doi:10.1111/j.0361-3666.2008.01054.x

Social vulnerability and the natural and built environment: a model of flood casualties in Texas

Sammy Zahran, Samuel D. Brody, Walter Gillis Peacock, Arnold Vedlitz and Himanshu Grover[1]

Studies on the impacts of hurricanes, tropical storms, and tornados indicate that poor communities of colour suffer disproportionately in human death and injury.[2] *Few quantitative studies have been conducted on the degree to which flood events affect socially vulnerable populations. We address this research void by analysing 832 countywide flood events in Texas from 1997–2001. Specifically, we examine whether geographic localities characterised by high percentages of socially vulnerable populations experience significantly more casualties due to flood events, adjusting for characteristics of the natural and built environment. Zero-inflated negative binomial regression models indicate that the odds of a flood casualty increase with the level of precipitation on the day of a flood event, flood duration, property damage caused by the flood, population density, and the presence of socially vulnerable populations. Odds decrease with the number of dams, the level of precipitation on the day before a recorded flood event, and the extent to which localities have enacted flood mitigation strategies. The study concludes with comments on hazard-resilient communities and protection of casualty-prone populations.*

Keywords: built environment, casualties, floods, social vulnerability

Introduction

Floods are the most lethal kind of hydro-meteorological disaster in the United States. According to data from the Spatial Hazard Events and Losses Database for the United States (SHELDUS), floods claimed the lives of 2,353 persons from 1970–2000. Over this period, fewer people were killed by hurricanes, tropical storms, and tornados combined. The Federal Emergency Management Agency (FEMA) estimates that flood events are responsible for the deaths of more than 10,000 persons in the US since 1900.[3] Increasingly, scholars note that the risk of death by natural disaster is greater in localities with higher percentages of socially vulnerable or disadvantaged populations (Thomas and Mitchell, 2001; Cutter, 1996; Cutter, Boruff and Shirley, 2003). Hurricanes Katrina (August 2005) and Rita (September 2005) appear to substantiate the claim that disasters inflict unequal harm by minority and income status. Research on the human costs of hurricanes, tropical storms, and tornados indicates that poor communities of colour suffer disproportionately in terms of human death and injury (Bates et al., 1962; Wright et al., 1979; Peacock, Dash and Zhang, 2006; Fothergill and Peek, 2004). However, few quantitative studies exist on the degree to which flood events affect socially vulnerable populations differently.

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

We address this lack of research on the intersection of flood outcomes and population characteristics by analysing 832 flood events at the county scale in Texas from 1997–2001. Specifically, we examine whether geographic localities characterised by high percentages of socially vulnerable populations experience significantly more casualties due to flood events, adjusting for characteristics of the natural and built environment. Texas is an ideal study area because it consistently outranks all states in deaths, injuries, and property loss resulting from flood events. Between 1960 and 1995, Texas reported 612 fatalities in flood events—by far the most of any state. According to the Centers for Disease Control and Prevention (CDC), the crude death rate in Texas by cataclysmic storms and floods is more than double the national rate (11.1 versus 4.4 per 10 million persons). From a demographic standpoint, Texas is an ideal study area because it is racially heterogeneous and highly segregated by race and income, creating a perfect testing ground for social vulnerability hypotheses.

Our investigation of flood casualties is organised in four sections. First, we examine the literature on disaster vulnerability from a social science perspective to derive testable propositions on the socioeconomic and natural and built environment variables that predict flood casualties. Second, we discuss elements of research design, including unit of analysis, variable measurement, and statistical procedures. Third, data analyses are presented, beginning with descriptive statistics and ending with zero-inflated negative binomial (ZINB) regression models. Fourth, we describe the limitations of our research and suggest future lines of inquiry into the relationship between natural hazards and their impacts on socially vulnerable communities.

Literature review

From physical to social vulnerability

In the disaster literature, the concept of vulnerability refers to a technical assessment of a population's susceptibility to the harmful consequences of a disaster event (Cutter, 1996; Mitchell, 1989; Deyle et al., 1998). Impacts include damage to private property, infrastructure, economic vitality, habitat, and productive ecosystems, as well as human death and injury. Traditionally, vulnerability assessments focused on the physical or structural properties of a hazard, and on features of the natural and built landscape, such as proximity to water bodies, fault lines, floodplains, wind fields, and the resilience of built surfaces and structures to hazard impacts. With regard to flood disasters, hydrologic or physical variables such as the amount of rainfall and flood duration, and built environment characteristics such as the presence of water embankments and the permeability and slope of built surfaces, are standard vulnerability predictors. Historically, engineering solutions such as strengthening or raising buildings, adding fill, and constructing dams, levees, or sea walls were promoted to reduce vulnerability to hydro-meteorological hazards.

Proximity or exposure to a hazard agent, the nature of the hazard itself, built environment characteristics, and engineering solutions are critically important in assessing and addressing population vulnerabilities to hazard impacts. However, towards the end of the twentieth century researchers began to question the unequal distribution of disaster effects within a population, with some localities and population subgroups afflicted disproportionately by disaster outcomes (Cochrane, 1975; Bates et al,, 1962; Bolin, 1976; 1982; 1985; 1986; Bolin and Bolton, 1986; Bates and Peacock, 1987). These scholars advanced a new dimension of vulnerability that focused on the social and economic forces that shape disaster outcomes, leading to the widespread adoption of the term social vulnerability (SV).

In their classic work, *At Risk: Natural Hazards, People's Vulnerability, and Disasters,* Blaikie et al. (1994, p. 9) define SV as 'the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impacts of a natural hazard. [Social vulnerability] involves a combination of factors that determine the degree to which someone's life and livelihood are put at risk'. In other words, SV is defined by the possession of social attributes that increase susceptibility to disasters. Social vulnerability scholars examine why types of persons locate in hazardous places, live in inadequate homes, fail to anticipate, resist, and/or recover from the aftermath of a disaster, and analyse the economic and social forces that mould and determine these dynamics. These dimensions of SV are particularly germane in predicting spatial variation in flood casualties.

