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Identifying population vulnerable to hydrological hazards in San Juan, Puerto Rico

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Abstract The hazards of place framework developed by Cutter (1996) has been applied to several areas across the United States. This article tests the applicability of that model for analysis of hydrological disasters in the *municipio* of San Juan, Puerto Rico. San Juan is chosen because it combines many socioeconomic attributes of a developing area while offering data availability befitting its status as a US commonwealth. The interoperability of principal components and arithmetically based methods for producing a social vulnerability layer are examined. For both methods, a basket of commonly cited demographic variables representing social and economic vulnerability is extracted from Census 2000 sample (SF-3) data at the census block-group level of analysis. These results provide insight on the strengths and weaknesses of the methods both methodologically and regarding policy implementation. A look at the neighborhood of La Perla suggests complex local positive and negative effects of local processes on vulnerability not captured by demographic analysis. These effects relate to possible census undercounts in peripheral areas and uncaptured coping ability provided by social networks.

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Hazards of place model

The hazard of place model, developed incrementally over the past 10 years, provides geographers with a powerful tool for manipulating numerous and varied demographic and physical data (Cutter 1996; Cutter et al. 2000, 2003; Boruff et al. 2005; Chakraborty et al. 2005). The deliverables produced using this method often include maps portraying the aerial extent of differential vulnerability in the study area. These maps collapse millions of human and environment interactions into visual representations that seek to capture how the products of these interactions translate into vulnerability experienced by people living in the study area. The simplification of reality offers policy makers and emergency managers with comprehensive, theoretically grounded tools for planning responses to future disasters, and addressing deeper causes of vulnerability in their communities of responsibility.

The hazards of place framework focuses on the integration of social and physical data. The creation of the social layer of vulnerability is demographically driven, relying on secondary data from US Census Bureau. While decennial census data provide the starting point for all hazards of place studies, the literature suggests researchers deploy methods of varying mathematical complexity to produce social vulnerability. The hazards of place analysis has only been implemented in an Anglo, North American context.

This paper has a twofold purpose. It seeks to compare two types of methodologies for producing social vulnerability that both owe their theoretical justifications to the hazards of place framework, and it discusses the ability of the hazards of place framework to capture the importance of social networks in attenuating vulnerability and the sensitivity of the model to uncounted population. The paper addresses these issues by deploying the hazard of place framework in a location outside the United States mainland for the first time.

Vulnerability and geospatial methodology

Geographers, first in collaboration with physical and applied scientists and then increasingly utilizing methodologies developed within the field, have made significant contributions in driving the clarification of disaster, risk, and vulnerability. Geographic treatments of vulnerability, disaster, and risk, are situated within the human and environmental interaction school of geography, though the perspectives of researchers vary (Fraser et al. 2003; Bankoff 2004; Zimmerer et al. 2003). Wood (2004) stresses the importance of the continual adjustment and accommodation humans make in response to their environment. He also emphasizes the interpretation of the environment as the space occupied by people rather than as some abstract natural place. This raises the question as to whether a place must support a human population to be considered vulnerable, whether the hazards of place framework makes such a claim warrants exploration. A vulnerable place in the context of literature considered in this research must be a human environment, again meaning any place where humans live.

A perceived divide between the cultural and physical worlds commonly manifests in research methodology concerning vulnerability (Cardona 2004). This may be in part due to the increased influence and premium placed on methods that integrate qualitatively different variables using GIS. The layer cake model of GIS seems to reinforce the notion of separate cultural and physical sphere (Harvey 1997). While analytically a reductionist process in which the components of both the social and physical sphere are examined in turn may be necessary due to current computational and methodological bottlenecks, no such division exists in any real sense.

Rather than view the cultural and physical worlds as two spheres with clearly mapped conduits for input and output relationships, the geography of human/environment interaction incorporates Wood's (2004) concept of coupling. Coupling represents the idea that humans and their environment mutually shape each other through constant contact and influence. Organized study of vulnerability currently requires reducing these interactions into manageable quanta. Only during the reduction process do divisions between cultural and physical become pronounced.

Out of its roots in human and environment interaction, the study of vulnerability (Liverman 1989; Wisner 1993; Watts and Bohle 1993; Bohle et al. 1994; Ribot 1995) has further divisions reflecting differing emphases and interpretations of the human and environmental sides of the issue. Cutter et al. (2003) briefly identifies three tracks in recent geographic thought on hazards. These tracks are the human ecological perspective focusing on exposure to physical hazards, the political ecological perspective focusing on differential access to power and competition for resources, and an integrative perspective that focuses on potential exposure and social resilience within bounded areas. Cutter and her colleagues position their own study on creating a nationwide index of social vulnerability, and her body of research in general, within this track.

This research is motivated primarily by the integrative approach advanced by Cutter. A pure human ecological approach would ignore or gloss over social processes and differences, such as unequal development and infrastructure that accentuate vulnerability in certain areas of San Juan. While a political ecological approach would fully address social difference, it provides no ideological or methodological basis from which to integrate biophysical data fully into the analysis. The integrative approach allows for the analysis of demographic data along with context provided by an awareness of the interests and perceptions of different groups in the study area. Development of an integrative approach with conduits for local input seems to combine the strengths of both the human and political ecological approaches.

This research address vulnerability to hydrological hazards in San Juan, Puerto Rico from this integrative perspective. This research will focus on the *municipio*, the county-equivalent territorial unit for San Juan, which encompasses the central business district and had a population of 434,374 at the time of the 2000 Census. The Estado Libre Asociado de Puerto Rico, or Freely Associated State of Puerto Rico, has commonwealth status within the United Status federal system. The unique political and cultural circumstances of Puerto Rico raise a question as to whether this article addresses the vulnerability of sprawling developing metropolises in the US. In the United States, the Federal Emergency Management Agency (FEMA) plays a role in redistributing the costs of disaster mitigation and recovery. Puerto Rico, due to its commonwealth status, has access to FEMA's technical and financial resources. The per capita income of the commonwealth's economy of $12,502 in 2005 would place it below the lowest category for US states, Puerto Rico would be considered in the middle income group internationally (Puerto Rico in Figures 2005) (Fig. 1).

Little work on vulnerability in general has been sited in Puerto Rico (Palm and Hodgson 1993). Recent empirical studies of vulnerability draw heavily upon the recent work of Cutter (1996) Cutter et al. (2003) for a methodology that considers many different data layers efficiently and produces easily accessible output. Cutter's influence in vulnerability research relating to natural hazards is profound. This is evident especially for studies that integrate aerial layers representing hazard zones and layers that examine the distribution and relative concentration of groups commonly portrayed within the literature as less able to resist and recover from disturbances caused by physical hazards (Wu et al. 2002; Chakraborty et al. 2005; Collins 2005). In their 2003 work, Cutter et al. suggested utilizing 80 demographic variables available from the US decennial census that capture some aspect of social vulnerability. This work also provided references spanning social science literature that support the inclusion of various demographic variables in vulnerability analysis. This theoretical framework forms the methodological basis for research utilizing the hazards of place approach and both the arithmetically and statistically driven methodologies discussed in the next section.

Principal components analysis and additive ratios: Two methods for producing a social vulnerability layer

Principal components analysis method

Cutter et al. (2003) identified over 250 variables available through the US Census decennial census at the county level that represent some facet of social vulnerability. While this overwhelming number was reduced to 85 raw variables by identifying groups of collinear variables and then further reduced to 42 normalized independent variables, it remains a difficult number with which to conduct research. The effect of any particular variable on the vulnerability for a particular spatial unit would be difficult to ascertain using all 42 variables.

Cutter et al. evaluated the 42 variables in a principal components analysis using varimax rotation to extract factors based on the original demographic variables that had high component scores for each factor, with each factor receiving a designation indicating the underlying facet of social vulnerability they represented, such as poverty, age, or population decline. The Social Vulnerability Index (SoVI) was produced by adding up the loading for each factor within a given census block, with a higher loading understood to be a proxy for higher vulnerability. When necessary, this led to the absolute or inverse value of the loading being included in the additive model. The sorting technique just described resulted in the identification of 11 factors of vulnerability. Additionally, while the researchers acknowledge that some of the 11 factors may influence vulnerability more heavily and through different channels, they also acknowledge the current lack a defensible method for assigning weight to the factors in the additive process. The result is that no group of variables loading heavily on any of the factors can be singled out as fundamental or solely sufficient to represent social vulnerability.

Boruff et al. (2005) applied Cutter's methodology in order to construct the social layer of vulnerability to erosion in US coastal counties. Three variables were left out because of their low loading in the

Fig. 1 Study area context

original 2003 study. The results produced ten factors that accounted for 82% of the variance among US coastal counties. In order of decreasing amount of variability explained, the extracted factors are poverty, age, development density, presence of Asian and immigrants, rural/urban dichotomy, race and gender, population decline, ethnicity (Native American) and farming, infrastructure employment reliance, and income, all of which were associated with higher vulnerability.

