Case Study

Estimating the Economic Losses of Hurricane Ike in the Greater Houston Region

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Abstract: Hurricanes Katrina and Rita in 2005 caused tremendous economic losses in the Gulf Coast region. Though Hurricane Ike in 2008 was relatively less severe, it still caused significant damage in the Gulf Coast Region, especially in Houston, Texas, the fourth largest city and the sixth largest metropolitan area in the United States. This study obtains the storm parameters of Hurricane Ike from the National Hurricane Center (NHC) and then employs a hurricane model to estimate the strength of wind and the property damages by census tract. To fill the gaps in disaster loss estimation models, this paper adopted a systematic method that combines disaster models, a regional input/output model, and a spatial allocation model to estimate the spatial distribution of property damage and business interruption losses of Hurricane Ike in the Greater Houston region. The modeling results of property damage are reasonably close to the estimates from insured damage claims after Hurricane Ike. The spatial distribution of economic losses in industrial sectors generated by the model is needed for policymakers and planners to identify the most cost-effective options for disaster mitigation and allocate manpower and resources for disaster relief efficiently and equitably. **DOI:** **10.1061/(ASCE)NH.1527-6996.0000146.** © *2014 American Society of Civil Engineers.*

Introduction

When Hurricane Ike made its U.S. landfall in Galveston, Texas, in the early morning of September 13, 2008, it had a wind speed of 177.0 km/h (110 mi/h) and also created a 3.0–4.6 m (10–15 ft) storm surge at the Galveston Coast (Berg 2009). Though the magnitude of the hurricane was less than what had been expected, it still wrecked some beach houses, inundated lower-elevation areas, and caused significant property damage and economic losses to the Gulf Coast region and throughout much of the United States directly and indirectly.

In Houston, Hurricane Ike caused a variety of physical damage on its way across the center of the region. High winds ripped away roofs of Reliant Stadium located close to the Texas Medical Center, broke windows of the JP Morgan Chase tower in downtown Houston, and tumbled walls and tore off exterior materials of houses and buildings. In many residential houses and commercial buildings, heavy rains caused water leakage from roofs into attics or from windows and doors into interior rooms. Fallen trees and branches crushed properties and blocked driveways. Storm surges and rising water triggered floods in coastal and lower-elevation areas. Power outages occurred in almost every community and caused millions of homes to lose power.

Hurricane Ike also caused many fatalities along its path. Before it reached the United States it had already claimed a total death toll of over 80 in various Caribbean countries, including Haiti, the Dominican Republic, and Cuba. The death toll in the United States was more than 100. Texas was the state that suffered the most and had 74 deaths directly or indirectly related to Hurricane Ike. Houston area losses included 28 fatalities in Harris County and 17 in Galveston County (Zane et al. 2011).

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Most direct property damage occurred during the storm, but economic losses of residents and businesses had lasted for a long period after the hurricane. The *Houston Chronicle* of October 21, 2008, reported that over half of the 2,000 apartment complexes in Houston were hard hit by Hurricane Ike and about 150 of these apartment complexes were severely damaged. All the evacuees from Galveston Island had to wait 11 days before they were allowed to return home. Overall, three-quarters of households in Houston had suffered from electric power cuts. On September 25, 13 days after the strike by the hurricane, there were still about one-quarter of the residents in the city with no electricity. Many communities in both central cities and suburban areas without electricity had curfews imposed. Most commercial stores, service facilities, schools, and firms had to close for a few weeks due to power outrages. The widespread damage of residential houses, commercial buildings, transport facilities, and utility service caused the region to take much longer than usual to recover.

An important step of disaster relief is to develop a quick estimate of hurricane damage losses which can help government agencies to identify cost-effective options for disaster mitigation and allocation of manpower and resources for disaster relief more efficiently. The National Hurricane Center (NHC) of Miami, Florida, has released the *Tropical Cyclone Report* for major hurricanes striking the United States. The report included an estimate of total losses, for instance, $80 billion for Hurricane Katrina, $10 billion for Hurricane Rita, and $24.9 billion for Hurricane Ike. These figures came from the application of a simple method that doubles the insured property damage estimated by the American Insurance Service Group to account for both insured and uninsured losses (Knabb et al. 2006a, b; Berg 2009). These estimates of uninsured losses were based on empirical studies, but the method to calculate the total losses by doubling the insured damage costs seems arbitrary. The NHC's reports included no information on the spatial distribution of damage in small areas within any of the large impact zones. It usually takes several months for the NHC to release its initial report, and the report is updated several times to reflect up-to-date changes of estimated losses. The NHC's report for Hurricane Ike became available in early 2009, about 4 months after Hurricane Ike made its U.S. landfall.

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Stakeholders and policymakers in government agencies like FEMA, professionals from insurance companies, scholars in research institutes, and citizens and taxpayers all gain from better estimates of losses from natural disasters. However, it is difficult to measure economic losses from natural disasters [National Research Council (NRC) 1999]. The total economic losses caused by natural disasters have not been consistently calculated because there are few organized efforts to collect and quantify economic impact data for weather extremes (Changnon 2003), and there are few widely accepted frameworks for estimating losses from natural disasters.

The NRC (1999) convened the members of the Committee on Assessing the Costs of Natural Disasters to develop a framework for loss estimation of natural disasters, which emphasizes the collection of standardized data for preidentified types of losses with a set of guidelines and recommendations to data collectors. In this framework, the direct loss data for natural disasters are collected from both public and private groups, including insurance claims compiled by the Property Claims Services (PCS) and the Institute for Business and Home Safety (IBHS), government agencies such as FEMA or the Small Business Administration (SBA), and the Department of Housing and Urban Development (HUD), insured or uninsured businesses and individuals, and nongovernmental organizations (NGOs). The types of losses include physical damage to government, business, and residential property, utility and transportation infrastructure, agricultural products, human losses, cleanup and response costs, and adjustment costs and temporary living aid, etc. The framework intends to develop a systematic compilation of losses to conduct more accurate loss estimates for various types of disasters. But it does not provide a modeling structure for professionals and researchers to estimate disaster losses in their practical work.

To facilitate hazard loss estimation, FEMA has made available the *Hazus-MH* package, a nationally applicable standardized risk assessment methodology and tool on a geographic information system (GIS)–based platform for analyzing potential losses from earthquakes, floods, and hurricane winds. The hurricane model of the *Hazus-MH* package was developed in 1997. It includes a nationwide building inventory database and engineering-based physical damage functions. The model is designed to examine the physical damage states of residential and commercial buildings, building-related economic losses, and income-related business interruption losses in a hurricane event. However, Rose et al. (2007) claimed that *Hazus* has done a poor estimation of direct economic losses from infrastructure failures. These authors developed a *Hazus* extension to fill the gap. Pan (2011) also found that the ratios of the direct losses of output to structure damage losses estimated by the *Hazus* hurricane model are far less than the ratios found in other studies.

This paper suggests a model framework to improve the estimate of economic losses from actual natural disasters. It examines the damage states of buildings using FEMA's *Hazus* package. It also develops functions for estimating direct, indirect, and induced economic losses based on the damage states of buildings. Indirect and induced losses are here defined as in standard economic input/output modeling. Indirect impacts represent the ripple effects from direct final demand changes on related industrial sectors, and induced impacts reflect the effects on regional industries caused by changes in household consumption responding to the direct and indirect impacts. The model framework is utilized for investigating the losses from Hurricane Ike in Houston. The losses are categorized by industrial sector and allocated to small analysis zones in the region (i.e., census tract in this study).

The rest of the paper is organized as follows: the second section reviews the relevant literature; the third section describes the methodology; the fourth section describes the empirical study; and the last section discusses findings and conclusions.