The research literature on SV is diverse, addressing a variety of hazards and attributes of social vulnerability, including race and ethnicity (Bolin, 1986; Bolin and Bolton, 1986; Perry and Mushkatel, 1986; Peacock, Morrow and Gladwin, 1997; Bolin and Stanford, 1998; Fothergill, Maestas and Darlington, 1999; Lindell and Perry, 2004), and measures of economic status such as wealth, income, and poverty (Peacock, Morrow and Gladwin, 1997; Dash, Peacock and Morrow, 1997; Fothergill and Peek, 2004). Because the literature on floods and SV is underdeveloped, particularly when compared to earthquakes or hurricanes, we review research on a variety of hazards and highlight results pertinent to the relationship between SV and flood casualties. In light of our empirical interest in flood casualties, we confine our literature review to front-end phases of a disaster event, including preparedness, warning communication and response, and physical impacts.[4]

Social vulnerability and phases of a disaster event

Preparedness refers to actions taken before a disaster event to reduce the expected ramifications. The literature suggests that socially vulnerable or disadvantaged households have lower levels of disaster preparedness. For example, Turner, Nigg and Heller-Paz (1986), Farley (1998), Edwards (1993), Russell, Goltz and Bourque (1995), and Mileti and Darlington (1997) all find that earthquake preparedness (that is, possession of first-aid kits, emergency food supplies, evacuation plans, and fire extinguishers) is less common in low income and minority populations. Peacock (2003) finds that both low income and Black households are less likely to have adequate shuttering to protect homes from hurricane damage. Similarly, Norris, Smith and Kaniasty (1999) note that Black households have constrained access to hurricane preparedness supplies. Scholars also observe that minority and lower income homeowners are less likely to hold earthquake (Blanchard-Boehm, 1998) and flood insurance instruments (Fothergill, 2004). Few studies contradict the observed relationship between disaster preparedness and social vulnerability (see Ives and Furuseth, 1983; Gladwin and Peacock, 1997; Lindell and Perry, 2000).

Studies of disaster *communication and response* suggest that minority and low income households are less likely to receive and believe official disaster warnings (Perry and Lindell, 1991; Perry and Mushkatel, 1986; Fothergill and Peek, 2004). To the extent that timely receipt and acceptance of a disaster warning limits the odds of human death and injury, socially vulnerable populations face higher risk (Perry and Mushkatel, 1986; Phillips and Ephraim, 1992; Perry and Nelson, 1991; Morrow, 1997; Perry and Lindell, 1991; Perry, Lindell and Green, 1982). Research also shows that low income and minority groups are less likely to act on evacuation orders, particularly with regard to flood events (Perry, Lindell and Greene, 1981). Lindell and Perry (2004, p. 90) maintain that persons of low human capital (that is, income and education) are less likely to obey evacuation orders, 'due to restricted material resources, knowledge, and skill'. Gladwin and Peacock (1997), in a large multivariate analysis of households in hurricane evacuation zones, find that low income and Black households are less likely to act on evacuation calls. They speculate that resource constraints, particularly the lack of privately owned vehicles, ineffective public transportation options, and few refuge alternatives outside of the evacuation zones explain the failure of low income and Black households to leave their homes.

Studies on the *physical impacts* of a disaster event clearly indicate that socially vulnerable populations suffer disproportionately in terms of property damage, injury, and death. On the physical consequences of Hurricane Audrey (June 1957), Bates et al. (1962) discovered significantly higher death rates for Blacks (322 deaths per 1,000) compared to Whites (38 deaths per 1,000). Wright et al. (1979) find that lower income households experience significantly higher rates of injury, particularly with regard to flood and earthquake events. Numerous studies indicate that socially vulnerable populations suffer greater property loss in disaster events. Scholars theorise that minority citizens are affected unevenly by disasters because they are more likely to reside in older, poorer, high-density, segregated, and disaster-prone areas (Foley, 1980; Bolin, 1986; Bolin and Bolton, 1986; Cochrane, 1975; Logan and Molotch, 1987; Massey and Denton, 1993; Phillips, 1993; Phillips and Ephraim, 1992; Peacock and Girard, 1997; Charles, 2003; Peacock, Dash and Zhang, 2006). Fothergill and Peek (2004) note that nearly 40 per cent of all tornado fatalities occur in mobile-home parks, which are significantly more likely to house persons of lower income.

Overall, research on the social attributes of disaster vulnerability indicates that disaster events differentially harm minorities and the poor. This does not mean that Blacks, Latinos, and the poor are intrinsically vulnerable. For reasons of economic disadvantage, lower human capital, limited access to social and political resources, residential choices, and evacuation dynamics are the social factors that contribute to observed differences in disaster vulnerability by race/ethnicity and economic class.

Social vulnerability in aggregate analysis

While the above discussion on social vulnerability indicates that minority status and income are important predictors of human death and injury in natural disasters, this research is far from conclusive. Many of the studies examined use descriptive and bivariate methods, focus on a single disaster event, and operate at the household or individual level of analysis. Although pioneering, many of these studies insufficiently address features of the social and physical environment shared by all residents of a locality, such as latitude and climate, public services, and socioeconomic characteristics that shape disaster outcomes and their pattern. The effects of the social and physical environment on disaster outcomes are observable at higher levels of aggregation and across a population of disaster events. Not until the late twentieth century did disaster research move towards systematic application of SV perspectives at the community level (see Morrow, 1999; Dash, Peacock and Morrow, 1997; Wright et al., 1979; Friesema et al., 1979).

Susan Cutter and colleagues are one of a few research groups to apply systematically SV perspectives at aggregate levels, ranging from counties to states (Cutter, Mitchell and Scott, 2000; Cutter, Boruff and Shirley, 2003; Boruff, Emrich and Cutter, 2005). Cutter, Boruff and Shirley (2003) assembled a set of 85 indicators of SV, ranging from age (median) to social security receipts per capita for more than 3,000 counties in the US in 1990. In our research, we adopt a more parsimonious approach to estimate the relationship between SV and flood casualties. We focus on two key dimensions of social vulnerability emphasised in the literature: minority and economic status. Moreover, in Texas, other indicators of social disadvantage from percentage of female-headed households with children to percentage of residents on public assistance correlate very highly with minority and economic status—including these other indicators is statistically redundant.

