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Examining the Impacts of Development Patterns on Flooding on the Gulf of Mexico Coast

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Abstract

This article addresses this understudied aspect of development patterns and community resiliency by examining a five-year record of insured flood loss claims across 144 counties and parishes fringing the Gulf of Mexico. Linear regression models are employed to isolate the effects of five different development patterns on observed flood losses from 2001 to 2005 while controlling for multiple contextual variables. A novel approach is taken to measuring development form by using a series of landscape metrics usually reserved for ecological analysis. These measures enable the assessment of the form of the regional built environment with more specificity than has been possible in previous studies. Results indicate that more connected and concentrated development patterns lead to a reduction in the amount of observed flood losses. These findings illustrate the importance of regional planning and design for fostering flood-resilient communities.

Introduction

Characteristics of the built environment are often considered critical aspects of healthy, liveable and sustainable cities. The form and footprint of major metropolitan areas, suburbs and small towns across the US ultimately shape the environmental and social conditions within which Americans live. For years, researchers have argued (and sometimes documented) that urban and suburban development patterns are responsible for environmental, social and economic conditions pervading local communities (Porter and Kinsey, 2000; Squires, 2002; Ewing, 2008; Freilich *et al.*, 2010).

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Characteristics including the building density, neighbourhood connectivity and development or land use proximity are particularly important when considering impacts in urban areas. However, little or no work has been done on the consequences of development patterns in terms of exposure to natural hazards, particularly flooding.

We address this understudied aspect of development patterns by examining a five-year record of insured flood loss claims across 144 counties fringing the Gulf of Mexico. Linear regression models are employed to isolate statistically the effects of different development patterns on observed flood losses from 2001 to 2005, while controlling for multiple contextual variables. We take a novel approach to measuring development patterns by using a series of landscape metrics usually reserved for ecological analysis. These measures enable us to assess the form of the regional built environment with more specificity than has been possible in previous studies. Results illustrate the importance of regional planning and design for fostering flood-resilient communities and provide guidance to decision-makers on how to mitigate the adverse impacts of storms over the long term.

The following section provides a background on different types of development patterns and their expected relationship to flooding. We then describe the research methods used to conduct the study, including sample size, concept measurement and data analysis. Next, the results of regression analyses are presented for five different forms of regional development along the Gulf coast. These statistical models identify the influence of specific development typologies by controlling for multiple contextual variables at the county level. Finally, we conclude the paper with an interpretation of the results from a planning perspective and suggest avenues for future research on the topic.

Development Patterns and Flooding

Development patterns can be characterised based on a spectrum of densities and forms. At one end lies 'sprawl'—a low-density, haphazard form of development spiralling outward from urban centres (Beatley and Manning, 1997; Burchell *et al*., 1998; Gillham, 2002; Jaret *et al*., 2009; Ewing *et al*., 2011)—that currently dominates much of the American landscape. While there is no universally accepted definition of sprawling land conversion, there are several common characteristics identified throughout the literature.

First are low-density, single-family dwellings. The most frequently cited feature of sprawl is the abundance of large-lot (usually 1–5 acres depending on the development context), residential housing developments that consume large amounts of previously vacant land (Song and Knaap, 2004). The second characteristic is automobile dependency even for short trips. Because sprawling development patterns create large distances between dwelling units and segregate different land uses, residents are forced to rely on automobiles at the expense of alternative forms of transport. Also, the *cul-de-sac*-dominated street patterns within these neighbourhoods foster a lack of spatial connectivity and serve as an obstacle for walking and biking to nearby destinations (Benfield *et al*., 1999). Thirdly, growth spirals outward from existing urban centres. sprawl is also conceptualised as low-density development rapidly expanding away from more compact urban cores. Approximately 80 per cent of the acreage used for recently constructed housing in the US is land outside urban areas; almost all of this land (94 per cent) is in lots of 1 acre or larger (Heimlich and

Anderson, 2001). This pattern results in a larger overall amount of built-up area consisting of multiple developed patches across a given landscape unit.

The fourth characteristic is leapfrogging patterns of development. Another well-known characteristic of sprawl is dispersed development that hurdles vacant lands adjacent to existing development in favour of parcels that are situated further out in the rural countryside (Ewing, 1997; Torrens and Alberti, 2000). Leapfrogging creates a haphazard development pattern that consumes large amounts of land. This development characteristic also produces a greater number of developed patches that are farther away from each other. Fifthly, land uses are separated. Many contemporary urban developments are homogeneous and lack a mixture of land uses, such as commercial, residential and recreation parcels (Song and Knaap, 2004). Segregated land uses encourage dispersed patterns of development and a reliance on the automobile due to the lack of proximity between areas of the built environment. Finally, the edge between urban and rural areas is undefined. Sprawling residential development extending outward from urban centres tends to blur the division between urban and rural domains (Heimlich and Anderson, 2001). This visual development pattern is often associated with the encroachment of open space and agricultural lands. At a regional level, this aspect of sprawl presents itself as a discontinuous and disconnected development pattern.