Literature Review

There are a variety of data inventory efforts and analysis methods available in the relevant literature for estimating the losses from hurricanes and other types of natural disasters. Rose (2004) suggested two types of data utilized in loss estimation (i.e., primary data and secondary data). Primary data are collected by property owners, residents, firms, or any other stakeholders for the self-evaluation of losses or collected by a third party through survey questionnaires, and secondary data are usually compiled based on primary data by government agencies, researchers, private companies, or nonprofit organizations. Rose (2004) also described some basic data approaches that have been utilized for hazard loss estimation. He pointed out that methods based on primary data are more applicable to evaluate direct losses and more suitable to assess damage retrospectively, while approaches based on secondary data are better suited to estimate indirect losses or high-order effects. The use of primary data approaches has been limited due to high costs.

Empirical studies have used both primary and secondary data to estimate disaster losses. Pielke (1995) utilized various sources for insurance claims to explore the losses from Hurricane Andrew in 1995. Gordon et al. (1998) and Boarnet (1998) each conducted surveys of business firms to estimate business interruption losses from the Northridge earthquake. To estimate the direct and indirect losses from that earthquake, Brookshire et al. (1997) obtained primary data from surveys of both business and households in the impacted areas and collected secondary data from insurance claims, loads, and other types of disaster relief funds. Burrus et al. (2002) utilized primary data collected from a convenience sample survey to examine industry-specific business interruption losses and related indirect and induced economic impacts caused by three low-intensity hurricanes in Wilmington, North Carolina, between 1996 and 1998.

A series of articles were published by Rose and his colleagues to examine the economic impacts of an earthquake on electricity lifelines (Rose et al. 1997; Rose and Benavides 1999; Rose and Lim 2002) and water service (Rose and Liao 2005). There were also a large number of research reports on economic losses of hurricanes published after Hurricane Katrina and Hurricane Rita in 2008, such as Baade et al. (2007), Vigdor (2008), Richardson et al. (2009), etc. Many of these studies employed both primary and secondary data to estimate economic losses. However, few of them addressed the data and methodology required for estimating business interruption losses in hurricane events explicitly.

In addition to a description of data and basic data approaches, Rose (2004) summarized statistical approaches for hazard loss estimation including basic statistical methods such as correlation or regression to recognize patterns from primary and secondary data, deterministic simulation methods such as engineering economic analysis at the microeconomic level, input/output (I/O) model or computable general equilibrium (CGE) model at the macroeconomic level, and stochastic simulation methods such as Monte Carlo models. He also examined the estimation and validation of economic losses of disasters through three comprehensive models, including I/O models, CGE models, and econometric models.

As an operational platform for disaster loss estimation, FEMA's *Hazus* package includes engineering and scientific models coupled with a national database of socioeconomic characteristics of residents as well as detailed structural information about residential and commercial buildings (Schneider and Schauer 2006). The economic data available for buildings in *Hazus* are estimated based on the physical characteristics of buildings, but some parameters are based on national averages [Multihazard Mitigation Council (MMC) 2005]. The *Hazus* package allows users to conduct preliminary studies without having to collect additional local data, or "Level 1" analysis. It also enables users to replace the default database with more accurate information or data and perform a higher-level or "Level 2" analysis. However, it is difficult to enter data for individual buildings or facilities.

The technical manual for the *Hazus* hurricane model explains the physical damage functions for different types of buildings and also explains the models for direct economic losses related to physical damage of buildings in detail (FEMA 2006b). Cochrane (2004) described an I/O-based indirect economic loss model (IELM) developed for *Hazus* to estimate indirect impacts (any loss other than direct loss) of disasters on employment and income. This is a flexible I/O methodology applicable for short-term and medium-term analyses.

However, all the technical manuals for the *Hazus* hurricane model offer no guidance for examining indirect and induced impacts of hurricane on industry purchase and household consumption (FEMA 2006b, 2012). The functions of the *Hazus* hurricane model are not suitable for long-term impact studies. It is mainly an event-driven model at the regional level, which is not designed to evaluate an individual project. It also contains some resilience-related parameters and allows sensitivity analysis, but the data and functions are quite limited. The impact analysis results from *Hazus* are deterministic, and uncertainty is not evaluated or reported.

Hazus has been elaborated by various researchers to estimate economic losses of disasters. Rose et al. (2007) extended *Hazus* by including applications for determining the full range of direct business interruption losses as well as indirect business interruption losses. This *Hazus* extension was employed to assess benefits with and without FEMA mitigation in regions across the country. The authors reported various cost-benefit ratios for FEMA mitigation grants in different types of disasters and also showed robust estimates in their sensitivity analysis. As an effort to replace the constant recapture factor available from the *Hazus* package, Park et al. (2011) developed some production recapture factor functions and a recaptured output path function on the base of economic assessment data and physical damage functions in *Hazus* to model the economic resilience of disasters.

As a case study of hurricane loss estimation, Pan et al. (2008) and Pan (2011) utilized wind storm parameters along with the *Hazus* hurricane model to analyze the damage states of both residential and commercial buildings in a hypothetical hurricane event. They adopted a GIS-based regional I/O model that combines the quantitative economic techniques of I/O analysis and spatial analysis approaches of GIS in a loosely coupled modeling system. Though the model is developed for economic loss estimation for a hypothetical hurricane event, it is possible to fine-tune the approach and incorporate it into a model framework for examining the economic losses of actual natural disasters.

Methodology

The NRC (1999) argued that total economic losses in natural disasters estimated by different agencies and organizations usually vary significantly, cover a wide range of costs, and change through time. This implies that it is important for planning professionals and disaster researchers to develop a general framework that implements appropriate analytical models to estimate economic losses from real natural disasters.

Pan et al. (2008) and Pan (2011) proposed a systematic method for estimating the economic losses of a hypothetical hurricane event and examining the spatial distribution of estimated losses. The approach was developed on the basis of the Southern California Planning Model (SCPM), a GIS-based metropolitan I/O model that interacts with a spatial allocation model in the Garin-Lowry tradition, to estimate economic impacts and assign them to small-area zones. It employs the physical damage state of buildings estimated by the *Hazus* hurricane model together with estimated building recovery time and some additional information to reestimate direct business interruption losses. It also incorporates economic analysis functions of an I/O model with GIS-based spatial analysis functions to quantify indirect and induced business interruption losses and estimate the spatial distribution of these losses. The I/O model component is able to estimate the indirect effects by tracing the interindustry linkages of final demand changes with other sectors and to measure the induced effects as the secondary consumption impacts associated with the reduced spending of workers by sector for both the direct and indirect effects. The spatial analysis functions in GIS are capable of allocating the direct, indirect, and induced effects to political jurisdictions or small impact analysis zones, such as regional analysis zones (RAZs), traffic analysis zones (TAZs), census tracts, etc. Due to the lack of transportation-related data, Pan et al. (2008) and Pan (2011) did not follow the standard procedures in SCPM to employ trip origin-destination matrices for induced impact spatial allocation. An alternative method was developed to apply building damage data from the *Hazus* hurricane model to allocating induced impacts.

Based on the work by Pan et al. (2008) and Pan (2011) on estimating economic losses from a hypothetical hurricane event, this study develops a general framework for the loss estimation of actual disasters, which includes guidelines and tools to analyze building damage states, examine direct business interruption losses, estimate total indirect and induced business interruption losses, and allocate losses to impact analysis zones. This approach is meant to improve the previous model by applying trip origin-destination matrices to allocate induced impacts, which follows the standard procedures of SCPM and avoids some unrealistic assumptions of household travel behaviors. It also intends to compare the losses estimated by the model against property damage reported by various insurance programs. The flowchart depicting the general framework for measuring losses of natural disaster is shown in Fig. 1.

