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ORIGINAL PAPER

Vulnerability of an industrial corridor in Texas to storm surge

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Abstract A conceptual framework for evaluating the vulnerability of industrialized coastal regions to storm surge was developed and implemented to evaluate the vulnerability of the Houston Ship Channel Industrial Corridor (HSC-IC) in Texas to storm surge. In the study, Hurricane Ike scenarios were modeled with SWAN + ADCIRC that involved changing the landfall location of the hurricane along the coast and incorporating the effect of increased wind speed. The storm surge data from the various landfall scenarios were cross-linked with geospatial and environmental data associated with facilities within the industrial region. This work uniquely combines the potential releases from storage tanks, records of past historical releases, and risk management planning to characterize environmental vulnerabilities using storage information and geospatial data. The resulting framework for vulnerability implemented within the HSC-IC found a relationship between storm surge and the total area inundated at a given storm surge level and between storm surge and the total number of storage tanks. Using the developed framework, it was possible to combine releases from storage tanks, records of past historical releases, and risk management planning to characterize environmental vulnerabilities on a facility by facility basis and for the modeled surge levels.

Keywords GIS · Hurricane · Risk management · Environmental impact

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1 Introduction

Vulnerability has been defined extensively and with great variability in various areas of study (Cutter 1996). In general, vulnerability is the degree to which a system cannot cope with adverse effects (Adger 2006). Ultimately, it is the understanding that vulnerability represents the potential for loss (Cutter 1996). From an engineering perspective, the focus is more on the flaws of a system, whether from design, implementation, operation, and/or management (Zio and Kroger 2009), while taking into account susceptibility for a system or structure to cope with adverse effects (Metzger et al. 2008). For this study, vulnerability is defined as the inherent characteristics that cannot be changed prior to an event occurring which could create the potential for damage.

Disaster vulnerability, in particular, is a topic of considerable interest that has been studied extensively over the past few decades (Morrow 1999; Petrova 2006; Sharma and Patwardhan 2008; Maio et al. 2012). Hurricane vulnerability, for instance, has received significant attention because of hurricanes that have affected the Gulf Coast in the past 10 years (e.g., Hurricanes Katrina, Rita, and Ike), causing significant damage and loss of human life (Anderson-Berry 2003; Cauffman et al. 2006; Cigler 2009; Link 2010). Bringing strong winds and rain, hurricanes are associated with storm surge that transports significant amounts of water into affected areas causing extensive damage and disruption of systems due to inundation and strong currents. While the impact of storm surge on the environment has been observed in Hurricanes Katrina and Rita, the economic impact related specifically to storm surge has yet to be fully understood. Pine (2006) noted over 50 oil spills that had been reported in the nearshore environment in Hurricane Katrina. These spills are attributed mostly to pipelines and tanks that were damaged by inundation and were thought to have short-term and long-term impacts to the environment. In addition to potential cleanup costs, the economic damage associated with facility inundation could include production downtime and supply loss which could represent a significant component of the total economic impact of storm surge on a region.

Hurricane vulnerability studies to date have focused on community vulnerability and developing resilience in coastal areas (Shuang-Ye et al. 2002; Wang and Yarnal 2012) and on addressing wind damage (Unanwa et al. 2000; Stewart 2003). While some studies have investigated the vulnerabilities to storm surge, the most costly aspect of a hurricane (Santella et al. 2010), these studies have focused on larger regional impact to the community (Rao et al. 2007; Kleinosky et al. 2007). Place-based models for understanding community response to natural hazards have been proposed and include additional ecological aspects such as biodiversity and erosion rates (Cutter et al. 2008). However, these models do not consider the impact industrial facilities have on the ecological or environmental vulnerability of a region. Another aspect that has yet to be addressed has to do with the impact on the environment related to the inundation of infrastructure and industry. Vickery et al. (2006), for instance, presented the HAZUS-MH hurricane model for assessing damage related to hurricanes; however, their study did not address the environmental damage components of storm surge on a highly industrialized region. Ding et al. (2008) demonstrated the benefit of using localized data in HAZUS-MH; however, their study did not address specific impacts to industrial facilities and the surrounding areas. Marc and Carol (2005) focused on the vulnerability of industrial and petrochemical facilities but only from the perspective of extreme winds associated with hurricanes. Stearns and Padgett (2011) demonstrated the impact that storm surge had on bridge infrastructure, but their study was limited to bridge crossings. Thus, a definitive investigation of storm surge and its relationship to the vulnerability of industrialized regions has yet to be fully elucidated. As more people inhabit coastal areas and share the landscape with industrial, shipping, and navigational corridors, it will be increasingly important to not only reduce community vulnerability but also understand and reduce the vulnerability of the industrialized components of the region to ensure sustainability and resilience of these coastal zones.

In this paper, a vulnerability framework is developed that characterizes storm surge vulnerability using the geographic, land use, and environmental properties of a region. The geographic information system (GIS)-based vulnerability framework is implemented for the industrial corridor along the Texas Gulf Coast known as the Houston Ship Channel Industrial Corridor (HSC-IC) (see Fig. 1). The HSC-IC covers an area of 225 km^2 with 866 industrial facility parcels covering 60 km^2 and includes more than 3400 aboveground storage tanks. Because of the chemical and petrochemical nature of this industrial complex, the potential for environmental releases during hurricanes and severe storms is of concern. From an economic standpoint, the HSC-IC generates more than 150 billion dollars in economic activity and over 1 million jobs (Port of Houston 2014). The Port of Houston, located on the west end of the HSC-IC, is one of the busiest ports in the USA based on foreign tonnage and the second largest in the world in terms of tonnage (Port of Houston 2012). Historically and based on the SURGEDAT database (http://surge.srcc.lsu.edu), there have been over 120 storm surge events related to hurricanes along the Gulf Coast since 1880; 14 of which have landed in the Houston–Galveston region and impacted the entire region including the HSC-IC. Hence, identifying vulnerabilities of this industrial region to hurricanes is critical from both environmental and economic standpoints, especially given the historical frequency of their landfall in the region (approximately once every 10 years).

