	1362499	29431	52	26359	569
Plaquemines	1746821	290050	196	8912	1480
St. Bernard	1797553	217440	52	34311	4150
St. Charles	376851	11602	8	46930	1445
St. John the Baptist	316730	11623	21	14870	546
St. Mary	311703	12723	74	4224	172
St. Tammany	1300907	24804	43	30317	578
Terrebonne	1074869	308926	72	14929	4291
Vermilion	353368	163610	73	4847	2244

*Variable used in the model.

The wetland classifications are summarized, according to Cowerdin et al. 1979, as:

Estuarine Marine Wetlands:

> …consists of deepwater tidal habitats and adjacent tidal wetlands that are usually semi enclosed by land but have open, partly obstructed or sporadic access to the open ocean, and in which ocean water is at least occasionally diluted by freshwater runoff from the land. The salinity may be periodically increased above that of the open ocean by evaporation. Along some low-energy coastlines there is appreciable dilution of sea water. Offshore areas with typical estuarine plants and animals, such mangroves and oysters are also included in the estuarine system.

Marine Deepwater Wetlands:

> …consists of the open ocean overlying the continental shelf and its associated high-energy coastline. Marine habitats are exposed to the waves and currents of the open ocean and the water regimes are determined primarily by the ebb and flow of oceanic tides. Salinities are high, with little or no dilution except outside the mouths of estuaries. Shallow coastal indentations or bays without appreciable freshwater inflow, and coasts with exposed rocky islands that provide the mainland with little or no shelter from wind and waves are also considered part of the marine system because they generally support typical marine biota.

The two wetland variables are relatively less correlated than other variable groups (0.275). However, the variance for these variables is distinct from the variance in the rest of the dataset. Correlation with nearly all other variables for both wetland variables is very low (<0.150). The notable exceptions are the correlation between estuarine wetlands and indicators of economic risk, and the correlation between marine wetlands and damage data. The relatively weak correlations between estuarine wetlands and population (-0.308) and property at risk (-0.316) is an indication of a trade-off between wetland conservation and structural development or population growth that ought to be distinguishable in the factor analysis. This is to be expected because the use of land, a finite resource, for either land cover is generally exclusive of the other. Marine wetlands are weakly negatively correlated (-0.274) to economic damages, indicating that marine wetlands may reduce damages, particularly in conjunction with the estuarine wetlands and the observed aforementioned trade-off.

3.2.4 Damage Data

Reliable storm damage data is a limiting factor in the economic analysis of storm events. Some analyses rely on broad scale (i.e. state level, regional level) damages to explore the relationship between wetlands and economic damages (Farber, 1987; Costanza et al. 2008). These studies have the benefit of inferring from actual observed damages, but the scale is only practically useful in exploratory contexts and is of little use for planning. Also, the validity of damage estimates for natural disasters can vary according to temporal proximity to the event and source of estimate, and confirming damage estimates is challenging. Alternatively, analyses use storm surge simulation models to assess the degree to which wetlands attenuated storm surge and assess the degree to which that attenuation is valuable (Georgiou et al. 2012). This method has the benefit of being able to analyze actual physical processes involved in damage mitigation at a scale that may be useful to coastal planners. However, any economic analysis is based on predicted damages. Although these physical models have been shown to be reasonably accurate (Schneider et al. 2006; Vickery et al. 2006), the analysis is not based on observed damages.

This analysis uses actual damages from coastal storm events and distributes the data across the landscape at a finer scale according to model predictions. Raw economic damages are gathered using the NOAA 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 making landfall in Louisiana only causes damages for Cameron and Vermillion parishes (the westernmost parishes), then the publication designates these counties as those experiencing economic loss, and the damage for these parishes are reported as the total damage between the two parishes. 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 power utility companies. The data are composed of losses sustained to private property (households, objects, crops, etc.) and public infrastructure and facilities (MacAloney, 2007). The damages from each storm are provided in Table 3.1.

These estimates are distributed between the counties or parishes that are reported to have been damaged. To do this, the FEMA CFLA damage predictions (predictions based on the SLOSH and HAZUS models mentioned above) 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 geographic units for a storm of a particular category. For example, the predicted value of property that is exposed to storm surge given the SLOSH MOM surge level for a category 3 hurricane, such as hurricane Rita, making landfall in Cameron and Vermillion 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 which 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.

Criteria were established for inclusion into the dataset 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 have area exposed to coast and have land cover composed of both estuarine marine wetlands and marine deepwater wetlands. Thirteen Louisiana parishes meet these criteria. Additionally, if the damages for a storm event included parishes that are not considered as part of the FEMA CFLA region, samples from those storms could not be incorporated into this study because key variables (those detailing storm surge exposure) could not be included for that sample. 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.

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 coastal exposure, no coastal wetlands and little structural vulnerability to storm surge flooding. 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 features 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 economic damage data are not particularly well explained by any other single variable. This phenomenon is somewhat surprising considering variables regarding economic risk during storm events were used to distribute the data between parishes. This suggests that observed damages are often vastly different than damages predicted by computer models, and that the use of computer simulations in the context of the *post eventum* observed damages may be important for the analysis of economic damages in the future. Additionally, the lack of explanatory power by any single variable and the poorly understood nature of the relationship between these factors of interest (economic risk, hurricane intensity and wetland protection) and economic damages promote the use of a factor analytic approach to reveal any underlying associations that simple dependence techniques (i.e., multivariate regression) may not deem sufficient for significance, perhaps due to obviously high degrees of collinearity in the data (Scott, 1966).

3.3 Analysis of Diminishing Effects

As scientists question the ability of wetlands to mitigate damage from waves and storm surge, it will be important to explore storm events on a case-by-case basis to identify any differences between storms of varying intensity. For the factor which describes the degree of wetland protection, factor scores are derived from the analysis. These scores measure the degree to which the trends described in that factor are embodied by an individual sample (based on prior research, it is hypothesized that wetland protection and economic damages will be inversely related, and that that relationship is represented by an eigenvector in the factor model). Parishes which, despite having high degrees of wetland protection, experience large damages for a given storm relative to the sample mean will receive negative scores. Parishes which exhibit a stronger-than-average negative correlation between damages and wetland protection will receive positive scores. Those samples who exhibit the relationship described by the wetland protection factor, to the approximate degree described by that factor (the average impact shown by the data), will receive scores near zero.

The wetland protection factor scores will be averaged according to the category of storm (tropical storm, category 1-5). Averaging these factor scores will allow an assessment of the degree to which storm intensity is related to the ability of a wetland ecosystem to mitigate storm damage. If the mitigating properties of wetlands are overwhelmed by stronger storms, such a phenomenon would be indicated by increasingly negative factor scores as storm intensity increases. Likewise, if the data shows that wetlands are more effective at mitigating damages at a certain storm intensity, such will be identified. Finally, if there is any discernible threshold past which wetlands attenuating properties are negligible, disaggregation of the samples by storm category would allow for recognition of that trend.