At the other end of the spectrum is a high-density, compact form of development often called 'smart growth'. This built environment form is often characterised by high-density, pedestrian-friendly development that can focus impact away from critical natural resources (Calthrope, 1993; Duany *et al.*, 2000). Compact or high-intensity development is an important element of 'smart growth' patterns, which have been hailed by many as a key to facilitating sustainable and resilient communities (Burchell *et al.*, 2002; Pollard, 2001). Like the concept of sprawl, smart growth has many characteristic, but high connectivity, proximity and density are underlying elements (Ye *et al.*, 2005). At the regional level, smart growth development patterns tend to limit the overall amount of built-up land and number of developed patches in favour of higher density/intensity development that results in a smaller overall area of impact.

Only recently have scholars and planners begun to consider the relationship between different forms of built environment (as described earlier) and flood risks. Those advocating anti-sprawl approaches to development support high-density development patterns as being more sustainable and hazard resilient over the long term (Beatley, 2009). For example, compact forms of development are better able to avoid vulnerable areas and focus development intensity on the most suitable land available (Stevens *et al.*, 2009). Also, a more focused urban core may deter the release and subsequent development of flood-prone land elsewhere (White, 2008). Finally, high-density, well-connected urban areas may be more likely to have in place a flood mitigation infrastructure that can appropriately handle large amounts of runoff. In general, urbanised communities have greater resources and commitment to provide municipal-level drainage and flood protection infrastructure.

On the other hand, when high-density development occurs in locations vulnerable to floods, such as low-lying areas receiving heavy rainfall, then more people and property may be exposed to flooding (Stevens *et al.*, 2009). In fact, Berke *et al.* (2009) found that one-third out of 318 new urbanist (often considered a type of smart growth) developments in the US were either completely or partially located within the 100-year floodplain. Even when development takes place outside the floodplain in a compact and cohesive fashion, the simple notion that more development results in increased flooding must be considered. The overall amount of built-up area across a region in the form of impervious surfaces can lead to flood losses regardless of its specific form. Increasing the amount of paved surfaces increases runoff and places added demands on sewer and storm-water infrastructure (White, 2008; Brody *et al.*, 2008). Finally, Burby *et al.* (2001) argued that 'smart growth' approaches to development that seek to confine building to a well-defined urban core can actually heighten the exposure to flooding and exacerbate flood losses. The authors argue that 'containment' policies can result in higher land values, which in turn create pressure to develop lower-priced, flood-prone parcels that were originally left vacant. This problem is especially evident where urban areas contain a large percentage of floodplains, such as within the coastal zone.

Low-density development patterns can also have both positive and negative consequences when it comes to flooding. On the one hand, sprawl could reduce the overall impacts of floods by spreading-out human settlements across vulnerable landscapes while avoiding the harmful impacts of concentrated development. For example, White (2008) argued that low-density development patterns offer the opportunity to incorporate more green spaces that absorb runoff. This type of suburban form can allow developers to effectively protect naturally occurring flood mitigation landscape features, such as wetlands and high-priority habitats (Brody, 2008).

However, sprawling development can also place more structures and residents in flood-prone areas by spreading-out population across the landscape. Low-density land conversion also generates a larger total area of impervious surfaces and fragmentation of drainage networks (Brody *et al.*, 2006), both of which can increase runoff and exacerbate flooding. Furthermore, unlike well-established urban centres, suburban and ex-urban communities are less likely to have adequate storm drainage systems and other infrastructure to accommodate increase surface runoff. Low-density, fragmented residential neighbourhoods, particularly at the fringe of metropolitan areas, vary greatly in their efforts to accommodate storm-water runoff. Drainage in these areas is often the responsibility of an individual sub-division, which could simply convey runoff offsite through hardened channels, exacerbating downstream flood impacts. Finally, sprawling residential development on the periphery of older urban areas and outside extraterritorial jurisdictions may be more likely to encroach on floodplains that were originally left as open space or low-impact uses. Indeed, Shuster *et al.* (2005) note that downstream flooding is especially prevalent in newer ex-urban fringe development, which often occupies land closer to the headwaters of a drainage basin.

Using Landscape Metrics to Measure Development Patterns

Landscape metrics have long been the domain of ecologists and conservation biologists (Botequilha *et al.*, 2006). These measures are essentially algorithms that quantify specific spatial characteristics of patches, classes of patches or entire landscape mosaics (Gustafson, 1998). In particular, metrics are often used to achieve a better understanding of natural landscape patterns (such as vegetation), identify important habitats and measure the status of ecosystem structure and function. Only recently have landscape metrics been discussed within the context of measuring human development patterns (Schneider and Woodcock, 2008; Jaeger *et al.*, 2010a, 2010b). Such metrics may be especially useful when various intensities or classes are represented across a landscape. No study to date, however, has correlated urban form-based metrics and flood hazard risks.

While there are hundreds of known landscape metrics identified in the literature, we select the following five as a starting-point for measuring development patterns: patch area, number of patches, patch density, proximity and connectance. A major challenge was to select metrics that can provide guidance on development patterns as opposed to ecological features, which is the traditional target. Metrics associated with shape, contrast or contagion may be important when focusing on wildlife habitat, but more difficult to relate to the notion of development patterns and flood vulnerability. However, focusing on the area or density of impervious patches is logical when considering the pattern of the built environment across a landscape. Proximity and connectivity also directly apply to the notion of development patterns and can be easily folded into a discussion of sprawl. We also wanted a certain degree of conceptual variation in the measures to facilitate comparison across the study area. The first three metrics focus on the amount and density of developed areas; the remaining two deal with the spatial positioning of these areas in relation to each other. A more specific discussion of each metric in the study is provided next. Measurement issues are addressed in the research methods section.