2 Vulnerability framework development

The developed framework in this research (Fig. 2) relates storm surge predictions from an SWAN + ADCIRC model (Hope et al. 2013) for hurricanes that approach the Texas Gulf

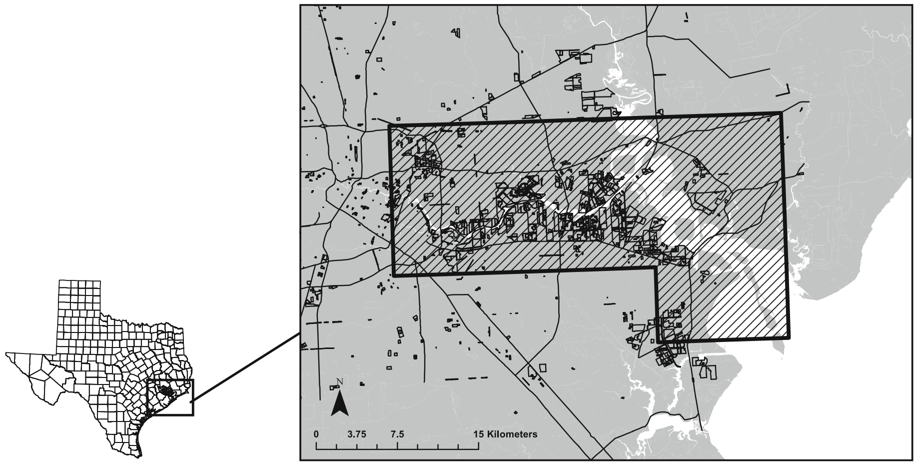


Fig. 1 Houston Ship Channel Industrial Corridor (HSC-IC) along the Gulf Coast in Texas. The parcels outlined in *black* are industrial facilities with the *shaded*-in region representing the study area

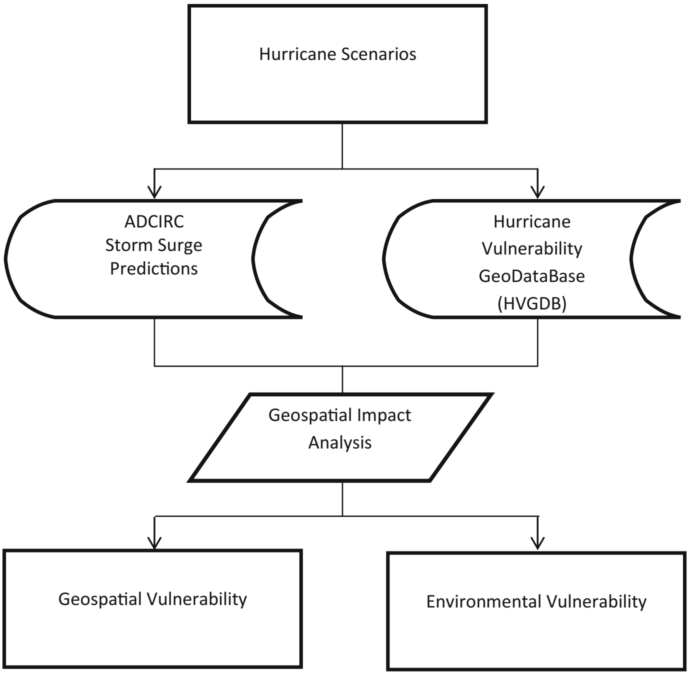


Fig. 2 A schematic of the conceptual model developed for characterizing vulnerabilities to storm surge

Coast to the topography of the HSC-IC, its environmental characteristics, and industrial infrastructure using a customized geodatabase for the region. Environmental characteristics in this research specifically refer to the potential for releases from facilities in the HSC-IC based on their chemical storage profile, past history of releases, and toxic storage amounts. As shown in Fig. 2, the framework hinges on developing modeling scenarios for hurricane landfall, modeling the landfall scenarios with the SWAN + ADCIRC model, developing a geodatabase for the region, and linking the latter two to allow an analysis of geospatial and environmental vulnerabilities. Each component of this framework is described in more detail below.

2.1 Hurricane scenarios

Hurricane Ike made landfall in 2008 along the Texas Gulf Coast on Galveston Island (landfall location shown in Fig. 3 and annotated as "original"). While not a catastrophic event for the HSC-IC, Ike was characterized by its unusually wide spatial coverage upon landfall. Within the Houston–Galveston region and the HSC-IC, Ike generated the equivalent of the 100-year flood event in the HSC-IC. Table 1 shows a list of the 14 hurricanes/severe storms that have made landfall in the Houston–Galveston region with their corresponding maximum storm surge that was observed. All 14 storms impacted the entire region including the HSC-IC, but Hurricane Ike ranked second among these storms in terms of storm surge height with the 1900 Galveston storm having the highest recorded storm surge at 6.1 m in Galveston (It is noted that the vulnerability of Galveston Island to hurricanes gave rise to the construction of the HSC-IC). While the Sea, Lake, and Overland