Arithmetic method

Chakraborty et al. (2005) constructed their index of social vulnerability for evacuation (SVEI) purposes without the use of principal component analysis, instead relying on an easily accessible arithmetic method using trivial mathematics. Wu et al. (2002) also used an identical arithmetic method, but using data from 1990 Census because of the earlier date of their study. Instead an arithmetical methodology, reproduced in Fig. 2, was utilized to compute the values used in vulnerability mapping. The ten variables analyzed by Chakraborty et al. (2005) were divided into three groupings, each group representing a different facet of vulnerability with respect to evacuation. These groupings, which consist of population and structure, differential access to resources, and population with special evacuation needs, are similar to the designations assigned by Cutter et al. (2003) to their empirical orthogonal factors. They differed in the number groupings, with Cutter et al. (2003) grouping the variables into eleven composite factors.

The similarity of these groupings to the designations provided by Cutter et al. speaks to the influence

Fig. 2 Chakraborty et al. (2005) methodology

Chakraborty et al. (2005) Methodology

1. Determine the ratio in the block group of each variable *i* to the total number of that variable in the county.
2. Compute a standardized social vulnerability for evacuation index for variable *i* using the maximum value calculated in step 1.

$$SVEI_i = \frac{R_i}{R_{total}};$$

Where;

$SVEI_i$=Social Vulnerability Index for Evacuation for the unit of analysis (i)

R_i=Value for variable in unit of analysis (i)

R_{total}=Total population for a variable in study area

3. Sum the values calculated in step 2 for each variable *i* to calculate the $\sum$ SVEI.

of their work on studies developed out of the hazards of place framework. Although the names are not exactly the same, the notions that sets of demographic characteristics accentuate vulnerability clearly carries powerful weight. Such a priori assumptions characterize the arithmetic methods based on the empirical framework developed for analysis carried out in the hazards of place framework.

In addition to calculating a social vulnerability index based on all ten variables, Chakraborty and his colleagues also calculated separate indices using only the variables assigned by the authors to each cluster. For example, in the population and structure group, only the total number of people, number of housing units, and number of mobiles homes were applied using the methodology shown in Fig. 2. It should be noted that the groupings are based on the authors' assumptions, contrasting with the statistical grouping utilized by Cutter et al. (2003). Regardless, the results of the four approaches using the three groupings and all ten variables were used to determine the number of people in the highest risk zones based on each approach.

Demographic data

The variables used in this study, shown in Table 1, were obtained from the US Census Summary Form 3 (SF-3) sample data at the block group level. Table 1 also displays the part of the methodology making use of each variable. The decision on which variables to include derived from a desire to avoid using redundant variables and tailor the variables included to the scale and location of the study. For example, some variables included in Cutter's framework such as those concerning racial composition, international migration, percent urban population, become inconsistent or inappropriate because of the smaller area under consideration or because of difference in Puerto Rican culture and overall demographic composition. Essentially, the criteria for variable inclusion were to preserve the multidimensionality of the Cutter framework while keeping the overall number of variables relatively small.

Statistically derived additive social vulnerability index

The variables shows in Table 1 were placed in a rotated principal components analysis in order to extract empirical orthogonal factors representing social vulnerability in the San Juan *municipio* according to the methodology of (Cutter et al. 2003). The unit of analysis used was the census block group, which had an average extent of 0.33 km^2 in the study area, in order to capture the maximum amount of variation within the study area as possible. The resolution of the areal unit has clear effects on the pattern of vulnerability produced. The census block group covers an extent appropriate to considering vulnerability at a local, neighborhood scale. Using the varimax rotation, four factors with eigenvalues >1.0 were extracted. These factors explain 76% of variance among census block groups in the San Juan *municipio*. Table 2 displays how each original variable loaded on the four extracted factors.

Table 1 Variables and their use

Variable	SoVI	SVAI	Used in Deriving %
Total population	✔	✔	✔
Total households	✔	✔	✔
Total occupied housing units			✔
Total population living in female-headed households	✔ (As %)	✔	
Population < age 5	✔ (As %)	✔	
Population > age 85	✔ (As %)	✔	
Median year structure built		✔	
Median age of structures	✔		
Institutionalized population	✔ (As %)	✔	
Population living below the poverty	✔ (As %)	✔	
Mobile homes	✔	✔	
Social security income per household	✔		
Population over 25 without a high school diploma	✔ (As %)	✔	

Table 2 Rotated variable loadings

Variable	Factor 1	Factor 2	Factor 3	Factor 4
Percent of population with no vehicle	0.860	–0.049	0.118	–0.008
Percent under Age 5	0.672	0.162	–0.220	–0.151
Percent over age 85	–0.291	–0.104	0.725	–0.127
Percent institutionalized population	0.047	0.062	0.811	0.081
Percent of households under the poverty line	0.941	–0.037	–0.079	–0.003
Number of mobile homes	0.004	0.082	–0.022	0.951
Social security receipts per household	–0.670	–0.301	0.242	-0.037
Percent with no high school diploma	0.839	–0.200	0.032	0.235
Percent female headed households	0.749	0.058	–0.202	–0.216
Total housing units	–0.073	0.970	–0.010	0.013
Per capita income	–0.782	0.131	0.012	–0.137
Total population	0.091	0.952	–0.028	0.069
Total number of households	–0.050	0.980	–0.009	0.007

The first factor, explaining 35.51% of total variance, loads highly on the common basket of vulnerability variables. These include percent of actual population with no motor vehicle available, percent under age 5, percent living in household below the poverty line, percent of population over 25 without a high-school diploma, and percent living in a female-headed household. These variables represent parts of the population least able to access resources needed to respond to physical hazards. It is therefore the factor most directly indicative of vulnerability tied to population social and economic characteristics.

The second factor, explaining 23.33% of total variance, indicates the block groups where the highest numbers of people live. Loading high on this factor were total population, total households, and total occupied housing units. These variables are not included in the Boruff et al. (2005) study; furthermore, it is obvious that they would group together in a data reduction procedure. They were included in this study primarily in order to facilitate and maintain the validity of comparison between the SoVI and social vulnerability averaged index (SVAI). A secondary aim was to de-emphasize large census block groups with few people and emphasize any block groups with relatively high concentrations of people. If census blocks maintained uniform size throughout the study area, this factor would indicate density. In the southern part of the *municipio*, block group sizes become considerably larger, however. Including this factor given variation in block group size has noteworthy consequences. These include masking observed vulnerability in some smaller block groups within the denser parts of the study area and the over-representation of vulnerability in southern block groups with high population only because they include more area.

The third factor, explaining 9.55% of variance, loads highly on indicators of dependent population (included in age groups 0–15 and 65+). The highest loadings on this factor were percent of the population over 85 and percent living in institutional quarters. Institutional quarters include such varied locations as nursing homes, prisons, and dormitories. No federal or commonwealth prisons are present in the study area, though municipal jails are likely present, though a detailed survey of which institutionalized populations are present was not conducted. The University of Puerto Rico's main campus is located in the east central cluster of high loadings for this factor. In the remainder of the study area, this factor mainly reflects block groups with high concentrations of the elderly due to the presence of nursing homes.

Puerto Rico also has a relatively high, 7.4% for Puerto Rico versus 3.7% for the United States as a whole, proportion of families living in multigeneration households (US Census 2001). The Census Bureau defines a household as multigenerational when more than two generations live under the same roof. Although the exact configuration of the relationship of the self-identified householder to others in the household may vary, multigenerational households tend to include an elderly person. Although loading at lower values, also positive were percent without a vehicle and percent without a high-school diploma. The repetition of variables from the first factor may indicate a linkage between multigenerational households and lower socioeconomic status, reflecting the economic motive of sharing housing expenses.

The fourth factor, explaining 8.11% of variance, loads highly positive on the number of mobile homes variable. Mobile homes are rare in the *municipio*, with only 781 people reportedly living in them. Other substandard housing exists in the study area although this analysis did not include any variables that could have captured this population. In Puerto Rico, 10,903 people live in mobile homes. The presence of mobile homes is an important indicator of vulnerability in the built environment. As such, a high loading value for a particular census block group indicates a concentration of mobile homes in the census block group. This factor displays no clustering, as the loading for the other variables are positive but very close to zero. The lack of a relationship between the number of mobile homes and any other variable leads to a muted recapturing of the first factor. Because of the ambiguous relationship between this factor and vulnerability resulting from recapture of the original pattern in conjunction with the overall lack of mobile homes, the absolute value was used in calculating the SoVI. Boruff et al. (2005) employed the use of absolute value when the effect of the factor on vulnerability was similarly ambiguous.

