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Examining the relationship between wetland alteration and watershed flooding in Texas and Florida

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Abstract Inland flooding remains one of the greatest threats to the safety of human population in the United States (US). While few large-scale studies exist, the potential role of naturally occurring wetlands in mitigating flood duration and intensity has been widely discussed. This study examines the relationship between wetland alteration and coastal watershed flooding in Texas and Florida over a 12-year period. Specifically, we geo-reference wetland alteration permits required under Section 404 of the US Clean Water Act and correlate the number of granted permits with the degree of flooding measured by stream gauge data. Results indicate that specific types of federal permits exacerbate flooding events in coastal watersheds while controlling for various environmental and socioeconomic characteristics.

Keywords Flooding · Wetlands · Watershed · Planning · Texas · Florida

1 Introduction

Despite planning efforts to mitigate the adverse impacts from floods in the United States (US), this environmental hazard continues to pose a significant threat to the property and safety of human populations (ASFPM 2000). Flood losses are exacerbated by increasing development, particularly in the coastal margin for residential, commercial, and tourism uses. Rising population density in coastal areas is associated with greater amounts of impervious surfaces, the alteration of hydrological systems (i.e., watersheds), and an overall diminished capacity for these systems to naturally hold and store surface water run-off. As a result, communities, households, and private property are becoming more vulnerable to damage from repetitive floods.

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The development or alteration of naturally occurring wetlands is considered central to the loss of natural water retention within watershed units and an increase in flood hazards for local communities. Wetlands not only provide the ecological infrastructure for watershed systems, but are also believed to provide natural flood mitigation. While the importance of individual wetlands for mitigating flood intensity and duration is understood, the degree to which wetland development affects flooding at the watershed or ecosystem level has never been thoroughly investigated. Aside from small-scale case studies based on hydrologic modeling principles, no study upto now has thoroughly tested the value of wetlands as a flood mitigation tool using long-term empirical data, large spatial scales, and controlling for multiple confounding factors.

Our study addresses this lack of research by examining the relationship between wetland alteration and coastal watershed flooding in Texas and Florida. We seek to answer the research question: *does regional wetland development exacerbate the level of flooding within a watershed unit?* Specifically, we measure individual wetland alteration permits required under the US Clean Water Act and correlate the number of granted permits with the amount of flooding measured by stream gauge data. First, we select a sample of 85 watersheds (fourth order watersheds based on the United States Geological Survey (USGS) Hydrological Unit Code (HUC) system) within coastal margins which are prone to flooding throughout Texas and Florida. Second, we geo-reference and analyze federal wetland permits within each watershed spanning a 12-year period. Third, we measure watershed flooding over the same 12-year time period using stream gauge data provided by the USGS. Multivariate regression analysis indicates the degree to which wetland alteration contributes to flooding after controlling for various socioeconomic, demographic, and environmental variables. Results from our study provide important information to watershed planners and flood managers on how the pattern of wetland alteration can influence watershed flooding. Such information is critical given the continued development of coastal areas and the increasing vulnerability of human populations to coastal flooding.

The following section reviews the literature on the role of wetlands in supporting hydrological systems, flood damage, and the link between naturally occurring wetlands and flood mitigation. Next, we describe the sample selection, measurement of variables, and data analysis procedures. The results are presented in two phases. First, we describe the spatial and statistical pattern of wetland development over the 12-year study period. Second, we use Ordinary Least Squares multiple regression analysis to identify the most important factors explaining watershed flooding in Texas and Florida. Finally, we discuss how the results can provide direction for planners, hazard managers, and policy makers to reduce the level of watershed flooding and buffer against future flood hazard events.

2 Wetlands and flooding

As mentioned above, wetlands are considered important for maintaining a properly functioning water cycle (Mitch and Gosselink 2000; Lewis 2001). Early research on wetlands and flooding focused on the differences between drained and natural wetlands as a basis for assessment. The results from these studies indicated that undrained peat bogs reduce low-return period flood flow and reduce overall storm flows when compared to their drained counterparts (Boelter and Verry 1977;

Heikuranen 1976; Verry and Boelter 1978; Daniel 1981). Additional work using mostly linear regression analysis yielded similar results. For example, Conger (1971) showed that the ability of wetlands to store water significantly reduced peak flows for recurrence intervals up to 100 years. Novitski (1979) studied four different types of wetlands and found that each had a negative effect on flood flows. Novitski (1985) concluded that basins with as little as 5% lake and wetland area might lead to 40–60% lower flood peaks.