Each sample will have an associated factor score and geographically referenced code that will enable the results for the wetland protection factor to be displayed in a map format. This will enable a visual assessment of how the involved factors are related spatially. Also, the map display will show how the degree of wetland protection impacts economic damages as storms intensify. This aspect of the analysis is important because it allows for the analysis of the relationship between wetlands, storm intensity and economic damage on a case-by-case (storm-by-storm) basis, which has the potential to identify knowledge gaps direct future research.

3.4 Adequacy of the Sample

The sample is composed of 118 impacts of a tropical storm or hurricane to a parish of Louisiana during the period 1995-2008. The sample includes data from 13 named storms which impacted some or all of Louisiana’s 13 parishes with exposure to open coastal water. Each sample has corresponding values for each of the following seven storm event variables: population, value of exposed property, maximum sustained winds, minimum barometric pressure, acres of estuarine emergent wetlands, acres of marine wetlands and economic damages. With a sample to variable ratio of greater than 16:1, the dimensions of the dataset are sufficient for factor analysis. The descriptive statistics for the dataset used in the model are provided in Table 3.4.

Table 3.4. Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
DAMAGE	118	101	933442912	41376903	140213345
POPULATION	118	7434	494294	144142	155185
PROPERTY*	118	604134	28274132	8097924.03	9522711
PRESSURE	118	931	999	972	21
WIND	118	35	125	76	27
ESTUARINE	118	172	4291	2058	1426
MARINE	118	4224	46930	19860	12359

*Thousands USD

The Kaiser-Meyer-Olkin (KMO) measure of sample adequacy is a test for comparing the observed correlation coefficients with the partial correlation coefficients to ensure that correlations among variables are small. In order for the dataset to be suitable for a factor analysis, the KMO measure must exceed .5 (Kaiser, 1974). This sample has a KMO value of .549. Because this value is not particularly high, it is expected that some variables are not explained well by the rest of the data, which is not surprising given the complicated nature of storm events. However, because the KMO value meets the threshold for adequacy, a factor analysis is not precluded.

Bartlett’s test of sphericity is also a measure of strength among variables in the dataset. Bartlett’s test is hypothesis test for the null hypothesis that the correlation matrix is an identity matrix. If the correlation matrix for this dataset were an identity matrix, then the variables in the sample would be uncorrelated and therefore not suitable for a factor analytic approach. The Bartlett’s test score is <0.001, therefor the probability that the correlation matrix is an identity matrix is very small and the null hypothesis is rejected. This is expected, as variables were chosen in pairs to represent underlying constructs (economic risk, natural protection, storm intensity). These measures of sampling adequacy for factor analysis are provided in Table 3.5.

Table 3.5. KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.	.549
Bartlett's Test of Sphericity	<.001

4. Results

4.1 Communalities

Communalities measure the proportion of the variance from each variable that is explained by the other variables or the extracted factors. These values are equal to the sum of the squared factor loading scores for each variable. Initial communalities represent the sum of the squared multiple correlations of each variable to the rest of the data. So, initial communalities provide an indication of how well each variable is explained by all the other variables. The extraction communalities are the proportions of variance that is explained by the extracted factors. In the case of this factor model, the extraction communalities are higher than the initial communalities for all variables, as is shown in Table 4.1. This implies that the retained factors explain more of the variance for each variable than does the rest of the dataset.

Table 4.1. Communalities

	Initial	Extraction
DAMAGE	.179	.228
POPULATION	.965	.982
PROPERTY	.965	.982
PRESSURE	.907	.955
WIND	.905	.943
ESTUARINE	.203	.307
MARINE	.187	.425

4.2 Extracted Factors and Variance Explained

The factor analysis retained three factors with eigenvalues greater than one. Eigenvalues measure the variance explained by each factor. The eigenvalue of all extracted factors will be equal to the number of variables. Factors are retained and used for rotation and analysis if their eigenvalue is greater than one, making that factor more explanatory of the dataset than any variable. The three retained factors in this analysis have a cumulative eigenvalue of 5.638, meaning that these factors explain greater than 80% of the variance in the data. The eigenvalues and corresponding percentages of variance explained for each factor is provided in Table 4.2. A scree plot diagram, useful for visually comparing the relative importance of the retained and unretained factors is provided in Figure 4.1.

4.3 Unrotated Factor Results

A common unrotated factor analysis allocates the highest amount of common variance possible on the first factor and the greatest remaining amount on each subsequent factor. The unrotated model seeks to create a single eigenvector, or factor, that is representative of the maximum amount of variance in the data. Given the dimensions of the data, a factor loading value of 0.3 is the criteria for significance of a variable loading onto any factor (Hair, 1995). The first two factors exhibit high factor loadings (correlations between the factor and the variables) for the two measures of economic risk (population and value of exposed property) and the two variables describing storm intensity (wind and pressure). The third factor exhibits high loadings for the wetland protection variables, suggesting that the variance in these variables is associated with each other and unique from other variables. The damage variable was not well explained by any unrotated factor.

Table 4.2. Total Variance Explained

	Initial Eigenvalues		
Factor	Total	% of Variance	Cumulative %
1	**2.370**	**33.859**	**33.859**
2	**1.983**	**28.323**	**62.182**
3	**1.285**	**18.363**	**80.544**
4	.737	10.533	91.077
5	.558	7.977	99.054
6	.049	.694	99.748
7	.018	.252	100.000

Factors used in the rotated analysis are emboldened.

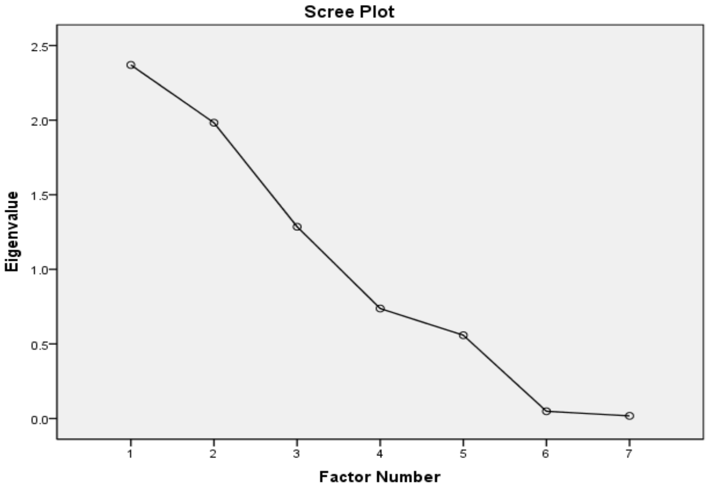

Figure 4.1. Scree Plot of Factor Analysis Results

Unrotated factors embody common variance, but the impetus of this research is the examination of unique variance. Therefore, this unrotated factor model is not useful in exploratory contexts beyond the interpretation just rendered, and will not be used in subsequent analysis. The unrotated factor matrix, which provides the correlations (factor loadings) between the unrotated factors and the variables in the analysis, is provided in Table 4.3.