Total Class Area (CA)

This metric represents the sum of the areas corresponding to a patch type within a landscape unit. When applied to the built environment or impervious surface, it provides a measure of the overall extent of development patterns or community imprint on a landscape. There is a substantial body of evidence to support the notion that a development-based impervious surface increases runoff volume, peak discharges and associated flood magnitudes. When pavement, rooftops and other impervious surfaces compromise hydrological conditions, the lag time between the centre of precipitation volume and runoff volume is compressed so that floods peak more rapidly. This reduced lag time occurs because runoff reaches water bodies more quickly when rainfall is unable to infiltrate into the soil (Hey, 2002). Such conditions set the stage for more regular flood events and associated human losses (Brody *et al.*, 2007a). Different intensities or classes of development can affect the degree of flooding and its impacts (see Brody, Gunn *et al.*, 2011 for more information).

Number of Patches (NP)

As already mentioned, urban development is not based simply on the percentage of different intensities of impervious surface, but rather on the pattern with which it imprints the landscape. Calculating the number of development patches across different classes of impervious surface can indicate the overall pattern of the built environment. For example, a landscape dominated by high-intensity development will take a different form from one with a large number of areas with low-intensity development. Also, a large number of a particular type of patch can indicate a more fragmented or leapfrogging development pattern. Overall, we expect an increasing number of developed patches across a landscape to result in increased flooding, but patches specific to medium-intensity development would have the most influence on exacerbating losses.

Patch Density (PD)

Development density is perhaps the most common approach for measuring sprawl because it can represent the abundance of large-lot, residential housing developments that consume large amounts of previously vacant land. Density is usually represented by median lot size, the number of dwelling units per neighbourhood or median floor space of single-family units (Song, 2005). In this study, we take a landscape perspective by considering where a patch is considered a contiguous area of development. A larger number of patches within each jurisdiction will indicate a denser pattern of development. We also distinguish between different intensities of developed patches (based on the percentage of impervious surfaces) to analyse the impacts of, for example, high-density urban development versus high-density suburban development. From a flood perspective, dense patches of high-intensity development will involve more impervious surface that could lead to increased damage. However, these same areas also tend to contain the strongest drainage infrastructure. Dense patches of low-intensity development, on the other hand, have more opportunity to utilise green space to mitigate flooding.

Proximity (PROX)

The proximity metric is also useful to characterise development patterns from the standpoint of fragmentation. This index, originally developed by Gustafson and Parker (1992), considers the size and proximity of all patches whose edges are within a specified search radius of the focal patch. Developed patches that are, on average, further apart are an indicator of sprawl or leapfrogging patterns, which may impact the degree of flooding within a landscape unit. Landscapes dominated by low-intensity, scattered development patches tend to have larger overall coverage of impervious surfaces and more fragmented hydrological systems.

Connectance (CONNECT)

Connectivity is an important aspect of regional development patterns. Just as ecological connectivity facilitates the movement of species, a well-connected built environment permits the flow of pedestrians, commuters and residents. Connectance is based on the number of functional 'joinings' between development patches of the corresponding patch type, where each pair of patches is either connected or not based on a user-specified distance criterion. A low score for this metric would indicate a fragmented, sprawling development pattern; such an urban pattern makes it difficult for residents to access different land uses without an automobile and requires a larger overall area of impervious surface. High connectivity among residential neighbourhoods can make it easier and more efficient to handle storm-water runoff from major precipitation events.

Research Methods

Study Area

The coastal study area consisted of 144 counties and parishes adjacent to the Gulf of Mexico as identified by the National Oceanic and Atmospheric Administration (NOAA) (Crossett *et al.*, 2004). This area arcs from the Florida Keys to the southern tip of Texas and includes counties/parishes from the following six states: Florida, Georgia, Alabama, Mississippi, Louisiana and Texas (see Figure 1). The NOAA

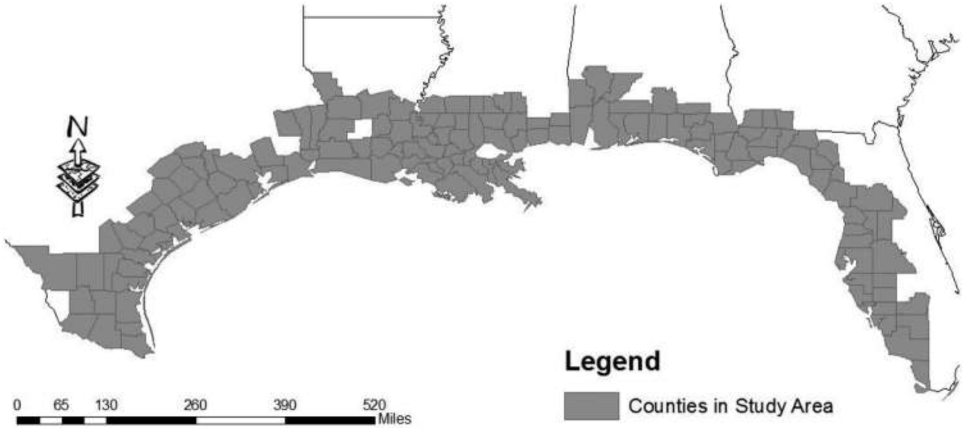

Figure 1. Gulf of Mexico coastal study area.