More recent research utilizing simulation models also demonstrates the flood-reducing role of wetlands. Ammon et al. (1981) modeled the effects of wetlands on both water quantity and quality of Chandler Marsh in South Florida. Results showed that maximum flood peak attenuation is higher with increasing areas of marsh. The authors concluded that Chandler Slough Marsh increases storm water detention times, changes run-off regimes from surface to increased subsurface regimes, and is "moderately effective as a water quantity control unit" (p. 326). Ogawa and Male (1986) also developed a simulation model to explore the potential of wetlands as a flood mitigation strategy. Using four scenarios of downstream wetland encroachment ranging from 25 to 100% loss, the authors found that increased encroachment resulted in significant increases in peak flow.

Other studies are not as clear on the benefits of wetland protection and restoration as a tool for flood mitigation. The 1994 Galloway Report concluded that upland wetlands could be effective for smaller floods, but diminish in value as storage capacity is exceeded for larger floods. It states that the effect wetlands have on peak flows for large floods on main rivers are inconclusive and that additional research is needed. Also, using model simulations, Padmanabhan and Bengston (2001) found that wetland restoration in the Maple River watershed in North Dakota would not have significant effects on high-return period flood events.

Research based on direct observation also supports the notion that wetlands play an important role in reducing the degree of flooding. For example, recent findings demonstrate that wetlands are able to absorb and hold greater amounts of floodwater than previously thought. Based on an experiment that involved constructing wetlands along the Des Plaines River in Illinois, it was found that a marsh of only 5.7 acres could retain the natural run-off of a 410-acre watershed. This study estimated that only 13 million acres of wetlands (3% of the upper Mississippi watershed) would have been needed to prevent the catastrophic flood of 1993 (Godschalk et al. 1999). Other observational research suggests, there is a critical threshold for the effects of wetland loss on flood storage. For example, in a study that utilized the record of stream flow data from stream gauge stations, Johnston et al. (1990) found that small wetland losses in watersheds with less than 10% of wetlands could have a significant effect on increased flood flows.

It is clear from the literature that the value of wetlands for flood mitigation and the intersection between environmental protection and flood management needs further study. Overall, it appears from the research that the presence of wetlands in a watershed will reduce or slow downstream flooding to some extent. In fact, a comprehensive review of the literature conducted by Bullock and Acreman (2003) showed that wetlands play a significant role in modifying the hydrological cycle. The authors found that for 23 of the 28 studies on wetlands and flooding, "floodplain wetlands reduce or delay floods" (p. 366).

3 Research methods

3.1 Sample selection

We selected for analysis a sample of watersheds as defined by the USGSs fourth order HUC within the coastal margin of Texas and Florida (Fig. 1). This hydrological unit is generally considered the most appropriate scale for assessing and implementing watershed approaches to management. The watershed unit of analysis has several advantages. First, when examining the effect of naturally occurring wetlands on flooding, it is most appropriate to focus on areas within ecological boundaries as opposed to those defined by humans, such as local jurisdictions (Williams et al. 1997). Second, a watershed unit of analysis reduces the potentially confounding effect of upstream development on downstream flooding. All HUCs within 100 miles from the nearest coastline were selected to yield a sample of 85 adjacent coastal watersheds (39 in Texas and 46 in Florida). Several watersheds had to be omitted from the sample on account that there is no stream gauge data available.

Selecting Florida and coastal Texas as the study area in which to examine the relationship between wetland alteration and watershed flooding provides an ideal basis for comparison. Both states border the Gulf of Mexico and are among prone to coastal flooding. However, their different geography, policy climates, and development patterns make for a powerful comparative analysis. Florida has experienced one of the largest percentages of wetland loss of any state in the country (Mitch and

