doi:10.1111/j.0361-3666.2007.01024.x

Identifying the impact of the built environment on flood damage in Texas

Samuel D. Brody, Sammy Zahran, Wesley E. Highfield, Himanshu Grover, and Arnold Vedlitz[1]

Floods continue to pose the greatest threat to the property and safety of human communities among all natural hazards in the United States. This study examines the relationship between the built environment and flood impacts in Texas, which consistently sustains the most damage from flooding of any other state in the country. Specifically, we calculate property damage resulting from 423 flood events between 1997 and 2001 at the county level. We identify the effect of several built environment measures, including wetland alteration, impervious surface, and dams on reported property damage while controlling for biophysical and socio-economic characteristics. Statistical results suggest that naturally occurring wetlands play a particularly important role in mitigating flood damage. These findings provide guidance to planners and flood managers on how to alleviate most effectively the costly impacts of floods at the community level.

Keywords: built environment, flood damage, wetlands, Texas

Introduction

Despite the prevalence of policy and engineering measures to reduce the adverse impacts of floods, they remain one of the greatest threats to the property and safety of human communities in the United States among all natural hazards. The economic consequence of floods is estimated to be in the billions of dollars per annum (ASFPM, 2000). Peilke (1996) estimates flood losses between 1975 and 1994 alone at USD 67.5 billion (1992 dollars). These losses are being exacerbated by increasing development associated with residential, commercial and tourism activities, particularly in the coastal margin. Rising population density in coastal areas (Rappaport and Sachs, 2003) is accompanied by greater amounts of impervious surfaces (pavement and buildings, for instance), the alteration of hydrological systems (that is, watersheds), and an overall diminished capacity for these systems to hold and store surface water run-off naturally. As a result, communities, households and private property are increasingly vulnerable to damage from repetitive floods (Mileti, 1999). For example, Kunreuther and Roth (1998) estimate USD 22 billion in flood losses from 1949–88 in the US compared to USD 80 billion from 1989–97. This evident spike in flood-related property damage cannot be explained away by inflation in monetary systems.

While the importance of maintaining the integrity of hydrological systems is well understood, the degree to which the built environment affects the level of damage sustained by a community has never been thoroughly investigated at the regional level

Published by Blackwell Publishing, 9600 Garsington Road, Oxford, OX4 2DQ, UK and 350 Main Street, Malden, MA 02148, USA

(Peilke, 2000). Aside from small-scale case studies conducted within a single watershed or jurisdiction, no study to date has thoroughly tested the impact of the human built environment based on multiple flood events over time, at large spatial scales, and controlling for an array of biophysical and socio-economic characteristics.

Our study addresses this lack of research by examining the relationship between the built environment and flood impacts in the eastern portion of Texas. Texas is an ideal study area since it has consistently experienced the most deaths and damage from flooding of any state. Of the 42 flood events listed as causing more than USD 1 billion in damage between 1980 and 1998, four were in Texas (NCDC, 2000). According to Federal Emergency Management Agency (FEMA) statistics on flood insurance payments from 1978–2001, Texas suffered USD 2.25 billion in property loss, more than the states of California, Florida and New York (see http://www.fema.gov/business/nfip/).

First, we calculate property damage resulting from 423 flood events over a five-year period between 1997 and 2001 at the county level. Second, using multiple regression analysis, we identify the impact of several built environment measures, including wetland alteration, impervious surface, and dams, on reported property damage while controlling for biophysical and socio-economic characteristics. Results from our study provide important information for environmental planners and flood managers on how development of and modifications to natural landscapes adversely affect flood outcomes. Such information is critical given the continued development of coastal areas and the increasing vulnerability of human populations to inland coastal flooding. Our findings may thus provide guidance on how to build more sustainable, resilient communities in the long term.

The following section examines the existing literature on the relationship between the human built environment and flooding, specifically the introduction of impervious surfaces and the alteration of naturally occurring wetlands. Next, we describe our sample selection, variable measurement, and data analysis procedures. We then report our results based on a multivariate regression analysis of three groups of variables: built, natural, and socio-economic environments. Subsequent to the results section, we interpret our findings and discuss their policy implications for facilitating more sustainable and hazard-resilient communities. Finally, we describe the limitations of our research and suggest an agenda for future research on examining the effects of human development on flooding.

Adverse impacts of the built environment on flooding

Impervious surfaces

In the US, rapid growth and sprawling development patterns have contributed to a marked increase in urbanisation and built-up land. As of 2000, almost 80 per cent of the population resided in urban areas (U.S. Census Bureau, 2000). Between 1982 and 1997, there was a 34 per cent increase in the amount of land devoted to urban or built-up uses; this area is projected to rise by 79 per cent in the next 25 years, raising the proportion of the total land base that is developed from 5.2 to 9.2 per cent (Alig, Kline and Lichtenstein, 2004). Conversion of agricultural and forest lands to urban areas can diminish a hydrological system's ability to store and slowly release water, resulting in more severe flooding (Carter, 1961; Tourbier and Westmacott, 1981).

A major component of urbanisation and contributor to flood occurrence is the increase in impervious surfaces. The link between impervious surface coverage and floods was established in the late 1960s (Leopold, 1968; Seaburn, 1969). As the area of impervious surface coverage increases, there is a corresponding decrease in infiltration and a rise in surface run-off (Dunne and Leopold, 1978; Paul and Meyer, 2001). According to Arnold and Gibbons (1996), as the per cent catchment (that is, drainage basin) impervious surface cover increases to 10–20 per cent, run-off increases twofold. Most recently, White and Greer (2006) found that as urbanisation in the Peñasquitos Creek watershed in southern California rose from 9–37 per cent, total run-off increased by an average of four per cent per year. This yearly figure represents a rise of more than 200 per cent based on the authors' study period, 1973–2000. Greater surface run-off volume often results in increased frequency and severity of flooding in streams.