special projects office defines a county (or parish if in LA) as coastal if one of the following two criteria is met: at a minimum, 15 per cent of the county's total land area is located within a coastal watershed; or, a portion of a county (or an entire county) accounts for at least 15 per cent of a coastal cataloging unit.

The coastal margin associated with the Gulf of Mexico is an ideal region in which to examine the relationship between development patterns and flooding for the following reasons. First, this low-lying coastal margin contains large amounts of floodplain area, making it extremely vulnerable to the adverse effects of rainfall and surge-based flooding events. For example, from 1996 to 2007, jurisdictions along the Gulf coast experienced the largest amount of insured property damage in the US (Brody, Highfield and Kang, 2011). Secondly, the Gulf coastal study area has a history of rapid population growth and associated land use change, creating a diversity of development forms and patterns. For example, the high-intensity, older urban cores of Houston, New Orleans and Tampa contrast with more recent, sprawling, low-density suburbs around these city centres. Harris County (Houston) and Hillsborough (Tampa) were among the top 10 jurisdictions in the nation from 1996–2001 for land conversion for development (NOAA, 2008). The Houston–Galveston area is perhaps the best example of land consumption from urban and suburban sprawl. Between 1970 and 1990 alone, Houston urbanised approximately 640 square miles of land, second only to Atlanta, GA, during the same time-period.[1]

Concept Measurement

The dependent variable for the study is flood-related loss as measured by National Flood Insurance (NFIP) property damage claims from 2001–05. The dollar value of individual insured claims was aggregated to the county or parish level and log-transformed to improve the approximation to a normal distribution (see Table 1 for variable measures).

The development patterns described here were measured across three difference 'classes' or development types based on the intensity of impervious surface coverage. The three development intensities were measured using NOAA's Coastal Change and Analysis Program (C-CAP) remote sensing data for 2001. The C-CAP land-cover classifications were previously derived

Table 1. Concept measurement

Variable	*Measurement*	*Source*	*Range*	*Mean*	*S.D.*
Flood loss	Logged NFIP paid claims for flood losses from 2001–05	FEMA	0–22.6	13.66	4.47
Total class area	Sum of all areas of specific patch type divided by 10 000	NOAA, Coastal Change and Analysis Program	755.28–183 260.2	10 991	18 441
Number of patches	Number of patches corresponding to a specific patch type	NOAA, Coastal Change and Analysis Program	145–16 08	2 918	2 073.68
Patch density	Number of patches for a corresponding patch type divided by total area (square metres) of a jurisdiction, multiplied by 10 000 and 100	NOAA, Coastal Change and Analysis Program	0.0648–2.975	1.393	0.635
Proximity	Sum of a patch area (square metres) divided by the nearest edge-to-edge distance squared (square metres) between the patch and all patches of the corresponding patch type whose edges are within 0.5 miles, divided by the number of patches of the same type	NOAA, Coastal Change and Analysis Program	0.428–30 168.9	601	3 018.6
Connectance	Number of functional joinings between all development patches within 0.5 miles of the corresponding patch type, divided by the total number of possible joinings between all patches of the corresponding patch type, multiplied by 100	NOAA, Coastal Change and Analysis Program	0.051–4.09	0.415	0.481
Soil permeability	Average soil permeability	State Soil Geographic Database	0–0.13	0.054	0.043
Floodplain area	Percentage of area within the FEMA-defined 100-year floodplain	Hazards Vulnerability Research Institute at University of South Carolina	0–0.97	0.351	0.245
Wetland alteration	Percentage area change in wetland cover 2001–05, based on summing 30 square metre pixels derived from Landsat Thematic Mapper remote sensing imagery	NOAA, Coastal Change and Analysis Program	2 0.38–0.002	2 0.004	0.005

(continued)

Table 1. (Continued)

Variable	*Measurement*	*Source*	*Range*	*Mean*	*S.D.*
Precipitation	Number of times precipitation exceeded the 75th percentile for during the study period	PRISM Climate Group	0–5	1.65	1.44
Storm surge	Number of storm surge events per jurisdiction during the study period	SHELDUS v8.0	0–7	0.68	1.62
Number of housing units	US census 2000 estimates of the number of housing units in each jurisdiction	US census	281–1 298 130	54 396	126 431
Median home value	US census 2000 estimates of the median household income for each jurisdiction	US census	28 900–195 700	67 654	21 490
FEMA mitigation plan	Percentage of population in a jurisdiction covered by FEMA approved mitigation plan	FEMA	0–100	87	32