Figures 3 through 6 illustrate the spatial pattern for each factor. The classification scheme for each map is based on the *Z*-score of each block group's PC (principal components) score with the highest values represented by the most saturated colors. Those block group with scores either slightly above or below the mean are not assigned a color in order to accentuate outliers and relative differences. In Fig. 3, a distinct SE to NW axis emerges for most of the municipio. Notable clusters of blocks with high values for the socioeconomic factor include the area around Israel-Bitimul, on the north and east of Old San Juan Island, near Puerto Nuevo, Cantera, and to the south of San Jose Lagoon.

Figure 4 shows block groups with the greatest number of people, while also suggesting the pattern of density for areas where block groups maintain a relatively uniform size. The pattern also reflects areas where population becomes less dense in the south. Larger census blocks in this area capture more of the population. As discussed, the contradiction inherent in this factor makes it problematic and the factor most clearly influence by the modifiable areal unit problem. However, its removal would jeopardized the validity of comparison between the statistical and arithmetic methods for deriving a social vulnerability layer.

The pattern shown in Fig. 5 suggests that older and institutional populations are concentrated in the older

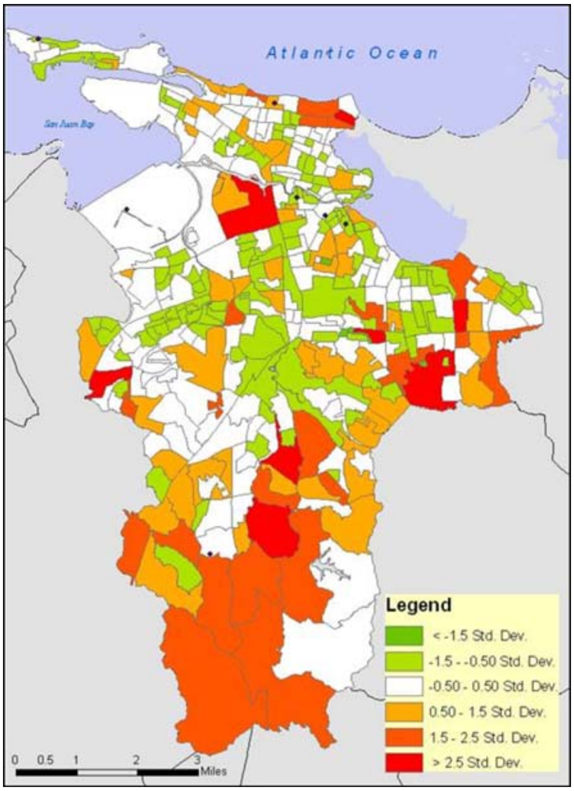

Fig. 3 Socioeconomic vulnerability

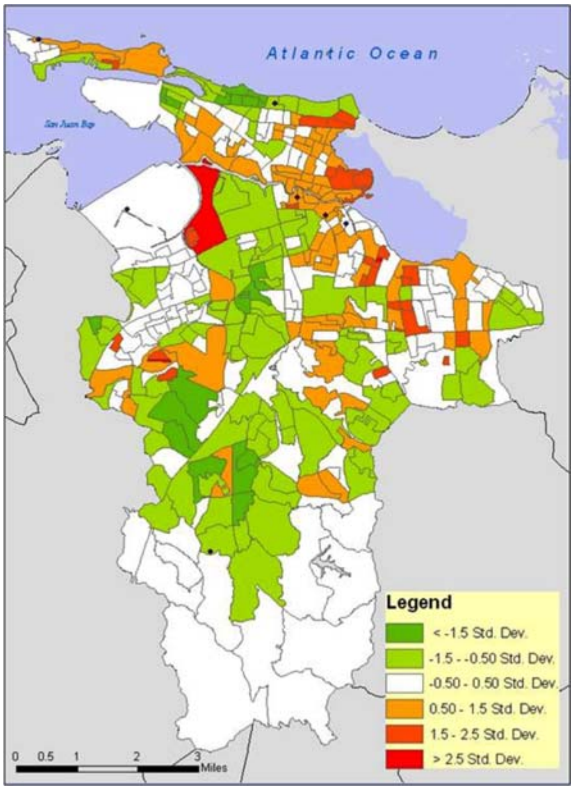

Fig. 4 Population distribution

parts of the city such as Hato Rey, Old San Juan Island, and Santurce. Figure 6 could easily be substituted with a map simply showing the distribution of mobile homes. The pattern likely represents a combination of mobile homes along with a significant portion of captured socioeconomic vulnerability. In the interest of consistency, it is included in the series.

The SoVI was derived by adding the loadings for each factor in each block group. Based on the clusters of variables that loaded for each factor, the SoVI represents an amalgam of factors that represent vulnerability as discussed above. Figure illustrates the spatial pattern for the SoVI. The socioeconomic factor seems to drive the overall SoVI pattern. The remaining three factors influence the SoVI in some areas, which represent a similar distribution as the original variables.

A cluster of contiguous low vulnerability appears in the city center and extends along two of the city's central highways, Carretera 1 and Expreso de las Americas. The highest contiguous SoVI values are found in the southern portion of the study area, where the city approaches the mountains of the Central Cordillera, on the eastern border of the study area around San Jose Lagoon and along the Caño Martin Peña. The last two areas mentioned are *communidades especiales*, or special communities. The commonwealth government recognized these areas as housing some of the poorest residents in the city.

Another of the *communidades especials*, La Perla, does not appear clearly in the SoVI. As will be discussed in later in the article, this may result from an undercounting of this areas residents due to a suite of effects related to the political and social isolation of the neighborhood within the study area. Undercounted areas, regardless of the reason for their undercounting, will receive lower social vulnerability scores using any methodology with a census-driven demographic basis. The lower values result from the inclusion of total population as a variable in both the arithmetic and statistical approaches.

Clusters and hotspots are shown in Figs. 3–6. Certain variables such as the location of mobile homes and institutionalized populations are

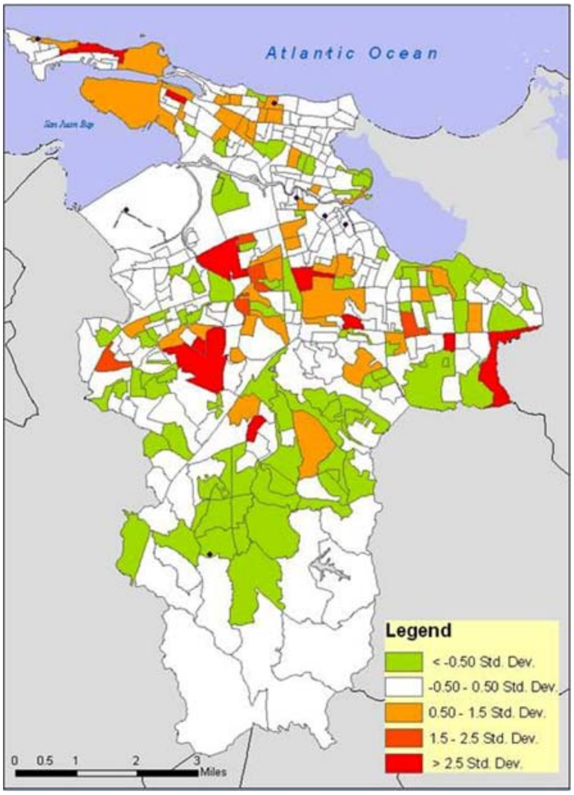

Fig. 5 Dependent population

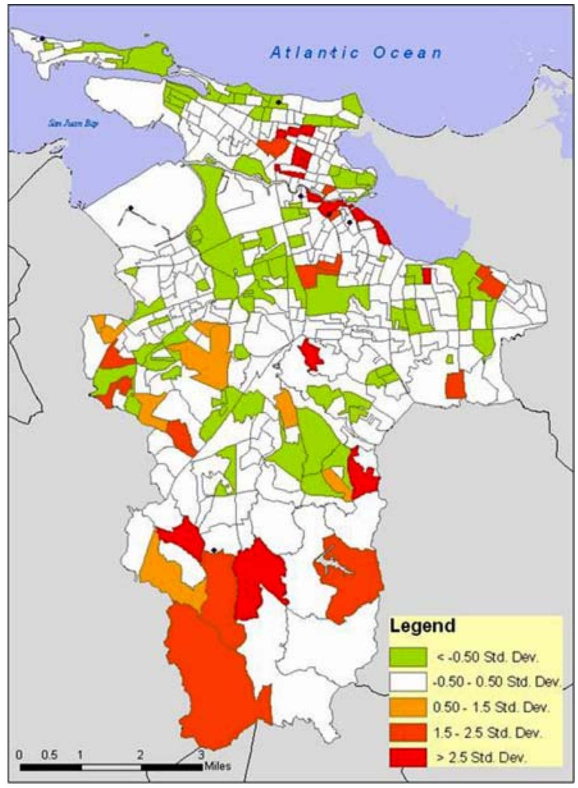

Fig. 6 Mobile homes

extremely unevenly distributed across the study area. This uneven distribution yields higher scores for block groups where mobile homes exist or institutional population lives compared to scores generated by the first factor. Essentially, this could be seen as building a weighting mechanism into those factors with highly uneven distribution when the final index is derived. Perhaps this weighting is justified considering the pronounced vulnerability of mobile homes or the special needs of institutionalized populations who cannot leave on their own due to physical or legal restraints. The effects of the uneven distribution of variables included in the analysis on the final index merits more research and underscores the important of locally derived interpreations of vulnerability.

