Published in final edited form as:
*Environ Manage*. 2017 December ; 60(6): 1116–1126. doi:10.1007/s00267-017-0943-z.

# Hurricane Recovery and Ecological Resilience: Measuring the impacts of wetland alteration post Hurricane Ike on the upper TX coast.

**Md Y. Reja**[a], **Samuel D. Brody**[b], **Wesley E. Highfield**[c], and **Galen D. Newman**[d]

[a]Post-Graduate Research Assistant, Hazard Reduction and Recovery Center, Texas A&M University, College Station, TX 77843, USA. rejreen@tamu.edu

[b]Professor and Director of the Center for Texas Beaches and Shores, Department of Marine Sciences, Texas A&M University, Galveston, TX 77553, USA. brodys@tamug.edu

[c]Associate Professor, Department of Marine Sciences, Texas A&M University, Galveston, TX 77553, USA. highfiew@tamug.edu

[d]Associate Professor, Department of Landscape Architecture and Urban Planning, Texas A&M University, College Station, TX 77843, USA. gnewman@arch.tamu.edu

## Abstract

Recovery after hurricane events encourages new development activities and allows reconstruction through the conversion of naturally occurring wetlands to other land uses. This research investigates the degree to which hurricane recovery activities in coastal communities are undermining the ability of these places to attenuate the impacts of future storm events. Specifically, it explores how and to what extent wetlands are being affected by the CWA Section 404 permitting program in the context of post-Hurricane Ike 2008 recovery. Wetland alteration patterns are examined by selecting a control group (Aransas and Brazoria Counties – the counties with no hurricane impact) versus study group (Chambers and Galveston Counties – the counties with hurricane impact) research design with a pretest-posttest measurement to analyze the effects of permitting activities based on the variables such as four permit types, pre-post Ike permits, land cover classes, and within or outside the 100-yr floodplain. Results show that permitting activities in experimental group have increased within the 100-year floodplain and palustrine (freshwater) wetlands continue to be lost compare to the control group. Simultaneously, post-Ike individual and nationwide permits increased in the Hurricane Ike impacted area. A binomial logistic regression model indicated that permits within the study group, undeveloped land cover class, and individual and nationwide permit type have a significant effect on post-Ike permits, suggesting that post-Ike permits have significant impact on wetland losses. These findings indicate that recovery after the hurricane is compromising ecological resiliency in coastal communities. The outcome of this study may be applied to policy decisions in managing wetlands during a long-term recovery process to maintain natural function for future flood mitigation.

### Keywords

CWA wetland permitting; landscape management; coastal resiliency; coastal flooding

## 1. Introduction

Naturally-occurring wetlands have long been recognized for reducing flood impacts and contributing to the overall ecological resiliency of coastal areas. Freshwater wetlands hold, store, and slowly release storm water that can result in significant reductions in flood loss (Brody et al. 2008, Gonzalez et al. 2014). On the other hand, estuarine wetlands can serve as storm surge buffers that attenuate waves and reduce the depth and extent of inundation inland (Barbier et al. 2013). According to the Millennium Ecosystem Assessment in 2005, wetland-based ecosystem services that support human life are possibly worth US$33 trillion per year (Acreman and Holden, 2013). Despite offering these critical functions that can help protect the property and lives of human communities located in coastal regions, wetlands continue to be altered at a rapid pace (Bruland, 2008), particularly in times of economic growth following large-scale flood disasters. Costal resiliency is heavily depended upon flood mitigation capabilities; mitigation involves both helping protect human infrastructure and lives, and providing a degree of flood protection to vulnerable regions (Berke at al., 2015). Inversely, recovery after disaster events often involves both reconstruction of damaged structures and new development in affected communities (Kates et al. 2006). A byproduct of recovery involves the alteration and loss of naturally-occurring wetlands. Current research concerning wetland decline coastal margins suggests that urban and suburban development is the central cause of wetland losses (USGS 1996, Highfield and Brody 2006). As a result, the U.S. is losing wetlands in flood-prone areas while at the same time coastal communities are becoming less resilient to rainfall-based and storm-surge flood events (Coast 2050: Newman et al., 2016; Newman et al., 2014; Toward a Sustainable Coastal Louisiana, 1998). By losing naturally occurring wetlands and their flood-protection value during recovery, coastal communities become more prone to flood impacts during future hurricane events (Sutton-Grier et al. 2015, Reja et al. 2017). In other words, the very act of restoring human communities may increase their vulnerability to future flood impacts.

This study directly addresses the issue of wetland loss post disaster by tracking wetland alteration permits following Hurricane Ike, severely impacted communities on the upper Texas coast in 2008. We seek to answer the following research question: *Does new development and reconstruction after Hurricane Ike exacerbate the loss of naturally occurring wetlands under the wetland alteration permitting program of section 404 of the Clean Water Act?* Specifically, we analyze individual wetland alteration permits to measure the difference between Pre-post hurricane permitting activities and its impacts on wetlands based on the permit types and their locations. This research should be considered a starting point for investigating the proposed theory that community recovery after a hurricane can accelerate the alteration of wetlands via permitting, which can erode the flood resilience of coastal communities over the long term.

The following section reviews the previous literature on the impacts of the Section 404 wetland alteration permitting program, the importance of wetlands on flood risk reduction, and the role wetlands can play on flood attenuation. Next, we describe the sample selection, concept measurement, and data analysis processes. Results are then presented in two phases. First, we conduct descriptive spatial analyses of permits across the experimental and control group, and calculate the percentage change to see the difference between post-Ike and pre-

Ike permits. Second, we analyze variables, such as experimental area permits, permit types, undeveloped land cover class from C-CAP (Coastal Change Analysis Program) land cover data, permits within the 100-yr floodplain using a binary logistic regression model to test their overall statistical significance with post-Ike permits in hurricane effected areas. In the final section, we discuss the implications of our results and provide guidance to planners, hazard mitigation managers, policy makers, and associated agencies on how to manage naturally-occurring wetlands during long-term recovery after hurricane events.

