Economic Risk, Tropical Storm Intensity and Coastal Wetlands: A Factor Analysis

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Abstract:

Coastal communities are highly sensitive to economic damage from tropical storms. Wetland restoration is often proposed as a measure of protection from storm damage. This paper investigates the relationship between coastal storms, wetlands and communities by analyzing storm events and resulting damages from storms making landfall in Louisiana. A factor analysis is used to describe the extent to which wetlands mitigate economic damages, and an assessment of factor scores suggest that there is a storm intensity threshold for mitigation provided by wetland ecosystems.

Key Words: coastal, damage, factor analysis, hurricane, risk, storm surge, wetlands

JEL Classifications: Q24, Q54, Q56, Q57

Introduction

Coastal communities are vulnerable to damage resulting from tropical storms and hurricanes. Most recently, Hurricane Sandy caused billions of dollars in damage to highly populated regions along the U.S. Atlantic coast. Even relatively weak coastal storms have the power to cause widespread damage, loss of life and interruption of economically vital activities (NCDC, 2012). Wetlands have been shown to attenuate energy associated with waves and storm surges (Barbier et al. 2008; Gedan et al. 2011), and wetlands construction is often advocated for as a means of damage mitigation (CPRA, 2007). However, in Louisiana, continued wetland loss and potential for sea level rise and more-impactful storm events places coastal communities in increasingly vulnerable situations.

Population along the coast of the Gulf of Mexico, which includes the land between the southern extent of Florida's western coast and the Yucatan Peninsula, is increasing. By 2025, the anticipated population of the U.S. Gulf Coast region is expected to reach 61.4 million, up 40 percent from 44.2 million in 1995 (EPA, 2013). Although population size along the coast is increasing, the coast of the Gulf of Mexico is still relatively rural (ONE, 2012), making the protection of coastal communities more challenging.

Coastal communities often rely heavily on natural resource based industry. The Gulf of Mexico region is responsible for approximately half of U.S. oil and natural gas production (US EIA, 2013). Tourism is also an important economic sector for most coastal regions. Along the U.S. gulf coast, tourism accounts for $45 billion annually with visitors coming primarily for cultural opportunities, outdoor sporting and nature viewing (CTO, 2010). Fishing, both commercial and recreational, is an important economic activity in the region. Louisiana alone accounted for approximately $250 million in dockside catch value in 2010 (NMFS, 2012). Heavy reliance on a few natural resource based industries that are sensitive to disturbance or environmental change makes the management of coastal resources and mitigation of coastal hazards important.

The relationships between coastal economies and coastal environments during storm events are somewhat poorly understood. In part, this is because data related to economic damages are not widely available, and the data that exists are usually crude estimates at scales that are not particularly useful for inference about local scale human-environmental interactions. Additionally, the manner in which environmental features, such as wetlands, interact with advancing storms and how that interaction is valuable for society is difficult to assess because of the complex nature of storm events (Barbier et al. 2008). Physical science experiments model have enabled the modeling of interactions between waves and the environment reasonably well, but these models generally lack any economic or social analysis (Gedan et al. 2011). The mitigation of damages from hurricanes is a potentially valuable ecosystem service. Because of the substantial damages that result from some coastal storms, proportionally small reductions in damages can result in high estimates for the value of storm mitigation, relative to other ecosystem services.

Economic analysis focusing on the protective services provided by wetlands could allow coastal management entities to more efficiently allocate scarce resources to meet mitigation objectives. Management of coastal resources is often performed by management entities that lack the resources for effective decision making. Understanding the relationship between wetlands and communities during storm events in terms that are relatable for evaluating trade-offs will be valuable for coastal managers and communities. Least-cost mitigation measures that serve a rural and growing population will be essential for ensuring efficiency in damage reduction. Wetlands are well suited to provide some of this mitigation, and that suitability is already realized in coastal management plans (CPRA, 2007).

Wetlands as Buffers

The attenuation of wave energy is a physical process that is performed by wetlands in two general fashions: direct mechanisms and indirect mechanisms. Direct mechanisms are those that involve the frictional effect of plants on water velocity, sediment deposition and cohesion (Gedan et al, 2011). Drag and friction cause wave energy and turbulence to decrease (Nepf et al. 2007), and partially submerged wetlands have the highest potential reducing turbulence and velocity (Neumeier and Ciavola, 2004). These processes are facilitated by emergent wetlands and wetlands forests, for example.

Alternatively, indirect mechanisms are associated with the effects of underlying bathymetric and geomorphological conditions. Because organic soils are more resistant to wave erosion than less nonorganic soils (Feagin et al. 2009), wetlands allow the accumulation of substrate that supports fully submerged vegetation. Because wave height is proportional to water depth (le Hir et al. 2000) and vegetation beyond one meter underwater has the potential to reduce wave energy (Gedan et al. 2011) the development of deepwater marine wetlands may reduce damages.

