Mapping the Vulnerability to Potential Toxic Substance Releases from Industrial Facilities under Emergency Situations: A Case Study of Galveston, Texas

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Abstract

This research investigates the spatial variations of vulnerability to toxic substance releases under possible emergency outbreaks in Galveston County, Texas. By identifying the potential risk and measuring the extent of possible impact, we provide useful information for the local government and the public to develop more effective evacuation strategies. Assuming that toxic substance releases occur during a worst-case scenario, we determine the vulnerability based on a combination of five factors at the census block level: (1) population density; (2) the percentage of people under 5 years old and above 65; (3) distance between residence and hazardous sites; (4) road network capacity; (5) density of hazardous sites. We employ the Areal Locations of Hazardous Atmospheres (ALOHA) dispersion model to define the impact areas. We calculate an index for each of the five factors. We weigh the indices equally and generate the overall vulnerability index. Results are visualized in a GIS environment.

Keywords

vulnerability, evacuation, toxic release, worst-case scenario, GIS

I. INTRODUCTION

We present an approach that assesses the spatial variation of vulnerability of exposure to toxic substances that may be released from industrial facilities under possible emergency situations. We use Galveston County, Texas to illustrate the approach. Galveston County is located two miles off the Texas coast in the Gulf of Mexico and has one of the world's highest concentrations of petrochemical plants(Brown, 2002). An accidental explosion of a chemical facility would impose a great threat to this area.

Vulnerability to environmental hazards refers to the degree to which populations may suffer from hazardous materials(Cutter et al., 2000). The general approach to assess vulnerability is first to delineate an area that may be affected by potential hazards, and then to take into account the number of factors, e.g., population size, population structure, house income, and residential proximity to hazards that affect the vulnerability of the area. Vulnerability in an emergency situation is related to the difficulty of evacuation; therefore, we examined the evacuation difficulty of the study area based on a combination of five factors: population density, the percentage of residents under age 5 and above 65, the distance between residence and hazardous sites, the density of hazardous sites, and the shortest amount of time needed to evacuate. The first four factors examine the extent to which the area suffers from toxic releases and the last factor evaluates the difficulty of evacuation. We weighed each factor equally and generated an overall vulnerability at the census block level. Our results revealed a spatial variation of each individual factor and the overall vulnerability of a worst-case scenario in Galveston.

This paper briefly reviews related work, describes the study area and methodology, discusses our results, and addresses issues related to future research.

II. VULNERABILITY TO TOXIC CHEMICAL RELEASES

A great deal of research concentrates on environmental equity and vulnerability(McMaster et al., 1997; Harner et al., 2002; Clickman et al., 1994; Lowry et al., 1995; Parrish et al., 1993; Bowen et al., 1995). In general, there are two major steps in evaluating vulnerability to toxic chemical releases. The first step is to determine the potentially affected area. To define areas that are susceptible to hazardous chemical releases, researchers usually draw a radius around a toxic release site or use the Areal Locations of Hazardous Atmospheres (ALOHA) dispersion model to estimate dispersion distance of toxic gases. The ALOHA model was developed by the National Oceanic and Atmospheric Administration(NOAA) and the Environmental Protection Agency (EPA)(National et al., 1999). The model was constructed especially for responding to chemical accidents and emergency planning. The ALOHA model uses toxicological and physical properties of released chemicals as well as weather conditions to predict impact distances from accidental toxic releases. After the potentially affected area is determined, we measure the vulnerability to toxic chemical releases based on socioeconomic variables and demographic characteristics. As a result, a vulnerability index is created which can then be used to present the variation of vulnerability in the affected area.