from Landsat Thematic Mapper data at a 30-metre resolution. Percentages of land cover were calculated in a GIS by using a shapefile of the 144 counties in the study area to compute zonal statistics. High-intensity development was previously measured by C-CAP as land that is 80–100 per cent impervious surface. This classification of landcover typifies high-density urban development, such as a city centre or industrial area. Medium-intensity development was measured as land that is 50–79 per cent covered by impervious surface. This type of coverage typifies dense suburban landscapes and some mixed uses. Low-intensity development was measured as land that is 21–49 per cent impervious surface. This type of development is characterised by low-density, large-lot suburban and rural sprawl interspersed with agricultural land use. A measure for each development type—high, medium and low development intensity—was created by summing pixel areas for each class and calculating their percentages for each county/parish in the sample. Using this approach, we derived a measure of development pattern, rather than simply a total area of impervious surface as has been done in the past.

Five major independent variables representing development patterns were measured for three classes of development intensity: high, medium and low. *Total class area* (CA) was measured as the sum of the areas (square metres) of all developed patches of the corresponding patch class, divided by 10 000 (to convert to hectares). CA approaches 0 as the patch type becomes increasingly rare within a jurisdiction. *Number of patches* (NP) equals the number of patches of the corresponding development patch type (class). Increasing values of NP for a particular class indicate greater fragmentation of the landscape. *Patch density (PD)* was measured as the number of patches of the corresponding patch type divided by the total area (square metres) of a jurisdiction, multiplied by 10 000 and 100 (to convert to 100 hectares). The patch density measure is similar to NP as an index, except that it expresses the number of patches on a per unit area basis, enabling comparisons across jurisdictions of varying size.

Proximity (PROX) equals the sum of a patch area (square metres) divided by the nearest edge-to-edge distance squared (square metres) between the patch and all patches of the corresponding patch type whose edges are within a specified distance of the focal patch. We selected 0.5 miles as the specified distance because it is a frequently used distance when planning transit-oriented development, reducing leapfrog development, and is a conservative estimate for how far pedestrians are willing to walk (Canepa, 2007). Low scores for proximity would thus represent a sprawling, car-dependent built environment. We measured the mean proximity defined as the sum, across all patches of the corresponding patch type, of the corresponding patch metric values, divided by the number of patches of the same type. It is important to note that, when the search buffer extends beyond a jurisdiction's boundary, only patches contained within the jurisdiction are considered in the computations. Also, edge-to-edge distances are from cell centre to cell centre. PROX equals 0 if a developed patch has no neighbours of the same patch class within the specified search radius. PROX increases as the neighbourhood (defined by the specified search radius) is increasingly occupied by patches of the same class and as those patches become closer and more contiguous (or less fragmented) in distribution.

Connectance (CONNECT) equals the number of functional joinings between all development patches of the corresponding patch type (sum of c_{ijk} where $c_{ijk} = 0$ if patches j and k are not within the specified distance (0.5 miles) of each other and $c_{ijk} = 1$ if patch j and k are within the specified distance of 0.5 miles), divided by the total number of possible joinings between all patches of the corresponding patch type, multiplied by 100 to convert to a percentage. CONNECT = 0 when either the focal class consists of a single patch or none of the patches of the focal class is 'connected' (i.e. within 0.5 miles of another patch of the same type). CONNECT = 100 when every patch of the focal class is 'connected'. Figure 2 illustrates low and high connectance based on developed patches in Harris County, Texas.

We also measured multiple contextual control variables consisting of a mixture of geophysical and socioeconomic characteristics known to affect flood damage. First, soil properties are shown to be an important factor in influencing coastal and inland flooding. Soil porosity directly affects infiltration capacity (Chang and Frankzyk, 2008), making this an important variable when explaining inundation from both rainfall and overland flow caused by storm surge. We hypothesise that jurisdictions containing soils with higher levels of porosity will experience significantly lower amounts of property damage from floods. Indicators of porosity and potential run-off were processed and analysed using the State Soil Geographical Database (STATSGO). The percentage average permeability, based on soil type, was generated for each jurisdiction, where higher percentages indicate a greater soil infiltration of rainwater.

Floodplain area is another important control variable when predicting the amount of flood losses. The 100-year floodplain (where there is a 1 per cent change of inundation each year) is the major marker of flood risk in the US. We expect that jurisdictions with larger percentages of floodplain area will experience significantly

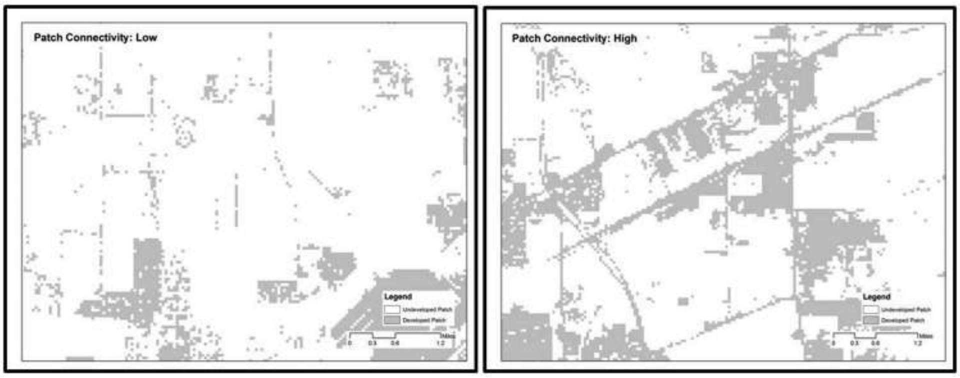

Figure 2. Low and high connectivity in Harris County, TX.