In addition to SV estimates, we include indicators of the hazard's physical characteristics and measures of the built environment. We test the salience of SV, as a determinant of flood causalities after controlling for dimensions of physical and structural vulnerability. Our major theoretical hypothesis is that *higher levels of social vulnerability result in higher casualties due to flooding in Texas counties, adjusting for characteristics of the natural and built environment.*

Research design

Scope and procedures

SHELDUS data on flood fatalities and injuries are organised at the county scale. Measurement and estimation of independent predictors of human death and injury is time sensitive to the day of each flood event. For example, to estimate the effect of precipitation on flood casualties we measure the level of precipitation on the day of and on the day before a recorded flood event. The geographic scope of analysis is coastal, southeast, and south-central Texas where the bulk of recorded flood events occurred during the study period of 1997–2001. With removal of duplicate cases (approximately 30), and validation of flood records with archival and newspaper sources, the final dataset includes 832 flood observations (488 of which occurred in 1997–98) for 74 counties in the eastern part of Texas.

The distribution of flood casualties is non-Gaussian. Zero counts significantly skew the distribution leftward—89.24 per cent of flood events resulted in no recorded injuries or fatalities. Mathematical transformation (logarithm, square root, or reciprocal) cannot resolve the statistical pattern. The standard deviation is 50.83 and the arithmetic mean is 7.11—dispersion is 7.15 times greater than the average. The variance is 2583.338. Furthermore, a Log likelihood ratio test of alpha equal to zero points to evidence of significant over-dispersion. Because our dependent variable is a non-negative integer exhibiting significant over-dispersion with a disproportionate number of zero counts, we analysed the data using a ZINB regression model, allowing us to assess the net effects of independent variables on flood casualties (Hausman, Hall and Griliches, 1984; Cameron and Trivedi, 1998). Correlation analyses and theory are employed to determine what variables to inflate in ZINB models, with the most highly correlated and theoretically relevant independent variables per variable dimension included.

Scale of analysis

Our analysis of flooding in Texas operates at the county scale. The decision to examine casualty outcomes at the county scale rests on three factors. First, and most important, comprehensive data on persons killed and injured by a flood event are only available at the county scale or higher in the US. The finest spatial resolution for hazard casualties—in both SHELDUS and data from the National Weather Service—is the county area. Compressed mortality data from the CDC are organised at the county scale to protect the identity of victims. Moreover, data for a critical predictor in our model—FEMA premium discount rating—is available only at scales higher than the census tract and block group.

Second, floods generally affect spatial areas broader than alternative spatial units like block groups or census tracts, which tend to be smaller than one kilometre square. Counties (and even larger units) are more empirically appropriate (particularly for cross-sectional analyses like ours) because they are large enough to capture the spatial scale of a typical flood event. SHELDUS shows that flood events often afflict many counties simultaneously. On 27 January 1997, for example, Brazoria, Chambers, Fort Bend, Galveston, Harris, and Liberty counties all suffered property damage due to flooding.

Third, alternative spatial units like census tracts and block groups do have the advantage of greater specificity and precision with regard to describing the population characteristics of an area (particularly because such units are crafted with the intent of achieving racial and income homogeneity), but these smaller units are not political or administrative entities. These smaller units have no planning authority. Land use and zoning decisions that influence flood outcomes are made at the city or county levels. The analytic trade-offs of our cross-sectional approach, like the loss of spatial specificity and psychological and physical suffering of human beings, are more profitably addressed by qualitative, finer grained analyses. Qualitative field studies can overcome the data limitations of secondary data approaches as deployed in our study.

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

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, 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.	+	National Climate Data Center, 1997–2001
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.	-	United States Army Corps of Engineers, 2004
Percent impervious surface	Percent 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.	+	National Aeronautics and Space Administration (NASA) Stennis Space Center, 1990–2000
Property damage (log)	Inflation adjusted (1997 base year) property damage caused by a flood event as inventoried in the SHELDUS database. This variable is log transformed for non-normality.	+	SHELDUS, 2004
Socioeconomic variables			
FEMA rating	FEMA insurance premium discount scores for Special Flood Hazard Areas corresponding to flood damage reduction and preparedness classifications.	-	FEMA Community Rating System, 2005
Population density (log)	Total number of persons residing in a country area divided by the total land area (square miles) of county area. Population density for each month is estimated using 1990 and 2000 data with even change assumed. This variable is log transformed for non-normality.	+	US Census Bureau, Population and Housing Files, 1990–2000
Social vulnerability	Additive index of standardised (z-scored) variables: percent non-poverty, percent White population, and median household income. Index scores are multiplied by negative one (1) for ease of interpretation.	+	US Census Bureau, Population and Housing Files, 1990–2000
Dependent variable			
Casualties	Total number of deaths and injuries caused by a flood event as inventoried in SHELDUS.		SHELDUS, 2004