The large area of vulnerability in the southern part of the *municipio* stems from the gradual transition away from the metropolitan area and toward the relatively less dense, rural areas of the Cordillera Central. Demographic values in these areas warrant their inclusion in the high value classes of the SoVI. However, their larger spatial extent had definite effects on Factor 2, skewing their final SoVI score. Since no method exists in the hazards literature for removing the effects of differently sized units of analysis, these results remain unaltered and open to critique based the modifiable areal unit problem (Fig. 7).

Arithmetically derived social vulnerability averaged index

The SVAI was calculated using largely the same methodology as Chakraborty et al. (2005). The solitary difference involved the inclusion of median age of structures in the block group based on the work of Papathoma et al. (2003), who looked at vulnerability to a tsunami in a relatively small study area and argued for the inclusion of a variable representing the overall health of the building stock. This study also used a ratio based arithmetical index for the creation of a human vulnerability layer. To reflect this difference and the overall difference in

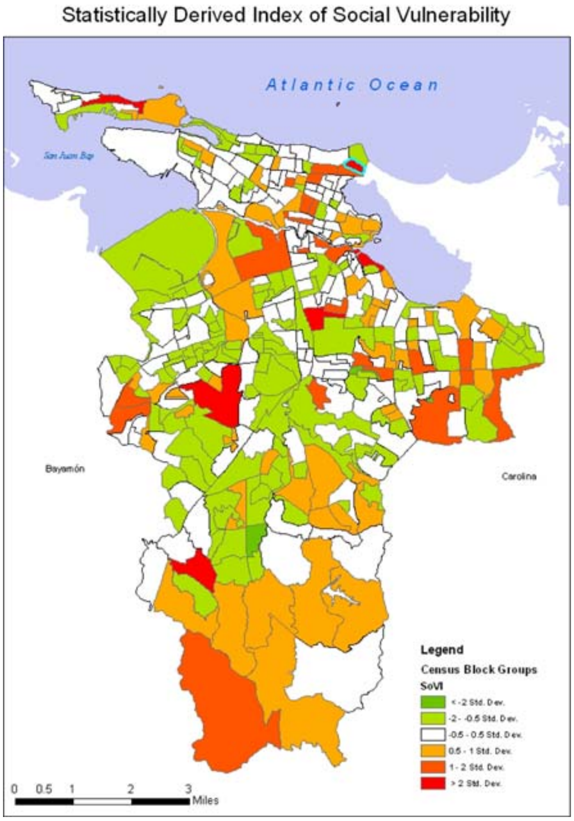

Fig. 7 Social Index of Vulnerability (SoVI)

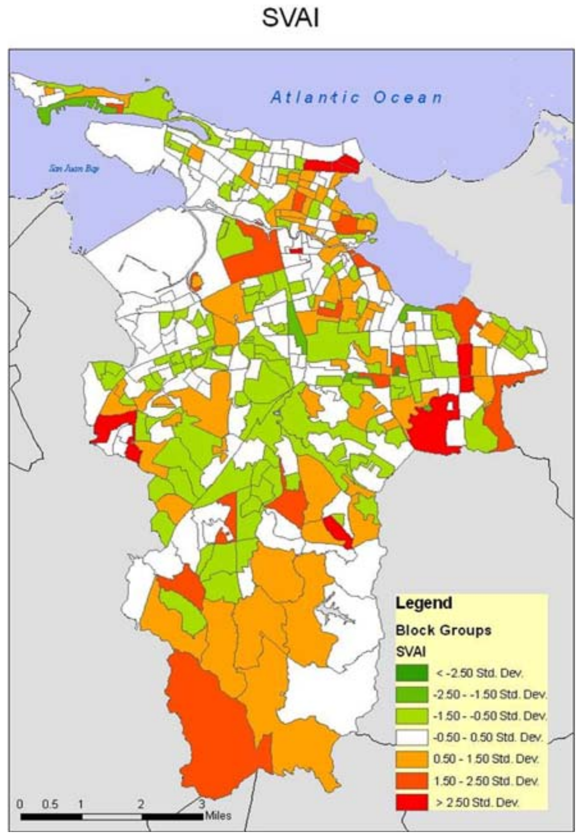

Fig. 8 Social Vulnerability Averaged Index

purpose of analysis here from the Chakraborty et al. (2005) study, the word evacuation is dropped from the name of the index produced.

For each variable *i*, the $SVAI_i$ was calculated according to the methodology in Fig. 2, except for the median age of structures in the block group. The $SVAI_i$ for this variable was computed by dividing the median age of structures in the census block by the maximum median age found in the study area, similar to the method used by Papathoma et al. (2003). The median age was found by subtracting the median year the structure was built from 2000, the year of the census and on which the value for each block group was based.

This allowed for the calculation of the ΣSVAI, the results of which are shown in Fig. 8. The pattern appears similar to the pattern of social vulnerability displayed in Fig. 7, but with more contiguity between areas of similar values. This stems from the normalization of all values and the lack of weighting built into the methodology. While the relatively smooth distribution of values is desirable at this level of analysis, it is impossible to examine the components of the scores, as in Figs. 3–6, without falling back on the assumptions of the researcher.

Results of comparison between SoVI and SVAI

An analysis was then done to compare the results of the statistical and arithmetic methods for producing a social vulnerability layer. The high correlation ($\alpha = 0.001$, $R = 0.772$) between the SoVI and SVAI suggests that the methodologies consistently used in social vulnerability research address the same underlying phenomena. Figure 9 plots the values produced by the two methods on the *X* (statistical) and *Y* (arithmetic) axes. Corresponding values cluster tightly around the line of best-fit but increasingly diverge for block groups identified by at least one of the methods as having higher vulnerability.

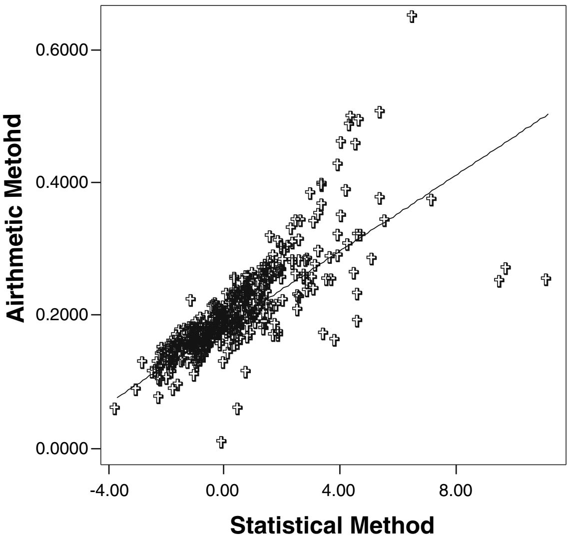

Fig. 9 Graphical comparison of SoVI and SVAI

Neither methodology assigns an explicit weight to either the variables or factors in their contributions to the final social vulnerability layer. As discussed earlier, a certain amount of weighting becomes implicit within the rotated PCA methodlogy. Analysis of the spatial patterns of the constituent factors that comprise statistical method (SoVI) provides for context and a more complete understanding of how facets of social vulnerability combine in its production. Nevertheless, the two methodologies appear largely interoperable. Selection of either methodology ideally depends on the intended use of the study and the confidence with which a researcher can chose from available variables. If the relationship of available demographic variables to each other are unclear, then the statistical technique has the benefit of grouping collinear variables without a priori knowledge. For policy analysis however, as in the case of an evacuation study, the simpler methodology may be more appropriate.

The statistical methodology was used to create the social vulnerability layer in this study even though it deals with a relatively small set of demographic variables. The index was chosen because of the methodologically derived clusters of vulnerability factors. These factors would aid when synthesizing field experience and the composite vulnerability layer as it would be possible to discuss certain areas of the city in relation to both the total SoVI score for the area and component factors. In addition, the factors could be placed in a linear regression along with the physical vulnerability layer in order to determine which parts of the city socioeconomic and physical determinants of vulnerability play a larger role as demonstrated by Boruff et al. (2005).