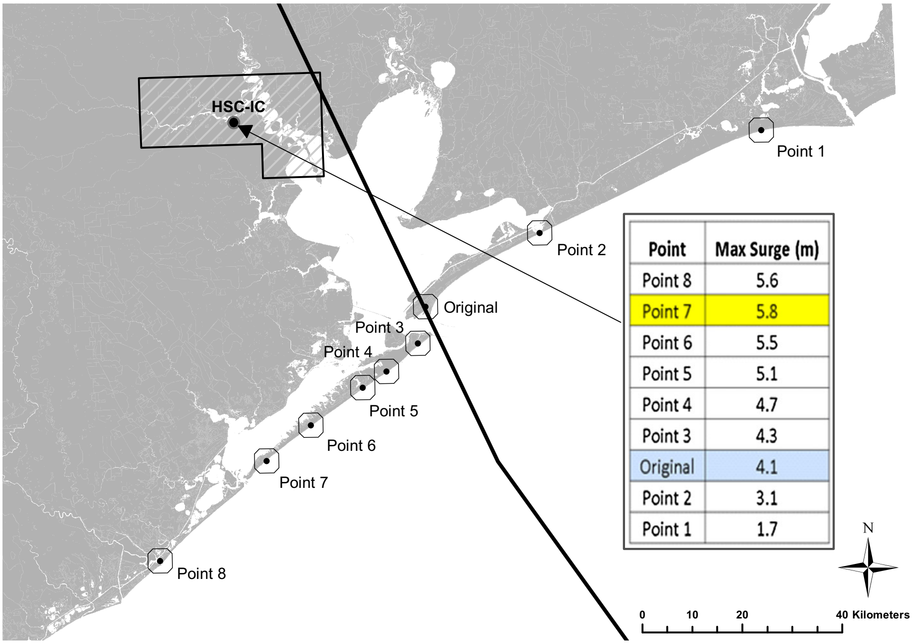


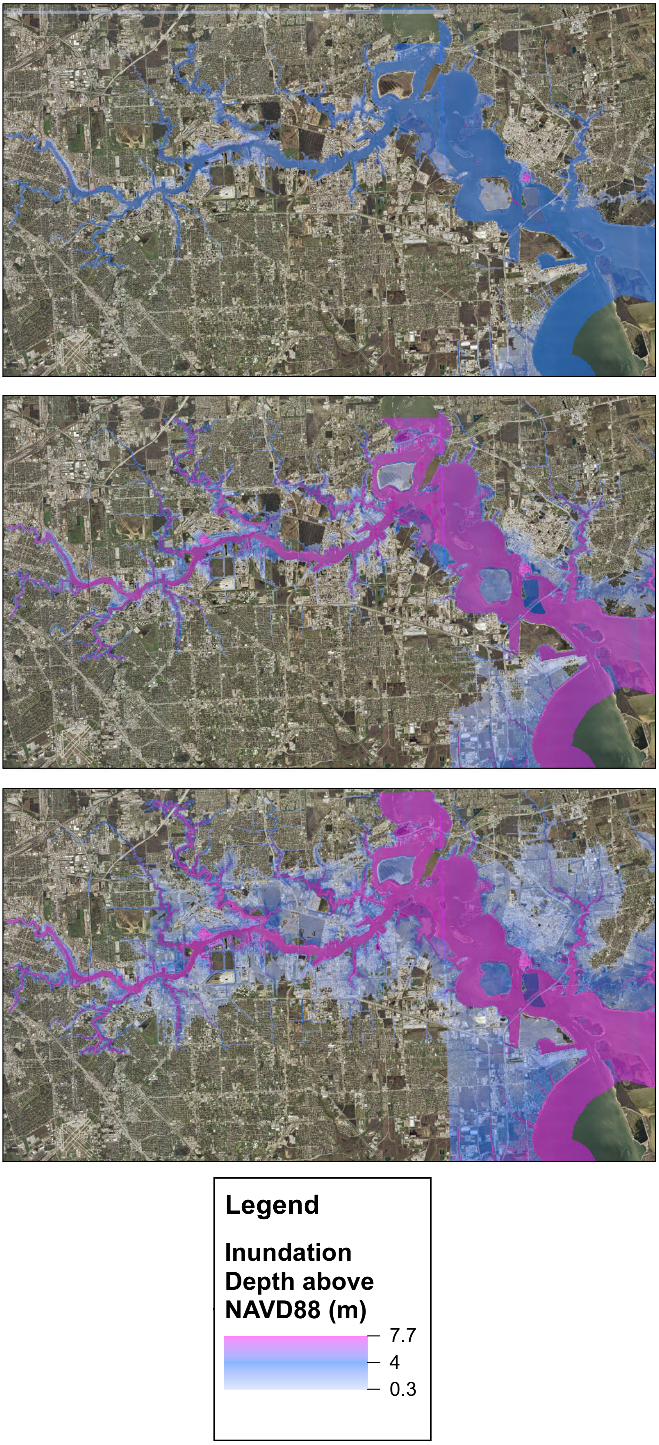
Fig. 3 Landfall locations for SWAN + ADCIRC modeling of Hurricane Ike. The *solid black line* represents the original track of Hurricane Ike. The *table* shows the change in storm surge for the simulated landfall locations of Hurricane Ike at the indicated point in the HSC-IC

Table 1 Storm surge events in the Houston–Galveston region since 1900

Storm surge event	Max measured surge location	Max surge height measured (m)
1900 Galveston Hurricane	Galveston Island	6.1
Ike (2008)	Chambers County (near Bolivar Peninsula)	5.3
1915 Galveston Hurricane	GLS Seawall (Galveston)	4.7
Storm of 1949	Houston Ship Channel (Harrisburg)	3.5
Debora (1959)	Morgan Point (HSC)	2.4
Jerry (1989)	Baytown (HSC)	2.1
Unnamed storm (1934)	Galveston Island	2.1
Unnamed storm (1921)	West Bay (Galveston Island)	2.1
Delia (1973)	Baytown (HSC)	2
Charley (1998)	Galveston Island	1.5
Unnamed storm (1947)	Galveston Island	1.2
Erin (2007)	Galveston Island	0.9
Felice (1970)	Galveston Island	0.6

Source: SURGEDAT

http://surge.srcc.lsu.edu/data.html. Accessed: 4/7/2014


Legend
Inundation Depth above NAVD88 (m)
7.7
4
0.3

◀**Fig. 4** Depth of inundation (m) at maximum storm surge for the three runs of interest Hurricane Ike (*panel 1*), Hurricane Ike at point 7 (*panel 2*), and Hurricane Ike at point 7 with 30 % increased winds (*panel 3*)