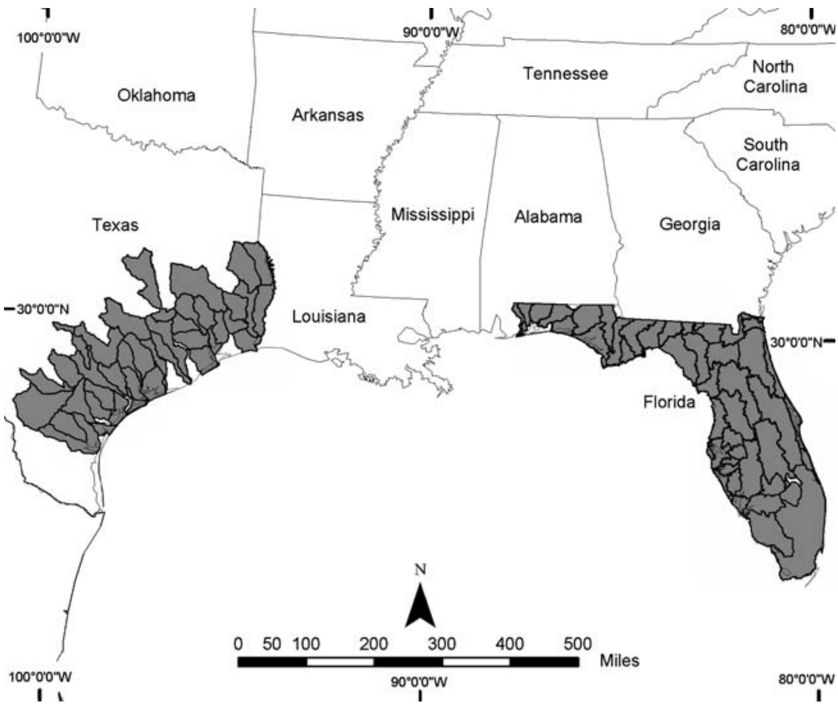

Fig. 1 Study area

Gosselink 2000). Since the 1700s drainage for agriculture, channelization for human water supply, and most recently urban and suburban development have contributed to the conversion of more than half of the original wetland acreage. Rapid population growth and associated development over the last decade has resulted in a concentrated pattern of wetland alteration in the fringe or outside of urban areas (see Brody and Highfield 2005).

In contrast, coastal Texas has not yet experienced the same degree of urban and suburban development, except for the Houston–Galveston metropolitan area. Most of the Texas coast is relatively undeveloped such that the natural hydrological structure of its watersheds is more intact compared to Florida. While Texas has a relatively small percent of the total US coastal population, population by shoreline mile is expected to double between 1960 and 2010 to 1,956 people per mile (Culliton et al. 1990). These trends indicate that the Texas coast will become one of the fastest growing coastal regions in the country. Projected increases in tourism and recreation, commercial and industrial projects, and second home ownership within the state's coastal zone will inevitably result in accelerated wetland alteration and potential corresponding problems with watershed flooding.

3.2 Concept measurement

We measured the dependent variable, watershed flooding, based on stream gauge data obtained from the USGS (see Table 1 for concept measurement). Average monthly stream flow data were recorded for each gauge in a selected watershed between 1991 and 2002. We then recorded the number of times a stream gauge exceeded its average for the study period. These counts were then averaged across all gauges within each watershed unit. This procedure gave us a measure of watershed flooding based on the average number of times stream flow exceeded its seasonal 12-year average.

We measured wetland alteration using federal wetland permits required by US Army Corp of Engineers (USACE) under Section 404 of the *Clean Water Act*. Wetland loss has been measured in the past using remote sensing techniques (Kingsford and Thomas 2002) as well as statistical analysis of historical records tied to probable causes of loss such as canal dredging (Turner 1997; Day et al. 2000). One underutilized method of quantifying wetland loss is analyzing permits issued by the USACE to alter or develop a wetland. Kentula et al. (1992) and Kelly (2001) were among the few researchers to use the permit record to estimate wetland losses. Stein and Ambrose (1998) also relied on similar data to assess pre-permit and post-permit conditions of areas along the Santa Margarita River in California. They concluded that the permit process had failed at minimizing overall cumulative impacts to wetlands associated with the riparian system. Most recently, Brody and Highfield (2005) and Brody et al. (in press) also used the federal permit record to identify hotspots of development and explain the degree of local level implementation of environmental policies in South Florida.

We obtained wetland permits issued under Section 404 of the *Clean Water Act* from the USACE District offices in Jacksonville, Florida and Galveston, Texas. The permit record included the type, the date issued, and the permit's latitude and longitude. Permit types issued by USACE and analyzed in this study fall into the following four categories:

Table 1 Concept measurement

Variable	Source	Description	Mean	Std. deviation
Flooding	USGS	Counts of months exceeding the 12 year average	32.23	13.14
State	GIS	Dichotomous variable denoting state identification	0.54	0.50
IP	US Army Corps of Engineers, Jacksonville District	Geocoded individual permit types	47.03	98.29
GP	US Army Corps of Engineers, Jacksonville District	Geocoded general permit types	85.78	226.66
LOP	US Army Corps of Engineers, Jacksonville District	Geocoded LOP permit types	26	52.80
NP	US Army Corps of Engineers, Jacksonville District	Geocoded nationwide permit types	228.69	330.97
Impervious surface change	Classified satellite imagery from 1990 and 2000	Percent change in impervious surface from 1990 to 2000	16.62	12.86
Area	USGS	Calculated from GIS coverage of hydrologic units	3274.64	2761.4
Mean percent slope	National elevation dataset	Calculated in GIS from digital elevation model	0.99	0.98
Stream length	National hydrography dataset	Calculated in GIS from stream segments coverage	1,337,563	1,064,222
Total annual wet days	National Climatic Data Center weather station data and locations. Natively, the number of days per year with 0.5″ or greater of rain	Interpolated surface of total number of wet days per year at each location summarized by watershed	108.27	23.07
Median household income	2000 US Census, GIS analysis	Median household income by hydrologic unit	37808.39	7639.39
Population density	2000 US Census, GIS analysis	Population per square kilometer by hydrologic unit	80.039	135.33
Dams	US Army Corp of Engineers	Number of dams in each hydrologic unit	7.70	16.40

(1) *Individual permits (IP)*. These permits are necessary for projects, which may result in significant impacts and are required for wetland alterations exceed 0.5 acres. Public notices, comment periods, and Section 401 water quality certifications are required under this permit type.
(2) *Letters of Permission (LOP)*. These permits are required for smaller projects including mosquito control, erosion control, and residential development in freshwater wetlands not exceeding 0.2 acres of fill material, minor modifications to previously issued IP, backfill to eliminate boat basins or ramps, and wetland restoration efforts (USACE 1996a; 1996b; 1997).
(3) *General Permits (GP)*. These permits are issued for specific types of activities on a nationwide or regional basis. GP are issued when, "activities are substantially similar in nature and cause only minimal individual and cumulative impacts" (USACE 2002). GP are reviewed every 5 years and an "assessment of the cumulative impacts of work authorized under the general permit is performed at that time if it is in the public interest to do so" (USACE 2002). Examples of activities falling under GP status include residential development or fill, After-the-fact filling, road and bridge repair and construction, and utility work (USACE 2005).
(4) *Nationwide Permits (NP)*. By far the most issued permit type, NP are issued for specific 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 2005, p. 2023). Some categories of NP allow up to 0.5 acres of wetland to be filled. Public notices are not required but 401 water quality certification may be required.

The permit database was geocoded in a geographical information system (GIS) and further subdivided by year and permit type. Of the 45,897 permits received from the USACE during the study period 32,939 had sufficient geographic information due to data entry errors or lack of geographic information altogether. Permits were then summed by type for each watershed in the study area.

Several sets of control variables were also measured and included in a model explaining flood loss estimates. First, we measured physical environmental variables for precipitation, topography, the drainage network, and watershed area. Precipitation data were gathered from the National Climatic Data Center as annual number of days with rainfall over 0.5 inches (wet days) at each weather station. The number of stations with available data ranged from a minimum of 165 in Texas and 98 in Florida to a maximum of 181 in Texas and 111 in Florida over the study period. For each year a raster surface was interpolated using an inverse-distance weighted procedure. Surfaces of total number of wet days by year were averaged by watershed and summed across years. Percent slope was derived from the National Elevation Dataset (NED) within the study area within a GIS. Average percent slope was calculated for each hydrologic unit. Total stream length and hydrologic unit area were also calculated within a GIS using the National Hydrography Dataset (NHD) and fourth order hydrologic units obtained from USGS.

Second, we controlled for human-induced environmental change variables by measuring the presence of dams and land use change in the study area from 1990 to 2000. Dam locations were gathered from the USACE and summed within hydrologic units. Impervious surface change was developed using GeoCover satellite imagery from NASA Stennis Space Center. Imagery from 1990 and 2000 was classified by utilizing several iterations of an unsupervised classification method followed by manual grouping of similar classifications. Digital Ortho Quarter Quads (DOQQ) imagery was used to confirm the accuracy of the classifications. We summed impervious surface area by hydrologic units for 1990 and 2000 and then calculated a change score.

Third, we included in the model several socioeconomic and demographic characteristics as control variables. Using 2000 US Census Bureau block group data, we distributed population and median household income across study area watersheds. Where block groups were intersected by watershed boundaries we used an area-weighted measure. Area-weighted socioeconomic data were then divided by watershed area to derive population density.

3.3 Data analysis

We analyzed the data in two phases. First, we report descriptive statistics related to the spatial pattern of wetland development over the 12-year study period. Second, we use robust multiple regression analyses to quantify the effect of wetland development and various control variables on coastal watershed flooding in Texas and Florida. Tests for estimate reliability including specification, multicollinearity, and spatial and serial autocorrelation exhibited no significant violation of regression assumptions. Based on statistical diagnostics, we did however suspect heteroskedasticity in the data leading us to analyze robust regression equations.