Estimation of Direct Impacts

The first step of the framework is to employ disaster analysis models to identify property damage states and then estimate the associated direct business interruption losses as measured in terms of jobs lost or the dollar value of output losses. FEMA's *Hazus* package includes multiple nationwide inventory databases of residential houses and commercial buildings by structure type by census tract. It also provides an engineering-based flood model, a hurricane model, and an earthquake model to investigate the damage states of building structures for different types of natural disasters. The building damage states are coupled with a building recovery time table to estimate business interruption time, which can further be used with associated employment in corresponding

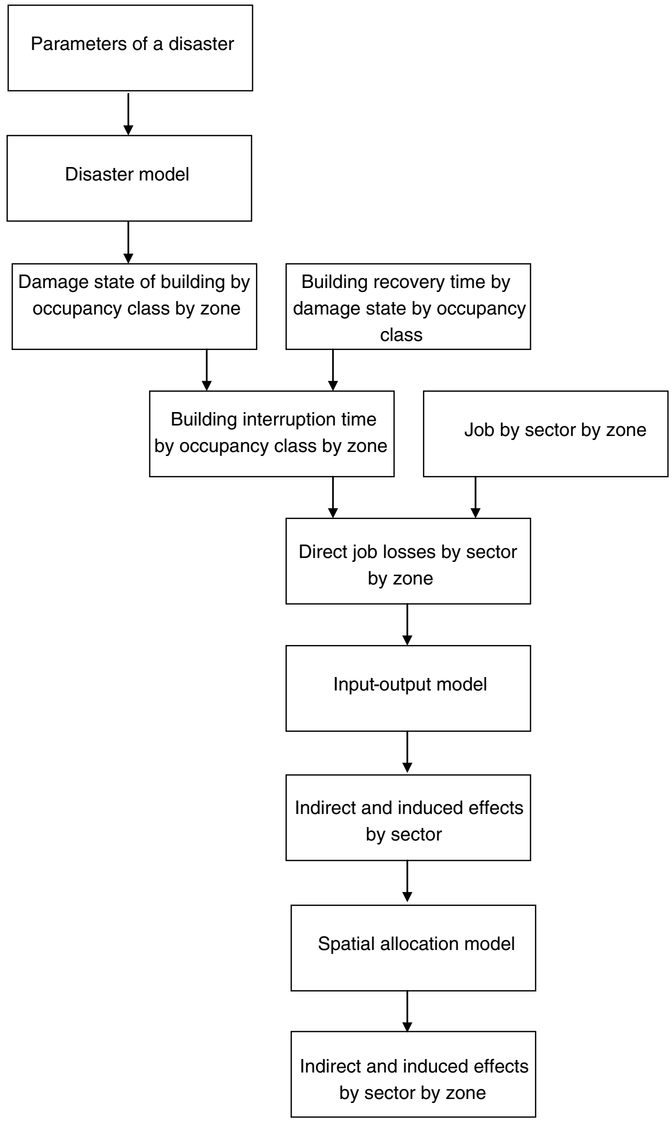

Fig. 1. General framework for estimating losses from natural disasters

type to estimate the direct losses of jobs by duration. The building recovery time represents the estimated time for recovery of normal building functions. It includes the time for actual cleanup and repair or construction and the time for some additional tasks, such as financing, negotiation, design, document preparation, etc. (FEMA 2006a).

Pan et al. (2008) and Pan (2011) developed a formula to calculate direct job losses in an impact analysis zone, as shown in Eq. (1)

$$L_{z,s} = J_{z,s} * \left[\sum_{d}(\mathrm{DS}_{z,s,d} * \mathrm{BRT}_{s,d} * F_{s,d})\right] \quad (1)$$

where $L_{z,s}$ = total losses of job · day in industrial sector s in zone z; $J_{z,s}$ = jobs in industrial sector s in zone z; $\mathrm{DS}_{z,s,d}$ = probabilities of damage states in damage state d, occupancy class (or sector) s, and zone z; $\mathrm{BRT}_{s,d}$ = building recovery times (including both cleanup and construction or repair time) measured in days for buildings in damage state d and occupancy class (or sector) s; and $F_{s,d}$ = building and service interruption time multipliers for buildings in damage state d and occupancy class (or sector) s.

The occupancy classes of buildings in Eq. (1) follow the definitions in FEMA's *Hazus* package, which classifies all the buildings into seven major occupancy categories: residential, commercial, industrial, agriculture, religion/nonprofit, government, and education. They are further refined into an occupancy classification system with 33 categories for data and model used in economic loss analysis. Residential buildings are classified into six occupancy classes, including single-family dwelling, mobile home, multi-family dwelling, temporary lodging, institutional dormitory, and nursing home. Similarly, commercial buildings are classified into 10 occupancy classes, and industrial buildings are classified into 6 occupancy classes. Both government and education buildings are classified into two occupancy classes, while agriculture and religion/nonprofit buildings have only one occupancy class (FEMA 2006a). It is straightforward to connect the building occupancy classes to the industrial sectors. A correspondence table (Table 1) was developed to bridge all the occupancy classes except for those of the residential buildings to the 17 industrial sectors that are defined in the census transportation planning package (CTPP), including agriculture, mining, construction, nondurable manufacturing, durable manufacturing, transportation, communication and utilities, wholesale, retail, FIRE (finance, insurance, and real estate), business service, personal services, entertainment, health, education, other professional services, and public administration.

The earthquake model or the hurricane model in *Hazus* employs five structural damage states for estimating building recovery time (BRT) after an earthquake or hurricane event, including none, slight, moderate, extensive, and complete. The structural damage states establish a basis for estimating loss of function and repair

Table 1. Correspondence Table between Building Occupancy Classes and CTPP Industrial Sectors

Category	Label	Occupancy class	CTPP industrial sector
Commercial	COM1	Retail trade	Retail
	COM2	Wholesale trade	Wholesale
	COM3	Personal and repair services	Personal services
	COM4	Professional/technical/business services	Business services
	COM5	Banks/financial institutions	FIRE
	COM6	Hospital	Health service
	COM7	Medical office/clinic	Health service
	COM8	Entertainment and recreation	Entertainment
	COM9	Theaters	Entertainment
	COM10	Parking	Transportation
Industrial	IND1	Heavy	Durable manufacturing
	IND2	Light	Durable manufacturing
	IND3	Food/drugs/chemicals	Nondurable manufacturing
	IND4	Metals/minerals processing	Mining
	IND5	High technology	Communication and utility
	IND6	Construction	Construction
Agriculture	AGR1	Agriculture	Agriculture
Religion/nonprofit	REL1	Church/membership organization	Religious
Government	GOV1	General services	Public administration
	GOV2	Emergency response	Public administration
Education	EDU1	Schools/libraries	Education
	EDU2	Colleges/universities	Education

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time. The *Hazus* models define loss of function as the time that a facility is not capable of conducting business, which is usually shorter than repair time because a business may rent alternative space to resume operating before the completion of repairs and construction of its original building. The BRT accounts for building repair, cleanup, and construction time as well as the delays in inspection, financing, decision making, etc. (FEMA 2006a). The BRT is dissimilar among the different type of buildings. For example, the BRTs of single family dwellings for the five damage states are 0, 5, 120, 360, and 720 days, respectively, while the BRTs of government buildings in emergency response for the five damage states are 0, 10, 60, 270, and 360 days, respectively.

Similar to the relationship between loss of function and repair time, business and service interruption time is usually shorter than the BRT because business owners or service providers may find alternative space or temporary accommodation. The *Hazus* package provides multipliers F to adjust the BRT for business and service interruption. However, both the multipliers F and the BRT in *Hazus* are judgmentally derived (FEMA 2006a). *Hazus* provides some default or constant recapture factors that represent the ability of business to reschedule or recapture lost production after a disaster event (Park et al. 2011). They do not explicitly consider the resilience of businesses.