1082-4006/06/1201-27$5.00

Using ALOHA model, Charaborty and Armstrong investigated the racial composition and household income distribution of those potentially affected by toxic substance releases at truck accident sites in Des Moines, Iowa(Charaborty et al., 1996). In a study of Cedar Rapids, Iowa, Charaborty and Armstrong identified the potential exposure of the city's special needs population (those require special assistance in case of emergency) to worst-case chemical releases(Charaborty et al., 2001). Their study provided detailed descriptions on how to develop worst-case chemical accident scenarios using the ALOHA model. In an early study, McMaster(McMaster et al., 1990) discussed the use of GIS to assess community vulnerability to hazardous materials for the City of Santa Monica, California. He developed a risk-assessment model, which incorporated demographics information as well as a hazardous materials component. Cutter *et al.* investigated the vulnerability of people to environmental hazards (chemical releases, hurricanes, floods, etc.) using both biophysical and social indicators in a case study of Georgetown County, South Carolina(Cutter et al., 2000). They used frequency of acute hazards and delineation of hazard zones to measure biophysical vulnerability and sociodemographic characteristics such as population, accessibility to resources, susceptibility to hazards, and socioeconomic status, to assess social vulnerability. They concluded that place vulnerability is a combination of both biophysical and sociodemographic vulnerabilities. By overlaying the infrastructure over the place vulnerability, they identified that vulnerability can be mitigated or aggravated from an evacuation perspective. They used the infrastructure information only as a context to depict the existing helpful resources to an evacuation instead of assessing the accessibility to the infrastructure. With respect to evacuation, Cova and Church developed a method to visualize evacuation vulnerability on transportation networks(Cova et al., 1997; Church et al., 2000). Taking into account population and transportation network capacity at the neighborhood scale, their study focused more on identifying difficulties in transportation networks so as to which neighborhood is at risk when an emergency evacuation is necessary.

Literature examining the vulnerability to hazards under an emergency situation is sparse. Unlike previous studies, we combined demographic characteristics and biophysical factors with evacuation difficulties to present the vulnerability given the necessity of evacuation.

III. STUDY AREA

Located in the upper Texas coast of the Gulf of Mexico, Galveston County has one of the world's highest concentrations of petrochemical plants (Figure 1). According to 2000 Toxic Release Inventory (TRI) from the Environmental Protection Agency (EPA), 18 facilities released toxic substances in Galveston County. Those facilities were mainly located around the eastern part of Texas City, which is situated in the eastern part of the county (Figure 1(c)). Based on the chemical releases and transfers reported by industrial facilities to the TRI in 2000, Galveston County ranked among the dirtiest and worst counties in the United States (Table 1)(Environmental 2003). If a chemical plant exploded by accident or an intentional attack occurred, it would impose a great threat to the people and property in the area.

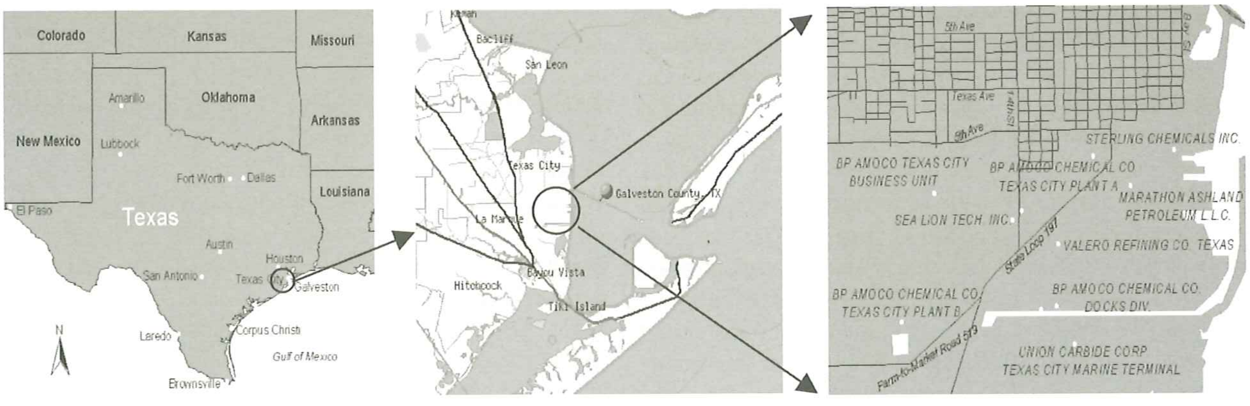
IV. ASSESSING VULNERABILITY IN EVACUATION

The assessment of vulnerability in evacuation consisted of four major steps:

A. Determine the main factors that are related to vulnerability in evacuation

In order to assess evacuation vulnerability, we first need to decide the factors that have an impact on evacuation. Here we focus on two issues. One is the degree to which toxic releases harm people. The other one is how quickly the affected area can be evacuated.