4.4 Rotated Factor Results and Factor Identification

Rotating the factors allows for a more meaningful representation of the latent components involved in the dataset by redistributing the variance explained in the initial factor to the latter factors. A factor rotation allows the reference axes to pivot about the origin, so that the factors in the model are simplified. The factors are considered simplified if the factor loadings are near -1, 0 and 1, and the variance described in each factor is distinct from the others. In this manner, rotated factors will describe unique variance in the data, as opposed to the common unrotated factors, which describe common variance. The results of the rotated factor analysis are described in Table 4.4, and the mean for each variable is plotted in rotated factor space (with the factors as the axes) in Figure 4.2 for a multi-dimensional expression of the model.

Table 4.3. Factor Matrix

	Factor		
	1	2	3
DAMAGE	-.279	.255	-.291
POPULATION	**.783**	**.605**	.052
PROPERTY	**.761**	**.633**	.044
PRESSURE	**.697**	**-.678**	-.103
WIND	**-.669**	**.685**	.161
ESTUARINE	-.197	-.290	**.429**
MARINE	.173	-.066	**.625**

*Significant loadings are emboldened.

Table 4.4. Rotated Factor Matrix

	Factor		
	1 (Economic Risk)	2 (Storm Intensity)	3 (Natural Protection)
DAMAGE	-.047	**.309**	**-.361**
POPULATION	**.988**	-.072	.029
PROPERTY	**.990**	-.039	.014
PRESSURE	.058	**-.971**	.096
WIND	-.031	**.970**	-.038
ESTUARINE	**-.324**	.010	**.450**
MARINE	.109	-.034	**.642**

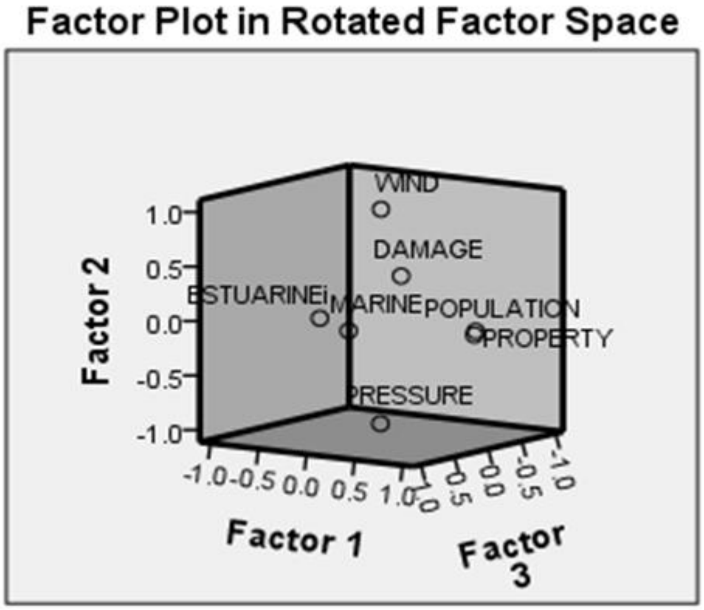

Figure 4.2. Variables Plotted in Factor Space

Factor one describes the variance related to the measures of economic risk and vulnerability to coastal storm damage. Both variables, parish population and property at risk of storm surge, exhibit high factor loadings with (are highly correlated to) factor one at 0.998 and 0.990, respectively. This factor will hereafter be referred to as the “economic risk” factor. All other variables, with the exception of the estuarine wetland protection variable, exhibit low correlation with the economic risk factor. The estuarine wetland protection variable is negatively correlated with the economic risk factor at -0.324. The negative factor loading for the estuarine wetland protection variable and the economic risk factor may demonstrate a trade-off between wetland conservation and structural development or population growth. This result is expected because the use of land, a finite resource, for either development or estuarine wetland conservation, could reasonably be said to be exclusive of the other.

The economic damage variable showed no significant correlation to the economic risk factor. This is somewhat surprising considering that storm surge risk for a parish at given storm intensities, a value derived from the same models as the “property” variable, was used to allocate the observed damages between parishes. This phenomenon suggests that modeled damage predictions and observed damages are divergent. This could result from the impact of singular exogenous events, such as the unforeseen failure of protective infrastructure (sea walls, levees, etc.), but certainly speaks to the need for available damage estimates at finer scales than are currently available so that those damages can be analyzed according to more specific environmental and socio-economic attributes.

Factor two describes the relationship between storm intensity and economic damage. Both measures of storm intensity, barometric pressure and maximum sustained winds, exhibit high factor loadings on factor two, which will hereafter be referred to as the “storm intensity” factor, at -0.971 and 0.970, respectively. This correlation is expected because wind speed is highly associated with pressure gradients, particularly over open water. The economic damage variable exhibits minimally significant factor loading onto the storm intensity factor at 0.309. This factor is indicative of the intuitive notion that, as low pressure systems (such as tropical storms and hurricanes) increase in strength, barometric pressure declines resulting in higher wind speeds. Low pressure and high winds both contribute to higher storm surges and, therefore, greater economic damage.

Factor three is the factor that best describes the relationship that this research seeks to explore. That is, that wetland presence is associated with reduced damages. The two variables that describe wetland presence, estuarine marine wetland acres per coastal mile and marine deepwater wetland acres per coastal mile, exhibit moderately high correlations with factor three, which will hereafter be referred to as the “wetland protection” factor. The estuarine wetland variable and the marine wetland variable have factor loading values of 0.450 and 0.642, respectively. While these loading values show only moderately strong associations with the wetland protection factor, more than 84% of the cumulative explained variance for these two variables is explained by the natural protection factor. The remaining variance is largely described by the economic risk factor; possibly an indication of a trade-off between structural development and wetland conservation. This allows the natural protection factor to sufficiently represent the unique variance associated with wetlands and storm damage.

The natural protection factor explains the greatest variance in the variable that describes the economic damage from coastal storms. With a factor loading of -0.361 for the economic damage variable, the natural protection factor explains approximately 13% of the variance for that variable. This constitutes 57% of the variance for the damage variable that is embodied by this model. The correlation is consistent with the idea that wetlands have the potential to mitigate damage from coastal storms. The variance described in this factor is unique from the variance describe in the initial factors and no other variable approaches the threshold for significance of loading, all having factor loadings less than an absolute value of 0.1. This result suggests that a greater presence of wetlands is associated with reduced economic damage during storm events in Louisiana.

4.5 Analysis of Factor Scores by Storm Intensity

To explore the effect of storm intensity on the ability of wetlands to mitigate damage, factor scores are derived from the analysis for the natural protection factor. Factor scores measure the degree to which the trends described in that factor are embodied by an individual parish and storm. For example, parishes which, despite having high degrees of wetland protection, experience large damages for a given storm relative to the sample mean will receive negative scores. Parishes which exhibit a stronger-than-average negative correlation between damages and wetland protection will receive positive scores. Those samples who exhibit the relationship described by the wetland protection factor, to the approximate degree described by that factor, will receive scores near zero. The magnitude of the score is computed according to the standard deviation from the mean for all samples. So, a factor score of “1” means that a sample displays the trends in the natural protection factor (inverse correlation between wetlands and damage) in a manner that is a full standard deviation greater than the mean.