4 Results

4.1 Describing the pattern of wetland permits

Of the total number of federal wetland permits analyzed in both states, 60% were Nationwide, 22% GP, over 12% IP, and only 6.7% LOP (Table 2). The large majority of these permits were granted in Florida (70%) where rapid growth and development has occurred over the last several decades. A significantly larger percentage of IP were issued in Florida, indicating construction of more large-scale development projects and resulting impacts on wetland systems. In contrast, almost twice the percentage of GP were issued in Texas involving mostly small-scale individual projects located outside or on the fringe of major urban areas.

In both states, the number of permits steadily increased each year until the middle of the study period, and then decreased in the late 1990s (Fig. 2). In Florida, the number of granted permits peaked in 1995, and then gradually decreased until 2000. The most intense wetland development occurred between 1994 and 1997. In Texas,

Table 2 Totals of wetland permits by type

State	Nationwide	%	Individual	%	Letter of permission	%	General	%	Total permits	%
Texas	4,987	0.51	919	0.09	873	0.09	2,943	0.30	9,722	0.30
Florida	14,452	0.62	3,079	0.13	1,337	0.06	4,349	0.19	23,217	0.70
Total	19,439	0.59	3,998	0.12	2,210	0.07	7,279	0.22	32,939	

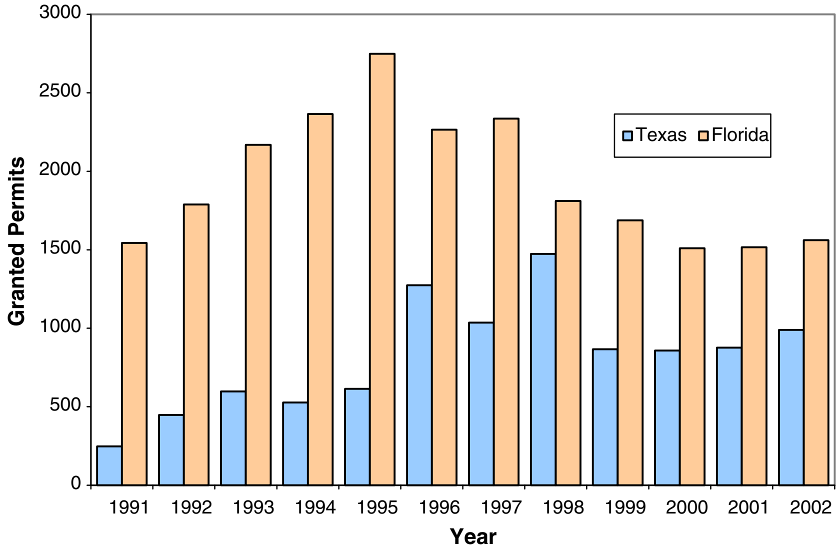

Fig. 2 Issued permits by year

the number of granted permits peaked in 1998 and then stabilized for the remaining 3 years of the study period. In terms of permit numbers, the most active period of wetland alteration in Texas occurred between 1996 and 1998.

In terms of their spatial distribution, the majority of wetland development permits in Florida were granted in the southern portion of the state and along the coastlines. Permit numbers are particularly high in the Southeast Florida Coast Watershed (watershed number 12) encompassing the urban corridor from Miami north to West Palm Beach (see Fig. 3). Results indicate extensive wetland alteration has also taken place in areas associated with the Jacksonville (watershed number 5), Orlando (watershed number 3), and Panama City (watershed number 39) metropolitan regions. In contrast, watersheds located in the central portions of the state generally have the lowest amounts of permits to alter an existing wetland.

In coastal Texas, the highest number of federal wetland permits also occurs in watersheds encompassing major urban areas and associated sprawling development patterns (see Fig. 4). For example, the Houston–Galveston area (watershed numbers 10 and 15), which experienced rapid suburban and industrial growth during the study period contains by far the greatest number and concentration of permits. The watershed comprising Lake Livingston (watershed number 5) further inland is another hotspot for wetland development due to its emergence as a popular location for recreation and second home ownership. In general, watersheds further away from the coastline (where the greatest opportunity for recreation, tourism, and energy development exists) contain the fewest numbers of wetland permits during the study period.