Dependent variable

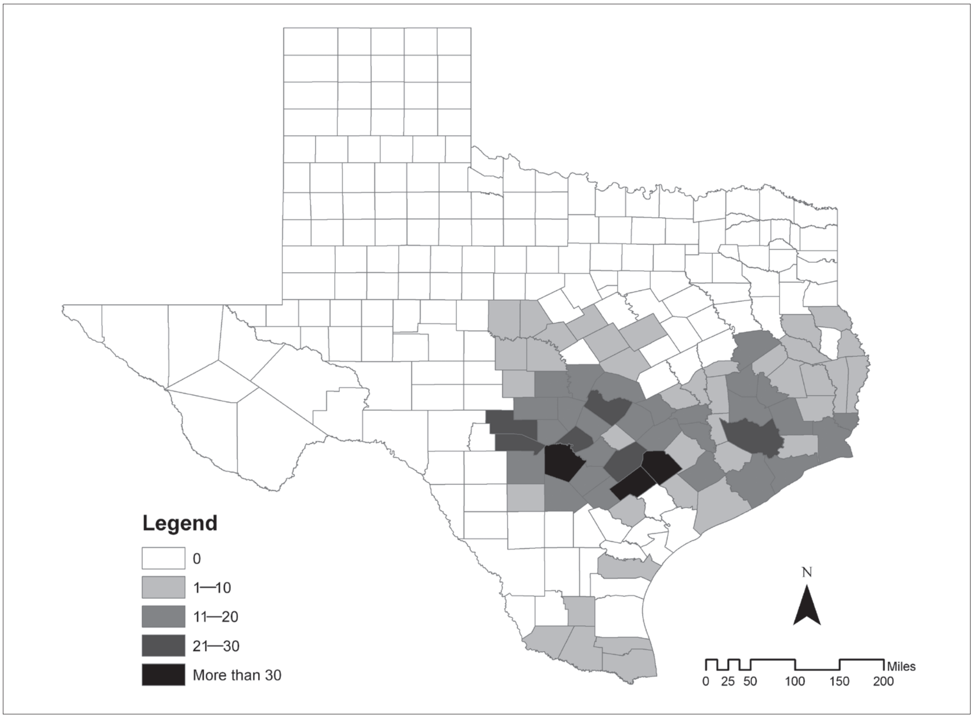
The dependent variable, *flood casualties,* is a count of injuries and fatalities in a flood event (see Table 1 for a summary of variable operations). Data on flood casualties are derived from SHELDUS at the Hazard Research Laboratory, University of South Carolina, Columbia. This database consists of a county-level inventory of 18 natural hazard types, including drought, floods, hurricanes, and wildfires. Hazard event records include a start and end date, estimated property damage and crop loss, and the number of human injuries and deaths. SHELDUS data are derived from public sources such as the National Climatic Data Center's monthly publications. Excluding zero counts, the range for our sample of Texas counties is 1–802 casualties (see Table 2 for descriptive statistics of variables). The flood event with the highest recorded human cost in terms of death and injury occurred in Comal County on 17–18 October 1998. The estimated property loss of the Comal flood is USD 50 million.

Figures 1 and 2 show the geographic distribution of the number of floods suffered by a county, and the cumulative number of persons killed and injured by flood events in the study period. The distribution of cumulative flood casualties and flood count are divided into equal intervals, with darker shades of grey reflecting higher values. Both figures reveal that flood events and flood casualties cluster spatially in south-central Texas (southern tip of Texas Hill Country, and the northern tip of the Texas Plains), intersected by the Colorado, Guadalupe, Nueces, and San Antonio Rivers. The natural and built environment and the socioeconomic variables discussed below are used to predict the spatial variation of flood casualties observed in Figure 2.

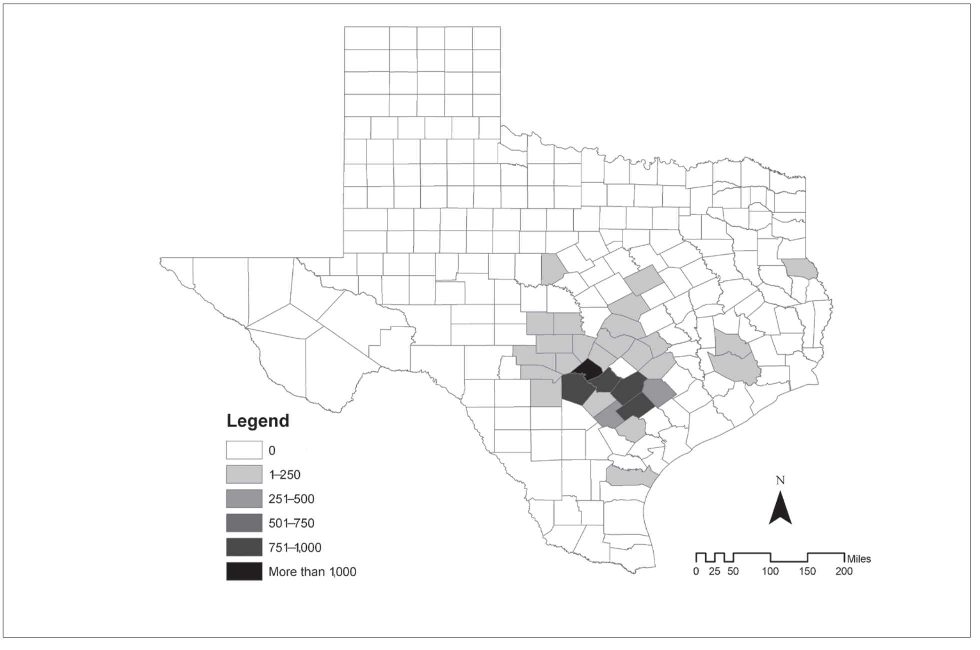
Table 2 Descriptive statistics of variables

	Minimum	Maximum	Mean	Standard deviation
Natural environment variables				
Precipitation (day of event)	.000	18.710	2.044	2.626
Precipitation (day before event)	.000	18.813	.879	2.005
Duration	0	1	.17	.377
Built environment variables				
Dams	0	19.000	2.24	3.201
Impervious surface	2.571	42.730	15.106	7.645
Property damage (log 10)	2.993	7.819	4.303	.782
Socioeconomic variables				
FEMA premium discount	0	15.000	2.02	4.482
Social vulnerability	.589	3.299	1.781	.611
Population density (log 10)	-6.092	13.784	.000	2.420
Dependent variable				
Casualties	0	802	7.11	50.827

Figure 1 Geographic distribution of the number of floods suffered by Texas counties, 1997–2001



Figures 2 Geographic distribution of flood casualties suffered by Texas counties, 1997–2001



Natural environment variables

We measure and analyse three variables to estimate the physical dimension or force of a flood. The first two, *precipitation (day of event)* and *precipitation (day before event),* are measured as the average surface precipitation (in hundredths of an inch) recorded by weather stations. The number of weather stations varies across counties and within a county longitudinally. Of all counties examined, Harris County has the highest number of weather stations (12). We used the National Oceanic and Atmospheric Administration (NOAA)'s Climate Data Online search engine to find daily surface precipitation data for each county. The search architecture of Climate Data Online allows users to browse stored data by climate division, state, county, and date. Search results include 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 level recorded for a flood event in our study period was Comal County on 17–18 October 1998 with 18.71 inches.

We restricted our measurement of precipitation levels to the day of and the day before a flood event in recognition of the shortened lag time between precipitation and run-off volumes within our study area, resulting in floods that peak more rapidly. This lag time can be justified by several characteristics. First, in Texas 'flash floods' are responsible for the vast majority of persons killed and/or injured by a flood event. Central Texas is arguably the most flash flood-prone area in North America, dubbed by the Flood Safety Education Project as 'Flash Flood Alley'.[5] A combination of intense periods of rainfall and poor soil composition creates a ubiquitous flash flood phenomenon not present in other states dominated by riverine flooding.