The natural protection factor scores were averaged for each category of storm present in the data set: tropical storm and Saffir-Simpson hurricane categories one, two and three. The results are displayed in Figure 4.3, which shows that the average factor score is near the mean for all categories except for category three storms. Category three storms score significantly lower than the other categories in the analysis at -0.321. This is a relatively strong departure from the tendencies observed in the natural protection factor compared to the other categories, which have average natural protection factor scores of -0.041, 0.158 and -0.006 for tropical storms, category one and category two storms, respectively. Samples from these weaker storms display average or above average negative correlations between wetland area and economic damage. Because these values represent to degree to which a sample is adherent to the structure of the natural protection factor, it does not follow that negative scores are indicative of non-negative correlations between wetlands and economic damages; only that the negative correlation is weaker and less distinct than the mean for the sample.

This result suggests that stronger storms may overcome the capacity of wetlands to reduce economic damages from storms. To explore this further, storms that are representative of each storm category are chosen in order to explore this phenomenon on a case-by-case basis. A

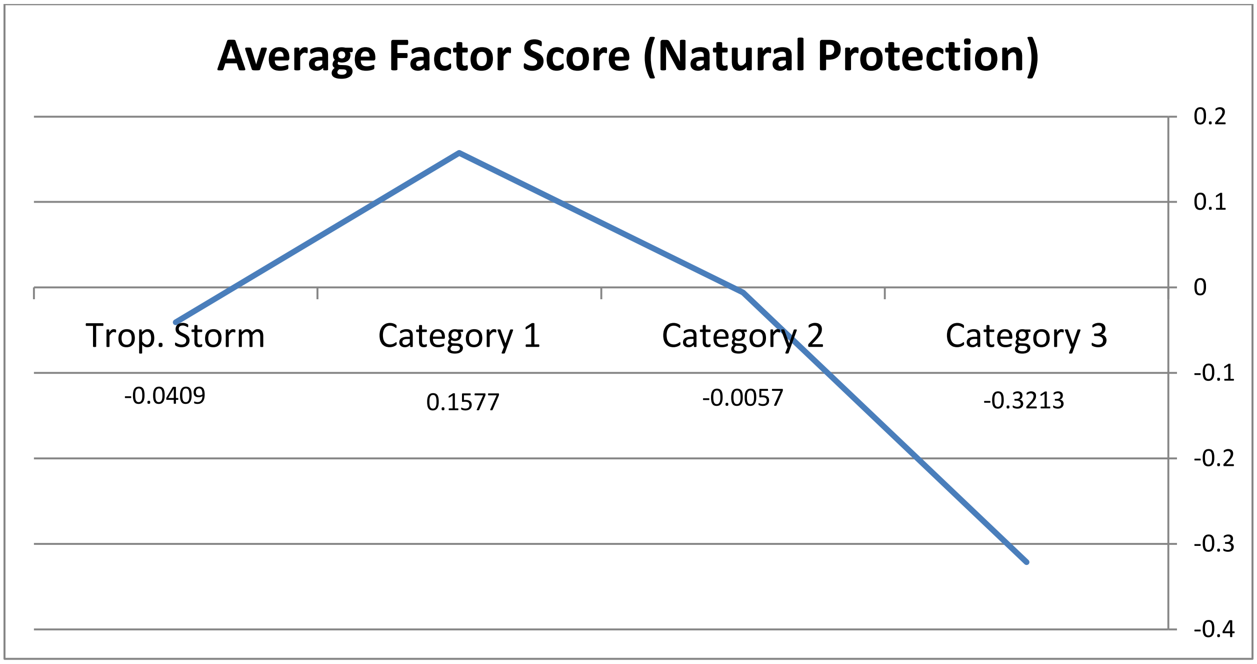

Figure 4.3. Factor 3 Score by Storm Intensity Category

geographic information system (GIS) analysis layer is built using each sample and the corresponding factor score so that the spatial patterns of the reduction in mitigating value are recognizable as intensity increases.

Figure 4.4 shows the factor scores for the impact zone during tropical storm Matthew, a relatively week storm at only 999 millibars of pressure and 35 mile per hour (MPH) sustained winds. For this storm, economic damages were strongly associated with the presence of wetlands, relative to other storms. All parish factor scores are greater than -0.5, with the exception of St. John the Baptist Parish (possibly because the value of property exposed to storm surge for a storm of this intensity is magnitudes less than surrounding, physiographically similar parishes). The average natural protection factor score for parishes impacted by tropical storm Matthew is .054, approximately the average for all tropical storms.

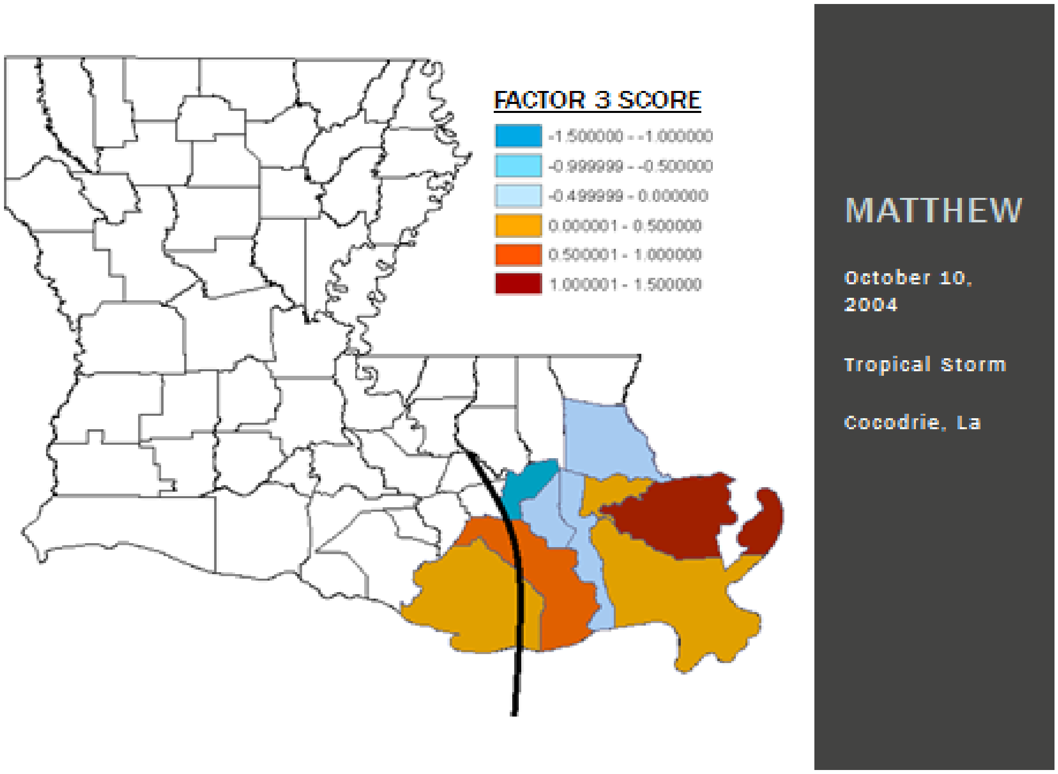

Figure 4.4. Tropical Storm Matthew Factor Score Output Map

Similarly, Hurricane Cindy, another relatively weak storm at 991 millibars of pressure and 65 MPH sustained winds, made landfall in Eastern Louisiana as a category 1 storm nearly two months prior to Hurricane Katrina. Parishes impacted in this storm display strong associations with the natural protection factor. All samples in this storm have factor scores greater than -0.5 and four of nine samples have scores above 0.5. The average factor score for all parishes impacted by Hurricane Cindy is 0.278, significantly higher than the average for all samples.