larger amounts of flood-related property damage. Floodplain area was calculated as the percentage of a county/parish occupied by FEMA-defined 100-year floodplains. Data were acquired from Oxfam America and the Hazards Vulnerability Research Institute at University of South Carolina, as well as FEMA Q3 data. On average, 35 per cent of jurisdictions in the study area are comprised of 100-year floodplain.

Naturally occurring wetlands have been shown to attenuate floods caused by precipitation and storm-surge events (Bullock and Acreman, 2003). The human alteration of wetlands, particularly in coastal areas, significantly increases flooding and flood damages (Highfield and Brody, 2006; Brody *et al.*, 2007b). Our hypothesis is that increased amounts of wetland loss over the study period will significantly increase the amount of reported property damage from floods. Wetland alteration was measured by calculating the percentage change in wetland landcover as classified by C-CAP from 2001 to 2005. Wetland cover types include: palustrine forested, palustrine scrub/shrub, palustrine emergent, estuarine scrub/shrub, estuarine emergent, palustrine aquatic bed and estuarine aquatic bed. This change measure represents loss (or, in rare cases, gains) of wetlands within a county/parish over the five-year study period and, when included in the models, helps to isolate the effect of development patterns.

Precipitation is usually the strongest predictor of flooding and associated impacts. Larger amounts of storm-induced rainfall result in increased flooding and resulting property loss. We calculated the precipitation measure based on annual rainfall amounts from the PRISM dataset aggregated to the county/parish unit. Annual precipitation data for the five-year period were mapped at a scale of 30 arc second normals and then averaged annually in millimetres for each jurisdiction in the sample. To capture precipitation events most likely to result in flooding, we totalled the number of times per year rainfall amounts exceeded the 75 per centile for the study period. As a result, the precipitation variable took the form of a count variable, where higher values represent a greater number of extreme rainfall events.

We also controlled for the number of storm-surge-based flooding events affecting the study area from 2001–05. During this time-period, there were several storm surges, most notably the one caused by Hurricane Katrina in 2005. As with precipitation, surge inundates the landscape, but more from overland flow, which can cause sudden and catastrophic damage. Statistically controlling for storm-surge events becomes as important as precipitation when isolating the effects of development patterns on flood losses along the Gulf of Mexico. We measured storm surge by summing the number of events over the study period as reported by the Spatial Hazard Events and Losses Database for the US (SHELDUS version 8.0). This count variable ranges from 0 to 7 surge events per jurisdiction during the study period.

Two additional socioeconomic measures were included as control variables in the statistical models. First, the number of housing units was derived from the 2000 US census at the county/parish level of organisation. We expect that jurisdictions with a greater number of housing units are more likely to report higher amounts of flood-related property loss. Secondly, median home value levels were calculated for each county or parish in the sample using 2000 US census data. We hypothesise that more expensive structures will result in increased flood damage at the local level. Finally, a policy variable was included in the model, measured as the percentage of the population within a county/parish covered by a FEMA-approved mitigation plan.

Data Analysis

We used ordinary least squares (OLS) regression analysis with robust standard errors to explain the variation in insured flood losses across the study area. Each development pattern metric was modelled for each development class (high, medium, low intensity), controlling for the same set of variables as already specified. We analysed different models for each development intensity and development pattern to avoid multicollinearity problems. Diagnostics for model mis-specification, variance inflation due to multicollinearity and spatial autocorrelation did not yield any major violations. We did find heteroscedacticity in the data, leading us to estimate the model with robust standard errors. No other violations of regression assumptions were detected.

Results

Multiple regression analyses illustrate the impact of different development patterns on flood losses, while controlling for multiple environmental and socioeconomic variables. Table 2 shows the standardised effects of each development class across the five urban development metrics. The various models explain between 45 and 52 per cent of the variance in the dependent variable, which is consistent with previous studies on the topic.

As shown in Table 2, increasing amounts of patch area composed of high-intensity development significantly reduce (p \ 0.01) insured property damages caused by floods within the Gulf coast study area. A patch area comprised of medium-intensity impervious surfaces has a negative, but non-significant, effect. In contrast, the low-intensity measure significantly increases (p \ 0.001) observed NFIP-based flood losses. These findings corroborate our previous work evaluating high- versus low-intensity development in relation to flood losses (Brody, Gunn *et al.*, 2011). Specifically, we find that, on average, a greater overall area of compact, high-intensity impervious surface reduces flood losses as long as dense urban development is situated away from vulnerable areas (such as the floodplain). Based on the standardised coefficient, this variable has the largest effect on flood losses compared with all other development metrics. In contrast, increasing percentages of sprawling, low-intensity development patterns that often encroach on vulnerable areas that sometimes lack substantial storm-water