Role and types of physiographic data

Cutter (1996) identifies three subelements of biophysical vulnerability, which include the type of hazard, the probability of occurrence, and the delineation of hazard zones. In the diagram used in that study, the terms *elevation* and *proximity* appear under geographic context. These variables suggest the types of data that address the question of exposure; however, Cutter does not offer an explicit list of variables for each hazard type that captures variability. The Cutter et al. (2000) study focusing on Georgetown, South Carolina, deals with chemical releases, drought, earthquakes, floods, hail, hurricanes, thunderstorms (wind), tornadoes, and wildfires. According to the researchers, the list does not exhaust the range of potential hazards encountered in Georgetown but suggests those most likely encountered by emergency planners in the city. Each of these hazards also lends itself to easy quantification of a return period.

In its most rigorous applications, the hazards of place model sums probabilities of occurrence in a matrix of hazards likely to affect the study area. The value obtained from adding the probabilities in their decimal form yields the biophysical vulnerability layer. Other methods, however, are also used including assigning ranks according to relative susceptibility. Susceptibility becomes a useful concept when exact probabilities are unknown or difficult to calculate but factors that increase relative vulnerability are known to exist at a place.

Flooding and mass movement hazards constitute the biophysical layer in this study. The decision to limit quantitative analysis to flooding and mass movement hazards derives from time and resource constraints but, more importantly, an interest in consistency and avoiding the pitfalls of analysis based on convenience. Data availability and quality, a constant issue for research with a GIS component, should not exert an unjustifiable influence on methodology. The process of overlaying many physical hazards as layers generates a comprehensive analysis but buries the influence of component hazards. Maintaining the transparency of methods used to produce biophysical vulnerability ensures the relevance of research to emergency planners who are usually interested in planning for specific types of hazards (Britton and Lindsay 1995; Morrow 1999).

Precipitation is the primary input in determining the extent of flooding or the occurrence of a landslide and is modified by other considerations such as soil types and type and extent of ground cover. While earthquakes and road-cuts also have the ability to trigger a landslide in Puerto Rico, precipitation causes the most frequent and costly landslides in Puerto Rico (DeGraff et al. 1989; Larsen and Simon 1993). Tropical disturbances ranging from unorganized lows to major hurricanes tend to deliver the majority of precipitation to Puerto Rico during the wet months of May through December. Cold fronts cyclones usually deliver less than a third of island's precipitation during the few winter months when mid-latitude cyclones penetrate into the Caribbean. The effects of topography and the importance of orographic lift exert a strong influence on local variation in rainfall intensity regardless of the type of system under consideration (Larsen and Simon 1993).

Northern Puerto Rico constitutes a relatively uniform climatic region based on both temperature and precipitation regime (Malgrem and Winter 1999). Precipitation varies only slightly across the study area because of its small size, with higher amount due to orographic lift found toward higher elevation. In the short-term, convective storms deliver highly localized amount of precipitation during the rainy season however, difference arising from localized precipitation generally equalize over time. Local bursts of precipitation may cause localized flooding or trigger a landslide, but the difference in overall susceptibility has more to do with ground considerations such as elevation and slope and other factors that affect permeability such as soil type, land cover, and underlying geology. Based on the long-term homogeneity of precipitation across the study area, it is taken as an exogenous factor in determining flooding and landslide susceptibility zones. The data included in the creation of the hydrological susceptibility layer represent these concerns using the best possible available data.

Flood hazard

Q3 Flood Maps, produced by FEMA in conjunction with the National Insurance Flood Program provide the flooding hazard zone. Q3 refers to the series of electronically available digitizations produced from paper copies of National Insurance Rate Maps (NIRM). The digital NIRM plates cover the same areas at the same scale as 1:24000 topographic maps produced by USGS. Many studies in the hazards field use Q3 maps to produce a flooding layer, including studies referenced by Cutter et al. (2000, 2003), Wu et al. (2002), and Chakraborty et al. (2005). Digital versions of Q3 flood zones were not immediately available for the study area of Puerto Rico in general. The process of transforming what were essentially on-screen paper maps to georeferenced spatial data involved the collection of control points and rectification on the basis of those control points. The FEMA Map Store (http://www.msc.fema.gov/), available at the FEMA website, offers Q3 Flood Products available for purchase and download.

Figure 10 shows digitized flood polygons from the FEMA maps. The classification scheme breaks the polygons between areas with either a 1 or 0.2% annual chance of flooding. A 1% annual chance indicates an average return period of 100 years, while a 0.2% chances indicates a period of 500 years. The 1% group is further divided between areas that experience an added storm surge saltwater velocity flooding (VE) and all other zones away from the coast. These groupings provide the basis for rudimentary quantification of the flood zones. Following the methodology of Wu and his colleagues, the flood zones were assigned the values as show in Table 3.

The risk values do not indicate a direct relationship between the different risk scores and vulnerability. For example, people living in an area whose risk value is 4 are not twice as vulnerable to flooding as those living in an area whose risk value is 2. Such comparisons wither under scrutiny even if concrete statistical relationships exist between the area such as those between 100 and 500-year flood hazard zone. The rankings have no deterministic value and imply relative susceptibility to the hazard in question only. With these limitations in mind, the values were to compute the total biophysical vulnerability score. Table 3 also includes the total areas for each flood hazard zone. Notice the small area encompassed by

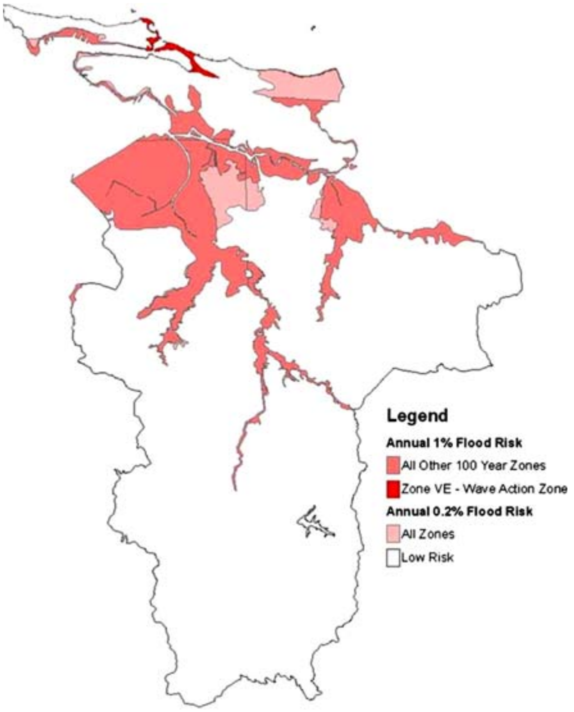

Fig. 10 Q3 derived flooding hazard zones

Table 3 Flood zone areas and susceptibility scores

Flood zone	Area	Risk score	Map shading
VE (wave action)	0.59 Km^2	4	
100 year	18.04 Km^2	3	
500 year	4.12 Km^2	2	
Low risk	101.29 Km^2	1	

the VE polygon in the northwest part of the study area. In addition to this area, a narrow strip, barely visible also exists along the easternmost extent of the study area coast. While only 30 m wide, the strip will influence values for the line of grid cells immediately along the coast.

Susceptibility to precipitation induced landslides

The landslide susceptibility layer resulted from three sources of data: Slope, soil type, and the extent of a preexisting risk layer produced by an office within the *Oficina de Planificación* (2003) within the Puerto Rican government. Determination of slope involved several steps of data preparation and reclassification described below. The remaining two layers were available digitally and required only minor processing for use in generating the landslide susceptibility layer.

Using the calculate slope tool in Spatial Analyst and a 30-m DEM of the study area, a raster with ground angle for each 30 m grid cell was produced. The resulting grid is a component of the map shown in Fig. 11. As the cells themselves are based on an average, a significant amount of generalization is introduced. The figure shows the spatial pattern of slope angle in the study area before reclassification.