Surges from Hurricane (SLOSH) model has previously been used extensively by the National Oceanic and Atmospheric Administration (NOAA) for hind casting and forecasting storm surge events, a newly developed SWAN + ADCIRC wave and circulation model was used to simulate storm surge during Hurricane Ike. In particular, Kerr et al. (2013) performed an analysis comparing the water-level results from the two models during Hurricane Ike and found that SLOSH produced less-accurate results compared to the SWAN + ADCIRC model for the Houston–Galveston region. The SWAN + ADCIRC model, discussed in more detail later in this paper, utilizes a detailed unstructured grid which accounts for bathymetric complexities and provides better implementation of bottom friction, an important advantage for modeling storm surge for the coastal estuary system of the Houston–Galveston region (Kerr et al. 2013, Sheng et al. 2012). In addition, this model was chosen since it has been extensively validated on a variety of storms in the Louisiana and Texas coastal shelf (Dietrich et al. 2012; Hope et al. 2013; Sebastian et al. 2014) and was considered to be an ideal simulation tool for quantifying storm surge in the region. In particular, the model was validated for Hurricane Ike by Hope et al. (2013), and Sebastian et al. (2014) successfully applied the SWAN + ADCIRC model for Galveston Bay using various storm locations and strengths related to Hurricane Ike.

Weisberg and Zheng (2006) indicated that the location of a hurricane's landfall has a significant impact on localized storm surge levels. Thus, for the modeled scenarios in this study, Ike's track was shifted to eight different landfall locations along the coast to the southwest and to the northeast to determine the effect of the landfall location on storm surge in the HSC-IC. Figure 3 shows the actual Hurricane Ike landfall location (labeled "original") and the eight additional modeled landfall locations. It is necessary to note that while landfall location changed in the modeled scenarios, the track alignment shown in Fig. 3 was maintained for all scenarios. The landfall location approximately 150 miles to the southwest of Hurricane Ike's actual landfall location (referred to in this paper as point 7) provided the highest storm surge elevations in the HSC-IC and was thus considered the worst-case scenario and used to illustrate the vulnerability framework developed in this study.

In addition to landfall location, wind speed as it affects storm surge is an important consideration. This is because the stress caused by winds accounts for approximately 95 % of the storm surge height (NOAA 2012; Weisberg and Zheng 2006; Irish et al. 2008). Prior to making landfall, Hurricane Ike was a category 4 hurricane with winds exceeding 135 mph, but it quickly subsided to a category 2 storm upon landfall, a 30 % reduction in wind speed. Thus and in order to incorporate the effect of wind speed into the modeled scenarios in this study, Hurricane Ike's winds were increased by 30 %, thereby elevating Hurricane Ike back to a category 4 (229 km/h) hurricane upon landfall (Sebastian et al. 2014). For the purposes of illustrating the vulnerability framework developed in this study, results from Hurricane Ike at the "original" location, Hurricane Ike at point 7, and Hurricane Ike at point 7 with 30 % stronger winds are presented. It should be noted that the focus of the modeling scenarios is on assessing vulnerabilities; the modeled scenarios were not intended to be used to develop relationships between wind speed, landfall, and impacts.

2.2 SWAN + ADCIRC storm surge predictions

This modeling system has been successfully validated for recent hurricanes Katrina, Rita, Gustav, and Ike (Westerink et al. 2008; Zijlema 2010; Dietrich et al. 2010; Dietrich et al. 2011a, b; Hope et al. 2013). When compared to observed high-water marks from Hurricane Ike, for instance, 94 % of modeled high-water marks were within 0.50 m of the measured values (Hope et al. 2013).

Inputs to SWAN–ADCIRC include a data assimilated Ocean Wind Field (OWF) and a high resolution computational domain encompassing the Western North Atlantic, Gulf of Mexico and Caribbean Sea. The unstructured finite element mesh incorporates a significant amount of detail around the Houston–Galveston region and consists of 3,323,388 nodes with resolution down to 30 m in the nearshore. The grid represents a subset of the grid (SL18TX33) presented in Hope et al. (2013) without the refinement that was undertaken for Louisiana. Storm surge data for calibration with 206 verified data locations that were derived from several sources including the US Geological Survey (USGS), the National Oceanic and Atmospheric Organization (NOAA), Texas Coastal Ocean Observation Network (TCOON), and the State of Louisiana Coastwide Reference Monitoring Station (CRMS).

Model results for the landfall location scenarios indicated that as Ike was moved from point 1 to point 7 (a distance of approximately 120 km southwest), storm surge in the HSC-IC increased from approximately 4 m for the actual landfall location to approximately 5.8 m at point 7 (a 1.8-m increase, identified as worst-case scenario for landfall location as mentioned previously). At point 8, storm surge begins to decrease. As shown in Fig. 3 for a select location within the HSC-IC, there is a steady increase in storm surge as Hurricane Ike is shifted to the southwest as a result of the strongest component (northeast corner) of the storm hitting the HSC-IC directly. When the winds were increased by 30 % at point 7, the storm surge level increased to approximately 7.7 m in the HSC-IC (1.9-m increase over the lower wind scenario), supporting the importance of wind speed effects on storm surge. When taken together, the swath defined by potential landfall locations between points 3 and 7 represents the critical zone of influence for storm surge in the HSC-IC from both a landfall and wind speed perspective. Figure 4 (panels 1–3) illustrates the extent of inundation based on the maximum storm surge elevation simulated in the HSC-IC in the three SWAN + ADCIRC scenarios (Ike, Ike at point 7, and Ike at point 7 with 30 % increased wind speed). As can be seen from the figure, and while most of the inundation is reasonably contained in the Ike scenario, inundation is extensive, widespread, and completely submerges the HSC-IC in Ike at point 7 with 30 % higher wind. In this manner and based on the modeled scenarios, vulnerability of the HSC-IC to landfall location and wind speed of hurricanes was characterized.

2.3 HSC-IC Hurricane Vulnerability GeoDataBase (HVGDB)

A specialized GIS geodatabase was developed in this research that includes topography, parcel boundaries, and critical infrastructure in the HSC-IC. The main purpose of developing the HSC-IC Hurricane Vulnerability GeoDataBase (HVGDB) was to link the modeled storm surge from the scenarios described in the previous section with the geospatial land use, topography, industrial facility, and environmental data. The HVGDB can be envisioned as a tool to analyze, interpret, map, and store the resulting vulnerabilities that can also serve as a means of communication and decision-making among its users (e.g., scientists, engineers, hurricane modelers, decision makers). Therefore, while not all stakeholders may be experts in SWAN + ADCIRC or hurricane modeling, they can still readily access the modeled results and make interpretations. Because of its dynamic format (e.g., direct linkage to existing spatial datasets), the HVGDB can be readily updated and expanded to include additional scenarios as they are developed as well as additional variables or considerations for analysis and decision-making.