We used four factors to account for the first issue. The first one is the number of people that will be affected. We used population density of each census block as an indicator. The



(a) (b) (c)

Figure 1. Geographical location of Galveston County [(a) and (b)] and chemical facilities located in Galveston County [(c)]

Table 1. Rankings of major chemical releases or waste generation in galveston county in 2000

Cleanest/Best Counties in US			Percentile			Dirtiest/Worst Counties in US				
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90% – 100%
Total environmental releases:										▓
Cancer risk score (air and water releases):									░	
Noncancer risk score (air and water releases):									░	
Air releases of recognized carcinogens:										▓
Air releases of recognized developmental toxicants:										▓
Air releases of recognized reproductive toxicants:										▓

Source: http://www.scorecard.org/env-releases/county.tcl?fips_county_code=48167#major _chemical_releases

second factor is the population below age 5 and above age 65 because it is generally more difficult for those people to evacuate quickly. This classification is also consistent with the age structure of census data. Therefore, we can obtain population statistics for those two groups directly from census. The next two factors are proximity to hazardous sites (toxic release facilities) and the number of hazardous sites that impact an area. If an area is at a higher risk of being affected by hazards than others, or if a residential place is closer to hazardous sites, then it is more vulnerable to hazards.

The other issue on how quickly the affected area can be evacuated is related to evacuation time. We used the shortest time needed to evacuate the affected population from the affected area to assess the difficulty in evacuation.

B. Define the area that may be affected by sudden chemical explosions at the worst-case scenario

After the major factors were decided, we then examined which areas could be affected by chemical explosions. First, we located the chemical facilities in Galveston using the 2000 TRI. We assume that chemical explosions happen in a worst-case scenario. According to EPA(United States Environmental Protection Agency, 1999), a worst-case scenario is the release, from ground level, of the largest possible quantity of a regulated substance through a vessel or process line failure that travels the greatest distance possible before dissipating sufficiently enough to become harmless. Ideally, the total quantity of hazardous materials stored on-site would be used to estimate the impact under a worst-case scenario. However, due to a lack of this kind of data, this study used the total toxic release reported in 2000 as a single accident at each TRI site. This assumption is consistent with the worst-case chemical accident scenarios commonly used by the local office of Hazardous Materials Safety (HAZMAT) for emergency response planning(Charaborty et al., 1997).

To define the potentially affected area, we applied the ALOHA dispersion model. With the input of atmospheric conditions (e.g. temperature, wind speed and direction, cloud cover), ground roughness, and the strength and characteristics of the released chemical, the ALOHA model can estimate the concentration downwind from the release source. In this model, we used the highest monthly average temperature recorded between 1961 and 1990 in Galveston from the National Climate Data Center (NCDC) and assumed a medium (50%) humidity as well as clear cloud cover. For the wind speed, we used the highest frequency from the annual wind rose plot provided by Texas Natural Resources Conservation Commission. We did not apply wind direction; we assume that possible toxic explosions potentially affect all areas within the distance that ALOHA calculates. We set the roughness of ground to urban. After we input weather conditions, ground roughness, and quantity of toxics released, the ALOHA model estimated the distance from the release source that the ground-level concentration of a toxic gas exceeds the Immediately Dangerous to Life and Health (IDLH) level(Environmental Release Report: Galveston County, TX, 2003). According to NOAA and EPA, a chemical's IDLH is an estimate of the "maximum concentration in the air to which a healthy worker could be exposed without suffering permanent or escape-impairing health effects." [9:202] The IDLH level is directly related to the release strength of toxic substances. A facility often releases more than one kind of toxic substance. The distance that a toxic gas exceeds the IDLH level is different for each event. It is related to the characteristics of the toxic substances and the amount released. Therefore, for each TRI site, we used the farthest impact distances of all potential toxic releases to create a buffer. Figure 2 shows the potentially affected area from each facility at a worst case-scenario. Some buffers overlap each other, which means that some blocks are potentially threatened by more than one toxic explosion. Using the buffers, we delineated the potential affected census blocks.