The reclassification scheme for slope angles is based on a report, "Elements of Slope Hazard Evaluation: Guidelines for Determining Landslide Risk"' produced by the USGS-San Juan Office (1991). The risk of landslide begins to increase markedly in slopes above 15° and reaches maximum on saturated slopes between 20° and 40°. Interestingly, the risk of landslide begins to decrease for most soils as slope increases beyond 40°. The highest slope value in the study area was slightly below 42°. The

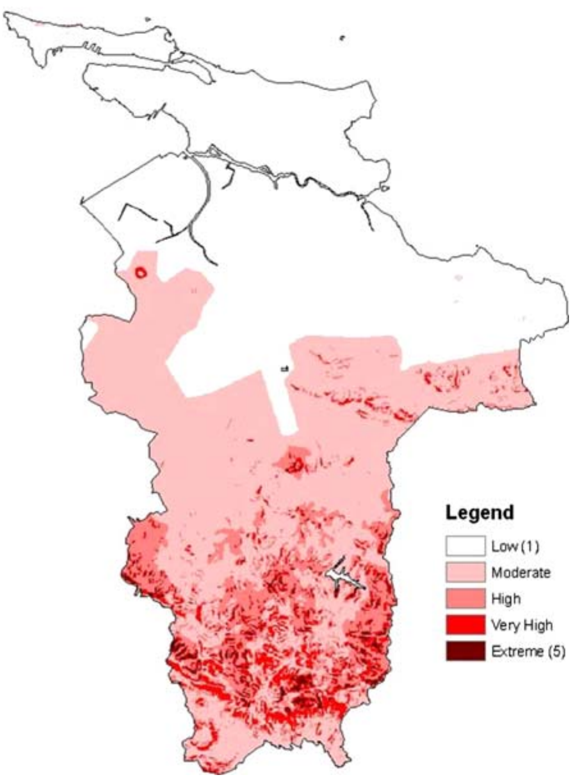

Fig. 11 Landslide susceptibility scores

susceptibility scheme therefore did not need to reflect the U shaped relationship between slope angle and landslide.

The *Plan de Mitigación Multi-Riesgo* (Multi-Risk Mitigation Plan) for the neighboring municipio of Bayamón identified soil types in the Bayamón-San Juan-Carolina area particularly prone to landslides (Oficina de Planificación 2003). These soils include Humatas clay, Mucara clay, and Tanama-Rock outcrop complex. Using digital data from the National Resources Conservation Service, a raster layer indicating the locations of these soil types provided an additional layer for incorporation into the landslide susceptibility map.

Finally, the *Oficina de Plan de Uso de Terrenos* (OPUT) produces a map based on USGS data that classifies Puerto Rico into zones of low, moderate, high, and extreme risk for landslides (*Oficina de Plan de Uso de Terrenos* de Puerto Rico, n.d.). Of these only low and moderate zones are present in the study zone. The scale of analysis for these zones would make sole reliance on the OPUT data unsuitable for the study. However, it seemed important to ensure that any area included within the area of moderate risk by OPUT for the island overall would score as relatively more susceptible than the lowest possible value or background value. In order to facilitate this result, all grid cells within the OPUT zone receive a plus 1 to their score.

The features representing soil types and the OPUT risk zone were rasterized and added with the slope raster according to the scheme shown in Table 4. The OPUT layer was included to avoid characterizing areas as low risk in this study that an office within the Puerto Rican government considered moderate risk. Precipitation, it should be remembered, is considered an exogenous factor in this analysis due to the relatively small size of the study area. As with flooding data, background areas were assigned a value of one rather than zero. Equal weights were assumed for each of the input factors. Therefore, possible values range from a low of one, meaning the grid cell received a zero in all three input layers to a maximum of five. A value of five indicates that the ground represented by the grid has a high slope, unstable soil, and was included in the OPUT island-wide zone of moderate risk. The completed landslide susceptibility layer is shown in Fig. 11.

The final pattern for landslide susceptibility highlights the rugged terrain in the south of the study area. The pattern of landslide susceptibility resembles that of flooding. During precipitation of sufficient intensity and duration, and especially during a hurricane, it appears the main hazard in the northern and more urbanized part of the study area would be flooding while landslides would be more common in the south. Again, these values have no deterministic weights but represent relative susceptibility to the hazard under consideration. Coastal areas lie almost completely outside the area susceptible to landslides. A notable exception is visible along the immediate northern coast of Old San Juan because of slope angles over the lower threshold of 15°.

Table 4 Scoring and sources for landslide component

Data value	Source	Raster
Slope	USGS/NED	
0–15		0
15–20		1
Over 20		2
High-risk soil type	NCRC	
Yes		1
No		0
Recognized risk zone?	OPUT/JP	
Within		1
Without		0

Creating the hydrological vulnerability layer

The values from the flooding and landslide layers comprise the physical vulnerability layer. The flood polygons were first converted to a 30-m grid with the same extent and cell size as the layers used in deriving the landslides susceptibility layer. The two values for the flood and landslides raster layers were added without any weighting or any other a prior assumption about the importance of those layers in producing physical vulnerability, Fig. 12 shows the resulting map. The physical vulnerability represented here is narrow. It refers to the physical geographic context of vulnerability when considering hydrological triggered hazards.

The pattern represents the overall pattern of landslides and flooding in the municipio. The most vulnerable areas are those toward the coast subject to

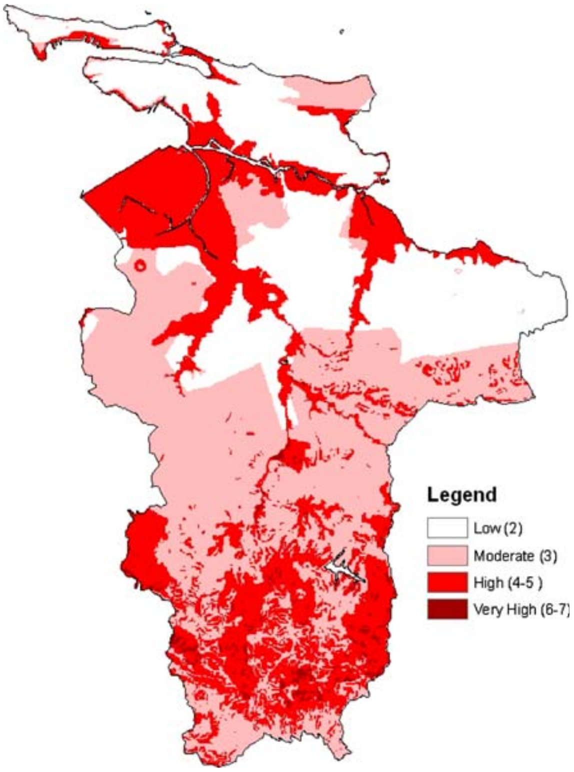

Fig. 12 Composite hydrological vulnerability layer

velocity, or wave-action flooding hazard. The lowest possible value is two, representing the background value for each hazard. Note that the highest two groups are grouped as only 15 cells registered the highest possible ordinal value. These cells lie on the highest slopes and probably do not support any human population. This layer will be normalized and combined with the SoVI to produce a total place vulnerability layer.

Vulnerability of place

Wu et al. (2002) regrouped both physical and social data into quartiles and multiplied the values. Their flood hazard data ranged from 1 to 4, corresponding to the nominal categories "low," "medium," "high," and "severe." The social index ranged from 0 to 1 as a result of using a normalizing methodology similar to that of Chakraborty et al. (2005). Chakraborty et al. (2005) also defined the composite layer as the product of the socioeconomic and physical layers without assigning weights a priori to the layers. Both authors, as with the development of their socioeconomic demographic methodologies identified Cutter et al. (2000) as the justification for their decisions.

Place vulnerability for San Juan municipio

Before being multiplied, the values for the social vulnerability layer (SoVI) and physical layers were normalized (Figs. 13, 14). Normalization involved dividing all grid values by the highest possible values so that both layers ranged between 0 and 1. In addition, the values from the social layer were rasterized to a 30-m grid exactly matching the extent and arrangement of the grid used in deriving the physical layer. This reproduced the borders between the block groups but allowed for a cell-by-cell evaluation of the relationship between the physical and social layers. Note that in Fig. 14 the legend displayed all possible values. This is because the normalized values for the physical layer were derived by dividing the ordinal values, two through seven, by the maximum ordinal value. The legend in Fig. 13, displaying the SoVI, uses a stretched scale to represent all possible values between the minimum and one because of the numerous possible values possible for the layer.

Two considerations led to the decision to rasterize the SoVI values to a 30-m grid. First, the degree of spatial resolution decreases the error introduced. Second, and more conceptually, people are fluid and affect their immediate neighbors and local community. Census data in raw form does not account for where people go and what they do during the day. Only in the crudest sense does rasterization begin to address this concern. Physiographic features, especially those implicit in the physical layer (elevation, soil type, and slope angle), do not possess the same fuzziness considering how they were operationalized in this research. The best landslide models include the effects of landslides not originating at the grid point; the one used in this study did not. As such, it seems better to reproduce demographic detail than to "smear" the effect of a steep slope or low-lying area where it certainly does not exist.