In Eq. (1), the probabilities of damage states are reported by *Hazus*. The multiplication of the probabilities of damage states ($\mathrm{DS}_{z,s,d}$), the building recovery times ($\mathrm{BRT}_{s,d}$), and the multipliers ($F_{s,d}$) yields the building and service interruption time for the buildings in a zone (z) at a given occupancy class (s) and a certain damage state (d). It can be further summed by damage state and then multiplying the outputs or jobs in the corresponding industrial sectors to estimate the direct impacts as job losses in person-day by sector s by zone z ($L_{z,s}$).

Estimation of Indirect and Induced Impacts

Once direct impacts are determined, the next step is to estimate total indirect and induced business interruption losses. It is a standard procedure to employ regional I/O models to calculate total indirect and induced effects from the changes of the direct final demand. For instance, the I/O model from the Minnesota IMPLAN Group (MIG) provides necessary tools to estimate indirect and induced effects from direct impacts at the county level.

Purchases for final demand (or final consumption) drive the IMPLAN I/O model (MIG 2004). Industries producing goods and services for consumption purchase goods and services from other producers. These other producers, in turn, purchase goods and services indirectly. Multipliers describe the iteration and break up the impacts on regional economic activities into three components: direct, indirect, and induced impacts. Direct impact represents the direct response of industries to which a final demand change is made. Indirect impacts stand for the changes in interindustry purchases as the response by all local industries caused by the iteration of industries purchasing from the directly affected industries. Induced impacts denote the changes in spending from households as income increases or decreases due to the changes in production caused by the directly and indirectly impacted industries.

The total indirect and induced effects estimated by I/O model typically do not have any spatial identification. The next step, therefore, is to allocate indirect and induced effects to impact analysis zones. Richardson et al. (1993) developed a method to allocate the indirect and induced effects spatially, which was incorporated into the first version of their Southern California Planning Model (SCPM). Cho et al. (2001) updated the model to incorporate a transportation network to estimate total business interruption losses for earthquakes and distribute the indirect and induced effects. Gordon et al. (2005, 2006) used a new version of the SCPM model to allocate the effects of port closure from a hypothetical terrorist attack to small areas. Pan et al. (2008) and Pan (2011) used an SCPM-type model to identify the distribution of the impacts from both terrorist attacks and natural disasters.

Indirect effects in SCPM are allocated using employment-weighted attractions and productions by sector by zone. The formula is as follows:

$$\mathrm{Indir}_{s,z} = \mathrm{Indirect}_s * E_{s,z} / \sum_z E_{s,z} \tag{2}$$

where $\mathrm{Indir}_{s,z}$ = indirect effects in sector s in zone z; $\mathrm{Indirect}_s$ = total indirect effects in sector s; and $E_{s,z}$ = number of jobs in sector s in zone z.

Induced effects in SCPM are allocated to impact analysis zones using a journey home-to-work origin-destination (O-D) matrix and a journey home-to-shop O-D matrix. In cases where the journey home-to-work and journey home-to-shop data are not available, an alternative is to allocate induced effects to impact analysis zones in terms of the damage states of residential buildings under the assumption that the impact analysis zone is large enough to accommodate all the shopping trips of residents living in the zone (Pan et al. 2008; Pan 2011). In this alternative method, induced effects are allocated using the following expressions:

$$\mathrm{Indur}_{s,z} = \mathrm{Induced}_s * \mathrm{Rdmg}_z / \sum_z \mathrm{Rdmg}_z \tag{3}$$

and

$$\mathrm{Rdmg}_z = \sum_s \mathrm{RInv}_{z,s} * \left[\sum_d (\mathrm{DS}_{z,s,d} * \mathrm{BRT}_{s,d} * F_{s,d})\right] \tag{4}$$

where $\mathrm{Indur}_{s,z}$ = induced effects in zone z and industrial sector s; $\mathrm{Induced}_s$ = total induced effects in sector s in the region; Rdmg_z = total damage on residential buildings (number of damaged buildings * recovery days) in zone z; and $\mathrm{RInv}_{z,s}$ = inventory of residential buildings in zone z and occupancy class s. The values of $\mathrm{DS}_{z,s,d}$, $\mathrm{BRT}_{s,d}$, and $F_{s,d}$ are the same in Eq. (1) but specified for residential buildings.

A limitation of this model for the allocation of induced effects is that it does not account for household income groups. Though IMPLAN provides household consumption data in nine household income classes, they are available at county level. The damage states of residential buildings estimated by FEMA's *Hazus* hurricane model are estimated at census tract level. The spatial discrepancy between household consumption data in IMPLAN and residential building damage makes it difficult to connect the damage of residential buildings to the change of household consumption directly. However, it is reasonable to assume that the damage to residential buildings proportionally affects the consumptions of residents. It is also reasonable to make an assumption that residents outside of the directly impacted region may be negatively affected about their consumptions in terms of the leakage of the induced effects.

Pan (2011) discussed the ability of Eqs. (3) and (4) in allocating induced effects. In the Greater Houston region, the average home-to-shop distance was around 16.1 km (10 mi) (HGAC 2001). Most of the tracts in the suburban areas are large enough to accommodate the home-to-shop activities of the residents inside, but some of the small tracts in central city are not. It is better to employ trip O-D matrices for cases with small impact analysis zones or long home-to-shop distance.

Empirical Study

In a previous study, Pan et al. (2008) and Pan (2011) created scenarios for a hypothetical major hurricane event in the Houston region and examined the spatial distribution of economic impacts, including direct, indirect, and induced losses. This study implements a general framework to estimate the economic losses from an actual hurricane event—that is, Hurricane Ike—in the eight-county Houston region, or the Houston Galveston Area Council (H-GAC) region.

To estimate the damage of Hurricane Ike, it is necessary to obtain its storm parameters, including the geographic location of storm tracks, storm speeds, wind speeds, radius to maximum wind, central pressure, etc. In order to track a hurricane, an advisory was issued to record the parameters of a hurricane once the storm was formed. More advisories were issued sequentially at time intervals of 1–3 h (Sea Island Software 2013). The NHC issued detailed information about all advisory points of Hurricane Ike. It provided the storm track information as inputs to the FEMA's *Hazus* hurricane model. The storm track and the corresponding advisory points for Hurricane Ike were collected for a specific time, 2:10 a.m. CDT on September 13, 2008, which was the moment Hurricane Ike made landfall on the Galveston Bay, Texas. The parameters of the storm track are shown in Table 2.

It is interesting to see the storm track of Hurricane Ike roughly follows the path of a hypothetical hurricane proposed by Pan et al. (2008), which shifted the storm track of Hurricane Rita to the southwest by about 136.8 km (85 mi) to have it make landfall at the coast of Galveston and follow Interstate 45 to cross Houston downtown, as shown in Fig. 2. The *Hazus* hurricane model uses the storm parameters of Hurricane Ike as inputs to calculate the wind speeds in peak gust in impact analysis zones (see Fig. 3), which in turn estimates building-related economic losses based on the inventory of buildings in each zone. *Hazus* utilizes census tract as impact analysis zone. There were 886 census tracts in the H-GAC region in 2000. To be consistent, this study also used these 866 census tracts as the basic geographic units for hurricane impact analysis.

Hazus classifies property damage as building damage, content damage, and inventory losses for different building occupancy types by census tract. Among the building-related economic losses estimated by *Hazus*, property damage is the dominant economic loss. In this case, *Hazus* reports a total of $24.5 billion building-related economic losses, which is about half of the losses in the hypothetical Hurricane "Rita" event reported by Pan et al. (2008) due to the smaller size and lower strength of Hurricane Ike in comparison to Hurricane "Rita." These include $20.6 billion of property damage losses and $3.9 billion of income-related business interruption losses, which are the results calculated by the *Hazus* hurricane model (Table 3). The spatial distribution of property damage losses is shown in Fig. 4.