The HVGDB includes geographic and topographic data for the HSC-IC, facility critical infrastructure information, data on aboveground storage tanks (ASTs) at each facility, information from toxic release inventories (TRI), and information on risk management plans (RMPs) for facilities within the HSC-IC. These components will be described briefly below to illustrate the rigor for the developed geodatabase and its adaptability to additional analyses.

2.3.1 Geographic and topographic data

The geography of the region was defined using light detection and ranging (LIDAR) data from the Harris County Flood Control District (HCFCD) that was developed in their Tropical Storm Allison Recovery Project (TSARP). The vertical datum for TSARP data that were collected in 2006 is the North American Vertical Datum of 1988 (NAVD88). Inundation depth within the HSC-IC was calculated as the difference between the modeled water level and the ground elevation above sea level. The LIDAR data were also used to determine the specific ground elevation of industrial facilities and select infrastructure along the HSC-IC.

2.3.2 Industrial facility data

Industrial facility information was obtained from EPA's EnviroFacts database (http://www.epa.gov/enviro/) and Harris County Appraisal District (HCAD) data. While EnviroFacts provides facility information and latitudes and longitudes from the Facility Registry System (FRS), it does not document facility boundaries. These were developed by spatially linking latitude and longitude data from the EnviroFacts database to parcel boundaries from HCAD data. The parcels associated with each facility were tagged and used to develop the property boundary for each facility within the HVGDB.

2.3.3 Aboveground storage tanks (ASTs)

Tank locations were determined using visual inspection of aerial photography. Within the study area, 1-ft by 1-ft aerial photography from the Houston–Galveston Area Council (HGAC) database from 2008 (http://www.h-gac.com/rds/gis_data/default.aspx) was used to identify locations of ASTs; a spatial point was then placed in the center of the tank within the HVGDB. Tank elevations were determined using the LIDAR data.

2.3.4 Toxic release inventory (TRI)

Past toxic releases from facilities along the HSC-IC were downloaded from EPA's EnviroFacts database (http://www.epa.gov/enviro/); data for facility ownership, past release yearly totals, and chemicals released to water bodies were assimilated. These data, as will be seen subsequently in this paper, were used to select facilities with a greater potential for releases based on their historical records.

2.3.5 *Risk management plans (RMPs)*

Data from RMPs submitted to EPA were collected from the Right to Know Network (rtknet.org, Accessed: 08/2011) database. The data included basic facility information, process toxic chemical amounts, past accidents, and prevention plans. Other sources of information such as Tier II submittals (http://www.epa.gov/oem/content/epcra/tier2.htm, Tier II are chemical inventory reports that are submitted to local emergency managers/ responders) were also consulted but were deemed to overlap with the information in RMPs and thus were not used. Information regarding prevention plans and past accident histories lacked necessary details in order to be included in this assessment; therefore, the key data extracted from the RMPs were the process toxic chemical amounts (kg).

Data from the developed HVGDB, joined with the SWAN + ADCIRC modeling results, were analyzed to develop geospatial and environmental vulnerabilities for the HSC-IC as described below.

2.4 Geospatial vulnerability

Geospatial vulnerability in this research refers to the potential for inundation from storm surge based on ground elevation. Inundated land was defined as any land with elevation that falls below the predicated storm surge height. As mentioned previously and from a flooding perspective, Hurricane Ike was equivalent to a 100-year flood event. Thus, the existing 100-year FEMA floodplain areas were first identified since these areas would not be considered geospatially vulnerable to storm surge below the 100-year level in the Hurricane Ike scenario. Storm surge inundation for the modeled Ike scenario was compared to the 100-year FEMA floodplain and areas not in the 100-year FEMA floodplain were then identified and their geospatial vulnerability was delineated. The initial findings confirm conclusions by Brody et al. (2012); they indicated that the 100-year FEMA floodplain boundary is not sufficient in representing actual economic losses during a flood. Since this analysis is evaluating specific events without a probability of occurrence, the results cannot be directly correlated to the FEMA 100-year floodplain. Rather, the purpose of the geospatial analysis described above is to identify inundated areas by storm surge that are not within the FEMA 100-year floodplain and to illustrate the potential for inundation of areas outside the 100-year floodplain for storm surge levels that are commensurate with the 100-year flood elevation. The FEMA 100-year floodplain provides a protection level for facilities within the HSC-IC. Identifying regions that are inundated outside the standard protection is a necessary and important component to the overall vulnerability analysis for the HSC-IC. Similarly, land areas within the 100-year FEMA floodplain that were not inundated during Hurricane Ike were also delineated and removed from the geospatial vulnerability analysis. The total area (km^2) of inundated land for each modeled scenario was calculated to determine the relationship between surge level (observed for each scenario) and geospatial vulnerability.

In addition, the geospatial vulnerability of individual facilities along the HSC-IC was quantified. Facilities with less than 40 % inundation were delineated. For the purposes of this study, facilities with greater than 40 % inundation were identified as candidates for total loss and failure, and consequently high geospatial vulnerability.

2.5 Environmental vulnerability

Environmental vulnerability is defined as the potential for releases to the environment due to inundation as discussed previously: (1) potential releases from inundated aboveground storage tanks, (2) potential releases of chemicals to the environment based on previous history of releases, and (3) potential releases of chemicals to the environment based on stored volumes of toxic chemicals. Two aspects should be noted regarding environmental vulnerability as defined in this research. First, the quantity of stored chemicals is as surrogate indicator for environmental damage under storm surge. Second, inundation (geospatial vulnerability) is used to delineate impacted ASTs and the inundated ASTs are used as a surrogate for potential chemical releases to the environment as described below in more detail.