C. Calculate the index of each factor for the affected census blocks

1) Population density index (PDI_j)

For each affected census block j with population P_j, the population density (PD_j) is defined as

$$PD_j = P_j / A_j$$

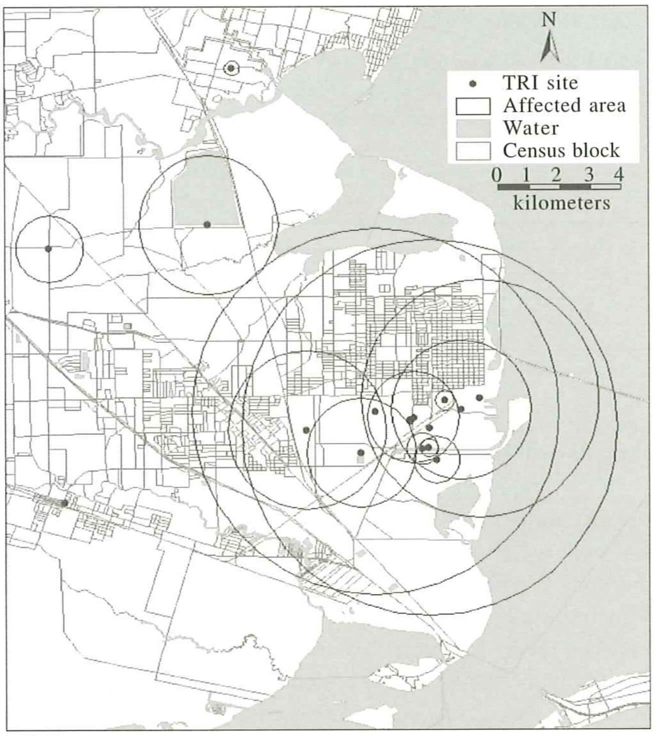


Figure 2. The extent of affected areas by the TRI sites

A_j is the area of the block j. Then, we calculated the PDI_j as

$$PDI_j = 100 * PD_j / Maximum\,(PD_j)$$

So, the higher the population density, the higher the population density index. The block with the highest population density gets a score of 100.

2) Population density index of special age groups ($SPDI_j$)
We first summed the population(SP_j) below age 5 and the population above age 65 for each affected block. Then we calculated the population density of special age groups(SPD_j) as

$$SPD_j = SP_j / A_j$$

and the population density index of special age groups as

$$SPDI_j = 100 * SPD_j / Maximum\,(SPD_j)$$

As population density index, the higher the population density of special age groups, the higher the population density index of special age groups.

3) Index regarding the number of hazardous sites that impact the area (NHI_j)
From Figure 2, we can see that some blocks are under impact from more than one potential toxic explosion. Given the possibility of multiple outbreaks, the number of hazardous sites that impact an area should be taken into account. So for each block, we counted the number of TRI sites that have an impact on the block in a worst case-scenario. Then we defined NHI_j as

$$NHI_j = 100 * \frac{number\ of\ hazardous\ sites\ that\ impact\ block_j}{Maximum\ (number\ of\ hazardous\ sites\ that\ impact\ block_j)}$$

So, the more hazardous sites that potentially affect a block, the higher value NHI_j of that block.