Reports of insured damage from Hurricane Ike provide a way to compare and validate the model estimates against real-world observations. The Tropical Cyclone Report released by the NHC in January 2009 (Berg 2009) estimated that the total damage of Hurricane Ike was about $24.9 billion in Texas, Louisiana, and Arkansas. It was based on a doubling of the total insured damage of $10 billion reported by the Property Claim Services of Insurance Services Office (not including inland flooding or storm surge) and insured losses of $2.5 billion from inland flooding and storm surge reported by the National Insurance Program. In a report of Texas hurricane history, Roth (2010) estimated a total of $19.3 billion damages of Hurricane Ike and showed that most of the damages were located in Harris County, Galveston County, and Chambers County in the Greater Houston region. The doubling of insured damage of $10 billion excluding inland flooding or storm surge in the three affected states was close to the $19.3 billion in damages estimated by Roth (2010) and the $20.6 billion of property damage by wind storm estimated by the hurricane model for the Greater Houston region. Because most of the insured damage was claimed by residents and businesses located in the Greater Houston region, it is reasonable to say that the property damage estimated by the model is close to the dollar damage reported by the insurance programs.

The *Hazus* hurricane model also estimates losses of output and employment. In this hurricane scenario, *Hazus* reports a total of $699.1 million output losses equivalent to 3,946 job losses, amounts much lower than the building-related economic losses. As Pan et al. (2008) and Pan (2011) pointed out, the losses of employment and output products estimated by the *Hazus* hurricane model are systematically lower than expectations based on the scale of the hurricane and the large number of business activities in the region. They suggested applying building damage states to estimate business interruption times and then utilizing employment data to calculate the business interruption losses, which is described by Eq. (1).

The business interruption durations were calculated by the building recovery time for the corresponding building damage states and the building interruption time multipliers, both available from the *Hazus* manual (FEMA 2006a, b). They were converted from a daily base to an annual ratio to have a consistent time span with employment data and the annual data used in the I/O model. Employment data came from the InfoUSA (2008) business database, which provides the number of jobs by standard industrial code (SIC) for the H-GAC region. The InfoUSA employment by business location was aggregated to census tracts, and the SIC codes were aggregated to a small number of industrial sectors. Similar to the economic assessment data in 528 sectors from IMPLAN, the employment data in SIC from the InfoUSA business database were aggregated into 17 CTPP industrial sectors. The proportions of InfoUSA employment in the 17 industrial sectors are

Table 2. Storm Track Information for Hurricane Ike

Latitude (degrees)	Longitude (degrees)	Translation speed [km/h (mi/h)]	Radius to max winds (mi)	Radius type	Wind speed [km/h (mi/h) @ 10 m]	Central pressure (mBar)
28.9	−94.5	19.3 (12)	20	34Kt winds	177.0 (110)	952
29.2	−94.7	19.3 (12)	20	34Kt winds	177.0 (110)	953
29.42	−95	20.9 (13)	20	34Kt winds	177.0 (110)	954
29.7	−95.01	19.3 (12)	20	34Kt winds	177.0 (110)	954
30.1	−95.09	19.3 (12)	20	34Kt winds	169.0 (105)	956
30.5	−95.3	29.0 (18)	20	34Kt winds	144.8 (90)	962

Note: Data obtained from Hurricane Ike Advisory Archive in NHC (http://www.nhc.noaa.gov/archive/2008/IKE.shtml).

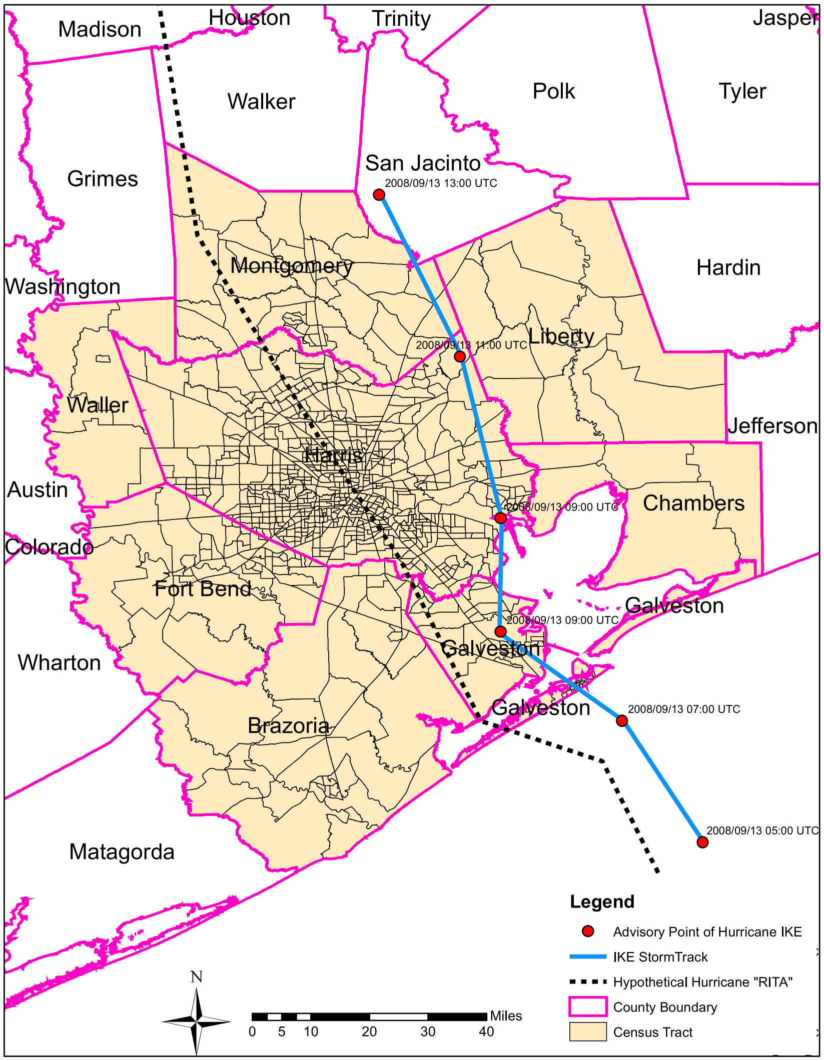

Fig. 2. Storm tracks of Hurricane Ike and hypothetical Hurricane "Rita" (data from the Hurricane Ike advisory archive of the NHC)

shown in Table 4. Retail, other professional services, health, education, and wholesale are the top five sectors with a large share of employment, accounting for 21.75, 12.65, 8.40, 8.22, and 6.67% of total employment, respectively.

Employment data enters Eq. (1) with the building recovery times to yield the economic losses of jobs by sector by census track, which are the direct impacts. Dollars per job ratios calculated from an I/O transactions table are utilized to convert economic job losses to losses in dollar value.

An economic I/O model (i.e., IMPLAN), was employed to calculate indirect and induced effects using the direct impacts in dollar or job. The IMPLAN I/O model has counties as the geographic units. It defined a sector scheme with 528 sectors in 2000. Multiple programs were developed to bridge the 17 CTPP sectors and the 528 sectors in IMPLAN 2000 sectors. IMPLAN's economic impact assessment data in 528 sectors were acquired in 2004, which were aggregated to 17 CTPP sectors. The indirect impacts of the IMPLAN I/O model are listed by county. Then Eq. (2) with employment data was utilized to allocate total indirect impacts to census tracts.