The urban built environment has also been linked to greater peak discharges (Leopold, 1994; Burges, Wigmosta and Meena, 1998; Brezonik and Stadelmann, 2002). In this instance, the lag time (time difference between the centre of precipitation volume and the centre of run-off volume) is compressed, resulting in floods that peak more rapidly (Hirsch et al., 1990). For example, Rose and Peters (2001) report peak discharge increases of approximately 80 per cent in urban catchments with a 50 per cent impervious area. Flood discharge in proportion to impervious surface cover was at least 250 per cent higher in urban compared to forested catchments in Texas and New York after similar storms (Espey, Morgan and Masch, 1965; Seaburn, 1969; Paul and Meyer, 2001). Examining mean peak discharges for 27 storms in the Croton River Basin in New York, Burns et al. (2005) observed a 300 per cent rise in a catchment with an impervious area of only 11.1 per cent. These studies demonstrate that urbanisation not only increases run-off volume, but also peak discharges and associated flood magnitudes.

Wetland alteration

One of the most significant ways in which impervious surface cover can exacerbate flooding is through the alteration or elimination of naturally occurring wetlands. The development of 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 also are believed to offer natural flood mitigation by 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. The results from these studies showed that undrained peat bogs reduce low-return period flood flow and overall storm flows in comparison to their drained counterparts (Verry and Boelter, 1978; Heikuranen, 1976; Daniel, 1981). Additional work relying primarily on linear regression analysis yielded similar results. For example, Conger (1971) demonstrated that the ability of wetlands to store water significantly reduced peak flows for recurrence intervals up to 100 years. Examining four different types of wetlands, Novitski (1979) found that each had a negative effect on flood flows. Novitski (1985) also concluded that basins with as little as a five per cent lake and wetland area may result in 40–60 per cent lower flood peaks.

More recent research utilising simulation models also demonstrates the flood-reducing role of wetlands. Ammon, Wayne and Hearney (1981) modelled the effects of wetlands on both the quantity and quality of water in Chandler Slough Marsh, south Florida. Results indicate that maximum flood peak attenuation is higher when there are increasing areas of marsh. The authors concluded that Chandler Slough Marsh increases storm water detention times, changes run-off regimes from surface to increased sub-surface regimes, and is 'moderately effective as a water quantity control unit' (Ammon, Wayne and Hearney, 1981, p. 326). Ogawa and Male (1986) also developed a simulation model to explore the preservation of wetlands as a flood mitigation strategy. Using four scenarios of downstream wetland encroachment ranging from 25–100 per cent 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. This report states that the effect of wetlands on peak flows for large floods along main rivers are inconclusive and that additional research is needed. In addition, using model simulations, Padmanabhan and Bengston (2001) found that wetland restoration in the Maple River watershed in North Dakota did 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 (Godschalk et al., 1999; Johnston, Detenbeck and Niemi, 1990). 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 (Godschalk et al., 1999). This study estimated that only 13 million acres of wetlands (three per cent of the upper Mississippi watershed) would have been needed to prevent the catastrophic flood of 1993. Other observational research suggests that there is a critical threshold for the effects of wetland loss on flood storage. For instance, in a study that utilised the record of stream flow data from stream gauge stations, Johnston, Detenbeck and Niemi (1990) found that small wetland losses in watersheds with less than 10 per cent of wetlands could have a significant effect on the degree of increased flooding.

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. A comprehensive review of the literature conducted by Bullock and Acreman (2003) showed that wetlands do play a major 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' (Bullock and Acreman, 2003, p. 366). Overall, research suggests that wetlands may reduce or slow downstream flooding.

Research methods and data analysis

Sample selection

As mentioned above, we selected for analysis 423 damaging flood events across a 37 county study area in eastern Texas between 1997 and 2001. This area is ideal for examining the impact of the built environment on inland flooding (excluding tidal or surge-based flooding) for the following reasons:

- Texas suffers significantly more property damage from floods than any other state in the country;
- these floods tend to be spatially repetitive over time;
- eastern Texas has been experiencing large increases in impervious surfaces and alteration of wetlands associated with rapid coastal development; and
- these development patterns vary spatially across counties.

Concept measurement

Dependent variable

The dependent variable, *flood property damage,* is measured as the total dollar loss (in consumer price index (CPI) adjusted 1997 United States dollars) from a flood event (see Table 1 for a summary of variable operations). This variable is log transformed to approximate a Gaussian distribution. Data on flood property damage were collected from the Spatial Hazard Event and Loss Database, US (SHELDUS) at the Hazards Research Lab, University of South Carolina, Columbia (Hazards Research Lab, 2006). The database consists of a county-level inventory of 18 natural hazard types, including drought, floods, hurricanes and wildfires. Each hazard event record includes a start and end date, estimated property loss, as well as the number of human injuries and deaths. Our property damage variable ranged from USD 1,000 to 69 million. It is important to note that dollar estimates of property loss from flooding are often obtained through 'windshield' observation or secondary reports that may underestimate or overestimate the true loss experienced by a property owner. While this is the best available information collected by the National Weather Service and we assume any error is unsystematic, the results should be interpreted with some level of caution. In addition, our property loss variable does not include indirect financial loss (such as loss of wages) from floods, which may prove to be a significant economic burden.