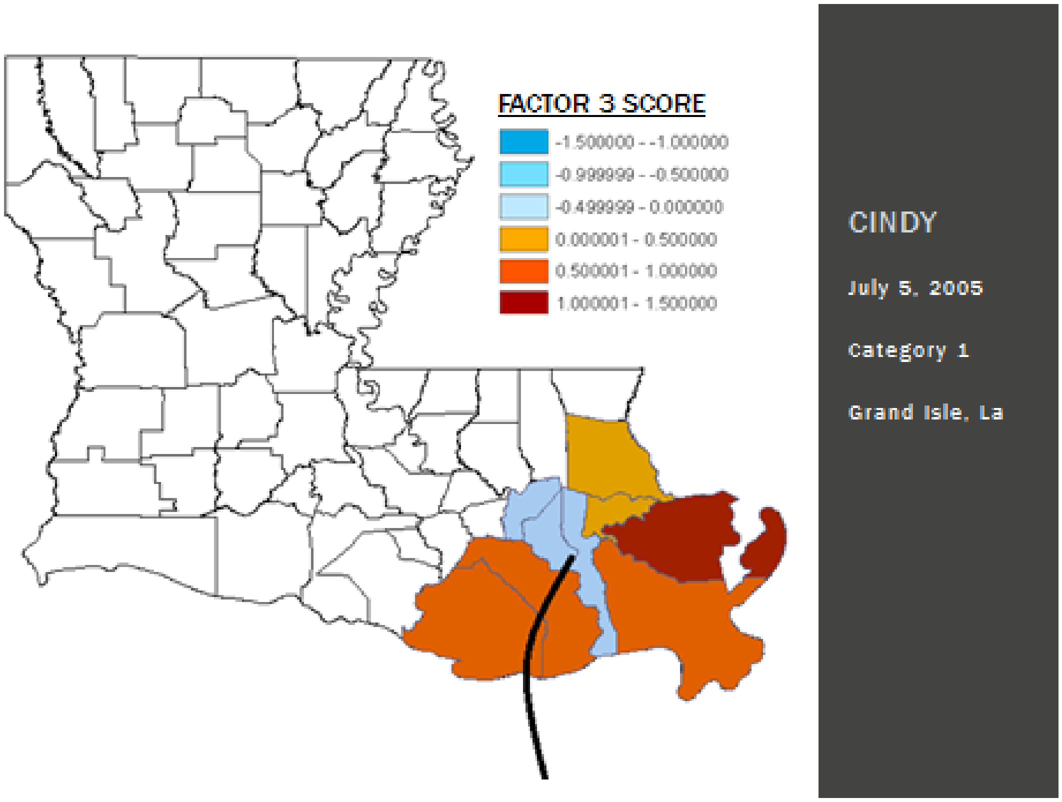

Figure 4.5. Hurricane Cindy Factor Score Output Map

Hurricane Gustav impacted the coast of Louisiana in 2008, making landfall near Cocodrie, Louisiana. Figure 4.6 shows the factor scores for parishes impacted by this category 2 hurricane. Parishes impacted by Gustav all receive factor scores greater than -0.5, indicating that wetlands were negatively associated with economic damages. However, nearly half of the impacted parishes display a weaker correlation than the average for the dataset. The average factor score for all parishes impacted by Hurricane Gustav is .033, very near the sample average.

Figure 4.7 displays the factor scores for a portion of parishes impacted by Hurricane Rita. All impacted parishes scored low associations with factor 3. Therefore, the tendencies described in factor 3 are not embodied by this sample. Although Hurricane Rita made landfall as a category 3 storm, the intensity of the storm was much greater prior to landfall (895mb; the strongest storm ever recorded in the Gulf of Mexico), making Rita much stronger in practical terms.

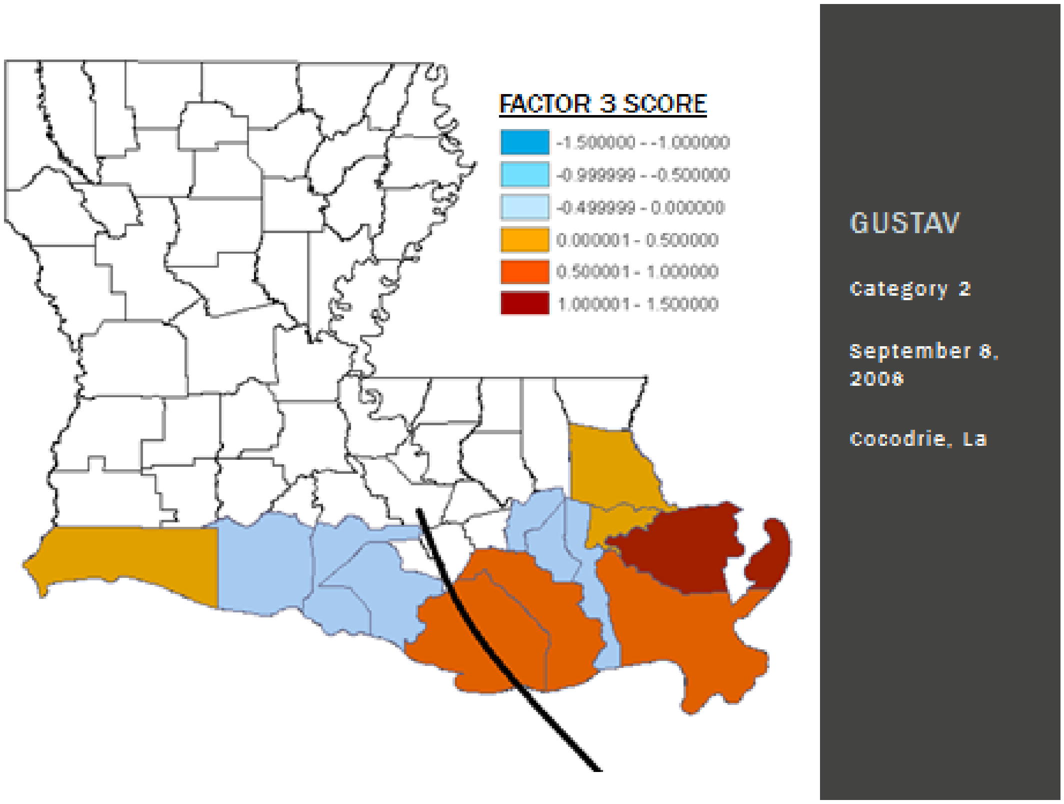

Figure 4.6. Hurricane Gustav Factor Score Output Map

Additionally, the temporal and geographic proximity of Hurricane Rita to Hurricane Katrina has caused some parishes involved in this storm to be unusable for this analysis because the integrity of the data was compromised. The included parishes meet the criteria outlined in the methods for inclusion in the analysis. The average factor score for parishes (included in the analysis) impacted by this storm is -1.453, significantly below the average for the dataset. This suggests that wetlands played little or no role in mitigating damages from this larger, more intense storm.