Similar to indirect impacts, the induced effects as the output of the IMPLAN I/O model are the regional total without spatial information. A journey home-to-work O-D matrix and a journey home-to-shop O-D matrix from the H-GAC 2000 base year model were used to allocate the induced effects to the 2,954 H-GAC TAZs, which are further converted to the 866 census tracts using the spatial analysis functions in GIS.

The results of direct, indirect, and induced effects measured by both dollar value and jobs for the City of Houston and eight H-GAC counties are listed in Table 5. It reports \$11.6 billion of output losses equivalent to 97,374 person-years of employment losses, which are combined with the \$20.6 billion of property damage to make Hurricane Ike the third most destructive and costliest hurricane in the United States, behind Hurricane Andrew of 1992 and Hurricane Katrina of 2005. However, the losses from Hurricane Ike are still much lower than the hypothetical Hurricane "Rita" event, which was estimated by Pan et al. (2008) to have a total of \$41 billion property damage losses, \$30.3 billion output losses, and 255,518 person-years of employment losses.

Table 5 also shows regional leakages, which refer to the payments made to imports or value-added sectors that do not in turn respend dollars within the region (MIG 2004). The regional leakages include the leakages of the direct effects out of the region and the spillovers out of the study area from the indirect and induced effects. They are calculated by comparing the difference between the results of the model using local purchase coefficients (LPCs) and those from the model assuming all the regional demands will be met by local production (i.e., 100% for LPC).

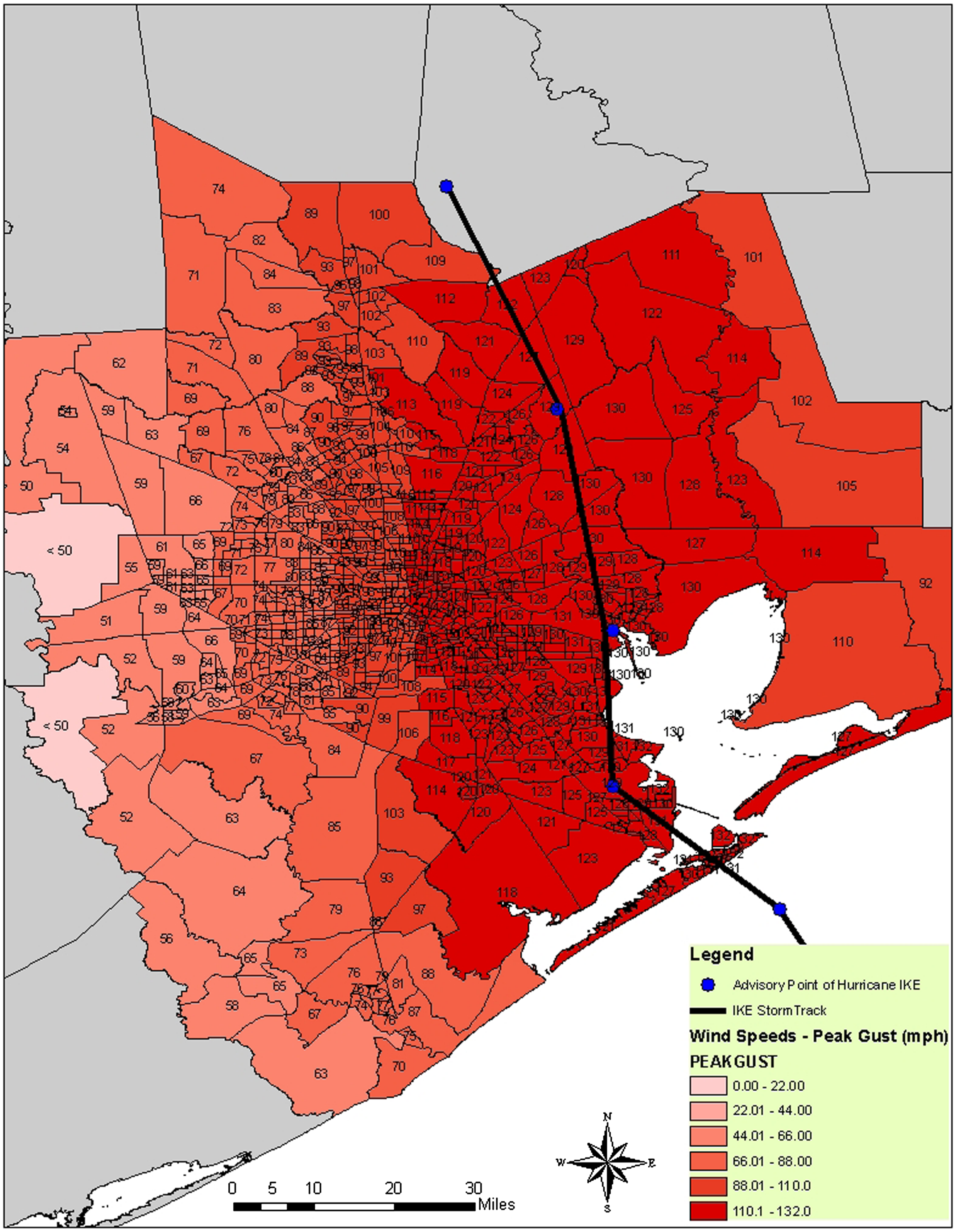

Fig. 3. Wind speeds of Hurricane Ike (data from author calculations using the *Hazus* hurricane model with the storm parameters of Hurricane Ike)

Table 3. Building-Related Economic Losses by County ($1,000)

County	Property damage				Income-related business interruption				Total
	Building	Content	Inventory	Subtotal	Relocation	Capital	Wage	Rental income	
Brazoria	498,335	184,573	3,083	685,992	82,034	5,660	6,972	28,649	809,306
Chambers	795,443	367,967	6,716	1,170,126	129,036	14,912	17,710	44,918	1,376,702
Fort Bend	50,651	4,130	11	54,792	1,666	106	86	919	57,569
Galveston	4,265,921	1,779,847	14,822	6,060,590	671,487	82,404	90,728	257,758	7,162,967
Harris	8,923,024	3,238,684	52,094	12,213,802	1,460,125	140,235	164,336	606,351	14,584,849
Liberty	130,497	50,779	597	181,874	24,303	1,526	1,998	7,836	217,537
Montgomery	166,767	49,761	480	217,008	19,621	1,712	1,993	7,741	248,076
Waller	184	48	0	232	0	0	0	0	232
Total	14,830,823	5,675,790	77,804	20,584,416	2,388,271	246,557	283,823	954,170	24,457,237

Note: Author calculations using *Hazus-MH*.