Table 1 Variable operations, data sources, and expected sign for flood-caused property damage

Variable name	Variable operation	Sign	Data source
Natural environment variables			
Precipitation (day of flood)	Average surface precipitation (inches) recorded by National Environmental Satellite, Data, and Information Service (NESDIS) weather stations in a county area on the day of the flood event	+	National Climate Data Center (NCDC), 1997–2001
Precipitation (day before flood)	Average surface precipitation (inches) recorded by NESDIS weather stations in a county area on the day before the flood event	+	NCDC, 1997–2001
Floodplain overlap	The percentage of a county area overlapping a FEMA-defined 100-year floodplain (where a flood has a 26 per cent chance of occurring in a 30-year period).	+/-	FEMA Digital Q3 Flood Data, 1999
Duration	Duration is measured dichotomously. Floods lasting more than one day are assigned a score of one (1), and floods lasting one day are assigned a score of zero (0)	+	SHELDUS, 2004
Built environment variables			
Dams	The total number of dams in a county area	-	US Army Corps of Engineers (USACE), 2004
Per cent impervious surface	Per cent of a county area covered by impervious surfaces. Impervious surface for each month is estimated using 1990 and 2000 digital data with even change assumed	+	Stennis Space Center, National Aeronautics and Space Administration, 1990–2000
Wetland alteration	Cumulative total of wetland permits issued from 1990 to the day of the flood event. Permits include: general permits, nationwide permits, letters of permission and individual permits	+	USACE, 2004
Socioeconomic variables			
FEMA rating	FEMA insurance premium discount scores for Special Flood Hazard Areas corresponding to flood damage reduction and mitigation classifications	-	FEMA Community Rating System, 2005
Median household income	Household income is the sum of money income received in calendar year 1999 by all household members of 15 years and over, including household members not related to the householder, people living alone and other non-family household members. Median household income for each month is estimated using 1990 and 2000 data with even change assumed	+	U.S. Census Bureau, Population and Housing Files, 1990–2000
Dependent variable			
Property damage (log)	Total property damage caused by a flood event as inventoried in SHELDUS. This variable is log transformed for non-normality		SHELDUS, 2004

Biophysical variables

To estimate properly the effect of the built environment on flood-related property damage, one must control for storm intensity and flood duration. In our model, we measure four biophysical predictors of flood damage: precipitation (day of the flood event); precipitation (day before the flood event); flood duration; and floodplain overlap. *Precipitation (day of the flood event)* and *precipitation (day before the flood event)* are measured as the average surface precipitation (in hundredths of an inch) recorded by county weather stations. The number of weather stations varies across counties and within a county longitudinally. Harris County has the highest number of weather stations (12). We collected daily surface precipitation data from the National Climate Data Center (NCDC)'s Climate Data Online search engine. Search results included latitude, longitude and altitude coordinates for weather stations, name and county location, and 'quality controlled' data on daily (24-hour observation period) surface precipitation. The highest precipitation total recorded for a flood event in our study was 14.11 inches in Jackson County in November 1998.

We measured *flood duration* as a dichotomous variable. A flood event was assigned a score of one (1) if it lasted more than one day, and a score of zero (0) if it lasted one full day or less. Duration estimates were derived from SHELDUS records on the start and end dates of a hazard event.

Floodplain overlap is calculated as the percentage of a county's area within a FEMA defined 100-year floodplain (delineated areas that have a one per cent chance of flooding in any one year) using Geographic Information Systems analytical techniques. Floodplain estimates were derived from FEMA Digital Q3 flood data. In our sample, Jefferson County had the highest percentage of its land area within the 100-year flood plain (approximately 60 per cent).

Built environment variables

We measured and analysed three built environment variables shown to affect the degree of community-wide flood damage. *Impervious surface* was calculated as the percentage of land covered by buildings and pavement, for instance, in a county area. An impervious surface data layer was made using GeoCover satellite imagery from the National Aeronautics and Space Administration (NASA)'s Stennis Space Center. Imagery from 1990 and 2000 was classified using several iterations of an unsupervised classification method. Digital Ortho Quarter Quads (DOQQ) imagery was used to confirm classification accuracy. We summed impervious surface area by county units for 1990 and 2000 and then calculated monthly values for the study period assuming an equal interval rate of change.

Wetland alteration is measured as the cumulative total of spatially defined wetland permits the day of a flood event. Wetland permits, required under Section 404 of the 1972 Clean Water Act, enable an applicant to alter a naturally occurring wetland for a construction project and were obtained from the US Army Corp of Engineers (USACE)'s District Office in Galveston, Texas. Permit records include permit type (general permits, nationwide permits, letters of permission and individual permits), the date of permit issuance, and the latitude/longitude coordinates of the permit approved development activity. Of the 10,921 permit records received from the USACE, 7,957 had sufficient information to be located geographically. The number of permits was then recorded cumulatively by county for each flood event. Finally, the number of *dams* in a county area was tabulated to estimate the extent to which water embankments function to reduce flood property damage. Locations of dams were obtained from the USACE and summed by each county unit. Harris County has four dams, the highest number in our sample.

Socio-economic variables

We measured two socio-economic predictors of flood property damage. *FEMA rating* scores are based on the FEMA Community Rating System (CRS). The CRS promotes mitigation of flood damage through insurance premium discounts and other financial incentives. To qualify for a FEMA discount, communities must enact measures that manage flood loss. Credit points are assigned for 18 measures organised into four broad categories of flood management: public information; mapping and regulation; flood damage reduction; and flood preparedness. Premium discounts correspond to credit points. Discounts range from five to 45 per cent and are applied to all written policies in a community. Communities with higher FEMA rating scores have implemented a greater number of the 18 flood mitigation measures and thus have received a higher premium discount for insurance coverage. In Texas, Galveston County has the highest FEMA rating, and thus enjoys a 15 per cent premium discount. To control for the economic status of a locality, we obtained income data from the U.S. Census Bureau's 1990 and 2000 Summary Tape Files.

Median household income is the sum of money income received in calendar year 1999 by all household members of 15 years and over, including household members not related to the householder, people living alone, and other non-family household members. We included household income in the statistical model to control for the degree of wealth and by proxy, the value of structures in each county. We presumed that wealthier communities have the financial capacity to mitigate flooding more effectively but at the same time can lose greater amounts of financial capital in damaging floods.