4) Index of distance from a residence to hazardous sites (DI_j)
The distance from a residence to hazardous sites is another factor that should be concerned in assessing vulnerability. Because census blocks are used for the analysis, we used the centroid of each affected block to represent the location of residence. Then we found the distance ($Dist_j$) from the centroid of each block to the nearest hazardous site. We defined DI_j as

$$DI_j = 100 * Minimum\,(Dist_j) / Dist_j$$

As can be seen from the definition, if the centroid of an affected block is closer to the closest hazardous site, then the DI_j of that block is higher.

5) Shortest evacuation path index (SPI_j)
The shortest path is a route that takes the least amount time for a resident to get out of the affected area. The solution of shortest path is related to two places (points): origin and destination. Obviously, it is difficult to define a shortest path between two blocks. As an alternative, we divided the census blocks into two groups: affected blocks and unaffected blocks. Then we set the centroids of the affected blocks as the origins and the centroids of the unaffected blocks as the destinations (Figure 3). We used the road network from Census 2000 and defined speed limits for roads according to the road classes. So, for each road segment, we calculated the shortest time needed to pass that road. Using shortest time, we then found the shortest path (SP_j) from the centroid of an affected block to the centroid of an unaffected block using Network Analyst

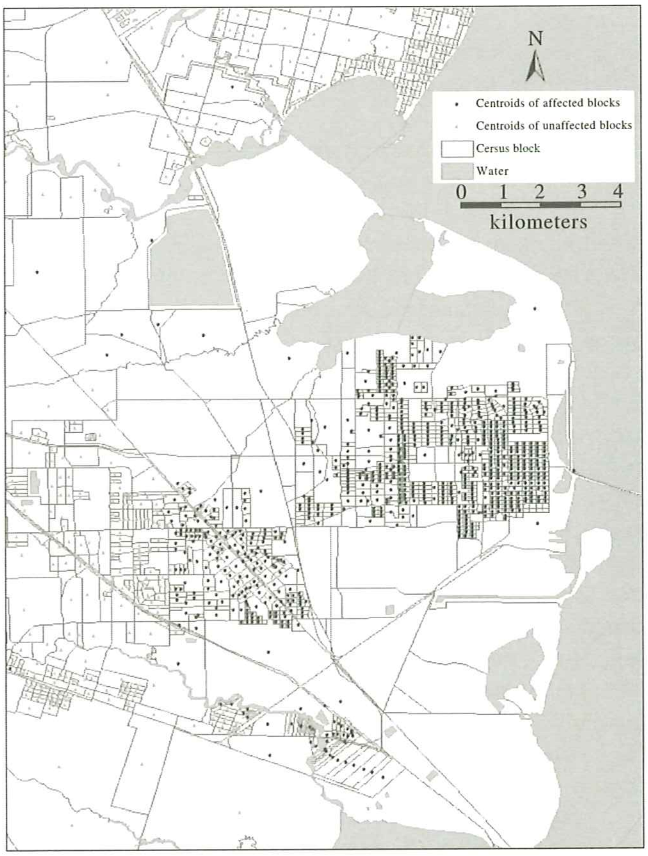


Figure 3. The centroids of affected census blocks (in black) and the centroids of the unaffected census blocks (in grey)

extension in Arcview 3.2.

Finally, the shortest evacuation path index was defined as

$$SPI_j = 100 * SP_j / Maximum\ (SP_j)$$

Therefore, if an affected block is closer to an unaffected block, then the value of SPI_j is lower.