2.5.1 *Releases from ASTs*

Godoy (2007) and Santella et al. (2010) found significant damage to 21 affected storage tanks in Hurricanes Katrina and Rita; the most severe effects being due mainly to surge- and inundation-related tank failures. In this research, the potential for releases from ASTs was determined by identifying the number of tanks that would be inundated for each modeled scenario. Since ASTs are typically surrounded by berms with berm elevation set at the 100-year FEMA floodplain; the analysis included affected tanks that were outside the 100-year FEMA floodplain level.

2.5.2 *Other toxic releases*

For this study, it was assumed that facilities with a history of releases to the water environment had a higher vulnerability for releases under storm surge. A given facility's historical annual amount released to the water environment over the past decade was calculated from the TRI data. It was assumed that the top 25 % of facilities based on released volumes are the most vulnerable to releases during a hurricane. The facilities (from the top 25 % list) within the modeled surge level were identified, and their potential for pollutant releases was estimated based on their historical records and their relative inundation for the specific hurricane scenario. Facilities with greater than 450 million kg of chemicals released into the water environment were identified as having high environmental vulnerability (potential for release). In order to account for facilities with high geospatial vulnerability based on areal inundation and the potential for releases from such facilities (independent of ASTs), their inundation was factored in as the second aspect of environmental vulnerability.

2.5.3 *Risk management plans*

The RMP database was initially used to identify industrial facilities that had prevention plans in place to handle large amounts of hazardous materials. Of the total number of facilities in the study area, less than 10 % had RMPs indicating a serious deficiency and signaling additional vulnerability in the HSC-IC. Due to this relatively low number of RMPs, their adequacy was not incorporated in the analysis at this stage. The analysis focused on accounting for vulnerability using a similar approach to the one used in the AST analysis, i.e., determining which facilities with RMPs had greater than 40 % inundation and were in the top 25 % of facilities in terms of the amounts of toxic process chemicals.

The next section will focus on the results from the vulnerability framework described above as it was applied to the Houston Ship Channel using the modeled SWAN–ADCIRC landfall and wind velocity scenarios.

3 Results

3.1 Geospatial vulnerability results

Figure 5 shows the inundated areas outside the 100-year FEMA floodplain from Hurricane Ike, Hurricane Ike at point 7, and Hurricane Ike at point 7 with 30 % increase in wind speed for the entire HSC-IC. A significant inundation area occurs at the mouth of the HSC-IC in the southeast corner of the study area. Figure 6 presents the developed correlation between the total inundated area and surge height. The storm surge values in the figure are based on the average storm surge observed in the HSC-IC (within the HSC-IC there is little observed variability in storm surge height from the model results, on the order of ±0.2 m). The figure presents the area of inundation increasing exponentially with increasing surge level described mathematically using Eq. (1):

$$\text{Area inundated outside floodplain} = 2.0162e^{0.5939(\text{surgeheight})} \tag{1}$$

where area is given in km^2 and surge height is given in meters.

3.2 Environmental vulnerability results

3.2.1 Releases from ASTs

Figure 7 illustrates tank inundation for the modeled storm surge scenarios. The three panels in the figure represent the three modeled storm surge events with a dot representing an inundated tank. The number of impacted tanks increases significantly with an increase in severity of the storm surge for the region and summarized in Table 2. Almost four times the number of tanks when Ike is moved to point 7 and winds are increased by 30 %. Similar to land inundation outside the FEMA 100-year floodplain, as the storm surge in the

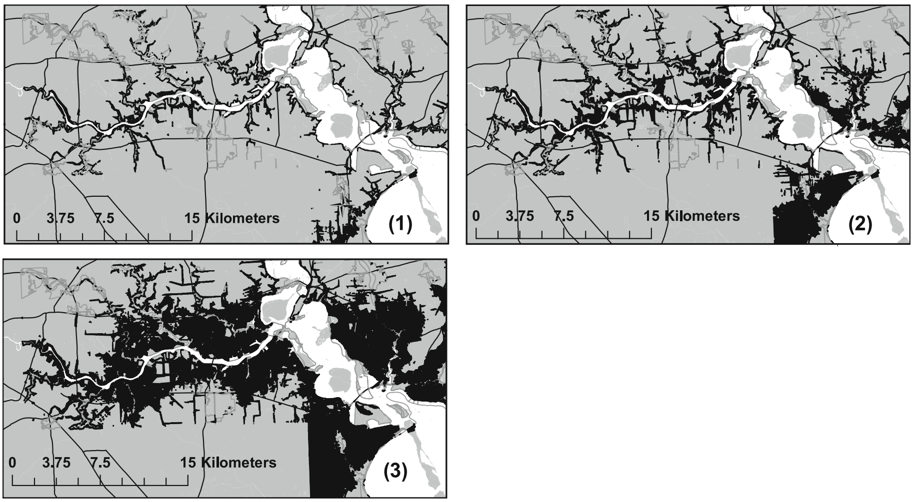


Fig. 5 Inundation due to storm surge outside the 100-year floodplain (*black region*) from the SWAN + ADCIRC model runs for Hurricane Ike (*panel 1*), Hurricane Ike at point 7 (*panel 2*), and Hurricane Ike at point 7 with 30 % higher wind speed (*panel 3*)

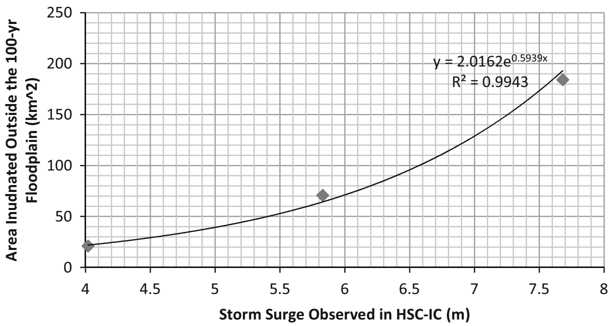


Fig. 6 Correlation between inundated areas (outside of the 100-year FEMA floodplain) and the modeled storm surge levels for the various hurricane scenarios

region increases, the number of inundated tanks increases exponentially; this relationship (shown in Fig. 8) can be represented mathematically using Eq. (2):

$$\text{Number of inundated tanks} = 89.165e^{0.4716(\text{surgeheight})} \tag{2}$$

where surge height is in meters.