There is evidence that wetlands may be less protective against stronger storms (Day et al. 2007; Gedan et al. 2011). Research suggests that the provision of protection provided by wetlands is reduced as storm surge increases, thereby increasing the depth of vegetation. Because of this, wetlands are thought to have a mitigating capacity for protection (Resio and Westerlink, 2008; Feagin et al. 2009; Wamsley et al. 2009). Such a notion could be critically important for estimating the value of damage mitigating ecosystem services, which are often estimated to be among the most valuable services provided by coastal wetlands (Barbier et al. 2008; Costanza et al. 2008).

The valuation of protective services provided by wetlands is relatively recent endeavor for economists. Values are generally estimated either according to what an equivalent measure of protection would cost to create or according to the degree to which wetland presence is observed to be associated with lower damages. The latter is called the damage cost avoided (DCA) method, and estimates a more reasonable lower bound for the value of the protection provided by wetlands (under the assumption that society is willing to pay at least as much as they would avoid losing).

For estimating the damage reduction that is attributable to wetlands there are two primary approaches. Computer models that attempt to predict the physical interactions between wetlands and advancing storms can be used to explore the expected reduction in localized storm surge for a given scenario. This allows the analyst estimate the reduction in the damage according to the expected damage for the area that was protected from inundation (Georgiou et al. 2012). Alternatively, economists rely on observations to measure the effects of wetlands on economic damages, which can be challenging when there is not reliable data at a scale that is inferentially useful (Costanza et al. 2008).

This paper presents a model that is useful for illustrating the relationship between social risk, coastal wetlands and economic damages during storm events. A method for using predictive models and observed damages together to estimate finer-scale damages is presented and used to estimate damages at the parish level for landfall making storms in Louisiana between 1997 and 2008. The resulting damage estimates are then used to analyze the extent that wetlands presence is associated with reduced damages. Additionally, the observed reduction in damages is assessed according to storm intensity to identify any threshold effects exhibited by wetlands as intensity increases.

Methodology

In order to explore the 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.

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.

A factor analysis derives eigenvectors, called factors, which describe variance in varying manners. For this analysis, a varimax rotated factor analysis is performed using IBM SPSS software. A varimax rotated factor analysis derives factors that represent common variance among unique variables. In other words, variables with similar variance structures are described by a single factor. In contrast, common unrotated factor analysis derives factors that describe the maximum variance for all variables, usually resulting in one highly representative factor and subsequent less-explanatory factors. The factors of a varimax rotation have more evenly distributed explanatory power and provide results that are more amenable for describing latent relationships (Hair, 1959).

The data used in this factor analysis are composed of seven variables. These variables were chosen to represent each of the components of interest: storm intensity, economic risk, wetland protection and economic damages. Two variables were chosen to represent each component with the exception of the damage component, which is represented by a single damage variable. Two variables are chosen to describe each factor to ensure that a similar amount of variance in the dataset is explained by each factor. A single variable is used to represent economic damages in order to detect relationships between damages and each factor, and that the relationship of these factors to the damage variable could be interpreted more simply.

Data

Data used to represent storm intensity were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC). The variables used are maximum 60-second sustained wind speed at landfall 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. These variables and statewide damages are provided in Table 1.

Parish economic risk is also characterized by two highly correlated variables. Raw population, from the U.S. Census Bureau, for each coastal parish is recorded for each year that the parish was impacted by a storm analyzed in this paper. The value of housing exposed to storm surge hazard was obtained from the FEMA Coastal Flood Loss Atlas (CFLA) risk assessment tool, a combination of two models (Longnecker, 2011). 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 and is useful for estimating damages for varying levels of surge inundation. This model was combined with the Sea, Land, Overland Surges from Hurricanes (SLOSH) model developed by the National Hurricane Center (NHC) to allow for a relatively high resolution estimate of storm surge inundation. The maximum surge level is calculated for all potential storm scenarios to estimate a maximum surge extent, and the estimated damage that would result from this maximum is used as the second variable, called PROPERTY (found in Table 2), describing economic risk. These variables are highly correlated (0.981) and provide an indication of the vulnerability of a community to economic damage from coastal storm.

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. To represent the wetlands responsible for direct mechanisms of wave attenuation, "estuarine marine wetlands" are used. These wetlands include intertidal forested wetlands, scrub-shrub wetlands, emergent vegetation, and other rooted and floating vascular plants. For indirect mechanisms, "marine deepwater wetlands" are used. These include aquatic beds and reefs, unconsolidated sea bottom and shallow near-shore habitats responsible for shaping coastal morphology and bathymetry. Both land covers are ubiquitous along coastal Louisiana.