### 1.1. Impacts of the Section 404 Wetland Alterations Permitting Program

The passage of the Clean Water Act (CWA) included the principle statute that regulates wetland alterations: Section 404. Section 404 gave the U.S. Army Corps of Engineers (USACE) the primary responsibility of the Section 404 program through the power to issue permits for dredge and fill activities. Additional oversight from the U.S. Environmental Protection Agency (EPA) is also provided, as the EPA is the primary agency charged with implementing the bulk of the CWA. Although the USACE administers the Section 404 permit program, the EPA controls the substantive water quality protection criteria that § 404 permit applicants must meet (Downing et al. 2003). The EPA has the authority to veto USACE permit decisions although in practice this power is seldom used. For example, from the period 1972 to 1990 the USACE issued roughly 10,000 permits per year; the EPA vetoed 11 projects during this time period—a rejection rate of 0.11% (Steiner et al. 1994).

Wetland management and regulation in the United States was formally initiated in 1972 with the passage of the Clean Water Act (CWA). The U.S. Army Corps of Engineers (USACE) began issuing permits to alter a naturally occurring wetland under the authority of Section 404 of the CWA, which was rolled out in three phases. July 1975 saw the implementation of the first phase of permitting program with its reach applying to coastal waters, navigable inland rivers and lakes, and wetlands adjacent to these waters. The second phase began in September of 1976 and included all lakes, primary tributaries, and their adjacent wetlands. Finally, in July of 1977 the USACE added all remaining jurisdictional waters including isolated wetlands (Downing et al. 2003).

Today, regulatory permits are broken-down into four categories (Table 1 for more information): 1) Individual Permits for activities that entail more than minimal impacts (usually over 0.5 acres); 2) Nationwide Permits for activities that are deemed to have “no more than minimal adverse effects on the aquatic environment, both individually and cumulatively” (Issuance of Nationwide Permits; Notice 2002, pg. 2023); 3) Letters of Permission for situations where, in the opinion of the district engineer, the proposed work would be minor, not have significant individual or cumulative impact on environmental values, and should encounter no appreciable opposition (33 CFR 325.5b2); and 4) General Permits, which are issued when, “activities are substantially similar in nature and cause only minimal individual and cumulative impacts” (USACE 2001). This category was created as an attempt to streamline the permit process for common activities.

### 1.2. Wetland Alteration and Flooding

Few studies have quantified the extent of the Section 404 program on wetland loss (see Table 2); fewer have examined the impacts of wetland alteration on human communities over time (Wilder et al. 2011). Naturally-occurring wetlands are increasingly being highlighted for their role in protecting property from flooding events by reducing flood velocities, flood peaks, and providing areas for storing precipitation-based flood waters (Acreman and Holden, 2013). In a recent review of wetland and floodwater retention, Bullock and Acreman (2003) found that 82% of studies showed that wetlands have a significant capacity to reduce or delay flood peaks. The US Corps of Engineers (1972) calculated that the flood reduction function of 3,800 ha of floodplain storage on the Charles River, Massachusetts saved US $17 million worth of downstream flood damage each year. Studies conducted in coastal Texas and Florida quantified the value of naturally occurring wetlands in reducing the adverse impacts of floods using the Section 404 permitting program. For example, Highfield (2012) found that wetland alteration as measured by the number of approved permits (under section 404 of the Clean Water Act) increased peak annual flows. Similarly, Brody et al. (2008) found that the loss of wetlands across 37 coastal counties in Texas from 1997 to 2001 significantly increased the observed amount of property damage from floods, when controlling for multiple socioeconomic and geophysical contextual characteristics. On average, wetland alteration permits added over $38,000 in property damage to a jurisdiction per flood. A comparison analysis for every county in Florida found similar results (Brody et al. 2007b). In this case, the alteration of wetlands increased the average property damage per flood by over $400,000.

Estuarine wetlands have also been implicated in mitigating surge-induced flooding (flooding caused by tidal rises caused by coastal hurricanes), although the evidence is mixed (Engle, 2011; Barbier and Enchelmeyer, 2014). For example, in an analysis of 34 major U.S. hurricanes Costanza et. al. (2008) found the area of wetlands to be effective in reducing damage per gross domestic product—derived by spatially allocating county level data—based on a regression analysis. A similar regression based analysis conducted by Farber (1987) for Louisiana that also relied on county-level data found that wetlands reduced wind damage, yet stated that effects on flood damage was too difficult to estimate. Resio and Westerlink (2008) found that wetlands may actually increase storm surge heights under wind-driven storm conditions, illustrating that the role of wetlands may vary spatially. Shepard et al. (2011) conducted the most extensive review to date of existing research related to wave attenuation and marsh wetlands. They addressed the following ecosystem services associated with coastal protection: *wave attenuation*, *shoreline stabilization*, and *floodwater attenuation*. The authors concluded that marshes did have a significant positive effect on wave attenuation as measured by reductions in wave height per unit distance across marsh vegetation. However, it was also noted that most of the identified wave attenuation studies evaluated small to moderate waves ($Hs<.5$ m) and there was a total lack of field studies quantitatively evaluating large waves and storm surge.