The values are grouped by quintile to accentuate relative differences among different parts of the municipio. The overall pattern reflects pronounced

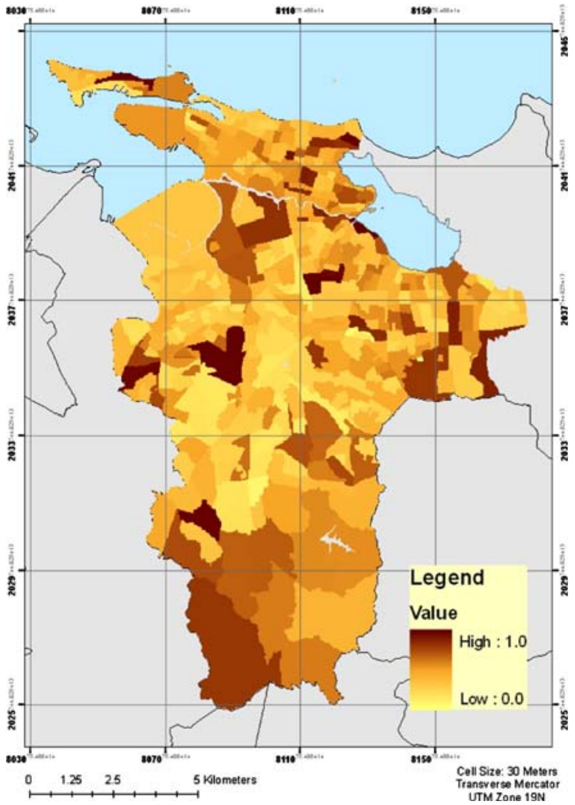

Fig. 13 Normalized and rasterized social layer

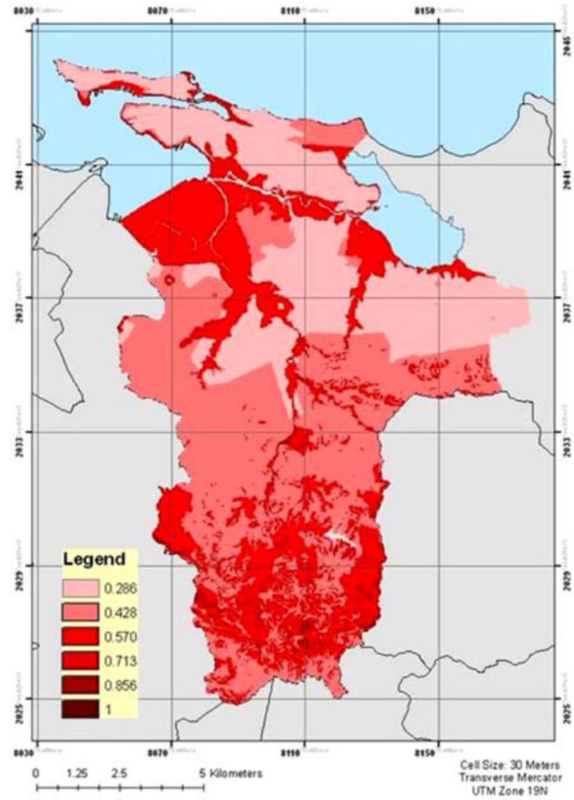

Fig. 14 Normalized and rasterized physical layer

vulnerability in the southern part of the *municipio* due to demographic and physical factors in addition to vulnerability concentrated around the Caño de Martín Peña and Laguna San Jose. The pattern appears to represent a combination of social and physical factors, with neither set component raster layer overwhelmingly affecting the overall picture of vulnerability. In areas such as Puerto Nuevo where a large swath of physical vulnerability exists, but demographic differences also exist, the borders of census block groups become apparent. Edging effects from the physical layer also become apparent in the borders between flood zones and areas outside those zones.

Figure 15 displays the spatial pattern for the total vulnerability of place layer. The lack of place vulnerability within the core of the city is the most striking feature at this scale of analysis. This area includes the central business district, including the "Magnificent Mile" where most Puerto Rican tertiary corporations maintain headquarters. San Francisco, an area of gated communities housing some of the most affluent Puerto Rican also lies within this area. A guided tour of this area provided by the assistant to the governor provided an opportunity to see what "low vulnerability" looks like on the ground. The houses appeared constructed to the same level of engineering as in the most current construction on the mainland United States. That the area registers in the lowest quintile supports the model.

The pronounced border between areas in the highest and lowest quintiles highlights the ability of the methodology to produce high detail. This pronounced border also emphasizes how vulnerability quickly varies over small distances. The juxtaposition of these differentially vulnerable areas also calls into question the role of connectivity. Perhaps the value of each pixel could influence the value of its neighbors. Calculating the mean composite value for each block group addresses this concern crudely. Block groups do not follow any sort of culturally relevant boundary, however. Methods based on fuzzy logic could

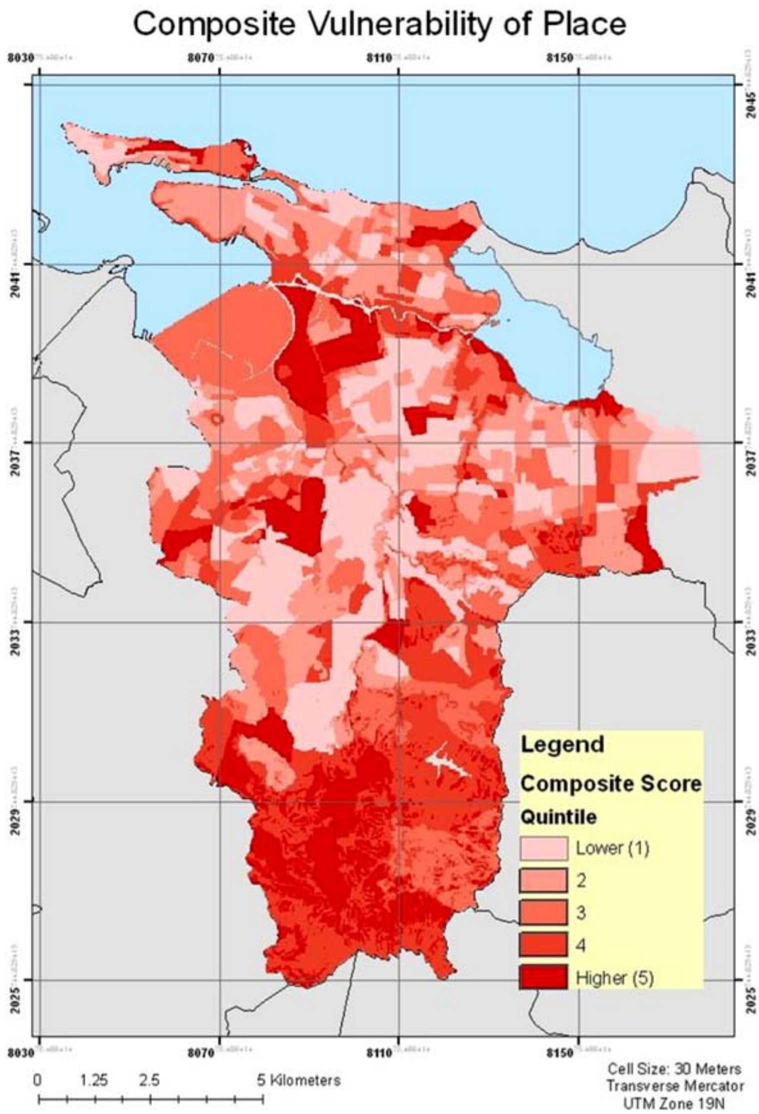

Fig. 15 Vulnerability of place for San Juan Municipio

help to smooth the results of vulnerability analysis in future studies (Rashed and Weeks 2003).

The interpretation of vulnerability scores should depend on the intended use. The incorporation of culturally relevant boundaries into the analysis process would help policy makers and planners. Boundaries that mark functional areas recognized by residents as having social and economic cohesion would signify culturally relevant boundaries. Until then, mitigation efforts need to target areas based on culturally relevant boundaries and incorporate elements that address insecurity, change, and other dynamic processes. Emergency planners and responders should pay less attention to these concerns and use the finest amount of detail possible in locating and offering aid to those in need. Regardless, this method offers a means for providing meaningful, detailed values that represent total vulnerability from which to structure such planning efforts.

La Perla: Hazards of place on the ground outside the mainland US

The neighborhood of La Perla sits directly below the city wall in Old San Juan, within easy walking distance to the cruise terminal, the governor's mansion, and many of the island's most exclusive dining and entertainment establishments. The neighborhood, a *comunidad especial*, provides an opportunity to examine a poorer neighborhood surrounded by wealthier areas encompassed by the study area. La Perla came into this study because it is convenient to access and because it was suggested to the researchers by *san juaneros* who took part in the study. It was not randomly selected and so there is no pretense of creating new falsifiable or general knowledge. It does however suggest two concerns that deserve consideration in future research situated within the hazards of place framework. The first concern deals with the effects of using census data as the basis for calculating the SoVI. The second suggests that the hazards of place framework may need to incorporate continually the continually accommodations made between communities and their environment.