The relationship between coastal wetlands and storm damages may be diluted if length of coastline is not taken into account. This is because parishes with longer coastlines can be expected to have more wetland area, but also more exposure to storm surge. 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 raw and adjusted wetland protection values that were used in the analysis are shown in Table 3.

For the single variable describing economic damages, this analysis uses observed damage estimates that are distributed to finer scales using model simulations. Raw economic damages are gathered from National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) storm reports (NCDC). These damage estimates are reported for a group of geographically similar parishes (i.e. southwest Louisiana, greater New Orleans, etc.) and are not typically reported for individual parishes. Data from FEMA CFLA model simulations are used to distribute the larger scale damages among parishes. This model simulation data describes the expected damage that is expected given a storm of a particular intensity. The observed damages for each storm are distributed according to the proportion of damage that could be expected according to the CFLA estimates for each parish given the intensity of that storm.

Analysis of Threshold Effects

Factor scores are computed for the factor which describes the degree of protection provided by wetlands. These scores measure the degree to which the trends described in that factor are embodied by an individual sample. 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. These scores will be assessed according to storm intensity to identify the threshold at which wetlands become less valuable for damage mitigation.

Results

The measures of sampling adequacy are given in Table 4. Together, these tests ensure that there is sufficient correlation among variables to establish relationships but not so much that it would preclude a factor analysis. The Kaiser-Meyer-Olkin (KMO) test 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). 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).

The results of the rotated factor analysis are given in Table 5. The results show that the variables representing economic risk have a large amount of unique variance among the variables in the dataset. This is demonstrated by the high factor loadings for these variables onto factor 1 (hereafter referred to as the "economic risk" factor). Factor loadings represent the correlation between the factor (eigenvector) and the respective variable. Factor loadings are considered significant for this analysis if they exceed an absolute value of 0.3 (Hair, 1959). With factor loadings of 0.998 and 0.990 for population and property exposure, respectively, this factor seems to describe economic risk well.

The only other variable to load significantly onto the economic risk factor is the estuarine marine wetland variable, which had a factor loading of -0.324. This negative correlation between economic risk and the more terrestrial of the two wetland types is expected. Given a fixed amount of land, increases in population and built wealth are exclusive of wetland conservation. While that relationship is not so simply defined, this result may indicate a trade-off between structural development and wetland conservation.

The variables representing storm intensity exhibit high factor loadings for factor 2, which will hereafter be called the “storm intensity” factor. Barometric pressure and maximum sustained winds have factor loading scores of -0.971 and 0.970, respectively. The difference in signs is expected because wind speed is expected to increase as barometric pressure decreases. The economic damage variable also exhibits significant factor loading for the storm intensity factor with a factor loading of 0.309. Significant loading by these three variables indicate that stronger storms are associated with greater damages. This is expected because lower barometric pressure and the ensuing high winds result in higher storm surges and, consequently, higher economic damages.

Factor three is of particular interest because it describes the primary relationship of interest for this analysis – the relationship between wetlands and economic damages. Factor three, called the “wetland protection” factor, is correlated with both variables that indicate the presence of wetlands. Estuarine marine wetlands per coastal mile and marine deepwater marine wetlands per coastal mile exhibit factor loadings of 0.450 and 0.642, respectively. The wetland protection factor is the only factor, besides the aforementioned economic risk factor, that describes wetland presence, embodying approximately 84 percent of the cumulative variance explained by the model for these variables.

The economic damage variable exhibits significant loading on the wetland protection factor, the highest among all factors. With a factor loading of -0.361, the wetland protection factor explains approximately 13 percent of the variance for the economic damage variable. The negative correlation is indicative of the concept that wetlands attenuate damage from coastal storms. The variance described by the wetland protection factor is highly unique, as is revealed by the low factor loadings for all other variables in the model. This result suggests that wetlands are valuable for protection against coastal storms in Louisiana.

For the wetland protection factor, factor scores are computed in order to analyze the effect of storm intensity on the ability of wetlands to mitigate damages. A factor score is a measure of adherence to the trends described in the factor. 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 which exhibit the relationship described by the wetland protection factor, to the approximate degree described by that factor, will receive scores near zero. A factor score of 1 indicates that a sample (one parish for one storm) exhibits the negative relationship between wetlands and economic damages by a full standard deviation greater than average in the data.