Despite the important functions of wetlands, substantial evidence suggests that flood exposure is growing as floodplain encroachment or development increases (Parker 2000). It is also evident that flood losses in the U.S. continue to escalate due to loss of natural floodplain storage and increasing impervious surfaces within the floodplain (Brody et al. 2007a; Brody et al. 2007c; Highfield and Brody 2006, Brody et. al. 2015). U.S. coastal communities have experienced flooding risk most likely due to increased human settlements in the floodplains in addition to upstream development that increases runoff. Moreover, research has shown how flood insurance and disaster assistance programs can intensify development in the floodplain by ignoring how and where development must be placed (Larson and Plasencia, 2001).

## 2. Research Methods

### 2.1. Sample selection

This study employed a control group versus study group research design with a pretest-posttest comparison to measure and explains differences in the wetland alteration permitting activities in Hurricane Ike effected area. Wetland permits were analyzed over five-year periods before (2004 – 2008) and after (2009 – 2013) Hurricane Ike made landfall on the upper Texas coast to quantify the intensity and location of changes in wetland alteration. The study group was comprised of two counties, Chambers and Galveston, which experienced the largest impacts from Hurricane Ike followed by recovery efforts. The control group consisted of two counties, Aransas and Brazoria, which are flood-prone, but were not directly affected by Hurricane Ike. From 2004–2013, a total of 937 permits were analyzed - 509 in the study group and 428 in the control group (Figure 1).

Among the study group, Galveston County has experienced substantial impact on wetlands due to urban development (Gonzalez et al. 2014). According to Dick and Hunt (2012), such development has contributed to the conversion of more than 70% of original wetlands. These losses are primarily associated with land conversion to agriculture and, more recently, suburban and urban development (Lester and Gonzalez, 2011). Conversely, Chambers County is more rural with a population of only 35,096 based on the 2010 U.S. Bureau of the Census estimate. This County has experienced little development activity, and less wetland losses over the period of time compare to Galveston County. Among control group counties, Brazoria is most comparable to Galveston, where historic agricultural practices and more recent suburban development has resulted in a steady decline of naturally occurring wetlands. Aransas, by contrast, is more rural, less populated, and more intact from an ecological perspective.

### 2.2. Concept measurement

We measured wetland alteration permit data from 2004–2013 under Section 404 of the Clean Water Act required by US Army Corp of Engineers (USACE) (see Table 3 for concept measurement). All of the permits in the database have geographic locations (latitude and longitude) as well as the type and year of permit issuance. The permit database was then geocoded in ArcGIS version 10.3.1 to analyze the pattern of wetland alteration over the study period. We also measured and included in our analysis a group of predictor variables to explain wetland alteration using a logit model. Variables included C-CAP land cover data 2006: developed and undeveloped land classes; FEMA (Federal Emergency Management Agency) defined 100-year floodplain: inside or outside; and four permit types: Individual

(IP), Nationwide (NP), Letter of Permission (LOP), and General (GP). C-CAP land cover data included 23 land classes, among them, low, medium, high density development, and developed open spaces were categorized as developed and all other classes were categorized as undeveloped. Post-Ike permits were used as the outcome variable while undeveloped land classes, area within the floodplain, study area permits, and types of permit served as predictor variables. In our statistical model, we considered post-Ike permit as dependent variable of binary outcome, where pretest permits were coded as 0 and posttest permits coded as 1. The total number of observations in our model is 937 (the total number of permits granted within 10-yr time period).

## 3. Data analysis

We analyzed the data in two stages. First, we used descriptive statistics to understand the spatial patterns of wetland development in both the study and control groups, and to calculate the percentage change of post-Ike compared to pre-Ike permits. This phase enabled us to identify the percentage increase or decrease of permits after Hurricane Ike in the study area compared to the control group based on permit types or locations, in or out of the floodplain, permits within developed or undeveloped land classes, and type of wetland impacted (palustrine or estuarine). Second, we calculated a logit regression model to explain the variation in post-Ike permits and identify significant variables contributing to this wetland loss.

## 4. Results

### 4.1. Describing the spatial-temporal pattern of wetland development permits

Of the total number of permits analyzed in this research, 53% were classified as Nationwide, 20% Individual, 15% Letter of Permission, and 13% General (Table 4). Of the total sample of wetland permits, 54% were issued in the study group. A significantly larger percentage of permits were issued in Galveston County (42%) compared to Chambers County (12%), where new growth and coastal development has occurred during the 10-year study period. It is also evident in Table 4 that Nationwide and Individual permits were the most granted types, indicating large-scale building initiatives (wetland impacts up to or exceed 0.5 acres by per permits) were primarily responsible for wetland loss (Table 1 and see Highfield and Brody, 2006 for more information).

### 4.2. Percent change of wetland permits: post-Ike vs. pre-Ike

Calculating the percent change in permits before and after Hurricane Ike provides an indication of the degree to which the storm triggered additional wetland alteration. As shown in Table 5, the overall number of permits decreased in both the study and control groups. However, the study group of counties experienced a much lower rate of reduction (20.77 percent) than the corresponding control group (37.26 percent). The change in wetland alteration is better illustrated by examining specific permit types. For example, there was a 50% post-Ike increase in individual permits in the study group compared to a 22.58% decrease in the control group. For nationwide permits, there was a 13.16% increase in the study group and a 10.08% increase in the control group. The overall increasing trend of individual and nationwide permits after Hurricane Ike in the study group counties indicates that redevelopment or construction of larger-scale development projects were most impacting naturally occurring wetlands. In contrast, for LOP and GP permits significantly decreased by similar amounts in both the study and control groups.