Data analysis

We analysed the data in two phases. First, we reported descriptive statistics related to the spatial and temporal pattern of flood damage over the five-year study period. Second, we used multiple regression analyses to estimate the effect of the built environment and various control variables on reported flood damage in eastern Texas. Tests for estimate reliability, including specification, multicollinearity and autocorrelation, exhibited no significant violation of regression assumptions. Based on statistical diagnostics, we did however detect heteroskedasticity in the data, leading us to analyse regression equations with robust standard errors.

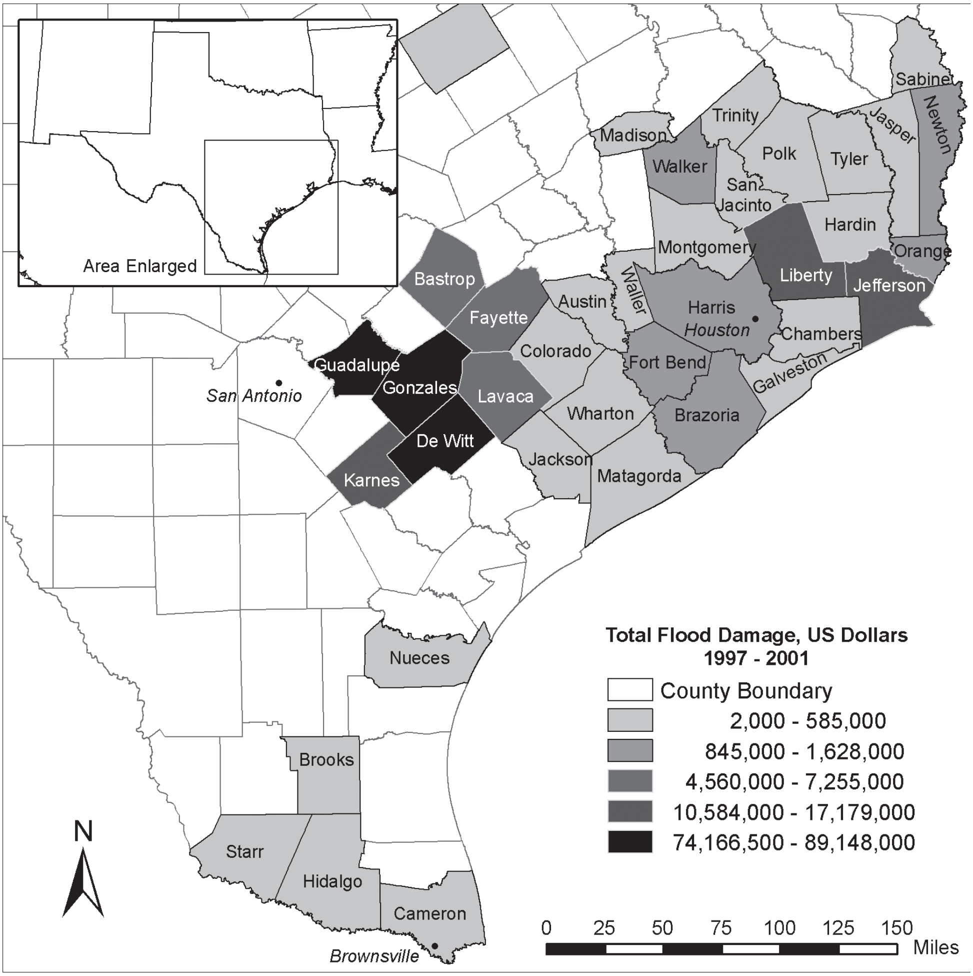
Table 2 Floods, property damage, and property damage per flood by Texas county, 1997–2001

Rank	County	Total floods	Total property loss	Average property loss
1	Guadalupe	20	89,100,000.00	4,457,400.00
2	Gonzales	23	88,900,000.00	3,867,022.00
3	DeWitt	33	74,200,000.00	2,247,470.00
4	Karnes	19	17,200,000.00	904,157.90
5	Jefferson	12	10,700,000.00	889,166.70
6	Liberty	12	10,600,000.00	882,000.00
7	Bastrop	12	7,255,000.00	604,583.30
8	Lavaca	34	6,653,000.00	195,676.50
9	Fayette	13	4,560,000.00	350,769.20
10	Harris	26	1,628,000.00	62,615.38
11	Newton	6	1,280,000.00	213,333.30
12	Brazoria	13	944,000.00	72,615.38
13	Fort Bend	10	926,000.00	92,600.00
14	Walker	12	882,000.00	73,500.00
15	Orange	17	845,000.00	49,705.88
16	Jasper	7	585,000.00	83,571.43
17	Hardin	6	555,000.00	92,500.00
18	Galveston	17	512,000.00	30,117.65
19	Polk	9	409,000.00	45,444.44
20	Montgomery	17	385,000.00	22,647.06
21	San Jacinto	16	319,000.00	19,937.50
22	Wharton	11	263,000.00	23,909.09
23	Jackson	10	255,000.00	25,500.00
24	Tyler	3	235,000.00	78,333.33
25	Chambers	9	217,000.00	24,111.11
26	Matagorda	4	206,000.00	51,500.00
27	Austin	11	196,000.00	17,818.18
28	Madison	9	180,000.00	20,000.00
29	Trinity	10	141,000.00	14,100.00
30	Colorado	10	117,000.00	11,700.00
31	Nueces	2	100,000.00	50,000.00
32	Starr	3	67,000.00	22,333.33
33	Sabine	1	45,000.00	45,000.00
34	Cameron	1	21,200.00	21,200.00
35	Waller	3	15,000.00	5,000.00
36	Brooks	1	10,000.00	10,000.00
37	Hidalgo	1	2,000.00	2,000.00
		423	**320,508,200.00**	**423,765.90**