D. Determine the overall evacuation vulnerability index (VI_j) for each census block

With the indices of the five main factors, we can then determine the overall vulnerability for each affected block. We weighed each index equally, so the overall vulnerability index is the average of the five indices.

$$VI_j = (PDI_j + SPDI_j + NHI_j + DI_j + SPI_j) / 5$$

V. RESULTS

From Figures 4,5,6,7, and 8, we can see the spatial variations of the five main factors. The distribution of population density is skew. The population density of most affected blocks is under 40% of the maximum population density of the blocks affected. The block with the highest population density is a very small area (Figure 4). The distribution of the population below age 5 and above 65 is even more biased than the distribution of population density. Most *SPDI* is under 30% of the maximum *SPDI* (Figure 5). Due to the high concentration of TRI sites in the eastern part of Texas City (Figure 2), the blocks in that area have higher values of *NHI* (Figure 6). In regard to the distance from residences to TRI sites, the closer the distance, the bigger the *DI* value (Figure 7). Few TRI sites are located within or near blocks with residences. The TRI sites in the eastern part of Texas city are mainly located in an unpopulated area. When assessing the shortest evacuation time, we learned it takes more time for people in the eastern area to evacuate (Figure 8). Combining all five factors, Figure 9 shows the overall evacuation vulnerability. The most vulnerable block is the one with the highest population density. The blocks closer to the TRI sites in the eastern area are relatively more vulnerable than other blocks because the eastern area is closer to those hazardous sites and more difficult to be evacuated.

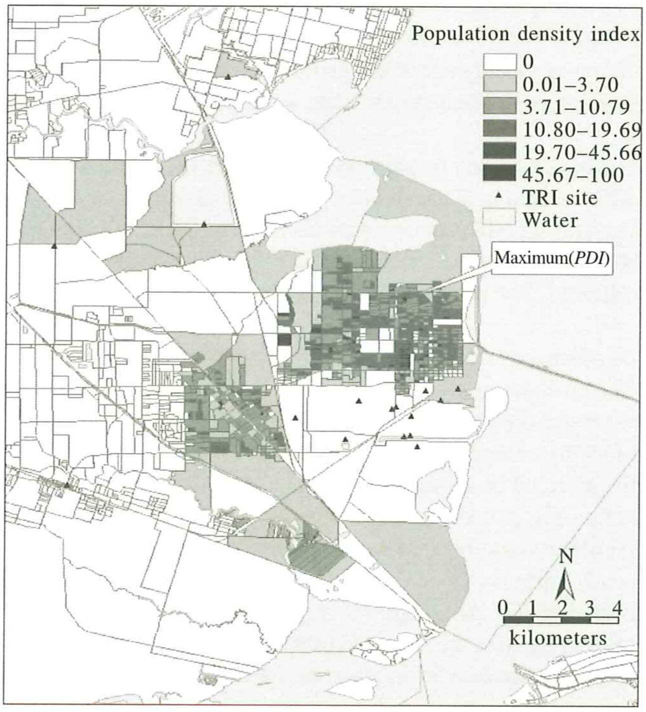


Figure 4. Population density index (*PDI*)

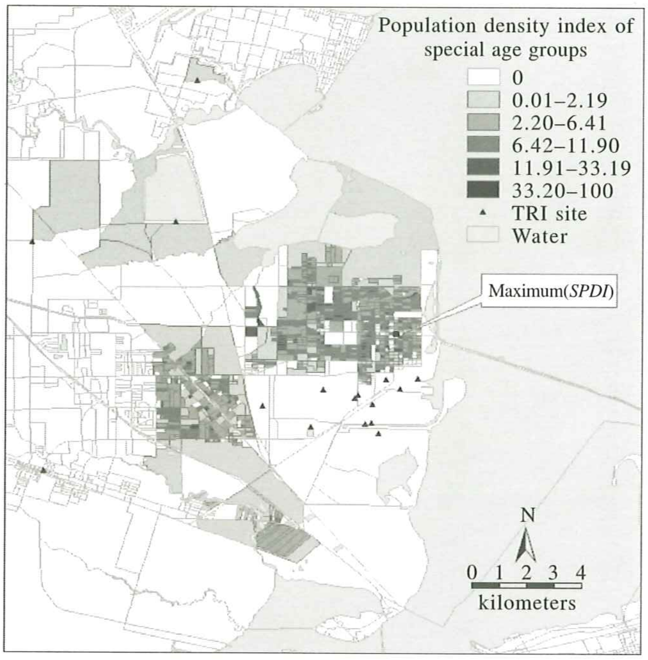


Figure 5. Population density index of special age groups (*SPDI*)