Change analysis of land cover data to indicate which type of environment is being impacted by permitting activities. Based on the C-CAP land cover data, post-Ike wetland permits decreased both on undeveloped land (4.06%) and developed land (46.36%) in the study area. Further, we categorized the undeveloped land class into two wetland types: palustrine and estuarine, to determine which wetland type is impacted by post-Ike wetland alteration. However, results show that permits issued on palustrine wetlands substantially increased (107.14%) after Hurricane Ike, suggesting that the study area is losing a high amount of flood-water storage capacity and increasing its risk of flooding to future storm events. In contrast, permits issued on estuarine wetlands decreased in both the study and control group.

During this 10-year time period, more than 72% of permits issued were located within the 100-year floodplain, meaning that impacts on wetlands outside of the floodplain are accounted for in only 28% of permits. Moreover, permits issued within the floodplain during the post-Ike period were increased by 1.64% in the study area; in the control group the permits decreased by 54.25%. In contrast, permits issued outside the floodplain decreased in the study area (61.39%) and increased in the control group (33.33%). Findings from the location of permits issuance suggest that permits are still taking place in flood vulnerable area after Ike those have ability to capture and store water runoff during flooding events, more specifically in hurricane effected areas.

### 4.3. Significance of correlated variables

In this phase of the analysis, we explain the effects of contextual characteristics on post-hurricane permits. For the regression analysis, we selected number of study area permits, type of permit, permits issued within undeveloped land type, and permits issued within the floodplain. As shown in Table 6, the overall model is statistically significant, where $p< 0.001$ (LR chi2= 175.69, p>chi2 = .000). The study area, dichotomous variable, has a significant ($P< 0.05$) positive effect on the amount of post-Ike permits, suggesting the wetlands were altered more in both Galveston and Chambers County (hurricane impacted area) compared to the control group counties. Of the four permit types analyzed, we found only two are significantly correlated with post-Ike permitting activities. First, Individual permits (wetland development impact over 0.5 acres) have a strong positive and significant impact on permit issuance after Hurricane Ike (where $p<0.001$). The coefficient (or parameter estimate) for the variable IP is 2.223. This indicates that for a one-unit increase in IP, we expect a 2.223 increase in the log-odds of the outcome variable, holding all other predictor variables constant. The effect of NP (most commonly used type) on post-Ike permits is also positive and significant. In contrast, both GP (represents small development and cumulative impact on wetland) and LOP (very small development and minor wetland impact) have no significant effect on whether a post-Ike permit is granted. It is important to note that regression results also support the findings from percentage change analysis of pre-post Hurricane Ike wetland permits described above. The logit model also indicates that significantly more wetlands permits were issued on undeveloped lands in the years following Hurricane Ike (P<0.001). However, permits issued within the 100-year floodplain were found to have no significant effect on the dependent variable.

## 5. Discussion

By analyzing federal 404 wetland alteration permitting data, we gained a better understanding of how redevelopment or construction activities during recovery are impacting wetlands at a local level. Our findings indicate that recovery after a major hurricane results in an accelerated loss of naturally-occurring wetlands and their associated value in buffering the adverse impacts of future flood events. Specifically, following Hurricane Ike, wetlands in Galveston and Chambers County were impacted to a far greater degree than similar areas unaffected by the storm. These findings have important implications for public decision makers charged with regulating development and permitting processes that want to avoid possibly compromising the ability of their communities to be resilient in the face of future flood events.

First, our results show that both Individual and Nationwide permits increased during the recovery period, suggesting mostly large-scale redevelopment or construction projects (0.5 acre or >0.5 acre of impact on wetlands) were increasing within the Hurricane Ike impacted area. Previous research found that such patterns of development, specifically associated with Individual permits, increase impervious surfaces (parking lots, roads, rooftops, etc.) resulting in large losses in the amounts of naturally occurring wetland (see Brody et al 2007a; Brody et al 2008). This increase in imperviousness can accentuate flood risk by decreasing infiltration and reducing the capacity of wetlands to collect, store, and discharge flood waters (Dunne and Leopold 1978, Paul and Meyer 2001, Brody et al. 2007b, Brody et al. 2007c). In addition to the impact from IP, Stein and Abrose (1998) showed that NP has proportionately more cumulative and profound impacts on wetlands compared to other federal permit types. Such transformations of wetlands through redevelopments and recovery of the built environment, can make hurricane prone areas more vulnerable to future flood events. Policy makers should pay additional attention that issuing authorities and other associated agencies must review and analyze the type of and amount of wetland alteration permits issued in previously impacted, flood-prone regions.

Second, land cover type analysis shows that wetland permits were issued significantly more in undeveloped parcels during a Hurricane recovery period. This result suggests that recovery for a major storm event can act as a catalyst for new development in addition to redevelopment of damaged structures. New development overwhelmingly impacted palustrine wetland types further inland within the study area, even though flood impacts incurred primarily on the coastline. Displaced development from a saltwater-based flood event, in this case, has led to a disproportional impact on freshwater wetlands known to reduce the impacts of rainfall flood events. Regulators may have unintentionally reduced resiliency to precipitation-based flooding in order to accommodate recovery from saltwater inundation. It is important that decision makers recognize coastal areas are subject to multiple types of storms (note Tropical Storm Allison in 2001 caused record rainfall and associated property loss) and that displaced, outwardly-expanding development during times of recovery can weaken the ecological system as a whole to protect residents from the next great flood event. Initial evidence suggests that future flood impacts, particularly from precipitation-based events, may be further exacerbated because wetland permits in the study group counties were issued disproportionally more in the 100-year floodplain (although this variable was not statistically significant in the explanatory model). As we stated in the introduction that wetland alteration permits within the floodplain: 1) increase impervious surface areas, which eventually intensify risk (Brody et al. 2008), and 2) exacerbate and elongate flooding events by disrupting the natural hydrological systems, which causes more economic disruption (see Highfield and Brody 2006 for more information). A long-term recovery plan could guide the location of wetland alteration away from riparian and floodplain areas through buffer or other land use policies.