Results

From 1997–2001, 423 flood events caused more than USD 320 million of reported property damage in Texas coastal counties. The average amount of damage per flood during this period was USD 423,765.90. Approximately 88.7 per cent of this damage occurred during a two-day tempest that began on 17–18 October 1998. This storm spread across much of the 37-county study area, from Galveston to Guadalupe County. Over the five-year study period, Guadalupe County incurred the most damage in the sample: approximately USD 89 million across 20 flood events (Table 2). Neighbouring Gonzales County experienced a similar degree of flood damage: almost USD 89 million across 23 events. In contrast, Hidalgo County reported the lowest amount of damage: USD 2,000 in only one event. Interestingly, the number of events does not always correspond to the amount of property damage. For example,

Figure 1 Cumulative flood damage from 1997–2001



Source: Environmental Planning and Sustainability Research Unit, Texas A&M University.

while Lavaca County experienced 34 flooding events during the study period, it reported only USD 6.6 million of property damage. Similarly, Harris County endured 26 flood events, but its total property damage was an estimated USD 1.6 million. Repetitive flood events caused most of the reported property damage to the west of the study area (within DeWitt, Karnes, Gonzales and Guadalupe Counties). Another geographic hotspot in terms of flood damage is located to the east in Liberty and Jefferson counties (see Figure 1).

Table 3 Ordinary Least Squares (OLS) regression models predicting property damage from floods in Texas, 1997–2001

	ß	Beta	ß	Beta	ß	Beta
Natural environment variables						
Precipitation (day of event)	.0515† (.0277)	.1636	.0464† (.0281)	.1476	.0473† (.0278)	.1504
Precipitation (day before event)	.1259** (.0336)	.3083	.1338** (.0342)	.3277	.1320** (.0338)	.3234
Floodplain overlap	.4516† (.2565)	.0665	.2177 (.2620)	.0320	.1748 (.2813)	.0257
Duration of flood	.4234** (.1311)	.1976	.4396** (.1327)	.2003	.4295** (.1311)	.2004
Built environment variables						
Impervious surface			.0100† (.0052)	.0826	.0085† (.0050)	.0702
Wetland alteration			.0004** (.0001)	.1161	.0005** (.0002)	.1581
Dams			-.0723* (.0401)	-.1061	-.0644† (.0392)	-.0944
Socioeconomic variables						
FEMA rating					-.0184† (.0102)	-.1073
Median household income					6.3e-06 (5.1e-06)	.0604
Constant	3.8428** (.0769)		3.7502** (.0857)		3.5867** (.1676)	
N	423		423		423	
F	20.80		15.96		12.88	
Probability > F	.000		.000		.000	
R-squared	0.2984		.3130		.3189	
Root Mean Square Error (MSE)	.71384		.70891		.70756	

Notes:
Robust standard errors are in parentheses.
Null test of coefficient equal to zero, †p<.10, *p<.05; **p<.01.

Multivariate regression analyses with standardised coefficients indicated which factors most influence the degree of flood damage in eastern Texas (Table 3). We added the following three suites of variables sequentially to the model to test their effects both individually and as a group: biophysical; built; and socio-economic environments. Biophysical variables as a whole explain the most variance on the dependent variable (more than 29 per cent). Adjusting for precipitation the day of the flood event, rainfall amount the day before the actual flood event is the strongest predictor of damage, followed by the duration of a flood (where $p<.05$). Precipitation the day of the flood event and the percentage of a county within the 100-year floodplain are, by comparison, weaker yet still statistically significant predictors of flood damage (where $p<.1$).

With the addition of human-built environmental factors to the model, the floodplain variable is no longer statistically significant at the .1 level. Increasing amounts of wetland alteration (the majority of which are located within the 100-year floodplain), correspond to a significant increase in reported property damage ($p<.01$). Of the built environment variables examined, wetland alteration is the strongest partial correlate of flood property damage (ß = .1161). Increasing amounts of impervious surfaces within each county also contribute to marked increases in flood damage (where $p<.1$). The presence of dams as flood control devices appears to reduce the amount of damage ($p<.1$) almost to the same degree to which damage is exacerbated by wetland alteration (ß = -.1061). In effect, what is gained by dams in the mitigation of flood outcomes is statistically offset by development activities in wetlands.

In the fully specified model containing socioeconomic variables, approximately 32 per cent of the variation in flood-related property damage is explained. Counties with higher FEMA CRS scores and corresponding reductions in insurance premiums experience lower amounts of flood damage at the .1 level of significance. The effect size of the variable FEMA rating (ß = -.1073), summarising the flood mitigation efforts undertaken by a locality, rivals the effect size of precipitation the day of a flood event (ß = -.1504). Increasing amounts of precipitation the day before the actual flood event remain the strongest predictor among the biophysical variables examined. Wetland alteration continues to have the largest effect on the dependent variable among built environment variables (ß = -.1581). The predictive power of the number of dams within a county, representing structural solutions to flood mitigation, decreases (ß = -.0944, $p<.1$) with the addition of socio-economic controls.

Discussion

Analysis of the data indicates that specific characteristics of the human built environment in eastern Texas have an important influence on property damage resulting from floods, even when controlling for biophysical and socio-economic factors. These findings provide guidance to planners and flood managers on how to mitigate most effectively the costly impacts of floods at the community level.

First, as expected, flood damage is largely governed by the amount and duration of precipitation associated with a given storm. Yet, our data show that the *timing* of precipitation is particularly important in terms of its effect on the amount of property loss. Heavy precipitation the day before the actual flood event is by far the strongest predictor of total property damage. This result may be a function of the delay between initial rainfall and the rise in water levels. In addition, saturated soil due to heavy rainfall can transform even modest amounts of precipitation during subsequent days into damaging flood events. In other words, the amount of rainfall before a flood event weakens the absorption capacity of hydrologic systems, increasing the probability and extent of property damage the day of the flood event. Even in urban areas where this lag time to peak discharge is shortened by increased run-off volumes, it is important for decision-makers and the public to understand that heavy precipitation followed by sunny skies can still result in significant flood damage the next day. This finding contrasts with a related study that finds a negative association between precipitation the day before a flood event and the number of human casualties, perhaps due to the surprise effects of flash floods and other sudden storm-related events (Zahran et al., forthcoming). Reacting to the relatively slow onset of floodwaters may thus enable communities to reduce property loss.