Table 2. Examining the effects of development patterns on flood losses, 2001–05

Development class	*CA*	*NP*	*PD*	*PROX*	*CONNECT*
High	2 0.683**	0.024	0.094	2 0.187	2 0.161*
Medium	2 0.332	0.358***	0.246***	2 0.061**	2 0.289***
Low	0.442***	0.203**	0.103	0.109**	2 0.106

Notes: *** p \ 0.01; ** p \ 0.05; * p \ 0.1.

infrastructure significantly exacerbate residential flood damage (for more details, see Brody, Highfield and Kang, 2011). For example, Harris County, Texas, in which Houston is located, contains by far the greatest area of low-intensity development in the study area (227 square miles). Residential sub-divisions are being built within or adjacent to floodplains on land that was previously designated for agricultural purposes. Storm-water drainage and flood control systems in these areas are marginal when compared with their more urban counterparts.

The number of developed patches within a jurisdiction also appears to have an effect on flood losses. An increasing number of medium-intensity patches (50–79 per cent impervious surface cover) typical of dense suburban settings has a significant (p \ 0.000) impact on property damage from floods (among the highest coefficients of 0.358), as is also the case for large numbers of low-intensity development patches. Greater numbers of high-intensity patches across a landscape, however, have a non-significant effect. Medium-intensity developed patches also appear to be a significant (p \ 0.000) trigger of property damage caused by floods when the density of these patches increases. When the area of a jurisdiction is factored in, both high- and low-intensity metrics for patch density are no longer statistically significant.

Taken together, analysis of the number and density of patches shows that medium-intensity development, characterised by 50–79 per cent impervious cover, is the most influential class in terms of significantly increasing the likelihood of insured property damage from flooding events. An increasing number and density of these developed patches lead to greater amounts of NFIP-based losses compared with the other development classes examined in this study. Closer examination indicates that this type of development primarily takes the form of dense, more recently built suburban environments located in areas outside an urban core. Lee County, Florida, for example, is among the highest-scoring jurisdiction for patch density for medium-intensity development. This county is well known for its suburban residential development patterns in and around Fort Meyers, Cape Coral and Lehigh Acres. These developments usually involve relatively large amounts of impervious surface that can compromise hydrological functions and require substantial storm-water infrastructure to deal with persistent flooding events. However, these residential areas as a whole often lack appropriate infrastructure due to wide variation in sub-division regulations and a piecemeal approach across neighbourhoods when it comes to the level of storm-water management. The result can be an inability to mitigate the adverse impacts of flooding events compared with other forms of development.

The proximity of impervious surface patches indicates the degree to which development is clustered within a jurisdiction. Increasing amounts of medium-intensity patches within 0.5 miles of each other significantly (p \ 0.05) reduce NFIP-based flood losses within the study area. In contrast, low-intensity development typical of sprawling suburban and rural settings increases (p \ 0.05) property damage from floods. The proximity metric is even more informative when considering the relationship of the built environment and flooding because it indicates the degree of regional clustering and smart growth development patterns. In this instance, medium-intensity development situated in close proximity (within 0.5 miles) significantly reduces residential flood damage. When suburban developments are clustered, there is a greater chance that a co-ordinated, regional-level storm-water infrastructure will be established with higher capacity to offset the increases in surface runoff. Because this class of development also includes interspersed areas of vegetation (including parks and golf courses), there is also more opportunity to incorporate green space for flood control into development patterns. In contrast, high proximity for low-intensity developed patches can exacerbate flood losses, possibly because it still represents a sprawling, haphazard development pattern, which places more structures in harm's way, even though it may be more clustered from a super-regional perspective.

Connectivity is another built environment form that provides guidance to planners along the Gulf coast interested in reducing the adverse impacts of floods. Increasing amounts of connectivity for all development classes generally reduce flood losses. However, the effect is statistically significant for only high- (p \ 0.1) and medium- (p \ 0.001) intensity patches when controlling for multiple contextual characteristics. Highly connected medium-intensity patches have by far the strongest effect based on the standardised coefficients listed in Table 2. Monroe County, Florida, which encompasses the Everglades National Park and the Florida keys, is among the highest-scoring jurisdictions in the sample for connectivity due to a constrained area for development. Residential development is limited geographically to a chain of island communities, lending to its connected development pattern. Our results show that, from a regional perspective, high connectivity for all classes of development is generally preferable for establishing a flood-resilient community (even though it may mean more roads and associated impervious surface). Again, in terms of connectivity, the form of medium-intensity development appears to be the most critical patch type for mitigating losses. In fact, based on our statistical models, every additional functional join of this development class within half a mile reduces NFIP-based flood damage within a county/parish, on average, by over $23.5 million per year.

Control variables generally behaved as expected. Soil permeability has a significantly negative effect across all models. Increasing percentages of 100-year floodplain area within a jurisdiction is also a strong predictor of flood losses across all models. A 1 per cent increase in floodplain area leads to significantly higher (p \ 0.01) losses; this is most likely to be due to the consistent development in flood-prone areas along the Gulf coast. Wetland alteration from 2001 to 2005 is also a consistent predictor of property damage from floods, although it has a comparatively weaker statistical effect (p-value is generally \ 0.05) on the dependent variable. As previously mentioned, naturally occurring wetlands have been shown to attenuate floods and reduce flood impacts. This ecosystem service is lost when wetlands are replaced by development.