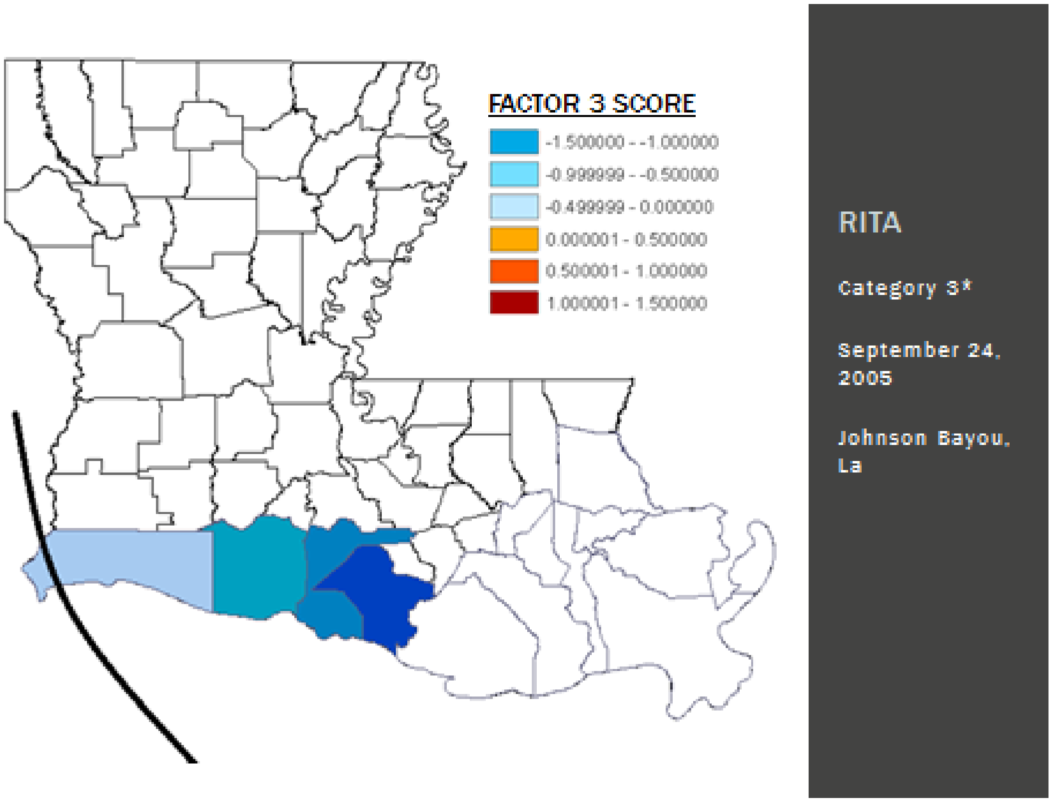

Figure 4.7. Hurricane Rita Factor Score Output Map

Some parishes had consistently low factor scores for the natural protection factor. These parishes include those with either extremely high or extremely low values for the population and property variables relative to the mean, and wetland area near the mean of the sample. The samples representing these parishes, especially those near greater New Orleans, have variance that is explained well by the economic risk factor, leaving little variance to be explained by other factors. This does not indicate that wetlands in these areas are less valuable for damage mitigation. In fact, the opposite may be true. It only suggests that the correlation between wetland presence and economic damage are not on the same *magnitude* as those samples with less extreme population and property characteristics. It should be noted that small degrees of change in the economic impacts from coastal storms have the potential to yield high monetary benefits because the magnitude of storm damages is so high. Again, negative factor scores do not indicate that the relationship described in the natural protection factor is absent in those samples, only that the relationship is weaker or obscured.

5. Limitations and Other Considerations

The results of this factor analysis suggest that the conventional wisdom regarding wetlands and their effect on coastal storm impacts is true. That is, wetlands seem to provide context dependent mitigation of economic damages. Recognizing the benefits of wetlands as buffers against storm surge has the potential to promote more responsible and efficient conservation and land use practices. Relative to other ecosystem services, coastal storm protection is commonly estimated as the most valuable ecosystem service provided by coastal wetlands (Ghermandi, et al. 2008; Woodward and Wiu, 2001).

5.1 Implied Degree of Economic Damage Protection

Because coastal storms can cause significant economic damage, small reductions in that damage can be valuable. For example, in this analysis the mean damage for the dataset is approximately $41.4 million. According to the factor loadings for the natural protection factor, the presence or absence of wetlands account for approximately 13% of the variance in the damage variable – $5.38 million at the sample mean. The parish mean for estuarine wetlands per coastal mile is 2,058. Taking into account the (small) factor loadings of all other variables in the natural protection factor, and assuming that the effect of estuarine wetlands on storm damages is proportional to the factor loadings for the corresponding variables, estuarine wetlands account for 35.4% of the variance in the natural protection factor, excluding the damage variable. Using these values, this model suggests that the value of estuarine wetlands for storm damage protection is $925.25 (2010 USD) per acre per storm ($374.72 per hectare) in avoided damages.

This estimate is similar to the values reported in past and recent valuation attempts that focused on Louisiana (Costanza et al. 2008). Generally, values are reported as a dollar value per hectare (or acre) per year. For example, Costanza et al. (1997) estimated the per hectare per year value of coastal “disturbance regulation” to be $129 (2010 USD) and Costanza et al. (2008) estimated that value to be $1749. Other estimates for Louisiana are consistent with these. The value from this study represents the value for a single “representative” storm. The data used in this research considers 13 storms over a twelve year period, and excludes very small storms, which wetlands are thought to be most protective against, and very large storm including hurricane Katrina. There insufficient data to develop a reliable recurrence interval for storms (for some reasonable attempts, see Costanza, 2008 and Georgiou, 2012). Georgiou et al.(2012) estimates the expected annual number of storms in Louisiana which cause a storm surge higher than 30 centimeters is 0.836. Using this frequency, the value of wetlands in Louisiana is $773.50 per acre per year ($313.27 per hectare per year). While this estimate is not derived from any conventional valuation method, the convergence of this value with the values reported in other, similar studies implies that the magnitude of protection described in this paper is consistent with prior work and provides some validation for this research.