Second, impervious surfaces associated with increasing urbanisation in our study area further compresses the time difference between centres of precipitation and run-off volume, leading to increased peak discharges (Leopold, 1994; Burges, Wigmosta and Meena, 1998; Brezonik and Stadelmann, 2002). This reduced lag time is a consequence of water reaching stream bodies more quickly because the ability of the hydrological system to store water is compromised (Hsu, Chen and Chang, 2000; Hey, 2001). For example, 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; Paul and Meyer, 2001). In general, there is ample empirical evidence to support the assumption that urbanisation not only increases run-off volume, but also peak discharges and associated flood magnitudes.

Our third variable of flood force is *flood duration,* measured on a scale from zero (0) to one (1). A flood event receives 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. Approximately 17 per cent of recorded flood events lasted more than one day, with the longest flood event (nine days) occurring in Orange County in 2001. Duration estimates are derived from SHELDUS records on the start and end dates of a hazard event. We expect precipitation levels and flood duration to be positively associated with casualty counts (on the linkage of heavy precipitation and flooding, see Zhao, Smith and Bradley, 1997; Zhang and Smith 2003).

Built environment variables

We estimate and model three built environment variables that theoretically affect flood outcomes. *Dams* are water barriers that direct and impound the flow of water. Dams are built for multiple reasons from irrigation and water supply management to electricity generation through hydropower schemes. Dams also function to reduce the risks of flood damage (Hawker, 2000). All things held equal, we expect a reduction in the odds of human death and injury from flooding as a function of the number of water embankments present in a county area. We measured our dam variable as the total number of structures within a county area. Locations of dams were obtained from the United States Army Corps of Engineers (USACE) and summed by each county unit. The dam inventory of USACE includes both public (federal, state, and local jurisdictions) and privately operated enterprises. This variable ranges from zero (0) to 19, with Coleman County possessing the highest number of dams.

The conversion of agricultural and forest lands to urban areas can diminish a hydrological system's ability to store and slowly release water, resulting in increased flood severity (Carter, 1961; Tourbier and Westmacott, 1981). Research shows that an increase in impervious surface coverage can decrease infiltration and increase surface run-off (Dunne and Leopold, 1978; Paul and Meyer, 2001). We calculate an *impervious surface* variable as the percentage of land area in a county covered by impervious surfaces (that is, pavement, buildings, etcetera). Impervious surface was developed using GeoCover satellite imagery from the National Aeronautics and Space Administration (NASA)'s Stennis Space Center. Imagery from 1990 and 2000 was classified by several iterations of an unsupervised classification method followed by manual grouping of similar classifications. Digital Ortho Quarter Quads (DOQQ) imagery was used to confirm the accuracy of the classifications. We summed impervious surface area by county units for 1990 and 2000. Based on our scores, we then calculated monthly values for the study period assuming an equal interval rate of change.

Our third built environment variable estimates the *property loss* of a flood event. We measure property damage as the total dollar loss (in consumer price index (CPI) adjusted 1997 USD) from a flood event as inventoried in SHELDUS. This variable is log-transformed (base 10) for non-normality of distribution. The most costly flood event occurred in Guadalupe County on 17–21 October 1998: an estimated USD 67 million in property loss. Because property damage figures partially approximate the force of a flood, we expect a positive correlation between property damage and flood casualties.

Socioeconomic variables

We measure three socioeconomic predictors of flood casualties: population density; local preparedness; and presence of socially vulnerable populations. *Population density* is measured as the total number of persons residing in a county area divided by its total land area (square miles). Data from the 1990 and 2000 Censuses are used to estimate monthly population density values assuming a linear rate of change. This variable is log transformed to correct for a non-normal distribution. All things held equal, it is reasonable to hypothesise that the more people one finds in a county area, the greater the probability of human death and injury during a flood event.

To estimate the degree of local (county) preparedness for a flood event, we collected FEMA insurance rating scores. *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 mitigate 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 applied to all written flood insurance policies in a community. Communities with higher FEMA scores have implemented a greater number of flood mitigation measures. In Texas, Galveston County has the highest FEMA rating with a 15 per cent premium discount. Ceteris paribus, we expect a positive association between FEMA rating and casualty count.

To estimate the presence of socially vulnerable populations in a county area we collected poverty, income, and race data from the US Census Bureau's 1990 and 2000 Censuses. Because these indicators are highly correlated, we construct a SV index to deal with the problem of item collinearity. Our *social vulnerability* variable is an additive index of three measures (alpha = .755): per cent non-poverty; median household income; and per cent non-Hispanic White population. Each measure is standardised (z-scored) and summed. For ease of interpretation, we multiply summed scores by minus one (-1). We flip the direction of our SV index scores so that higher scores reflect higher levels of social disadvantage. Therefore, higher scores on our SV index reflect greater presence of socially vulnerable populations in a county area. Consistent with the literature review above, we expect casualty counts to increase with the SV scores. It is important to note that, by design, our study does not estimate the disaster risk faced by individuals—our analysis operates at the aggregate level, examining population characteristics of a locality that may predict spatial and temporal variation in recorded flood casualties.