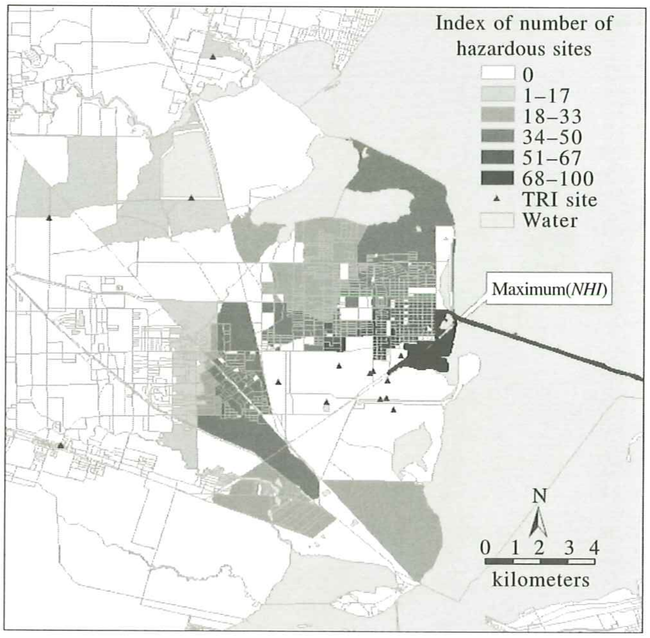


Figure 6. Index of number of hazardous sites that impact the area (*NHI*)

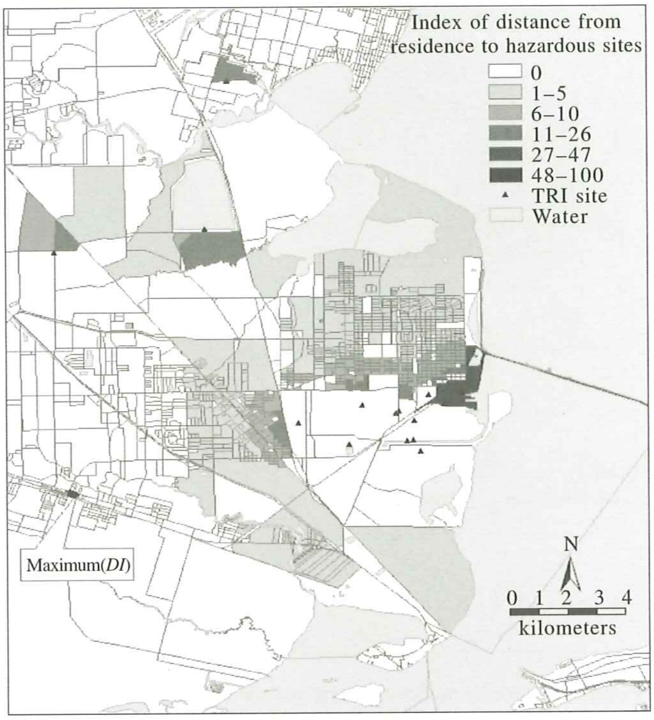


Figure 7. Index of distance from residence to hazardous sites(*DI*)