This study also suggests that the ability of wetlands to mitigate storm damages is context dependent, and that storms with higher intensities may overcome this ability. Because the methods used in this study prohibited the use of some larger storms due to data limitations, the effects of more intense storms on the attenuating function of wetlands may not be fully realized. Future research will require damage data at a finer scale if damages for stronger storms are to be analyzed. However, the findings presented here show a clear reduction in the negative relationship between wetland presence and economic damage as storm intensity increases. This follows conclusion of some recent physical models and experiments (Resio and Westerlink, 2008; Feagin, 2009; Wamsley et al. 2009).

These data are not purely time series and cross sectional. Because land cover and model output data are not available for every year, the values used for the variables describing property value and wetland coverage were from approximately the mean year of the dataset. One would expect only small changes in these variables over the relatively short time period under consideration. Given the very high correlation between the population variable and the property variable this minor deficiency is unlikely to cause any change in the interpretation of the results. Wetlands area also changes from year to year. In modern times, there are generally fewer acres of wetland in any year than the year before. However, an examination of the natural protection factor scores does not show any discernable or consistent difference from any time period to the next.

5.2 Structural Protection

This research seeks to explore the effect of natural protection against storm damage, but there are other types of structural protection that would affect the degree to which an area is impacted. In Louisiana, built infrastructure plays an important role in managing floods and storm surges. This infrastructure includes levees, sea walls, breakwaters, artificial reefs and pump stations. These structural protection measures are maintained by dozens of federal, state and local entities. A relatively small number of these measures are meant explicitly to reduce storm surge damage, as most structural protection focuses of the control of riverine waters. This infrastructure is difficult to account for in a factor analytic model because many measures of structural protection are incomparable (sea walls vs. levees vs. flood gates etc.) and unevenly distributed between parishes (ALBL, 2012).

Because few parishes have storm surge reduction systems in place to mitigate damages (ALBL, 2012), this attribute could not be included in the model. The parishes which have extensive hurricane protection infrastructure are located along the east bank of Lake Pontchartrain and maintained by the Pontchartrain Levee District. Yet, of the 125 miles of structural flood protection, only 10 miles are meant for hurricane protection, with the other structures intended for control of river flows (PLD, 2013). It is of note, however, that the parishes with more extensive hurricane damage reduction infrastructure (including St. John the Baptist, St. Charles and Jefferson parishes) displayed consistently low natural protection factor scores (See Figures 4.4-4.6). These lower scores may be the result of the omission of important variables for *these* parishes. Although, because of the descriptive (not inferential) nature of factor analysis, it cannot be concluded that this is the case.

Because of the concentration of hurricane protection in these parishes and the general absence of such protection elsewhere, a variable representing pumps stations, sea walls, etc. is not appropriate for this analysis. Additionally, regardless of how hurricane protection measures are qualified, there is no basis for the inclusion of such a variable onto any of the factors in the model. It is not likely that such a variable would be highly associated with wetland presence or hurricane intensity. However, in order to warrant costly mitigation infrastructure, it is probable that these structural measures are present primarily in areas where there are significant human and economic assets to protect. A high loading onto the economic risk factor would not lend itself to any meaningful interpretation, and may obscure the results of the analysis by the inclusion of a third variable which would give that factor unequal explanatory power.

Finally, a large proportion of the structural measures intended for storm surge reduction (excluding those that mechanically reduce surge, such as spillways and pump stations) are inherently included in the analysis for two related reasons. First, the variable that describes the value of property at-risk of storm surge inundation was obtained from a model that accounts for many structural measures with its use of terrain data. Second, the economic damage from each storm is distributed among the constituent parishes using those same model specifications under specific storm scenarios. The HAZUS model used to obtain these values uses elevation data from LIDAR (LIght Detection And Ranging) imagery (Longnecker, 2011).

LIDAR technology has been used to map terrain at very high spatial resolution, in some cases to within centimeters of accuracy, and is becoming increasingly common in monitoring phenomena of interest to coastal managers such as land use change, sea-level rise, wetland loss and hazard vulnerability (Brock, 2009). The values that are used for the "property" variable and used to obtain the "damage" variable were obtained using FEMA's HAZUS model, which employs independently gathered LIDAR data with 3-meter point spacing and horizontal accuracy of 0.75 meters. In this manner, non-mechanical measures of storm surge reduction (sea walls, levees, etc.) are recognized and accounted for in these variables, making the addition of variables describing these feature redundant.

5.3 Storm Duration

Storm duration, the period of time that a storm is impacting an area, influences the damages resulting from that hurricane (Georgiou, 2012). It is reasonable to expect that the longer a storm impacts an area, the greater the impact will be. A measure of duration could be used, in conjunction with wind speed and barometric pressure, as another measure of storm intensity. For this analysis, simple measures of storm duration were developed and employed in the model, but failed to produce any significant results. First, tropical storm warning (issued by the National Weather Service) length was assessed as a measure of duration. This did not have any significant correlation with any of the other variables of interest – wind speed, pressure or damage. Additionally, these warnings are often issued well in advance of any impact, are based on predicted storm tracks, and are not issued according to any consistent standard (NHC, 2010). Alternatively, the quotient of the radius of tropical storm force winds from the "eye" of the storm and forward speed was thought to be a reasonable approximation of duration. However, storms a generally asymmetric and change speed upon landfall. This measure was also unassociated with any variable of interest.

Little research has been completed regarding the effect of duration on economic damages. Of particular interest is research by Nordhaus (2006), who 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. If any of the measures used in that study (which, according to Nordhaus, would be highly correlated to those variables that are included in this analysis) were used in this model, the storm intensity factor would display unequal explanatory power because that factor would contain three representative variables, and may obscure the relationships displayed in the other factors. So, while it is reasonable to think that storm duration is associated with economic damage, such a variable was not included.

5.4 Bathymetric Conditions

Coastal bathymetry has been shown to effect storm surge dynamics (Gedan et al. 2011). Coastal areas that exhibit high degrees of local bathymetric heterogeneity may see widely varying storm surge levels under similar storm conditions. Therefore, describing near-shore bathymetry in the model may impact the results. However, according to a preliminary GIS analysis of bathymetric data from the National Oceanic and Atmospheric Administration, the Louisiana coastline is remarkably homogeneous with respect to the depth of the seafloor near the shore, though, admittedly, the shore can be difficult to define in Louisiana. However, for the following described analysis, best judgment was used in delineating the “shore”.

Using transect analysis, a common ecological and spatial sampling technique (Longley and Bates, 1996), depth measurements were taken at one, five, and 10 kilometer (km) distances from shore. Five equidistant data points were gathered at each off-shore distance for each parish. At one and five km offshore, all parishes had depth measurements that are very uniform, with no measurement exceeding ten meters. At 10 km offshore, there are some notable differences in depth between parishes. These values are reported for each parish in Table 5.1. The average 10 km depth for each parish was applied to the dataset. Only one variable, the marine wetland variable, is correlated (0.409) to the depth variable. The results of a rotated factor analysis using an additional variable that describes the average 10 km depth for each parish are described in Table 5.2.