Second, our results show that the alteration of naturally occurring wetlands is the most important built environment indicator of flood damage. Impervious surfaces have long been criticised for their contribution to increased flooding and associated damage. However, the most significant impact may not depend solely on the total amount of imperviousness in a watershed or drainage basin, but rather on where exactly these built surfaces are placed. Altering or removing a wetland to construct car parks, roads and rooftops, for instance, effectively eliminates its ability to capture, hold and store water run-off. This general trend is evident when looking more closely at our data. For example, 3.15 inches of rainfall in October 1997 caused approximately USD 15,000 of reported damage in De Witt County, where at the time only five wetland-altering permits had been granted. Four years later, when there were 17 wetland alteration permits, roughly the same amount of rainfall caused USD 150,000 of damage. Similarly, 1.5 inches of rainfall in April 1997 caused some USD 50,000 of reported damage in Wharton County, where 17 wetland alteration permits had been issued up until that point. Four years later, with 26 wetland development activities permitted, more or less the same amount of rainfall caused USD 100,000 of damage. Finally, a rainfall event of 0.09 inches in April 1997 caused USD 5,000 of property damage in Galveston County, where 546 wetland permits had been issued up until that point. In September 2000, the same amount of precipitation caused USD 100,000 of damage. At this time, 921 wetland permits had been issued.

Disrupting the natural hydrological system can exacerbate flooding or create flood problems in areas not originally considered vulnerable to this hazard. Thus, developments initially believed to be safe from flood threats become an unexpected target of expensive flood damage over time. If wetlands serve as a natural flood mitigation device, this positive function should be appraised by local land use and zoning ordinances before regional developments takes place. The planning goal in this situation is to allow development to proceed without reducing the hydrological function and value of wetland systems. Achieving this objective will involve identifying the location of naturally occurring wetlands and then protecting these critical areas through local land use policies, such as zoning restrictions, land acquisition programmes, clustered development, density bonuses, and transfer of development rights (see Brody and Highfield, 2005). Such a proactive approach may result in net economic benefits to a locality by reducing costs related to both repair of damaged structures and engineering solutions (for example, culverts, retention ponds and storm drains) used to mitigate floods when the natural systems are compromised.

Third, structural solutions to flood mitigation significantly reduce flood damage, as evidenced by the performance of our variable measuring the number of dams in each county. However, based on the standardised coefficients in our fully specified model, wetlands may be more effective than dams in mitigating property loss over time. Dams are also extremely costly mitigation alternatives, can exacerbate development in flood-prone areas out of a false sense of security (Harding and Parker, 1974; Tobin, 1995; Pielke, 1999), and can present a hazard in themselves in the case of structural failure.

Fourth, our empirical results suggest that mitigation measures under FEMA's CRS programme reduce property damage from floods. Communities that engage in mitigation activities related to public information, mapping and regulations, and flood damage reduction in exchange for reduced flood insurance premiums experience significantly lower amounts of flood-related property damage at the .1 level of significance. In fact, the effect of CRS participation appears to reduce community-wide flood damage more than dams, which are far more costly. This finding lends support to the implementation of non-structural mitigation strategies to reduce community-wide flood damage. Strong mitigation initiatives may partly explain why our floodplain measure does not perform as strongly as anticipated in fully specified models. We speculate that counties with a greater percentage of flood-prone areas are also better prepared for the damaging effects of floods (there is in fact a significantly positive association between CRS participation and the percentage of floodplains within a county).

In addition to comparing the relative effects of predictor variables on flood damage (by interpreting standardised coefficients), because our dependent variable is measured in dollar figures, we can address the questions: *what is the price of a wetland permit and what are the economic tradeoffs of various mitigation measures?* Based on our fully specified model, a single wetland permit translates into an average of USD 211.88 in additional property damage per flood. Likewise, 10 permits issued correspond, on average, to approximately USD 2,188 in added property damage per flood. By comparison, the presence of a dam results in a USD 27,290 decrease in average property damage for each flood event in our sample. This means that, on average, only 129 wetland alteration permits offset the flood-reducing effects of dams. Given the expense of building dams, their negative environmental ramifications, and the possibility of structural failure, protecting naturally occurring wetlands may be a more rational policy alternative.

The economic gains obtained by non-structural mitigation measures are also evident for those counties participating in the FEMA CRS programme. Based on our results, a unit increase in FEMA rating produces a 1.84 decrease in average flood cost. In dollar terms, this equals USD 7,797 less in property damage per flood. Because FEMA scores move in five per cent increments, a real unit increase in FEMA rating corresponds to a USD 38,989 reduction in average cost per flood. If all localities in our sample achieve the maximum premium discount of 45 per cent, the average damage of a flood is reduced to less than USD 100,000, roughly a quarter of the average flood in our study. Consequently, mitigation is an essential component of any flood reduction programme aimed at protecting the property and safety of communities.

Conclusion

Our study provides evidence that flood damage is not solely a function of rainfall, but also is driven by the scale and type of human development. Furthermore, property damage is influenced not so much by how much is built, but precisely where within an ecological system development unfolds. Location-based development decisions thus become critical in mitigating property damage from floods in the future. As stated by the Task Force on Federal Flood Control Policy (TFFFCP) in 1966, 'floods are an act of God; flood damages result from the acts of [people]' (TFFFCP, 1966, p. 14). Assuming that communities have a choice as to where and how they develop, decision-makers would be wise to build places to live, work, and recreate that simultaneously maintain the functionality of hydrological systems and the flood moderating features of naturally occurring wetlands.