Results

The first phase of our analysis reports descriptive statistics. Table 3 ranks counties on total flood casualties for the study period 1997–2001. Overall, 5,922 persons were either killed or injured in a flood event for the sampled Texas counties. Of the total casualties recorded during the study period, only 49 are deaths and the remainder injuries. The majority of casualties occurred on three days in late June 1997, mid-October 1997, and mid-November 2001. During the entire study period, approximately one-third of all recorded flood casualties occurred in Comal and Bexar Counties. Generally, the pattern of casualties follows the amount of property loss. However, the number of flood events does not always correspond to the number of

Table 3 Top 20 Texas Counties in terms of flood casualties, 1997–2001

Rank	County	Casualties	Injuries	Deaths	Property loss (USD)	Crop loss (USD)	Floods
1	Comal	1,060	1,058	2	127,383,000	630,000	24
2	Bexar	891	880	11	36,550,000	327,500	34
3	Guadalupe	859	854	5	89,148,000	722,500	20
4	DeWitt	808	808	0	74,166,500	2,800,000	33
5	Gonzales	759	759	0	88,941,500	1,106,667	23
6	Lavaca	356	355	1	6,653,000	1,043,000	34
7	Karnes	258	258	0	17,179,000	522,500	19
8	Wilson	237	237	0	53,706,000	247,500	14
9	Hays	196	194	2	28,143,000	496,667	19
10	Travis	170	165	5	4,535,000	200,000	24
11	Bastrop	113	113	0	7,255,000	225,000	12
12	Medina	51	50	1	13,529,000	320,000	20
13	Bandera	27	25	2	5,435,000	1,010,000	22
14	Kerr	21	20	1	608,000	190,000	25
14	Llano	21	20	1	5,358,000	140,000	17
16	Kendall	20	20	0	5,331,000	1,110,000	18
17	Fayette	18	18	0	4,560,000	325,000	13
18	Williamson	12	10	2	1,366,000	70,000	19
19	Blanco	11	10	1	1,382,000	190,000	17
19	Gillespie	11	7	4	2,465,000	275,000	18
	State totals	**5,922**	**5,873**	**49**	**626,827,067**	**13,476,333**	**832**

casualties. For example, Kerr County is ranked 14 for casualties, but experienced 25 flood events—the fourth most of all counties in the sample. Meanwhile, Bexar County's flood history, natural and built environment characteristics, and socioeconomic composition seem to fit the various hypotheses tested below. Bexar County's impervious surface cover is significantly higher than average, it received a score of zero in the FEMA premium discount scheme, and approximately 63 per cent of its residents are non-White. In addition to human costs, flood events in Texas caused an estimated USD 626 million in property damage.

In the second phase of analysis, we examine the influence of natural and built environment and social vulnerability variables using multiple regression analysis. Table 4 reports ZINB regression coefficients and odds ratios for flood casualty counts. Three separate models are analysed, with predictors loaded incrementally

Table 4 Zero-inflated negative binomial regression models predicting flood casualties

	Model 1 Coefficients	Exp (B)	Model 2 Coefficients	Exp (B)	Model 3 Coefficients	Exp (B)
Constant	1.6394** (.4384)		-2.3230* (.9766)		-2.0478* (.9201)	
Natural environment variables						
Precipitation (day of event)	.1692** (.0717)	1.184	.1514* (.0760)	1.163	.2211** (.0637)	1.247
Precipitation (day before event)	-.0448 (.0686)	.956	-.6588 (.0625)	.936	-.1152* (.0507)	.891
Duration	1.7755** (.5704)	5.903	.9666* (.4135)	2.629	.6225† (.3740)	1.864
Built environment variables						
Dams			-.0659 (.0447)	.936	-.2302* (.0876)	.794
Impervious surface			.0580* (.0261)	1.060	-.0018 (.0243)	.998
Property damage (log 10)			.6620** (.2132)	1.939	.5469** (.2378)	1.728
Socioeconomic variables						
FEMA premium discount					-.0894** (.0325)	.9144
Social vulnerability					.3531** (.0956)	1.424
Population density (log 10)					1.0958** (.5826)	2.992
	Coefficients	**Z**	**Coefficients**	**Z**	**Coefficients**	**Z**
Inflated variables						
Precipitation (day of event)	-.4027** (.0484)	-8.32	-.1983** (.0599)	-3.31	-.2137** (.0628)	-3.40
Dams			-.1772* (.0634)	-2.80	-.2264** (.0517)	-4.38
Property damage (log 10)			-1.7362** (.2655)	-6.54	-1.8091** (.2657)	-6.81
Social vulnerability					-.2396† (.1375)	1.74
Constant	3.0847** (.3087)	9.99	11.4113** (1.2693)	8.99	12.0170** (1.2865)	9.34

/lnalpha	1.0936** (.2187)	5.00	.4568** (.1650)	2.77	.3012† (.1683)	1.79
Alpha	2.9851 (.6529)		1.5791 (.2605)		1.3515 (.2275)	
Non-zero observations	78		73		73	
Zero observations	754		753		753	
Log pseudo likelihood	-548.9213		-463.8492		-457.4785	
Wald chi^2 (12)	52.31		127.72		216.69	
Probability > chi^2	0.0000		0.000		0.0000	

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

by variable domain. Because there is no direct equivalent to R-squared in ZINB regression, variance inflation factors cannot be accurately derived. To screen independent variables for multicollinearity we analysed zero-order correlations and Variance Inflation Factor (VIF) tests in Ordinary Least Squares (OLS) regression. No two variables appearing in the model are correlated over .650, and all VIF scores are well below acceptable standards (the average equals 1.89). Detection of heteroskedasticity in the model led us to estimate regression equations with robust standard errors. With the exception of impervious surface cover, variables behave reasonably stably across restricted and fully saturated models.

In Model I (natural environment measures only), results indicate that precipitation on the day of a flood event is positively associated with flood casualties. With each inch of rainfall on the day of a flood event, the odds of human death or injury increase by a multiplicative factor of 1.184. In contrast, precipitation level on the day before a flood event is not statistically significant (b = -.0448, p = > .05). As expected, the duration of a flood positively predicts the likelihood of flood casualties. Multi-day flood events are 5.903 times more likely to kill or injure a person than single day flood events. Results from the inflated model show that the odds of a casualty-free flood decrease significantly with the level of precipitation on the day of a flood event (b = -.4027, p = > .01). With a theoretically sensible and well-behaved baseline model of natural environment variables, we move to built environment predictors.

We add several built environment variables in Model 2. In this model, precipitation on the day of a flood event positively predicts flood casualties (odds ratio = 1.163, p = < .05). Precipitation on the day before a flood is statistically insignificant, but again facing in a negative direction. Flood duration significantly increases the odds of death or injury, with multi-day floods 2.629 times more likely to cause a flood casualty than single day floods. Adjusting for characteristics of the built environment, the odds ratio on flood duration is reduced by more than half. With regard to built environment characteristics, a per cent increase in impervious surface cover significantly heightens the odds of death or injury by 6.0 per cent, where $p = < .05$. Similarly, the odds of flood casualties rise with the amount of property damage caused by a flood. For every unit increase in property damage, we observe an increase in the odds of human death and injury by a multiplicative factor of 1.939. Inflated variables significantly predict zero count outcomes. An augmentation of precipitation levels the day of a flood event significantly decreases the likelihood of a casualty-free flood ($b = -.198$, $p = < .01$). Somewhat unexpected, an increase in the number of dams in a county area significantly reduces rather than boosts the probability of a casualty-free flood event ($b = -.1772$, $p = < .01$).