The depth variable exhibits significant loading onto the wetland protection variable, which is expected. However, as was the concern for adding additional variables to the other factors, the inclusion of another variable that is associated with geographic conditions allows some of the variance from factor 3 to be redistributed so that variance is explained more evenly

Table 5.1. Bathymetric Conditions

Parish	Bathymetric Transect Average (10km)
Cameron	11.6
Iberia	4.4
Jefferson	10.8
Lafourche	12.4
Orleans	3.6
Plaquemines	23.2
St. Bernard	5.2
St. Charles	3.6
St. John the Baptist	3.6
St. Mary	4
St. Tammany	3.6
Terrebonne	7.2
Vermilion	6

Table 5.2. Rotated Factor Matrix (Three-Factor Alternative Results)

	Factor		
	1	2	3
DAMAGE	-.052	.329	-.263
POPULATION	.989	-.086	-.042
PROPERTY	.987	-.052	-.052
PRESSURE	.046	-.996	.031
WIND	-.021	.953	.008
ESTUARINE	-.299	-.022	.349
MARINE	.168	-.062	.926
avg10kdepth	-.144	-.035	.456

between factors. The directions and interpretations of the relationships remain unchanged, but the damage variable has dropped below the threshold of significance for the analysis on the third factor. To explore the nature of the relationship between damage, bathymetry and marine wetlands, a fourth factor was extracted and used for a rotation. The results of the 4 factor rotation are shown in Table 5.3.

In this model, the trends exhibited are consistent with those in the primary model used in this research. Estuarine wetlands are negatively associated with population and value of property, suggesting a trade-off between development and conservation. Higher storm intensity is associated with greater damages. Finally, the presence of wetlands is negatively associated with economic damage. These factor correlations are approximately the same as the primary analysis. The fourth factor exhibits variance that is unique to off-shore physiographic conditions, with marine wetlands and bathymetric depth being the only variables with significant factor 4 loadings.

The depth of the seafloor at 10 km may be too distant to significantly influence storm surge, as is suggested by these results. However, the loadings on the fourth factor suggest that shallower waters contribute to the development of marine wetlands and, therefore, indirectly contribute to lower damages over time. But, less abrupt changes in depth are known to allow energy from waves and surges to advance with greater force and cause higher storm surge heights (Resio and Westerlink, 2008). So, one could not say that the bathymetric conditions in Louisiana reduce damages from storm surge.

The interpretation of this analysis is not practically different from the interpretation of the primary research. The homogeneous coastal bathymetry in Louisiana seems unlikely to play a significant role in influencing damages from parish to parish. Also, the inclusion of a third variable that describes physiographic condition confounds the interpretation because it redistributes variance away from the natural protection factor. For these reasons, no bathymetric variable was used in the analysis.

Table 5.3. Rotated Factor Matrix (Four-Factor Alternative Results)

	Factor			
	1	2	3	4
DAMAGE	-.042	.320	-.308	-.047
POPULATION	.986	-.078	.031	-.075
PROPERTY	.986	-.044	.014	-.067
PRESSURE	.053	-.990	.057	.018
WIND	-.029	.957	-.013	-.006
ESTUARINE	-.318	-.011	.362	.102
MARINE	.138	-.041	.761	.398
avg10kdepth	-.130	-.027	.249	.592

5.5 Data Specification

This data is not purely time series and cross sectional. Because land cover and model output data are not available for every year, the values used for the variables describing property value and wetland coverage were from approximately the mean year of the dataset. Given the very high correlation between the population variable and the property variable, this minor deficiency is unlikely to cause any change in the interpretation of the results. Wetlands area also changes from year to year. In modern times, there are fewer acres of wetland in any year than the year before. However, an examination of the natural protection factor scores does not show any discernable or consistent difference from any time period to the next, suggesting that wetland change would not change the interpretation of the results or the relationships between the constructs of interest. Table 5.4 shows the average natural protection factor score for each quartile of the sample. All are less than .1 standard deviations from the mean.

Table 5.4. Sensitivity to Temporal Data Specifications

Range (quartile)	**Average Natural Protection Factor Score**
1997-2002 (1)	**0.099**
2002-2003 (2)	**-0.097**
2003-2005 (3)	**-0.040**
2005-2008 (4)	**0.037**

6. Conclusion

Coastal communities are at risk of extreme economic damage, interruption of economically necessary activities and loss of life from coastal storms. These events are expected to increase in frequency and severity in the foreseeable future. Moreover, demographic trends suggest that, even under current climate regimes, economic damages will increase drastically as populations grow and develop in vulnerable areas. Measures must be taken to develop strategies to mitigate the impacts of tropical storms and hurricanes in a way that is least-cost and mindful of the relationships between society, the environment and disturbance events.

Wetlands conservation and preservation is, and likely will be, an important component of any comprehensive disaster mitigation strategy implemented in Louisiana. Wetland ecosystems have been shown to help communities avoid damages, particularly in less intense storms. Beyond their capacity to reduce damages, wetlands provide multiple benefits that promote the resilience of coastal communities. These ecosystems support valuable fisheries and attract important tourism activity. Wetlands are well-distributed throughout the Louisiana coast and are naturally occurring, making them valuable resources for protecting geographically wide-ranging and well-distributed vulnerable populations.

This research confirms the notion that wetlands provide some protection against damage from coastal storms. Additionally, the factor score analysis suggests that the value of that protection declines as storm intensity increases due to a supposed attenuating capacity beyond which the protection against damages is not as distinct. The results of this research also describe the degree to which wetlands mitigate economic damages in approximately the same magnitude as previous similar studies. While this paper does not present a valuation study, and the analytical approach used in this research may be inappropriate for an explicit valuation, the similarity between the estimated degrees of damage mitigation provided by wetlands offers some validation for each study.

As these concepts become consensus, analysts must pursue research that describes the capacity of wetlands to reduce damage from hurricanes not only in physical terms, but in terms that can be used by coastal managers. Computer models are capable of describing the effect of wetlands and their associated vegetation on storm surge and flooding relatively well. However, as is the case for Louisiana's Coastal Master Plan, analysis of the economic significances of wetland's mitigating properties is often absent in management strategies. Given the consistently high values estimated for this ecosystem service, and the tremendous amount of resources allocated to coastal restoration and conservation for storm protection, developing models that better describe the relationship between economies, ecosystems and coastal storms will be critical for improving the efficiency of coastal conservation plans. Specific research is needed on the context in which wetlands mitigate damages. Such research should explore how the value of mitigation provided by wetlands changes with storm intensity, how intervals between storms affect economic damages and wetland coverage, and how the value of storm surge mitigation is associated spatially with populations and ecological features.

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Vita

James Luke Boutwell was born in Alabaster, Alabama to Robin Boutwell and the late Angela Boutwell in 1988. He graduate from Alabama Christian Academy in 2006 and received his dual Bachelor of Science degree in Geography: Natural Resources and the Environment and Geography: Geographic Information Systems from the University of Alabama in 2011. Mr. Boutwell is currently a Ph.D. student and United States Department of Agriculture National Needs Fellow whose research focuses of using natural systems to promote disaster resilience for human communities.