3.2.2 Other toxic releases

The facilities with greater than 1 billion pounds of released chemicals to the water environment annually that fell in the top 25 % of facilities historically reporting releases in the HSC-IC are identified in panel 1 of Fig. 9 (a total of 27 facilities). Panels 2 and 3 of the figure combine the historical release information and modeled inundation by showing facilities having high tonnage of releases to the water environment and high geospatial vulnerability (greater than 40 % inundation) for Hurricane Ike at point 7 and Hurricane Ike at point 7 with a 30 % increase in wind speed, respectively. Facilities filled in black are vulnerable to toxic release. For the Hurricane Ike scenario, no facilities were deemed vulnerable to toxic releases (true in reality during Ike) and only two vulnerable facilities were identified when Ike was moved to point 7. However, a storm surge of over 7 m produced by increasing Ike at point 7 showed significant number of facilities vulnerable to toxic release shown in Panel 3 of the figure. The number of vulnerable facilities for each scenario is shown in Table 2.

3.2.3 Risk management planning

Table 2 presents the number of RMP reporting facilities that had greater than 40 % inundation for each of the modeled hurricane scenarios. Facilities with greater than 94 kg of stored chemicals (top 25 % among HSC-IC RMP reporting facilities) were assumed to be the greatest threats to the environment. A total of 25 facilities fell into this category, and these facilities are shown in panel 1 of Fig. 10. Similar to the analysis used for the TRI facilities, panels 2 and 3 of the figure combine this environmental threat based on the RMP reported toxic process chemical amount with the facilities having high geospatial vulnerability (shaded in black). Confirming the reality of the Hurricane Ike, no facilities deemed threats to the environment under the Ike scenario. Panel 2 of the figure presents a large number (12) of vulnerable facilities compared to the two facilities identified under this same scenario for the TRI facilities. In addition, panel 3 of the figure and the data in Table 2 indicate that 20 facilities were vulnerable during Ike at point 7 with increased wind speed.

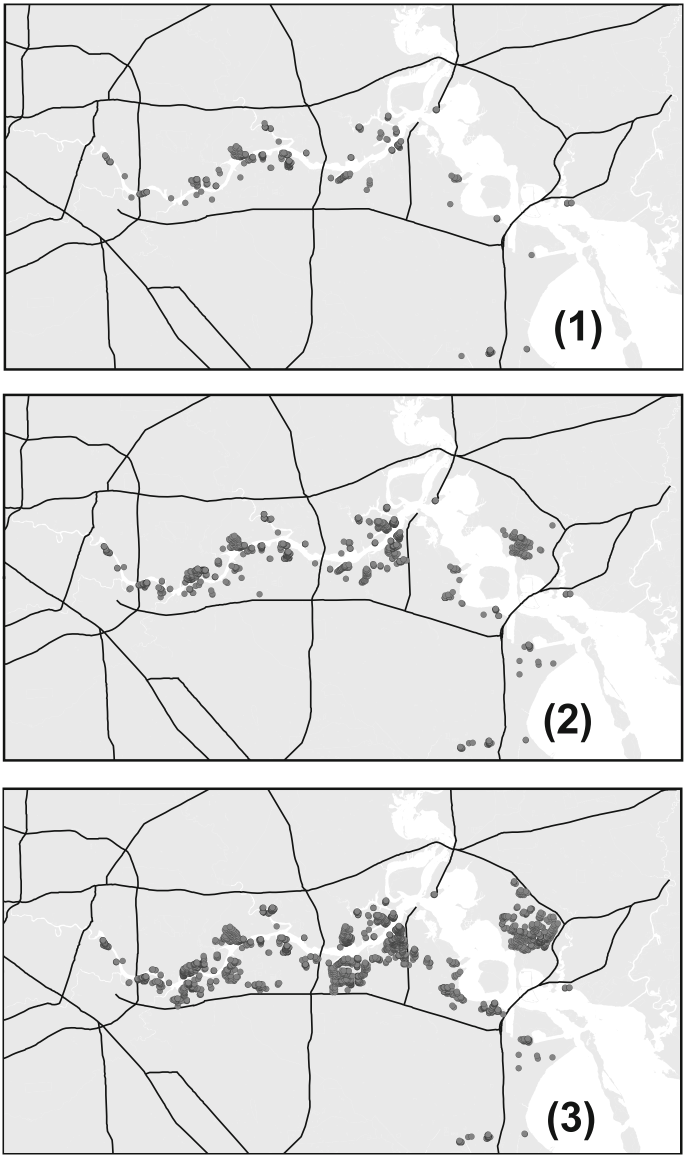


Fig. 7 Inundated tanks for the modeled scenarios. The dots represent tanks that would be inundated based on their elevation and storm surge level—Hurricane Ike (*panel 1*), Hurricane Ike at point 7 (*panel 2*), and Hurricane Ike at point 7 with 30 % increase in wind speed (*panel 3*)

4 Discussion

The geospatial and environmental vulnerability framework developed in this paper resulted in relationships for storm surge levels and inundation of area outside the FEMA 100-year floodplain and tanks in the HSC-IC. Due to the limited number of storm surge levels used to determine these relationships, additional data points (i.e., storm surge events) would be

Table 2 Summary of geospatial and environmental vulnerability of facilities along the HSC-IC

		TRI facilities with history of release		RMP reporting facilities	
Hurricane scenarios	Number of tanks inundated	Greater than 40 % inundation	High geospatial and environmental vulnerability	Greater than 40 % inundation	High geospatial and environmental vulnerability
Hurricane Ike	579	36	–	47	–
Hurricane Ike at point 7	1464	88	2	57	12
Hurricane Ike at point 7 with 30 % increase in wind speed	3256	182	21	67	20