## 6. Conclusion

Our study indicates that post-storm recovery is one of the important causes behind wetland alteration in hurricane impacted areas, as recovery encourages redevelopment or new construction under federal 404 permitting processes. Particularly, redevelopment or construction of large scale projects (more than 0.5acre impact), converting undeveloped lands, increasing impervious surfaces in floodplains, and losing palustrine (freshwater) wetlands were taking place during the recovery process. As recovery is more of a regionally based phenomenon, the cumulative impacts on wetlands should not be neglected. Additionally, previous literature on impacts of wetland permitting program highlights that the cumulative impact of this activity is poorly understood and under accounted. Therefore, a comprehensive understanding of wetland development during recovery after hurricane events and its impacts on coastal resiliency should be a priority for issuing authorities, policy makers, hazard mitigation specialists, and recovery planners.

While our research provides some important statistical insights, it should be considered only a starting point towards understanding the effects of long-term hurricane recovery on ecological functions and overall resiliency. First, our study only focuses on a single disaster event: Hurricane Ike. Future investigations need to be carried out on other hurricane events across the region to establish a more complete understanding of how wetlands are being impacted by the permitting program during recovery. Second, this study does not consider the socioeconomic or political factors that may drive permit issuance. Future research should analyze wetland alteration permits based on land use attributes and socioeconomic characteristics, such as income, economic performance, and shifting demographics. Third, our study only examines two hurricane-effected counties on the upper Texas coast. Future research should cover a larger study area to form a more comprehensive understanding of the relationship between the permitting program and its impact on wetlands during the recovery process. Finally, we also suggest that future goal should be to produce quantitative methods to assess coastal resiliency in the same philosophical manner that on the continent, investigators have been able to quantify calculations for surface water runoff and hydrology for watersheds to minimize the impact of development upon flooding and investigators have been able to manage watershed phosphorus contributions to influence water-body quality.

## Acknowledgements

This article is based on the research project jointly funded by the Hazard Reduction Recovery Center, Texas A&M University, College Station, Texas, and the Center for Texas Beaches and Shores, Texas A&M University, Galveston, Texas.

## References

Acreman M, Holden J. How wetlands affect floods Wetlands. 2013; 33(5):773–786.

Barbier EB, Enchelmeyer BS. Valuing the storm surge protection service of US Gulf Coast wetlands Journal of Environmental Economics and Policy. 2014; 3(2):167–185.

Barbier EB, Georgiou IY, Enchelmeyer B, Reed DJ. The value of wetlands in protecting southeast Louisiana from hurricane storm surges PloS one. 2013; 8(3):e58715. [PubMed: 23536815]

Berke P, Newman G, Lee J, Combs T, Kolosna C, Salvensen D. Assessing networks of plans and vulnerability to coastal hazards and climate change Journal of the American Planning Association. 2015; 81(4):287–302.

Brody SD, Highfield WE, Ryu HC, Spanel-Weber L. Examining the relationship between wetland alteration and watershed flooding in Texas and Florida Natural Hazards. 2007a; 40(2):413–428.

Brody SD, Zahran S, Highfield WE, Grover H, Vedlitz A. Identifying the impact of the built environment on flood damage in Texas *Disasters*.. 2007b; 32(1):1–18.

Brody SD, Zahran S, Maghelal P, Grover H, Highfield WE. The rising costs of floods: Examining the impact of planning and development decisions on property damage in Florida Journal of the American Planning Association. 2007c; 73(3):330–345.

Brody SD, Davis SE, Highfield WE, Bernhardt SP. A spatial-temporal analysis of section 404 wetland permitting in Texas and Florida: Thirteen years of impact along the coast Wetlands. 2008; 28(1): 107–116.

Brody SD, Highfield WE, Blessing R. An analysis of the effects of land use and land cover on flood losses along the gulf of Mexico coast from 1999 to 2009 JAWRA Journal of the American Water Resources Association. 2015; 51(6):1556–1567.

Bruland GL. Coastal wetlands: function and role in reducing impact of land-based management Coastal watershed management. 2008; 13:40.

Bullock A, Acreman M. The role of wetlands in the hydrological cycle Hydrology and Earth System Sciences Discussions. 2003; 7(3):358–389.

Conservation, Louisiana Coastal Wetlands, Restoration Task Force, Wetlands Conservation, and Restoration Authority. “ Coast 2050: Toward a sustainable coastal Louisiana” Louisiana Department of Natural Resources , Baton Rouge, Louisiana (1998 ). Retrieved from http://www.coast2050.gov/products/docs/orig/2050report.pdf.

Costanza R, Pe´rez-Maqueo O, Martinez ML, Sutton P, Anderson SJ, Mulder K. The Value of Coastal Wetlands for Hurricane Protection Ambio. 2008; 37(4):241–248. [PubMed: 18686502]

Engle VD. Estimating the provision of ecosystem services by Gulf of Mexico coastal wetlands Wetlands. 2011; 31(1):179–193.

Dick JA, & Hunt GH. (2012 ). Status and trends of wetlands for Galveston County, Texas 2004–2009. Fisheries and Habitat Conservation, U.S. Fish and Wildlife Service Albuquerque, NM 27pp.

Downing DM, Winer C, Wood LD. Navigating Through Clean Water Act Jurisdiction: A Legal Review. Wetlands. 2003; 23(3):475–493.

Dunne T, & Leopold LB. . (1978 ). Water in Environmental Planning Freeman , New York p. 818.