4.2 Explaining the impacts of wetland alteration on watershed flooding

The spatial pattern of wetland alteration between 1991 and 2002 was primarily associated with rapidly and outwardly growing urban areas. The second phase of

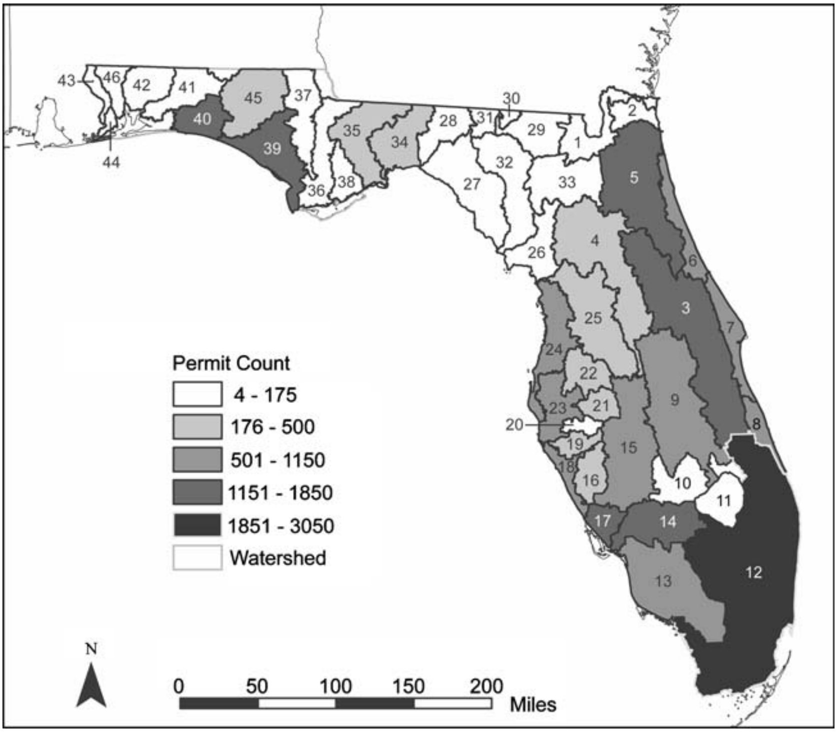

Fig. 3 Permit counts by watershed, FL

analysis seeks to explain the impacts of wetland alteration (via granted federal wetland permits) on coastal watershed flooding. As shown in Table 3, the number of wetland permits as a whole has a statistically significant effect on our flooding measure. This effect varies according to the type of permit issued. For example, IP required for wetland alterations over 0.5 acres have a significant positive impact on flow exceedance where $P < 0.01$. GP involving small but cumulative wetland development over time have an even greater positive influence on the dependent variable, where $P < 0.001$. In contrast, LOP representing very small and minor development projects significantly reduce watershed flooding ($P< 0.05$) compared to the other permit types. NP, the most common and variable category has no significant effect in the regression model.

The addition of several control variables to the regression model does little to change the direction or overall significance of wetland permit types, indicating the robustness of their effects (Table 4). The state dichotomous variable, however, becomes a strong negative predictor suggesting coastal Texas has significantly greater flooding or flow exceedance than Florida. As expected, among the physical environmental variables measured precipitation has a significant positive effect on coastal watershed flooding ($P< 0.000$) and is the strongest predictor in the fully specified model. Increasing slope or topographic variability appears to reduce flooding, although the effect is not statistically significant.