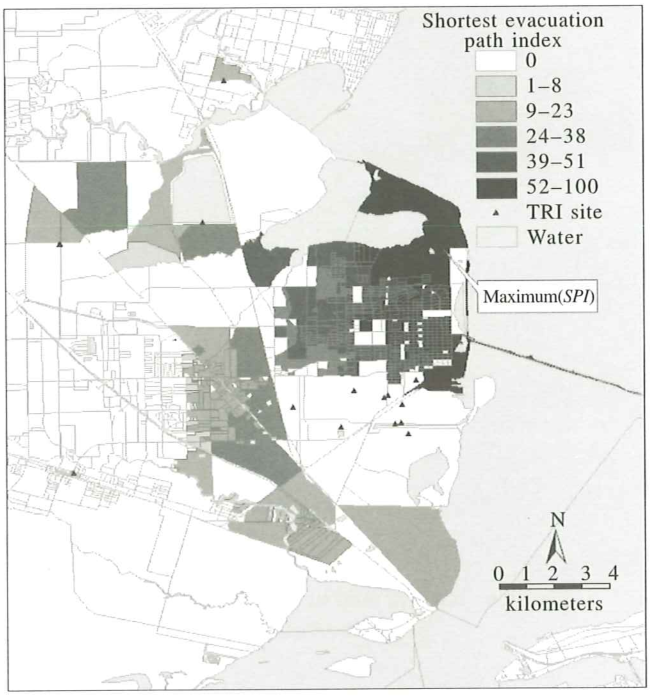


Figure 8. Shortest evacuation path index (*SPI*)

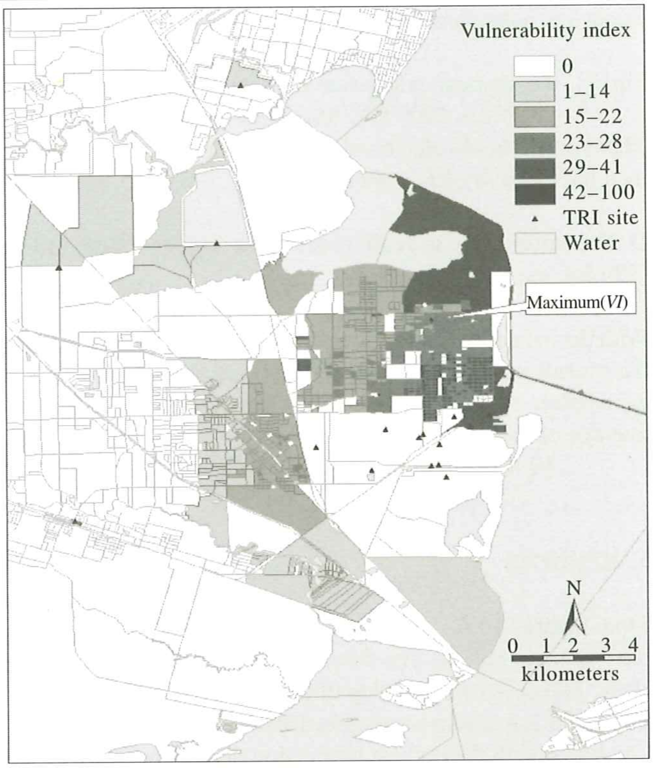


Figure 9. Overall vulnerability index (*VI*)

VI. DISCUSSION

In this study, we developed a method to investigate vulnerability to toxic releases in a worst-case scenario when evacuation is necessary. We took into consideration demographic factors, biophysical factors, and evacuation difficulty. Our study revealed the spatial variation of evacuation vulnerability in Galveston, Texas. However, a number of factors are subjected to future research.

First, due to lack of data regarding the quantity of toxic substances stored on-site, we delineated the worst-case scenario using the total toxic releases in 2000. We would have rather used the on-site data so that the geographic extent of the affected area can be defined closer to the worst-case scenario.

Furthermore, we treated the population distribution in the affected area as static. However, the population in an area can vary during different time periods in a day. Therefore, it would be more reasonable to investigate the population density at different time periods during the day.

Another important point is the calculation of shortest path. Because we conducted this study at the census block scale, we determined the shortest evacuation time of an affected block by computing the shortest path between the centroid of the affected block to the centroids of unaffected blocks. The solution is not very ideal to present the actual shortest path. Another issue related to the shortest path problem is that road capacity in real time is expected to be taken into consideration. Although we assigned speed of roads according to road classes, we assumed that traffic flow does not exceed road capacity. However, given the fact that more vehicles might be running on roads in an emergency evacuation, a traffic jam is possible and can affect the evacuation time greatly.

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