Finally, our full Model 3 includes socioeconomic variables. All natural environment variables in this model are statistically significant. Again, precipitation on the day of a flood event increases the odds of a casualty by 24.7 per cent, where $p = < .01$. Precipitation level on the day before a flood event is also significant, but in a negative direction ($b = -.1152$, $p = < .05$). All things held equal, rainfall conditions on the day before a flood event are negatively related to flood casualties, lessening the odds of human injury and death by a multiplicative factor of .891. That is, the higher the rainfall the day before a flood event, the lower the odds of death and injury.

With the addition of socioeconomic variables, our dams measure is statistically significant, where $p = < .05$. An increase in the number of dams decreases the odds of a flood casualty by 21.6 per cent. Our property damage variable remains statistically significant ($b = .5469$, $p = < .01$), but is weakened slightly by the inclusion of socioeconomic predictors. A unit rise in property damage caused by a flood increases the odds of death and injury by a multiplicative factor of 1.728. In our fully saturated model, impervious surface cover is no longer statistically significant, where $p = < .05$.

Results show that local flood mitigation efforts (as summarised by our FEMA premium discount measure) significantly reduce the odds of death and injury, where $p = < .01$. For every unit increase in our FEMA premium discount, the odds of death and injury decrease by 8.6 per cent. Because FEMA premium scores move in increments of five per cent, a real unit change in the FEMA score reduces the odds of a flood-caused human casualty by 36.05 per cent (where the computed Exp (B) = .6395). These results suggest that FEMA incentives for flood mitigation not only save communities money with regard to flood insurance, but also translate into a significant reduction in the odds of human death and injury. Similarly, for every unit increase in population density, the odds of flood casualties rise by a factor of 2.99 ($b = 1.0958$, $p = < .10$). Not surprisingly, as one increases the number of persons in a county defined area, the odds of a resident being killed or injured by a flood event mount.

Finally, and as predicted, a unit increase in the level of socially vulnerable or disadvantaged populations in a county area augments the odds of death or injury by 42.4 per cent. This result indicates that one can statistically order the distribution of flood casualties on the basis of socioeconomic disadvantage. Localities with higher than average composition of poor and minority residents are more likely to experience human injury and death from flooding ($b = .3531$, $p = < .01$). This observation holds with statistical adjustment for many natural and built environment characteristics, as well as population density and estimation of the flood mitigation efforts undertaken by a locality. These results for socioeconomic variables are supported by an examination of a subset of 17 flood-resilient counties in Texas: Atascosa, Austin, Brazoria, Burnet, Colorado, Fort Bend, Galveston, Houston, Jackson, Jefferson, Liberty, Orange, San Jacinto, Trinity, Walker, Washington, and Wharton. These counties routinely experience flood events (at least two per year), but have not suffered a single casualty. They are distinguishable with regard to two socioeconomic dimensions: 1) they have considerably higher FEMA premium discount scores, indicating that they are safer by virtue of mitigation efforts undertaken; and 2) they have a significantly smaller percentage of socially vulnerable populations. Moreover, the floods that afflict these resilient counties are, on average, more intense as measured by property loss, with statistically equivalent precipitation levels.

In the zero-count model, inflated variables of precipitation (the day of a flood event) and property damage behave as expected. Both variables significantly reduce the probability of a casualty-free flood. Somewhat surprising, dams decrease the likelihood of zero deaths and injuries ($b = -.2264$, $p = < .01$). That is, as the number of dams in a county increases the likelihood of at least one person dying or being injured by a flood event mounts. Why do dams mitigate flood casualties in one model but their presence decreases the odds of zero counts in another? First, dams are more likely to appear in areas with higher flood counts. The correlation between flood count and the number of dams is positive ($r = .440$, $p = .000$). Second, with more floods the odds of at least one person being injured or killed by a flood event increase ($r = .539$, $p = .000$).

The presence of a dam may therefore lessen the likelihood of a casualty-free flood event because they appear in areas most likely to suffer repetitive flooding. Regarding the actual number of people killed or injured—or the intensity of a flood outcome—our results suggest that dams appear to limit the overall odds of human death and injury. Short of breach or structural failure, it seems that dams work to mitigate flood casualties. Therefore, on the one hand, the presence of dams signal reduced odds of a casualty-free flood event, while on the other hand the number of dams appears to diminish the overall odds of injury and death, adjusting for natural and built environment and social vulnerability variables. Our social vulnerability variable is in the correct direction, but is only significant at the .10 level. Therefore, with interpretive caution, the probability of casualty-free flood event increases with a decrease in the percentage of socially vulnerable persons residing in a county area.

Conclusion

The results of our study suggest that while casualties from floods in Texas are relatively rare, specific factors related to the natural, built, and socioeconomic environment contribute to increased rates of deaths and injuries. First, we find that the amount of precipitation is not as important as its timing in terms of a greater probability of casualties in Texas. That is, precipitation on the day of the flood event significantly increases casualties while heavy rainfall events on the day before a flood actually decrease incidences of death and injury. These results suggest that communities can be caught by surprise by floods that appear with little warning, as with flash floods, and do not have the time to prepare or to evacuate to less vulnerable areas. Our empirical capture of the flash flood phenomenon is supported by the finding that a day without rainfall before a flood event followed by sudden heavy rainfall on the day of a flood event significantly boosts the odds of human death and injury from flooding. Furthermore, the majority of casualties occur in the western portion of the study area where flash floods are far more likely to occur.