Espey WH, Morgan CW, and Masch FD. (1965 ). A Study of Some Effects of Urbanization on Storm Runoff from a Small Watershed Tech. Rep. 44D 07–6501 CRWR-2. Center for Research in Water Resources. University of Texas , Austin, TX .

Farber S. The value of coastal wetlands for protection of property against hurricane wind damage Journal of Environmental Economics and Management. 1987; 14(2):143–151.

Gonzalez LA, Jacob JS, Kinney EA, Neish BS, Davanon RM. Galveston Bay Wetland Mitigation Assessment and Local Government Capacity BuildingTexas Land Office: Land Management Program; 2014

Highfield WE, Brody SD. Price of permits: Measuring the economic impacts of wetland development on flood damages. Florida. *Natural Hazards Review*. 2006; 7(3):123–130.

Highfield WE. Section 404 Permitting in Coastal Texas: A Longitudinal Analysis of the Relationship between Peak Streamflow and Wetland Alteration Environmental Management. 2012; 49(4):892–901. [PubMed: 22437432]

Issuance of Nationwide Permits Federal Register, Department of Defense, Department of the Army. Corps of Engineers. 2002; 67(10):2023.

Kates RW, Colten CE, Laska S, Leatherman SP. Reconstruction of New Orleans after Hurricane Katrina: a research perspective Proceedings of the National Academy of Sciences. 2006; 103(40): 14653–14660.

Kentula ME, Sifneos JC, Good JW, Rylko M, Kunz K. Trends and patterns in Section 404 permitting requiring compensatory mitigation in Oregon and Washington. USA. *Environmental Management*. 1992; 16(1):109–119.

Kelly NM. Changes to the landscape pattern of coastal North Carolina wetlands under the Clean Water Act, 1984–1992 Landscape Ecology. 2001; 16(1):3–16.

Larson L, Plasencia D. No adverse impact: New direction in floodplain management policy Natural Hazards Review. 2001; 2(4):1.

Lester LJ, & Gonzalez LA. Eds. (2011 ). The State of the Bay: A Characterization of the Galveston Bay Ecosystem, Third Edition. Texas Commission on Environmental Quality, Galveston Bay Estuary Program , Houston, Texas .

Newman G, Kim JH, Berke P, Merrill J, Wang Y, Li Q. From idle grounds to ecological infrastructure: The resilient design of Manchester neighborhood in Houston Landscape Architecture Frontiers. 2016; 4(5):68–84.

Newman G, Sohn WM, Li MH. Performance evaluation of low impact development: Groundwater infiltration in a drought prone landscape in Conroe, Texas Landscape Architecture Frontiers. 2014; 2(4):122–133.

Owen CR, Jacobs HM. Wetland protection as land-use planning: the impact of section 404 in Wisconsin. USA. *Environmental Management*. 1992; 16(3):345–353.

Parker DJ. Introduction to floods and flood management Floods. 2000; 1:3–39.

Paul MJ, Meyer JL. Streams in the Urban Landscape. Annual Review of Ecological Systems. 2001:333–365.

Reja MY, Brody SD, Highfield WE, Newman GD. Understanding the Notion between Resiliency and Recovery through a Spatial-Temporal Analysis of Section 404 Wetland Alteration Permits before and after Hurricane Ike World Academy of Science. Engineering and Technology, International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering. 2017; 11(4):348–355.

Resio DT, Westerink JJ. Modeling the physics of storm surge Physics Today. 2008; 61(9):33–38.

Shepard CC, Crain CM, Beck MW. The Protective Role of Coastal Marshes: Systematic Review and Meta-Analysis PLoS One. 2011; 6(11):e27374. [PubMed: 22132099]

Sifneos JC, Kentula ME, , & Price P. (1993 ). Impacts of Section 404 permits requiring compensatory mitigation of freshwater wetlands in Texas and Arkansas (No. PB-93–212462/XAB) ManTech Environmental Technology, Inc. , Corvallis, OR (United States)

Sifneos JC, Cake EW, Kentula ME. Effects of Section 404 permitting on freshwater wetlands in Louisiana, Alabama, and Mississippi Wetlands. 1992; 12(1):28–36.

Stein ED, Ambrose RF. Cumulative impacts of Section 404 Clean Water Act permitting on the riparian habitat of the Santa Margarita, California watershed Wetlands. 1998; 18(3):393–408.

Steiner F, Pieart S, Cook E, Rich J, Coltman V. State Wetlands and Riparian Area Protection Programs. Environmental Management. 1994; 18(2):183–201.

Sutton-Grier AE, Wowk K, Bamford H. Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems Environmental Science & Policy. 2015; 51:137–148.

USACE. (2001). *2001 Annual Regulatory Statistical Data*. Retrieved May 6, 2016, retrived from http://www.usace.army.mil/cw/cecwo/reg/execsem01.pdf

US Corps of Engineers. (1972 ). An overview of major wetland functions and values US Fish and Wildlife Service, FWS/OBS-84/18

USGS (United States Geological Survey). (1996 ). National Water Summary on Wetland Resources USGS Water-Supply Paper 2425 Washington, DC, USA .

Wilder TC, Ford WM, , & Perkins MM. ; (2011 ). A Bibliography of Selected Literature on Indirect Impacts Associated with Clean Water Act Section 404 Permits (No. ERDC/EL-TR-11–6) Engineer Research and Development Center Vicksburg MS Environmental Lab .