As expected, heavy precipitation and storm-surge events are among the strongest predictors of flood losses across all models. Major rain events and storm surges (such as caused by Hurricane Katrina) during the study period were responsible for a large portion of the reported property damage. Interestingly, while both variables are statistically significant (where p \ 0.05), storm surge has a consistently more powerful effect on the dependent variable than precipitation. Among the socioeconomic control variables, median house value performs the strongest in predicting flood losses. Increasing levels of median house value significantly increase property damage from floods in all models, which is expected considering that the dependent variable measures structural damage. In contrast, the number of housing units within a jurisdiction performs less consistently. The p-value for this variable ranges from very significant (p \ 0.000) to entirely non-significant, depending on the metric being evaluated. Finally, having an adopted FEMA mitigation plan does not significantly reduce the amount of flood losses within the study area and in some models actually has a positive effect. Table 3 illustrates the full model results across all five development patterns for high-intensity development.

Policy Implications and Conclusions

The results of our study indicate that the specific form of the built environment along the Gulf of Mexico coast significantly affects the amount of property damage caused by floods, even when controlling for multiple environmental and socioeconomic contextual variables. The statistical performance of the five landscape metrics indicates that specific development patterns mitigate losses, pointing the way for regional planners and decision-makers to facilitate the emergence of more resilient coastal communities over the long term.

In general, our results support smart growth, spatially targeted development patterns as more flood resilient at the county/parish level along the Gulf of Mexico coast. Regional planners should generally encourage high-intensity, clustered development rather than low-intensity, more sprawling development patterns. When pursuing medium-intensity types of development, these patches should be in close proximity and have high connectivity. It is important to note that this built environment form could also generate coincidental benefits, such as clean air and water, critical habitat protection and protection of open space.

Low-intensity development in any form should be generally avoided if flood mitigation is a priority. There are multiple tools and policies that planners can choose from to encourage the development of a more concentrated built environment. These include, among others, density bonuses, transfer of development rights, clustering and conservation easements (see Duerksen *et al.*, 1997; Beatley, 2000; and Brody *et al.*, 2006, for more details). The current planning landscape is quite varied across the Gulf of Mexico coastal study area. For example, counties in Texas cannot effectively plan from a regulatory standpoint; in contrast, until very recently, counties in Florida have been required by the state to implement a prescriptive, regulatory comprehensive plan (Chapin *et al.*, 2007).

Our study may be the first to use ecologically based landscape metrics to examine the relationship between development form and flood losses. This is an important contribution to the field because it draws upon a wide scope of local and landscape measures with which quantitatively to assess development patterns for a variety of topics. While we hope the research methods and results provide insights on alternative ways of measuring and modelling development patterns, this work should be considered only a

Table 3. Landscape metrics and flood losses for high-intensity development

	Model 1 Beta	*Model 2 Beta*	*Model 3 Beta*	*Model 4 Beta*	*Model 5 Beta*
100-year floodplain	0.214**	0.202**	0.202**	0.209**	0.190**
Wetland change	0.159*	0.147	0.152	0.155*	0.160
Housing units	0.930**	2 0.066	0.171*	0.419**	0.208***
Median home value	0.270***	0.316***	0.307***	0.308***	0.281***
Precipitation	0.187**	0.183**	0.190**	0.182**	0.170**
Storm surge	0.212***	0.250***	0.223***	0.235***	0.231***
Soil permeability	2 0.171**	2 0.145*	2 0.147*	2 0.168*	2 0.139*
FEMA mitigation	2 0.009	2 0.024	2 0.027	2 0.029	2 0.031
CA high	2 0.683**				
NP high		2 0.024			
PD high			0.094		
PROX high				2 0.187	
Connect high					2 0.167
Constant	8.403***	8.102***	8.271***	8.409***	9.556***
	(0.93)	(1.994)	(0.975)	(0.983)	(1.22)
R^2	0.466	0.445	0.483	0.456	0.474
Degrees of freedom	134	134	134	134	134

Notes: *** p \ 0.01; ** p \ 0.05; * p \ 0.1.

starting-point for further examination of the topic. First, we examine only five landscape metrics as surrogates of development patterns. There are literally hundreds of additional measures that could be used to assess development patterns and the built environment. Future research should build on our initial set and include a larger array of metrics in analyses. Secondly, our study area is confined to the Gulf of Mexico coastline as defined by NOAA. Future study on the impact of the built environment on flood losses should consider a larger geographical area and the ability to compare coastal with inland regions. Thirdly, the spatial scale of our analysis is limited to the county or parish. Additional work must be done at a finer resolution, such as the neighbourhood level, to detect more localised nuances in the built environment and its form. Finally, we provide a 'high altitude' empirical analysis over multiple jurisdictions and a large geographical region. Future research should complement and confirm our findings with case-based qualitative assessment. Such an approach could provide a contextual understanding that is overlooked by broad-brush statistical analyses.

Note

1. See: www.sprawlcity.org.

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