Storms are categorized according to their intensity category. That is, each storm and the corresponding impacted parishes were grouped into one of the following intensity categories: tropical storms and categories 1-3 on the Saffir-Simpson scale. Tropical storms in the analysis display average factor scores at approximately the mean for all intensities with an average factor score of -0.041. Category 1 hurricanes appear to be most effectively mitigated by wetlands, having a somewhat above average factor score mean of 0.158. Category 2 storms, with a mean factor score of -.006, are also approximately average with respect to the degree to which their damages are shown to be mitigated by wetlands. However, parishes impacted by category 3 hurricanes average significantly lower wetland protection factor scores. A mean factor score of -0.321 is symptomatic of a departure from the relationships described in the wetland protection factor. So, parishes impacted by more intense storms do not seem to benefit from wetland protection to the degree described in the factor analysis. It should be noted that negative factor scores do not indicate that the correlations in the factor are not present. Rather, the correlations are weaker than the average for those samples with negative factor scores. These results are provided graphically in Figure 1.

Discussion and Conclusion

Small reductions in the proportion of economic damages from storms can be highly valuable due to the large damages incurred during powerful storms. In this analysis, the mean damage for the dataset is approximately $41.4 million. According to the factor loadings for the wetland 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 factor loadings of all other variables in the wetland protection factor, estuarine wetlands account for 35.4% of the variance in the wetland 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 value of coastal “disturbance regulation” to be $129 per hectare per year (2010 USD) and Costanza et al. (2008), using the same damage data resources as this analysis, estimated that value to be $1,749. 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 storms including hurricane Katrina because of insufficient data. There are also 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 and the values derived in this section, the value of wetlands in Louisiana is $773.50 per acre per year ($313.27 per hectare per year).

The estimates derived above are not meant as valid empirical estimates of the protective ecosystem services provided by coastal wetlands. However, the similarity in magnitude between the degree to which this analysis describes the effect of wetlands on damages and the degree to which recent research has describe that same effect does provide some measure of validation to these results. Additionally, this paper shows that the protection provided is dependent on the intensity of the disturbance from which it is protecting. Therefore, any empirical valuation of damage mitigating ecosystem services must necessarily include a reliable recurrence interval for and the disaggregated value of protection against storms of varying intensity to account for these nonlinearities.

Because key components of a valid valuation of protective services are not available, there is much research still to be done before the value of wetland protection can be estimated, especially at a scale that would be useful for planning. It is clear that mitigating damages from these storms will involve a holistic approach involving preparedness, mitigation, response and recovery, and that mitigation will require larger and more powerful flood protection measures where they are warranted (Lopez, 2009). Wetlands are, however, uniquely able to provide a suite of other services that are known to be valued by society (Woodward and Wui, 2001). These should be accounted for when evaluating the potential value of wetland restoration. Additionally, wetlands already exist across Louisiana in areas that would otherwise be exposed to direct impacts from storms. The conservation of existing wetland ecosystems is important for securing those mitigating services into the future.

Most importantly, coastal resource managers must be able to evaluate trade-offs associated with resource allocation decisions. In order to maximize the benefits that accrue to society, these trade-offs must be assessed in terms that are comparable. Economic analysts are well suited to this task, and research in this area is relatively undeveloped. Helping coastal manager make decisions that are best for the public will require more precise forms of accounting for this and other ecosystem services, which will likely require interdisciplinary research. This research highlights areas of promise and need for future such research.

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Tables

Table 1: Coastal Storms and Associated Variables

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

*Values represent total damage to Louisiana, not those used in the analysis

Table 2: Potential Damage under Maximum Storm Surge Extent

Parish	HAZUS Damage Potential (Thousands of Dollars, 2002USD)
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

Table 3: Wetland Area (Raw and per Coastal Mile) by Parish

Parish	Acres-Marine Deepwater Wetlands	Acres-Estuarine Marine Wetlands	Miles of Direct Surge Exposure	Marine Index Value*	Estuarine Index Value*
Cameron	548,628	371,223	96	5706	3861
Iberia	285,574	45,896	30	9651	1551
Jefferson	674,744	71,104	41	16574	1747
Lafourche	1,246,251	224,063	68	18379	3304
Orleans	1,362,499	29,431	52	26359	569
Plaquemines	1,746,821	290,050	196	8912	1480
St. Bernard	1,797,553	217,440	52	34311	4150
St. Charles	376,851	11,602	8	46930	1445
St. John the Baptist	316,730	11,623	21	14870	546
St. Mary	311,703	12,723	74	4224	172
St. Tammany	1,300,907	24,804	43	30317	578
Terrebonne	1,074,869	308,926	72	14929	4291
Vermilion	353,368	163,610	73	4847	2244

*Values used in model

Table 4: Diagnostic Test Results

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

Table 5: Rotated Factor Matrix

	Factor		
	1 (Economic Risk)	2 (Storm Intensity)	3 (Wetland 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**

Figures

Figure 1: Mean Wetland Protection Factor Score by Storm Category