Figure 16 offers a close-in view on the island of Old San Juan. The north central census block stands out with a high composite value. This particular census block scored particularly high on Factor 3, loaded highly by variables indicating high numbers of dependent population including institutionalized persons. This relates to the implicit weighting of unevenly distributed variables. The highly unequal distribution of certain variables such as institutionalized populations and mobile homes caused census block groups with those variables to register high eigenvalues. Because of the existence of a jail or assisted living facility, an essentially zero-dimensional or point feature at this analysis scale, an entire polygon scores highly in the model. This is a weakness of the model.

The primary reason behind this weakness may stem from undercounting of neighborhood residents in the Census 2000 data. One census block (FIPS 72127/0004/003) covers the approximate area of the community. According to the census SF-3 tabular data, the block has only 360 residents divided into 360 households. The ratio of people to households seems suspect based on the Census Bureau's characterizations of the high number of multigenerational, lower-income households in Puerto Rico (US Census Bureau C2KBR/01–8). Even based on a visual inspection of the area, this number seems low based on building density observed. The perception of the neighborhood as an enclave on the part of local officials further supports the possibility of

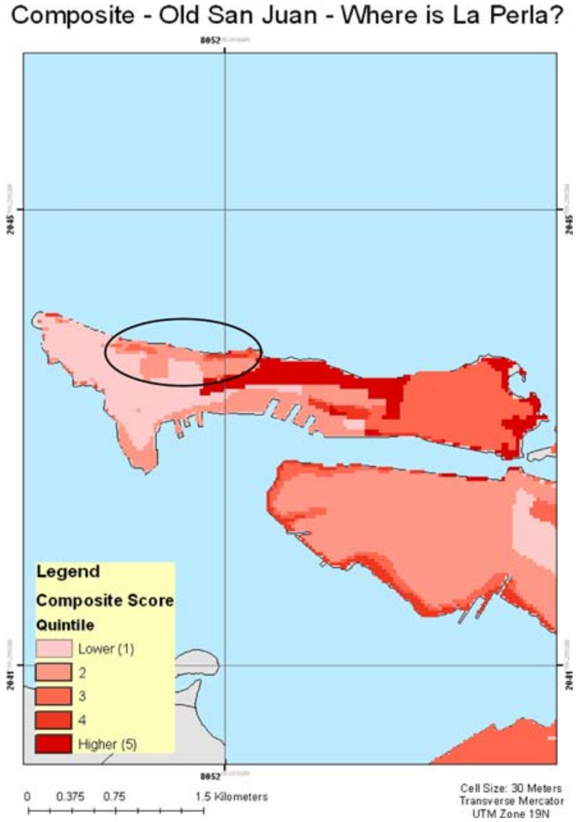

Fig. 16 Focus on old San Juan: *Circle* indicates location of La Perla

undercounting in the neighborhood. Of these 360 enumerated residents, 235 live below the poverty line. While the absolute number of people counted appears low, this proportion fits with the neighborhood. Because the absolute number of persons living in a census block as well as the characteristics of that population influenced the SoVI score, La Perla is underscored in the model. La Perla does not show up clearly in the final analysis, possibly due to the effects of implicit weighting and undercount caused by reliance on census data.

The second point raised by La Perla relates to the separateness of this neighborhood as manifested physically, as it is outside the city wall and below the rest of Old San Juan and politically. Miguel Arroyo, personal assistant to the Governor, characterized La Perla as, "...like the Vatican, those people, they take care of themselves, and we don't bother them (Interview, 8/18/2005)." He went on to note that the widow of a recently deceased drug lord "took care" of the community, and that the governor knew of the arrangement but had no interest in trifling with the historical isolation and self-reliance of the community. Residents of La Perla say that they expect no access to city emergency resources such as police, fire, or EMS. In return, police authority impinges little on the area, with the exception of occasional raids, usually at the behest of the US Department of Drug Enforcement (AP 2002).

The residents of La Perla lives do not revolve around the consideration of and preparation for disaster. In fact, they probably do not think about future hurricanes or landslides very much at all. They like all people are continually adjusting to their environment and to each other, as individuals and in groups. At first glance, the housing stock and relative wealth of the area seems to suggest higher vulnerability. The methods used in this study and other vulnerability studies fail to capture the dynamic social networks of places like La Perla, however. Without more insight concerning human-environment systems within culturally relevant boundaries, it is difficult to characterize La Perla as more or less vulnerable. Future research must determine the *precise* conduits through which resources provided by stakeholder social networks are accessed and how these resources are accessed in response to a hazard. Schröter et al. (2005) suggest that the human-environment system reacts to hazards and that the entirety of this system must be considered. This quick look at La Perla confirms the validity of such an approach.

Limitations

Moving the hazards of place framework outside of the mainland United States context suggests areas for further research concerning the applicability of the technique in the developing world. As discussed earlier, San Juan has unique position between the developing and developed worlds. Even in this hybrid context, the hazards of place framework demonstrate a tendency to submerge issues concerning the completeness of data and the importance of informal social networks in peripheral areas. This suggests the need for more studies that test the applicability of hazards-of-place in the developing world, rather than prohibiting the deployment of the analytical technique in the developing world. The framework has clear uses in the developing world because of its ability to combine a wide variety of data based on solid theoretical grounds.

Undercounting of vulnerable populations presents an important limiting factor when using demographic data tied to other biophysical data. Undercounting especially affects methods that take the total number of population into consideration as a specific factor. Similarly, uncounted people with vulnerable characteristics also lead to an under representation of vulnerability. This limitation suggests the importance of integrating methods for ground verification of census based demographic data, especially in peripheral areas.

The assessment of temporal dimensions of vulnerability represents an underdeveloped component of current methodologies. Current vulnerability studies use one census, one survey, one data capture point to deal with people living in an urban area. In the developed world, regularized daily, weekly, and seasonal patterns characterize the movements of people between and within urban areas. In the developing world, such patterns also exists though perhaps slightly less regularized and with varying parts of the population removed from these cycles, though one could argue that patterns are more regularized in either developed or developing contexts. Regardless, the inclusion of time geography into vulnerability research presents a formidable but necessary methodological hurdle.

The methods used to construct physical vulnerability would benefit from the application of more rigorous, probability based methods. An improvement on the methods used in this research would involve using a layer based on actual probabilities of a landslide affecting a location based on certain amounts of rain as explored by Larsen and Simon (1993). The flood layer could also be made to reflect finer detail variation in the landscape using a higher spatial resolution DEM and modeling methods that account for the original landscape variability masked by DEM acquisition (Manson et al. 2002).

Finally, this research needed to use far fewer variables than employed in the much-referenced Cutter et al. (2003) article. As stated earlier, this decision marks an attempt to keep the amount of data considered consistent between the statistical and arithmetic approach. This decision could have effects on the continuity of method between this research and the analysis carried out by Cutter and her collaborators. These limitations underscore the importance of data availability and inclusion in vulnerability analysis. Although the analysis conducted in this research may have included less data than other studies cited throughout the article, the amount of demographic and physiographic data marshaled would still prove extremely difficult to duplicate in the developing world.

Conclusion

The goal of this research was to assess vulnerability to hydrological hazards in San Juan based on demographic and physical data while grounding these quantitative methods in context through fieldwork. Several recommendations using data produced within the study are possible, assuming the willingness of policy makers to accept differential vulnerability as both meaningful and valid. The factors used as components in deriving the social vulnerability index represent opportunities for a range of officials to direct planning and mitigation. In a GIS application utilizing output produced in this study, the components of social vulnerability would likely be useful as separate layers.

Emergency management officials would, for example, have much to gain by working with the dependent population factor, the factor characterized by high numbers of the elderly, disabled, and college students. The evacuation needs of dependent populations require specific resources before the onset of a physical hazard. The deployment of these resources could be better orchestrated using components of the model developed in within the research presented here. Similarly, the socioeconomic layer suggests areas for targeting the distribution of basic needs during the immediate aftermath of a physical hazard. The most important use of the composite vulnerability map, the final quantitative product of this study, is in locating previously overlooked areas, or previously unknown pockets of vulnerability. While many areas already known to city officials register as vulnerable, other unrecognized islands of vulnerability exist. These are possibly in extra peril because of their isolation. This study has corroborated that vulnerability is quantifiably detectable at an intermediate, urban scale of analysis. Awareness of vulnerability is the first step toward action by any interested individual or party.

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