Although this study offers some important insights into the relationship between the human built environment and flood damage, it should be considered a first step in understanding the topic more fully. Further research is needed on several fronts. First, our study is limited by relying on counties as the unit of analysis. Although many variables, including flood damage, are collected only at the county jurisdictional level, it is an administrative unit that does not conform to functioning hydrological systems. Future studies could focus on the watershed level to account better for upstream and basin-wide effects (see Brody et al., 2007). Second, our study examines only a five-year time span. Future research should consider a broader historical time frame even if it limits analyses to a single watershed. Third, our study includes only a few measures of the built environment. Future research could examine additional ones, such as building permits and infrastructure projects, to understand better the impact of physical development on flood outcomes. Finally, we rely on reported flood damage estimates as our dependent variable. Additional work could triangulate data from stream gauge records to ensure greater measurement precision.

Acknowledgements

This article is based on research supported in part by US National Science Foundation Grant No. CMS- 0346673 and the Institute for Science, Technology and Public Policy at Texas A&M University. The findings and opinions reported are those of the authors and are not necessarily endorsed by the funding organisations or those who provided assistance with various aspects of the study.

Correspondence

Samuel D. Brody, Associate Professor and Director, Environmental Planning and Sustainability Research Unit, Hazard Reduction and Recovery Center, Department of Landscape Architecture and Urban Planning, Texas A&M University, TAMU 3137, College Station, Texas 77843-3137, US. Telephone: +979 458 4623; fax: +979 845 5121; e-mail: sbrody@archmail.tamu.edu.

Endnotes

[1] Samuel D. Brody is an Associate Professor and Director of the Environmental Planning and Sustainability Research Unit, Hazard Reduction and Recovery Center, Department of Landscape Architecture and Urban Planning, Texas A&M University, US; Sammy Zahran is an Assistant Professor at the Department of Sociology, Colorado State University, US; Wesley E. Highfield is a research assistant at the Environmental Planning and Sustainability Research Unit, Hazard Reduction and Recovery Center, Department of Landscape Architecture and Urban Planning, Texas A&M University, US; Himanshu Grover is a research assistant at the Environmental Planning and Sustainability Research Unit, Hazard Reduction and Recovery Center, Department of Landscape Architecture and Urban Planning, Texas A&M University, US; Arnold Vedlitz is a Professor and the Director of the Institute for Science, Technology, and Public Policy, George Bush School of Government and Public Service, Texas A&M University, US.

References

Alig, R.J., J.D. Kline and M. Lichtenstein (2004) 'Urbanization on the US landscape: looking ahead in the 21st century'. *Landscape and Urban Planning.* 69(2–3). pp. 219–234.

Ammon, D.C., H.C. Wayne and J.P. Hearney (1981) 'Wetlands' Use for Water Management in Florida'. *Journal of Water Resources Planning and Management.* 107(WR2). pp. 315–327.

Arnold, L.A. and C.J. Gibbons (1996) 'Impervious Surface Coverage—the emergence of a key environmental indicator'. *Journal of the American Planning Association.* 62(2). pp. 243–258.

ASFPM (Association of State Floodplain Managers) (2000) *National Flood Programs in Review – 2000.* ASFPM, Madison, WI.

Brezonik, P.L. and T. H. Stadelman (2002) 'Analysis and Predictive Models of Stromwater Runoff Volumes, Loads and Pollutant Concentrations from Watersheds in the Twin Cities Metropolitan Area, Minnesota, USA'. *Water Resources.* 36. pp. 1743–1757.

Brody, S.D. and W.E. Highfield (2005) 'Does Planning Work? Testing the Implementation of Local Environment Planning in Florida'. *Journal of the American Planning Association.* 71(2). pp. 159–176.

Brody, S.D., W.E. Highfield, H. Ryu and L. Spanel-Weber (2007) 'Examining the Relationship between Wetland Alteration and Watershed Flooding in Texas and Florida'. *Natural Hazards.* 40(2). pp. 413–428.

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

Burges, S.J., M.S. Wigmosta and J.M. Meena (1998) 'Hydrological Effects of Land-Use Change in a Zero-Order Catchment'. *Journal of Hydrological Engineering.* 3(2). pp. 86–97.

Burns, D. et al. (2005) 'Effects of Suburban Development on Runoff Generation in the Croton River Basin, New York, USA'. *Journal of Hydrology.* 311. pp. 266–281.

Carter, R.W. (1961) 'Magnitude and Frequency of Floods in Suburban Areas'. *Short Papers in Geologic and Hydrologic Sciences.* U.S. Geological Survey (USGS) Professional Paper 424-B. pp. B9–B11.

Conger, S. (1971) *Estimating magnitude and frequency of floods in Wisconsin, U.S.* Geological Survey open-file report. US Geological Survey, Madison, WI.

Daneil, C., III. (1981) 'Hydrology, geology and soils of pocosins: a comparison of natural and altered systems'. In C.J. Richardson, M.L. Matthews and S.A. Anderson (eds.) *Pocosins: a Conference on Alternative Uses of the Coastal Plain Freshwater Wetlands of North Carolina.* Hutchinson Ross Publishing Co., Stroudsburg, PA. pp. 69–108.

Dunne, T. and L.B. Leopold (1978) *Water in Environmental Planning.* Freeman, New York. p. 818.

Espey, W.H., C.W. Morgan and F.D. Masch (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.

Godschalk, D.R., T. Beatley, P. Berke, D. J. Brower and E. J. Kaiser (1999) *Natural Hazard Mitigation: Recasting Disaster Policy and Planning,* Island Press, Washington, DC.