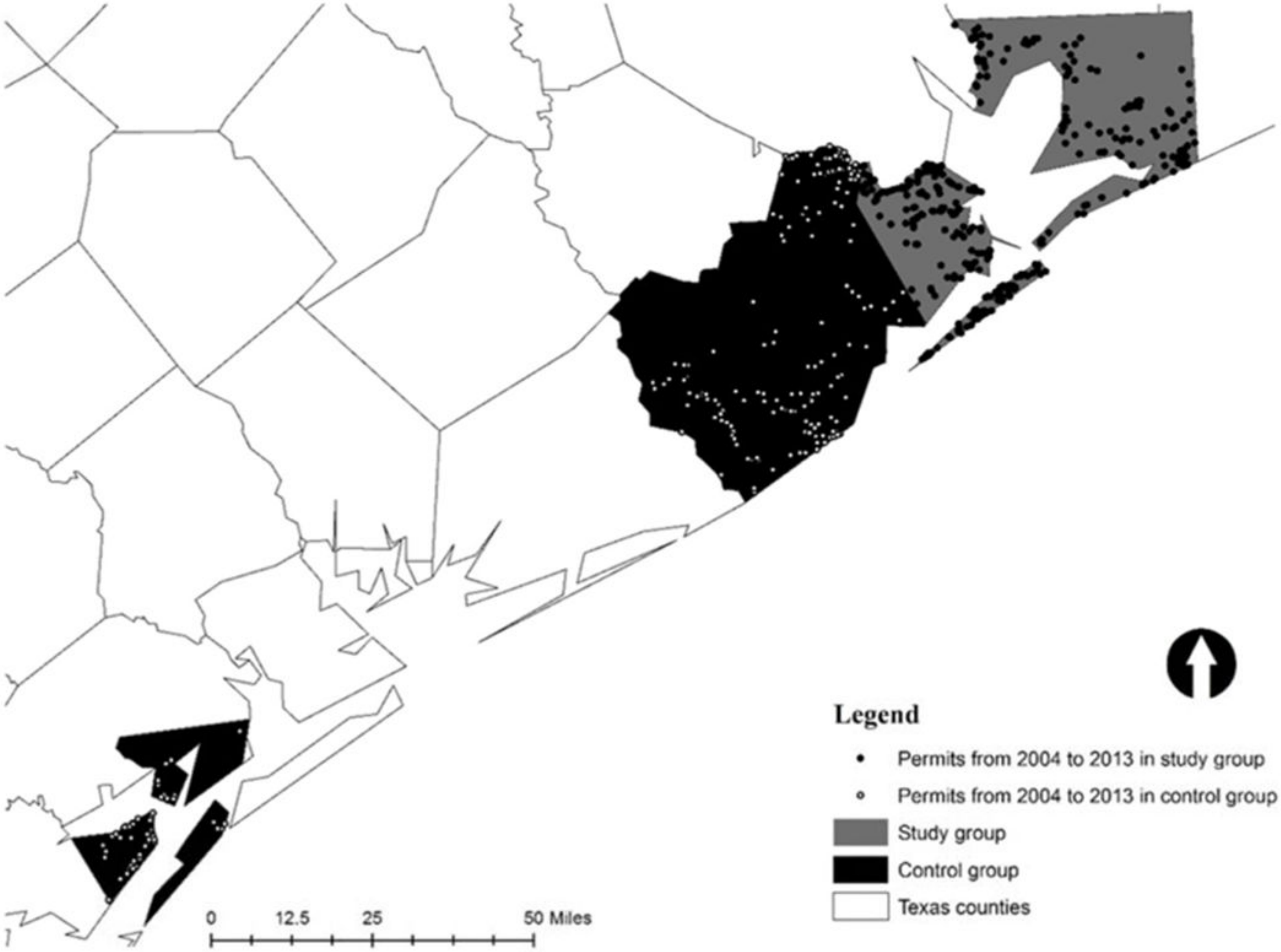


**Fig 1.**

Wetland alteration permits from 2004 to 2013 in study area counties (Chambers and Galveston counties –hurricane impact) and control counties (Aransas and Brazoria counties – no hurricane impact)

Author Manuscript

Author Manuscript

Author Manuscript

**Table 1.**

Types of Permits showing the impacts on naturally occurring wetlands under USACE jurisdiction (Highfield and Brody 2006; Brody et al. 2007a; Wilder et al. 2011; Highfield, 2012)

| Permit type | Impacts on wetlands under USACE jurisdiction | Type of activities and requirement of other certification |
|---|---|---|
| **General Permit (GP)** | Resulting in minimal impacts (individual and cumulative) | -Specific type of activities<br>-Example: residential development, or fill, after-the-fact-filling, repair and construction of roads and bridges, utility work |
| **Individual Permit (IP)** | Significant impacts that exceed 0.5 acres of wetland alteration | -Large developments or projects<br>-Public notices, comments within a specific period of time, and Section 401 water quality certifications are required |
| **Letter of Permission (LOP)** | Minimal impacts not exceeding 0.2 acres | -Mainly smaller projects<br>-Restoration of wetland efforts, minor modification of IP, erosion control, mosquito control |
| **Nationwide Permit (NP)** | No more than minimal adverse impacts, but some NP resulting up to 0.5 acres of permanent impacts | -Specific type of activities<br>-Section 401 water quality certification required sometimes |