Even in urban areas where flood control structures are often in place, it is vital that decision-makers and the public understand that sunny skies followed by heavy precipitation can still result in dangerous flooding immediately, rather than several days later. Being able to react to the quick onset of flood waters may thus enable communities to reduce the loss of life and limb. It is important to note that this timing phenomenon associated with precipitation stands in contrast to a sister study on economic damage caused by floods, which finds that heavy precipitation on the day before the actual flood event is a strong positive predictor of total property damage (Brody et al., 2008). This seemingly contradictory finding may be a function of the delay between initial rainfall and the resulting rise in water levels that causes damage. In this case, the amount of rainfall before a flood event weakens the absorption capacity of hydrologic systems, increasing the probability of property damage and its extent on the day of the flood event.

Second, structural solutions to flood mitigation significantly reduce flood casualties, as evidenced by the performance of our variable measuring the number of dams in each county. While structural engineering solutions to flood control are an effective strategy for reducing the probability of loss of life and property, there are several concerns with this approach that decision-makers should weigh carefully:

- dams are extremely costly mitigation alternatives that require substantial public investment;
- dams can exacerbate development in flood-prone areas, increasing the presence of vulnerable populations by providing incoming residents with a false sense of security; and
- dams and related devices can present a hazard in themselves in the event of structural failure (Harding and Parker, 1974; Tobin, 1995; Pielke, 1999).

Third, in addition to structural solutions to flood loss it is essential to note that non-structural mitigation solutions have important consequences as well. Specifically, we find that, based on the statistical performance of our FEMA CRS programme variable, flood mitigation policies and community preparedness significantly lower risks to human safety. 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 levels of flood-related casualties. This finding lends support to the implementation of non-structural mitigation strategies to reduce community-wide flood damage. The deployment of mitigation strategies may explain why we observe a decreasing percentage of floods involving death and injury,[6] while observing an increase in the number of floods, population size, and property damage from flood events in the US.

Fourth, our results support the conclusion that communities with socially vulnerable populations experience more casualties in a flood event. This finding empirically reveals an important disadvantage of low income and minority populations that warrants the full attention of policymakers. The highly publicised impacts of Hurricanes Katrina and Rita revealed that poor communities of colour suffer disproportionately in terms of human death and injury. The socially vulnerable populations of New Orleans perished in floodwaters because of disaster response failures during each phase of the disaster process, from preparedness to evacuation. Our study more systematically corroborates both scholarly and journalistic claims that flood impacts are unequally distributed in affected communities by their racial and income composition.

Because our study provides empirical evidence that socially vulnerable populations at the county level experience a significantly greater amount of casualties from floods in eastern Texas, local flood planners and decision-makers must make it their priority to ensure that all population sectors are informed of flood dangers, have the opportunity to reside in flood-resilient structures, and are fully included in mitigation policies, plans, and procedures. According to Mark Pelling of the United Nations Development Programme, 'natural disasters are in fact social disasters waiting to happen that may be triggered by a particular natural force' (UNDP, 2004, p. 1). Our study shows that in addition to the importance of natural and built environment factors in the mitigation of a natural disaster outcome, social factors matter.

Although this study offers some important insights into the relationship between social, natural, and built environments and flood casualties, it should be considered only a first step in understanding these connections. Further research is needed on several fronts. First, our study is limited by relying on counties as the unit of analysis. While many variables, including flood casualties, are collected only at the county jurisdictional level, it is an administrative unit that does not conform to functioning hydrological systems. Future studies should focus on the watershed level to account better for upstream and basin-wide effects (see Brody et al., 2007). Moreover, because counties are relatively large entities, some population characteristics are more usefully examined at lower levels of aggregation that more closely approximate the sociological notion of community. Qualitative studies can delve into data patterns observed in our study to achieve a more refined understanding of how socially disadvantaged persons and populations experience flood events.

Second, our study area consists of 74 counties in the eastern portion of Texas. Greater statistical power would be attained if future work focused on larger geographical areas across multiple states.

Third, our study period is limited to five years. Future research should consider a broader historical time frame even if it limited analyses to a single watershed.

Fourth, our study cannot make conclusions about individuals harmed by flooding. More information regarding the socioeconomic status of those persons actually killed or injured by floods would help to establish better a relationship between social vulnerability and casualties.

Fifth, because of the longitudinal study design, we had difficulty controlling for flood casualties occurring in adjacent counties. Measuring potential adjacency effects when using the county as a unit of analysis and incorporating this effect into statistical models may increase the amount of variance explained, and may reduce estimation errors.

Finally, future studies should include additional control variables in explanatory analysis, such as low water crossings, stream density, floodplain overlap, specific local flood policies, and building permits.

Correspondence

Sammy Zahran, Assistant Professor, Department of Sociology, B235 Clark Building, Colorado State University, Fort Collins, CO 80523-1784, United States. E-mail: szahran@colostate.edu.

Endnotes

1 Sammy Zahran, Assistant Professor, Department of Sociology, Colorado State University, United States; Samuel D. Brody, Associate Professor, Environmental Planning and Sustainability Research Unit, Department of Landscape Architecture & Urban Planning, Texas A&M University, United States; Walter Gillis Peacock, Director and Professor, Department of Landscape Architecture & Urban Planning, Hazard Reduction and Recovery Center, Texas A&M University, United States; Arnold Vedlitz, Director and Professor, Institute for Science, Technology and Public Policy, George Bush School of Government and Public Service, Texas A&M University, United States; Himanshu Grover, PhD Candidate, Environmental Planning and Sustainability Research Unit, Department of Landscape Architecture & Urban Planning, Texas A&M University, United States.

2 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.

3 See http://www.nssl.noaa.gov/primer/flood/fld_damage.html.

4 This disaster process typology and corresponding literature review draw heavily on two excellent summaries of the disaster literature related to race and ethnicity (Fothergill, Maestas and Darlington, 1999) and poverty (Fothergill and Peek, 2004).

5 See http://www.floodsafety.com/texas/index.htm.

6 The large majority of recorded flood events in the US produce zero casualties. Of the 56,149 recorded flood events (at the county scale) from 1 January 1960 to 31 December 2002 in SHELDUS, 81.45 per cent were free of human injury and death. In fact, the percentage of recorded floods events with casualties has decreased markedly over the past 40 years. This decrease in the percentage of floods with human death or injury corresponds with an increase (not a reduction) in the number of floods per year, and a rise in annual property damage (inflation adjusted USD) from

flood events. Over the same 40-year period, the population of the US swelled by more than 100 million residents.

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