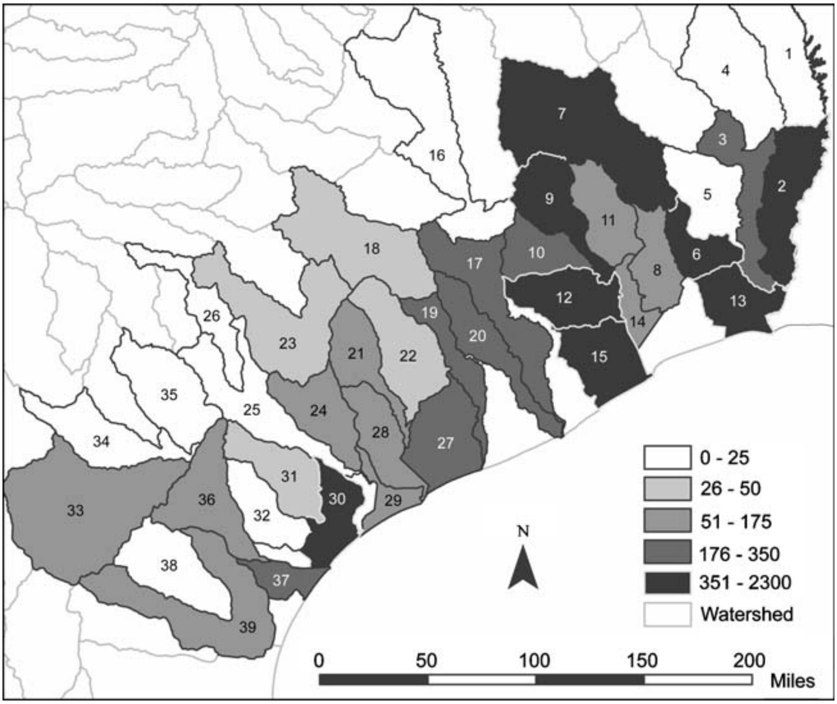

Fig. 4 Permit counts by watershed, TX

Table 3 Effect of permit types on watershed flooding

Variable	Coefficient	Std. error	*t*-value	Significance
NP	0.0018	0.0062	0.29	0.769
IP	0.0598	0.0202	2.96	0.004
LOP	–0.1032	0.0415	–2.49	0.015
GP	0.0204	0.0045	4.51	0.000
State	–4.8607	3.0113	–1.61	0.110
Constant	32.5597	2.7137	12.00	0.000

R^2 = 0.1142, n = 85, $F(5, 79)$ = 7.10, p = 0.000

Among the human-induced environmental change variables, land use change from 1990 to 2000 has a significant positive effect on watershed flooding at the 0.1 level. That is, an average percentage increase of impervious surface within a watershed corresponds with a significant increase in the degree of flooding. An increasing number of dams (a flood control device) on a water body has a mild impact on reducing the amount of flooding within the study area. Finally, the socioeconomic and demographic variables we measured have a negative but statistically insignificant effect on the dependent variable. Median household income has the strongest impact of the two variables indicating that more wealthy communities may experience less flood-related events.

Table 4 Effect of permit types on watershed flooding with contextual controls

Variable	Coefficient	Std. error	*t*-value	Significance
NP	–0.0047	0.0066	–0.72	0.4720
IP	0.0826	0.0363	2.27	0.0260
Letter of permission	–0.1656	0.0509	–3.25	0.0020
GP	0.0200	0.0075	2.66	0.0100
State	–20.4130	3.7493	–5.44	0.0000
Area	0.0008	0.0012	0.66	0.5150
Slope	–1.8770	1.7153	–1.09	0.2780
Stream length	0.0000	0.0000	0.21	0.8340
Precipitation	0.4902	0.0728	6.73	0.0000
Median household income	–0.0003	0.0002	–1.42	0.1590
Population density	–0.0038	0.0106	–0.35	0.7250
Impervious surface change	0.1801	0.1069	1.68	0.0960
Dams	–0.0642	0.0816	–0.79	0.4340
Constant	–2.0757	10.0121	–0.21	0.8360

$n = 85$, $F(13, 71) = 5.26$, $p = 0.000$

5 Discussion

Analysis of the data indicates that federal permits issued to alter a naturally occurring wetland exacerbate flooding events in coastal watersheds along the Gulf of Mexico. These permits are generally associated with areas experiencing rapid urban and suburban development between 1991 and 2002. The importance of our findings for planners and policy makers interested in reducing the adverse impacts of coastal flooding is that flood events are regulated not solely by the effect of permit counts, but by the type of permit granted. First, as expected, IP significantly increase flooding because they signify development projects requiring large amounts of wetland (>0.5 acres) to be disrupted. These projects usually involve the addition of impervious surfaces (e.g., parking lots, roads, rooftops, etc.) that reduce the capacity of a wetland system to store, hold, and slowly discharge flood waters. This result is an initial indication that the extent of wetland alteration from development, even at the project level, has a profound impact on the incidence of flooding over time. Decision makers should carefully monitor the number and location of IP granted within a watershed to ensure the hydrological system remains relatively intact.

Second, while we expect large development projects and associated impervious surfaces to increase the rate of flooding, the even stronger positive effect of GP is somewhat surprising. This result indicates that relatively small-scale wetland alteration such as with the case of residential development have more serious "cumulative impacts" on flooding over time. GP may be indicative of sprawling development patterns where each individual project may not cause a severe impact, but the total sum of all small disruptions to a watershed unit results in loss of hydrological function and resulting increased flood events. This "death by a thousand cuts" phenomenon should be a primary concern for environmental and hazard mitigation planners. Officials need to steer their focus away from site-based review and incremental decision making toward the watershed level where cumulative impacts are more easily detected.