**Table 2.**

Evidence of empirical studies where federal permits were used to estimate the loss of naturally occurring wetlands

| Study area | Time period | Wetland loss estimation using federal permit record | References |
|---|---|---|---|
| **Texas** | 1982–1986 | A net loss of 371 ha of wetland losses in the Fort Worth District | Sifneos et al. 1993 |
| **Louisiana** | 1982–1987 | 226 permits issued and a potential loss of over 10,000 ha; Compensatory mitigation required for 41% of permits issued, only 8% of the total area was mitigated | Sifneos et al. 1992 |
| **Oregon** | 1977–1987 | A net loss of 43% of wetlands, with 74 ha of wetlands impacted and 42 ha created | Kentula et al. 1992 |
| **Washington** | 1980–1986 | A net loss of 26% of wetlands, with 61 ha of wetlands impacted and 45 ha created | Kentula et al. 1992 |
| **Wisconsin** | first half of the federal fiscal year 1988 | 171 ha of wetlands permitted, only 16 ha created in the first six months of 1988 | Owen and Jacobs 1992 |
| **North Carolina** | 1984–1992 | Not only a net loss of wetlands, but also habitat fragmentation occurred in 80% of areas adjacent to permit sites | Kelly 2001 |
| **Texas and Florida** | 1991–2003 | Texas: Permits issued typically located outside the urban areas (78%) and outside 100-year floodplains (61%); most affected wetland type: estuarine (47%)<br>Florida: Permits Issued within urban areas (57%) and outside 100-year floodplains (51%); most affected wetland type: palustrine (55%) | Brody et al. 2008 |

**Table 3.**

Concept measurement

| Variable Categories | Variables | Description | Source | Mean | Std. deviation |
|---|---|---|---|---|---|
| **Outcome variable** | Post-Ike | Geocoded permit after Hurricane Ike | USACE | 0.4162 | 0.4931 |
| **Predictor variables** | Study group | Geocoded permit in Hurricane Ike effected area | USACE | 0.5432 | 0.4983 |
| | GP | Geocoded general permit type | USACE | 0.1259 | 0.3319 |
| | IP | Geocoded individual permit type | USACE | 0.1974 | 0.3983 |
| | LOP | Geocoded letter of permission permit type | USACE | 0.1505 | 0.3577 |
| | NP | Geocoded nationwide permit type | USACE | 0.5261 | 0.4996 |
| | Undeveloped | Coded land cover classes except the high, medium, low density development and developed open space | NOAA, Coastal Change and Analysis Program (2006) | 0.7353 | 0.4414 |
| | Inside of SFHA (100-yr floodplain) | Coded permit within the 100-yr flood plain | FEMA Q3 data | 0.7236 | 0.4475 |

**Table 4.**

Wetland alteration permits by type from 2004–2013 in study and control group

| Study-Control Group | County | GP | % | IP | % | LOP | % | NP | % | Total permits | % | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Study | Chambers | 10 | 0.08 | 40 | 0.22 | 9 | 0.06 | 54 | 0.11 | 113 | 0.12 | 0.54 |
| | Galveston | 62 | 0.53 | 90 | 0.49 | 55 | 0.39 | 189 | 0.38 | 396 | 0.42 | |
| Control | Aransas | 25 | 0.21 | 16 | 0.09 | 24 | 0.17 | 44 | 0.09 | 109 | 0.12 | 0.46 |
| | Brazoria | 21 | 0.18 | 39 | 0.21 | 53 | 0.38 | 206 | 0.42 | 319 | 0.34 | |
| Total | | 118 | 0.13 | 185 | 0.20 | 141 | 0.15 | 493 | 0.53 | 937 | 1.00 | |

**Table 5.**

Percentage change of wetland alteration permits before and after Hurricane Ike

| Variable | | Study-Control group (Study – S, Control – C) | Pre-Post Ike | | % change |
|---|---|---|---|---|---|
| | | | Pre-Ike (no. of permits) | Post-Ike (no. of permits) | |
| Number of Permits | From 2004–2013 | S(N=509) | 284 | 225 | -20.77% |
| | | C(N=428) | 263 | 165 | -37.26% |
| Permit type | GP | S | 67 | 5 | -92.54% |
| | | C | 40 | 6 | -85.00% |
| | IP | S | 52 | 78 | 50.00% |
| | | C | 31 | 24 | -22.58% |
| | LOP | S | 51 | 13 | -74.51% |
| | | C | 73 | 4 | -94.52% |
| | NP | S | 114 | 129 | 13.16% |
| | | C | 119 | 131 | 10.08% |
| C-CAP land cover data 2006 | Developed | S | 110 | 59 | -46.36% |
| | | C | 52 | 27 | -48.08% |
| | Undeveloped | S | 174 | 166 | -4.60% |
| | | C | 211 | 138 | -34.60% |
| | Palustrine wetlands | S | 28 | 58 | 107.14% |
| | | C | 49 | 30 | -38.78% |
| | Estuarine wetlands | S | 45 | 35 | -22.22% |
| | | C | 28 | 10 | -64.29% |
| SFHA (FEMA- defined 100-yr floodplain) | Within | S | 183 | 186 | 1.64% |
| | | C | 212 | 97 | -54.25% |
| | Outside | S | 101 | 39 | -61.39% |
| | | C | 51 | 68 | 33.33% |

**Table 6.**

Logistic regression analysis of post-Ike permits (from 2008–2013)

| Post-Ike | Coefficient | Std. error | z-value | Significance |
|---|---|---|---|---|
| Study | 0.3085 | 0.1503 | 2.05 | 0.040 |
| General permit (GP) | -0.3197 | 0.4145 | -0.77 | 0.440 |
| Individual permit (IP) | 2.2237 | 0.3033 | 7.33 | 0.000 |
| Nationwide permit (NP) | 2.1375 | 0.2776 | 7.70 | 0.000 |
| Undeveloped | 0.6212 | 0.1685 | 3.69 | 0.000 |
| Within 100-yr floodplain | 0.0147 | 0.1646 | 0.09 | 0.929 |
| Constant | -2.6517 | 0.3363 | -7.88 | 0.000 |

Note: Number of obs. = 937, LR chi2(12) = 175.69, Log likelihood = -548.4165, Prob>chi2 = 0.0000