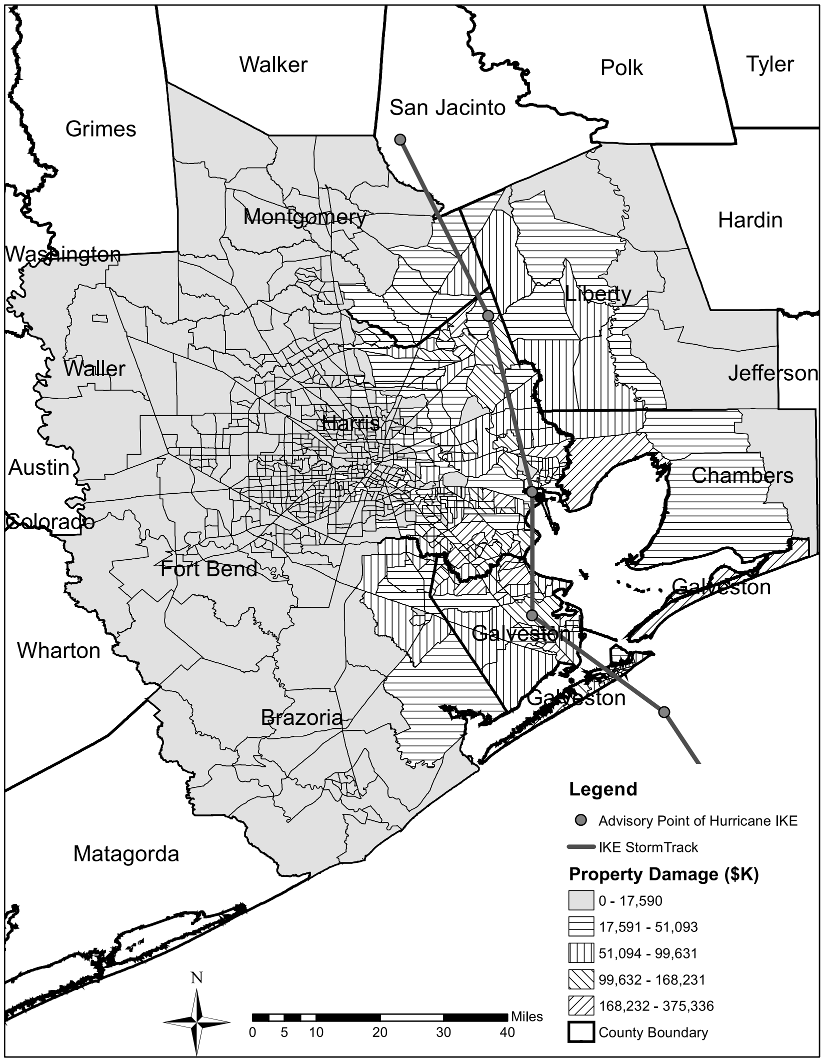

Fig. 4. Property damage losses of Hurricane Ike (data from author calculations using the *Hazus* hurricane model)

Because not all direct demand is satisfied by local production, this approach allows some of the direct effects out of the region. The total leakages of the impacts are large ($8.1 billion of output and 55,449 person-years of employment), and the direct leakages are significant ($3.4 billion of output and 14,515 person-years of employment), which reflects the fact that the local components of the manufacturing and mining sectors are relatively high, with heavy reliance on trade with those outside the region.

Table 4. Proportions of InfoUSA Employment in the 17 Industrial Sectors

Index	Sector	Job share (%)
1	Agriculture	0.94
2	Mining	2.32
3	Construction	5.90
4	Manufacturing (nondurable)	3.61
5	Manufacturing (durable)	5.49
6	Transportation	2.88
7	Communication and utility	1.25
8	Wholesale	6.67
9	Retail	21.75
10	FIRE	5.69
11	Business services	6.45
12	Personal services	2.27
13	Entertainment	1.57
14	Health services	8.40
15	Education	8.22
16	Other professional services	12.65
17	Public administration	3.93

Note: Author calculations using the InfoUSA employment data (2008).

It is interesting to see the notable variation of multipliers across counties in Table 5. Type II multipliers that capture the direct, indirect, and induced effects are 2.25 for the whole region without considering the leakages. Harris County has a Type II multiplier (i.e., 2.26), very close to the regional average because it is the largest county of the region and accounts for most of the effects. Both Galveston County and Chambers County have the Type II multipliers about 1.37 and 1.69, respectively, much lower than the regional average because they are located right in the storm track of Hurricane Ike and suffered direct losses significantly higher than their indirect and induced losses. In contrast, Liberty County, Brazoria County, Montgomery County, Fort Bend County, and Waller County have relatively low direct impacts because they are either located far away from the storm track of Hurricane Ike or a long distance from the coastline. Their indirect and induced effects are relatively high because the firms located in these counties have a close connection with the businesses in the direct impact areas or a large number of residential workers living in these counties are working in the direct impact areas. For example, Fort Bend County has a diverse industry in retail, education, energy,

Table 5. Output and Job Losses from Hurricane Ike

County or city name	Output ($1,000s) Direct	Indirect	Induced	Total	Jobs Direct	Indirect	Induced	Total
City of Houston	491,661	260,449	499,804	1,251,914	6,616	2,649	5,265	14,530
Brazoria county	48,813	14,217	90,361	153,391	762	152	994	1,908
Chambers county	38,379	4,883	21,610	64,871	629	46	234	909
Fort Bend county	1,038	33,870	157,695	192,602	9	375	1,659	2,044
Galveston county	351,852	24,824	106,740	483,416	5,595	251	1,186	7,033
Harris county	1,058,963	361,334	975,820	2,396,117	14,366	3,710	10,293	28,369
Liberty county	7,160	1,160	12,625	20,946	116	12	140	268
Montgomery county	19,727	19,346	75,906	114,979	338	205	809	1,351
Waller county	13	554	3,455	4,022	0	6	38	44
Sum of eight counties	1,525,945	460,187	1,444,211	3,430,343	21,816	4,757	15,353	41,926
Regional leakages	3,422,245	1,785,626	2,926,258	8,134,128	14,515	9,731	31,201	55,449
Total	4,948,190	2,245,813	4,370,469	11,564,472	36,331	14,488	46,554	97,374

Note: Author calculations.

hospitality, and other sectors and has promoted population growth for decades. It is located in the west side of the region, far from the storm track of Hurricane Ike, which causes it to suffer only small direct losses. However, it had a large amount of indirect and induced losses because it had a large number of high-income families and its businesses were shut down for a while after Hurricane Ike due to power outage, supply shortage, or shrinking demands. Many of its residential workers working in downtown Houston or Texas Medical Center had to stay at home due to the closure of workplace offices. Therefore, these multipliers are reasonable though they are much higher than a typical multiplier between two and three times the direct loss for a major metropolitan region estimated by Rose (2004).

Among the eight counties in the H-GAC region, Harris County accounted for over two-thirds of the losses in output and employment. Galveston County, where Hurricane Ike made landfall, ranked second by losing $483 million of output and over 7,000 jobs. Brazoria County, located in the south of the region, ranked third in terms of direct output and job losses. It is interesting to find that Montgomery County, in the north of the region, also suffered large losses, a total of $115 million output losses and 1,351 person-years of employment. Though the strength of Hurricane Ike became slightly less when it reached Montgomery County, its wind speed was still 144.8 to 177.0 km (90 to 110 mi). Rainfall in parts of southern Montgomery County and northern Harris County was about two times the rainfall in other areas of the region. Many trees fell down and even killed several people in the county. All these contributed to the notable losses of the county from Hurricane Ike. The spatially allocated dollar values of output losses are shown in Fig. 5. A comparison between Hurricane Ike's property damage losses illustrated in Fig. 4 and its total losses of output in Fig. 5 shows that the losses of output