Third, there is evidence that one permit type, LOP, may actually reduce the number of extreme flooding events compared to other permit types. We explain this result based on the fact that LOPs represent the smallest disturbance to a naturally occurring wetland (<0.2 acres), are often minor modifications to previously issued permits, and can involve wetland restoration which actually results in a net gain of wetland acreage within a watershed. Florida has the highest number of wetland mitigation banks (large areas of restored wetlands) in the US and currently administers 38 banks covering more than 107,000 acres across 15 watersheds (DEP 2004). While there is little empirical research testing the relationship between restored wetlands and flood mitigation, the benefits of creating artificial wetland systems even if it requires altering small, naturally occurring wetlands should not be over-looked. It is also important to note that permits involving small projects can be based on flood control devices such as detention ponds, swales, or culverts. In any case, the impact of LOPs on flood-reduction is small since only 7% of all wetlands fall into this permit category.

In the fully specified model, the state dichotomous variable becomes a very powerful negative predictor of watershed flooding, indicating coastal Texas has significantly more flood events than Florida. This result may at first seem counter intuitive since Florida has more wetland alteration permits, impervious surface, population growth, and associated urban development. However, only when we control for precipitation (the most significant predictor of floods) in the model does this strong negative effect emerge. Florida receives much more rainfall than Texas, a factor that overpowers any impact human-induced environmental change has on flooding. Furthermore, Florida has significantly shorter average stream length and a significantly greater number of dams than Texas. Extensive channelization and redirection of stream flow in Florida (particularly the southern portion) reduces the possibility of site-level flood events than would occur under more natural conditions.

Finally, there are several other variables in the fully specified model that deserve discussion in terms of their effects on flooding. For example, the significance (at the 0.1 level) of increased impervious surfaces as a result of land use change has important implications for watershed planners and floodplain administrators. While curtailing human development may not be possible, regulating the degree to which a watershed is converted to impervious surface and where this surface is located may be important to reducing the number of flood events. As mentioned above, this approach demands a watershed planning focus where cumulative impacts of impervious surfaces and their spatial distribution across watersheds can be effectively monitored. Also, while not statistically significant, regression results suggest that wealthier communities could experience less flooding events. Local jurisdictions with the financial resources and planning expertise to implement both structural and non-structural (e.g., land acquisition, zoning, education programs, etc.) flood-reduction measures are generally better protected from the threats of persistent floods. Past research has shown that wealthier communities adopt higher quality plans with respect to mitigating natural hazards such as floods (Berke et al. 1996). This result may also contribute to the explanation of why Florida, which is significantly wealthier than coastal Texas, has a comparatively lower number of flood events.

6 Conclusion

While our study provides some important findings, it should only be considered an initial step in understanding more fully the relationship between wetland alteration and watershed flooding. Further research is needed on several fronts. First, our flood measure is based solely on the number of exceedances from the average flow for each stream gauge. We do not incorporate data on the intensity of specific events or the actual damage caused by flooding. Additional flood measures are needed that take into account the size of floods (e.g., stream gauge height) and impact floods have on local communities (e.g., actual damage in dollar amounts). Second, while we account for the alteration of wetlands, we do not control for wetland restoration or mitigation efforts. It is possible that replacing or creating additional wetlands may counter-balance the effect of disrupting existing, naturally occurring wetland systems. Given the pervasiveness of wetland mitigation in Florida, these data should be incorporated into future models.

Third, our study is limited to the quality and quantity of existing datasets. Many permit records we obtained from the Army Corps of Engineers could not be geo-referenced due to significant gaps in record keeping. In some cases, we had to make our own datasets as with the land use change variable. As new and more accurate data becomes available, they should be included in future models explaining watershed flooding. Fourth, although we examine wetland development over a 12-year period, we do not adequately incorporate a temporal dimension into the data analysis. Cross-sectional analysis provides only a snapshot in time with respect to impacts on flooding. Future research should make use of analytic procedures, such as panel analysis that can account for temporal issues. Fifth, our wetland alteration variables are based on counts of permits within watersheds. However, the effect of wetland alteration may not be based just on raw numbers of permits. Future research should analyze more spatially precise measures of wetland alteration, such as density of permits, position of permits within a watershed, and proximity of permits to other watershed features (e.g., stream segments, stream gauges, etc.). Finally, while our study is spatially extensive, we are still only able to analyze 85 watersheds. Future research should increase the sample size and associated statistical power to include all states along the Gulf of Mexico. Only then we can more fully understand the impact of human development on coastal flooding within the context of large ecological systems.

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