Harding, D. and D. Parker (1974) 'Flood Hazards at Shrewsbury, United Kingdom'. In Gilbert F. White (ed.) *Natural Hazards: Local, National, and Global.* Oxford University Press, New York. pp. 43–52.

Hazards Research Lab (2006) 'The Spatial Hazard Events and Losses Database for the United States, Version 4.1'. University of South Carolina, Columbia, SC. http://www.sheldus.org.

Heikuranen, L. (1976) 'Comparison between runoff condition on a virgin peatland and a forest drainage area'. *Proceedings of the Fifth International Peat Congress.* International Peat Society, Iyvaskyla. pp. 76–86.

Hirsch, R.M., J.F. Walker, J.C. Day and R. Kallio (1990) 'The Influence of Man on Hydrological Systems'. In M.G. Wolman and H.C. Riggs (eds.) *Surface Water Hydrology.* Vol. 0-1. Geological Society of America, Boulder, CO. pp. 329–359.

Johnston, C.A., N.E. Detenbeck and G.J. Niemi (1990) 'The cumulative effect of wetlands on stream water quality and quantity. A landscape approach'. *Biogeochemistry.* 10(2). pp. 105–141.

Kunreuther, H.J. and R.J. Roth (1998) *Paying the Price: The Status and Role of Insurance Against Natural Disasters in the US.* John Henry Press, Washington, DC.

Leopold, L.B. (1968) *Hydrology for Urban Planning—a guidebook on the hydrologic effects of urban land use.* USGS Circular 554. 18 pp.

Leopold, L.B. (1994) *A View of the River.* Harvard University Press, Cambridge, MA.

Lewis, W.M. (2001) *Wetlands Explained: Wetland Science, Policy, and Politics in America.* Oxford University Press, New York.

Mileti, D.S. (1999) *Disasters by Design: A reassessment of natural hazards in the United States.* Joseph Henry Press, Washington, DC.

Mitch, W.J. and J.G. Gosselink (2000) *Wetlands.* 3rd edn. John Wiley & Sons, New York.

NCDC (National Climatic Data Center) (2000) 'Billion Dollar U.S. Weather Disasters'. http://www.ncdc.noaa.gov/ol/reports/billionz.html.

Novitski, R.P. (1979) 'Hydrologic characteristics of Wisconsin's wetlands and their influence on floods, streamflow, and sediment'. *Proceedings of a Conference on Wetland Functions and Values: The State of our Understanding.* American Water Resources Association, Bethesda, MD. pp. 377–388.

Novitski, R.P. (1985) 'The effects of lakes and wetlands on flood flows and base flows in selected northern and eastern states'. *Proceedings of a Conference on the Wetlands of the Chesapeake, Easton, Maryland.* Environmental Law Institute, Washington, DC. pp. 143–154.

Ogawa, H. and J.W. Male (1986) 'Simulating the Flood Mitigation Role of Wetlands'. *Journal of Water Resources Planning and Management.* 112(1). pp. 114–128.

Padmanabhan, F.G., and M.L. Bengston (2001) 'Assessing the influence of wetlands on flooding'. *Proceedings of a Conference on Wetlands Engineering and River Restoration.* American Society of Civil Engineers (ASCE), Reston, VA. pp. 1–12.

Paul, M.J. and J.L. Meyer (2001) 'Streams in the Urban Landscape'. *Annual Review of Ecological Systems.* 32. pp. 333–365.

Peilke, R.A. (1996) *Midwest Flood of 1993: Weather, Climate, and Societal Impacts.* National Center for Atmospheric Research, Boulder, CO.

Peilke, R.A. (1999) 'Nine Fallacies of Floods' *Climatic Change.* 42(2). pp. 413–438.

Peilke, R.A. (2000) 'Flood Impacts on Society: Damaging floods as a framework for assessment'. In D.J. Parker (ed.) *Floods.* Routledge, London and New York. pp. 133–155.

Rappaport, J. and J. Sachs (2003) 'The United States as a coastal nation'. *Journal of Economic Growth.* 8(1). pp. 5–46.

Rose, S. and N. Peters (2001) 'Effects of Urbanization on Streamflow in the Atlanta Area (Georgia, USA): a comparative hydrological approach' *Hydrological Proceedings.* 15(8) pp. 1441–1457.

Seaburn, G.E. (1969) *Effects of Urban Development on Direct Runoff to East Meadow Brook, Nassau County, Long Island, New York.* USGS Professional Paper 627-B. 14 pp.

TFFFCP (Task Force on Federal Flood Control Policy) (1966) *A Unified National Program for Managing Flood Losses.* Report No. 67-663. US Government Printing Office, Washington, DC.

Tobin, G.A. (1995) 'The Levee Love Affair: A Stormy Relationship'. *Water Resources Bulletin.* 31(3). pp. 359–367.

Tourbier, J.T. and R. Westmacott (1981) *Water Resources Protection Technology: A handbook of measures to protect water resources in land development.* The Urban Land Institute, Washington, DC.

U.S. Census Bureau (2000). http://www.census.gov/main/www/cen2000.html (accessed 26 July 2006).

Verry, E.S. and D.H. Boelter (1979) 'Peatland Hydrology'. In P.E. Greeson, J.R. Clark and J.E. Clark (eds.) *Wetland Functions and Values: the State of our Understanding.* American Water Resources Association, Minneapolis, MN. p. 389.

White, M.D. and K.A. Greer (2006) 'The Effects of Watershed Urbanization on the Stream Hydrology and Riparian Vegetation of Los Peñasquitos Creek, California'. *Landscape and Urban Planning.* 74(2). pp. 125–138.

Zahran, S., W.G. Peacock, H. Grover and A. Vedlitz (forthcoming) 'Social Vulnerability, Natural, and Built Environments: Flood Casualties in Texas, 1997–2001'. *Disasters.*