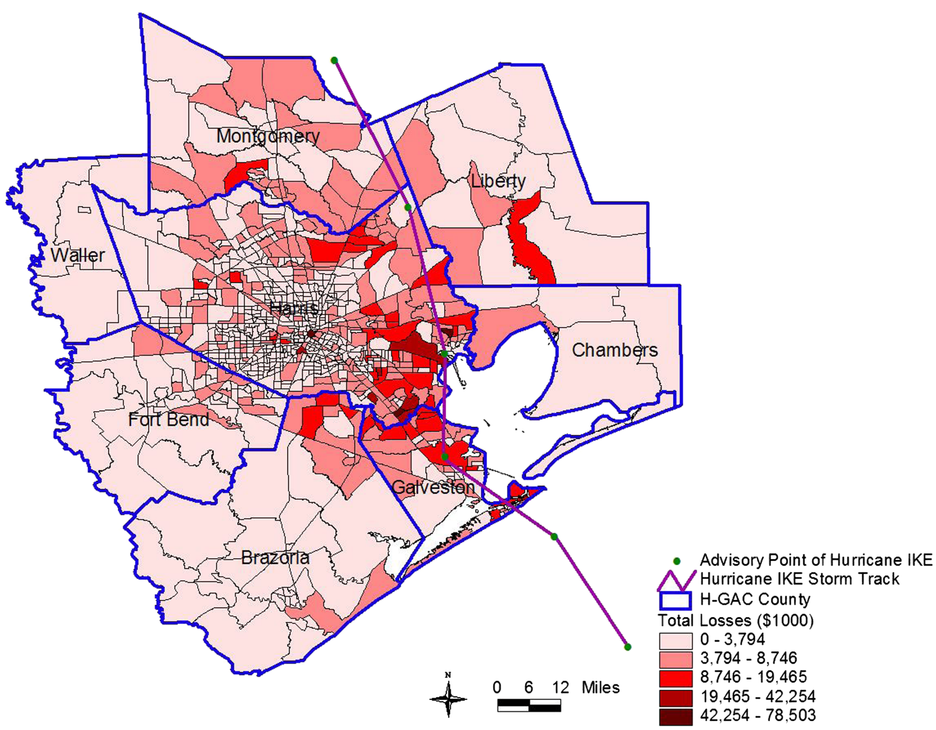

Fig. 5. Total losses of output from Hurricane Ike event (data from author calculations using the *Hazus* hurricane model, the IMPLAN I/O model, the InfoUSA employment, and the H-GAC 2000 base year trip matrices, etc.)

Table 6. Twenty Cities with Highest Losses of Output from Hurricane Ike Event

Index	City name	Output ($1,000s)				Jobs			
		Direct	Indirect	Induced	Total	Direct	Indirect	Induced	Total
1	Houston	491,661	260,449	499,804	1,251,914	6,616	2,649	5,265	14,530
2	Pasadena	124,673	9,580	39,337	173,590	1,705	90	421	2,216
3	Galveston	125,630	5,441	13,838	144,909	1,642	57	158	1,856
4	Baytown	95,548	2,907	13,825	112,280	1,233	30	150	1,414
5	Webster	88,283	1,919	3,115	93,317	1,164	21	35	1,220
6	League city	59,064	2,446	16,874	78,385	1,287	32	189	1,509
7	Texas city	37,280	3,413	13,850	54,542	528	32	154	714
8	La Porte	31,690	2,406	10,403	44,499	496	24	111	631
9	Pearland	27,060	2,462	14,363	43,885	429	27	155	610
10	Deer park	25,011	2,428	9,823	37,262	359	24	105	487
11	The Woodlands	5,091	7,720	21,781	34,592	68	76	224	369
12	Atascocita	21,382	1,360	9,794	32,536	376	17	105	498
13	Friendswood	22,402	1,103	8,357	31,862	395	13	92	500
14	Sugar land	386	8,413	22,810	31,608	3	82	237	322
15	Channelview	19,993	2,228	7,791	30,012	294	19	82	395
16	Missouri city	201	3,195	20,194	23,590	2	41	211	255
17	Alvin	11,725	1,639	4,742	18,106	177	15	51	243
18	Conroe	3,937	3,850	8,292	16,079	67	43	90	200
19	Nassau Bay	12,771	487	701	13,959	155	5	8	168
20	Aldine	7,171	2,233	4,524	13,929	94	22	48	164
Total		1,210,961	325,679	744,218	2,280,858	17,091	3,318	7,890	28,299

Note: Author calculations.

spread out in the region far beyond the corridor along the storm track, in which property damage losses are concentrated.

Table 6 shows the top 20 cities in the region ranked by their losses of output in Hurricane Ike. The City of Houston, the biggest city in the region, experienced the largest impacts on the list, losing about $1.3 billion output and 14,530 jobs, about seven times larger than the second city on the list, the City of Pasadena, and also one-third of the regional losses excluding the leakages. The City of Galveston, regardless of its size, ranks third on the list with losses of $144.9 million output and 1,856 jobs. All the other cities among the top 10 are located in the south of the region along the storm track. They illustrate wide geographical dispersion, which makes it inequitable to distribute disaster relief funds evenly by population among the directly impacted cities. Quantifying economic losses by city can help policymakers allocate manpower and resources for disaster relief more efficiently and fairly,

Conclusions and Discussion

As some of the economic losses of residents and businesses extend well after Hurricane Ike, it has taken the region much longer than usual to recover. Disaster relief plans have to be based on a careful study of damage states and economic losses in each impact zone, which are not limited to the areas directly impacted. To obtain a better estimate of the economic losses from actual natural disasters, this study develops a systematic method with a general framework that is a combination of disaster model, an economic I/O model, and a spatial allocation model. The method complements the *Hazus* hurricane model with a more reasonable estimate of direct output and job losses and fills the information gaps by developing the functions to estimate indirect and induced losses. It also utilizes GIS spatial analysis functions to allocate the losses to multiple types of impact analysis zones or political jurisdictions. The model framework presented in this paper has incorporated various state-of-the-art components into an integrated framework for efficient hurricane loss estimation.

This systematic approach was implemented to investigate the economic losses of Hurricane Ike in the Houston-Galveston region. It found that Hurricane Ike caused significant economic losses in the Houston region. Its property damage and business interruption losses made Hurricane Ike the third costliest hurricane event in the United States of all time. The property damage and economic losses were not limited to the corridor along the storm track. The losses were over a widely extended area from the south coast in the Galveston Bay to Montgomery County in the north of the region. Some areas such as those in Fort Bend County receive few direct impacts but a fair amount of indirect and induced impacts, which makes the total impacts quite large.

These model results are in line with observations from the real world. It is important to develop spatially refined models for estimating disaster losses, and the quick, proper, and detailed estimate of hurricane damage losses from the approach described in this paper can help policymakers and planners identify the most cost-effective options for disaster and mitigation and efficiently and equitably allocate manpower and resources for disaster relief.

One limitation is that this study employed the default database in the *Hazus* hurricane model to estimate physical damage losses of buildings from Hurricane Ike. Due to time and budget constraints, there was no effort to collect additional local data and customize inventories to perform a high-level analysis using the *Hazus* hurricane model. It is possible, however, to replace the default database with more accurate information for more advanced loss estimation in future research.

Another limitation of the approach lies in the use of an I/O model that is not applicable for long-term impact analysis. Though most commercial buildings restored functions and many of their businesses were back to normal conditions in a short period of time after Hurricane Ike, some suffered from serious damage in the badly hit areas, for example, the Galveston Island area took a considerably long time to recover. It is desirable to collect additional information and extend the model to take into account the long-term effects. The use of models to assess long-term effects is, in any case, controversial.

As Rose et al. (2007) pointed out in a benefit-cost analysis of hazard mitigation grant using *Hazus*, there were few factors that could be subjected to sensitivity analysis of direct business interruption in *Hazus*. Sensitivity analyses would probably have been redundant because direct business interruption estimates were derived to a great extent from direct property damage. It was the same in this study. Because the approach developed in this paper for measuring direct impacts using the physical damage estimate from *Hazus* as input, and *Hazus* assumes a constant ability of businesses to reschedule or recapture lost production after disasters, the model has not been refined to examine the resilience of direct economic losses to hurricane events. The model framework has not incorporated uncertainty factors into I/O models, such as resource availabilities, resiliency, or speed of recovery, and has not adjusted the major parameters of the model or performed sensitivity tests of their influence on the results. These tasks can be included in future studies.

This study does not provide a detailed comparison with the IELM model or the CGE model. As Rose and Liao (2005) pointed out, the CGE model provides a lower-bound estimate of losses due to its consideration of regional economic resiliency, while the I/O analysis in this study provides an upper-bound estimate. The IELM model includes an estimate of the indirect effects falling between the lower bound calculated by the CGE model and the upper bound reported in this study. This can be further analyzed in a future study.

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