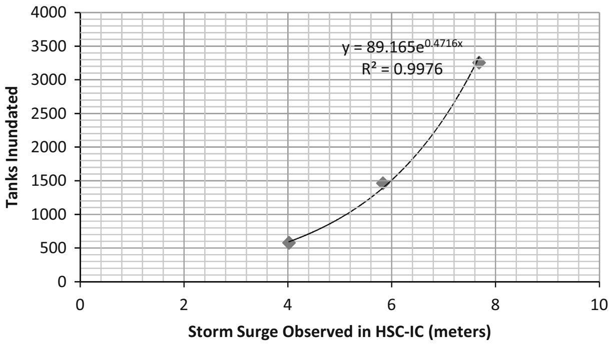
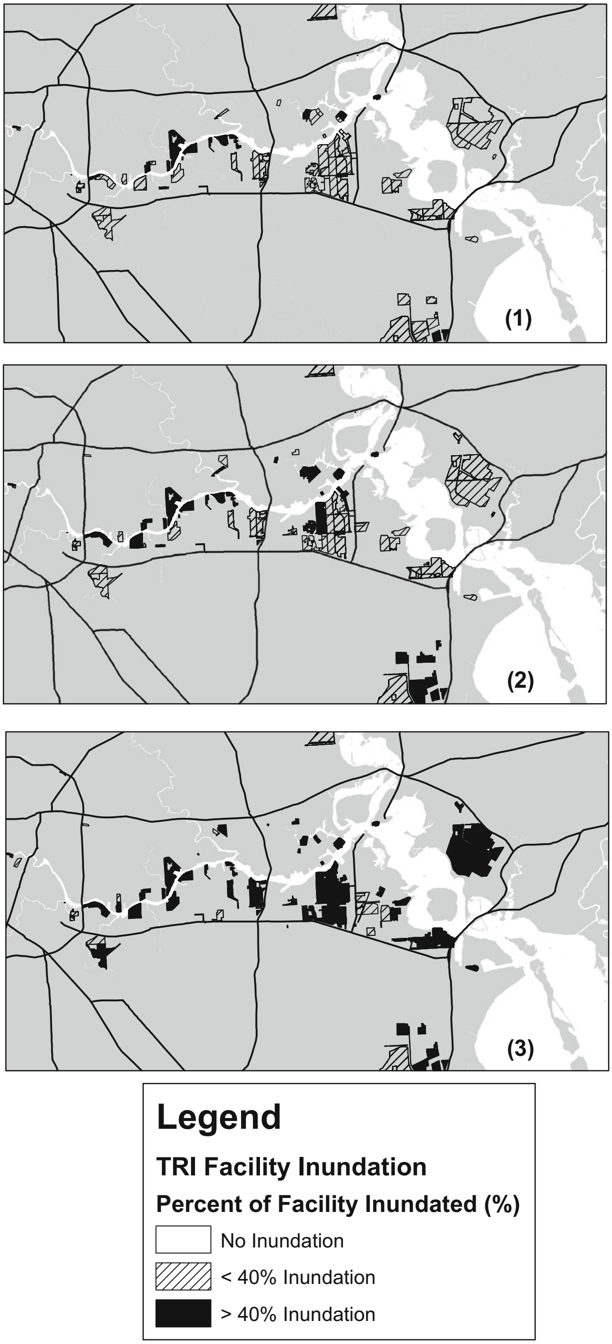


Fig. 8 Correlation between the number of inundated tanks and storm surge levels in the HSC-IC

required to get more reliable relationships. However, the purpose of this analysis was not to provide an exact relationship, but to illustrate the increasing impact for the region as predicted surge levels increase. It is important to note that the nonlinear nature of this relationship shows that impact from storm surge events on the HSC-IC will increase quickly as storm surge height projected for a given storm increases.

While the main purpose of the innovative framework presented in this work is to evaluate vulnerability from a geospatial and environmental perspective, the human vulnerability, evaluated extensively as it directly relates to hurricanes and flooding (Chakraborty et al. 2005), can be readily incorporated using the developed framework. For example, census block data for the US Census of 2010 for the region surrounding the HSC-IC were incorporated into the evaluation of the results.

There are 489,089 people within the study area based on the 2010 US Census. More than half of those in the study area (274,262 people) are in the census blocks inundated from Ike at point 7 with 30 % increase in winds. A detailed evaluation of census blocks directly affected by the facilities with high geospatial and environmental vulnerability shows that 18,461 persons would be potentially impacted (3.7 % of the population for the study area). These census blocks represent the potential indirect human impact from releases of hazardous material as a result of inundation of tanks within these facilities.



Studies have connected environmental risk and vulnerability to human health for industries (Topuz et al. 2011) and accidental spills (Bonvicini et al. 2015; Cutter et al. 2003; Sengul et al. 2012). However, natural hazards research has yet to incorporate this understanding to

◀**Fig. 9** TRI facilities with high environmental vulnerability historical releases and high geospatial vulnerability due to inundation. In *Panel 1*, outlined parcels have released over 1 billion pounds of chemicals into the water environment over the past decade (top 25 % among TRI facilities in the HSC-IC). Facilities filled-in in *black* represent TRI facilities that are the most vulnerable to releases to the environment due to storm surge for Hurricane Ike at point 7 (*panel 2*) and for Hurricane Ike at point 7 with 30 % increase in wind speed (*panel 3*)

the vulnerability of facility failures in an extreme storm surge event. While more detailed population data would be required to make appropriate conclusions about facility impact on the surrounding human life, these details emphasize the need for a vulnerability analysis that incorporates the industrial characteristics of a region as demonstrated in this study.

5 Conclusions and recommendations

This study demonstrated a conceptual model for evaluating the vulnerability of industrialized coastal regions to storm surge. The framework used hurricane scenarios modeled from SWAN + ADCIRC and cross-linked the results with geospatial information for facilities within the industrial region to identify geospatial and environmental vulnerabilities to storm surge. The implementation of the framework within the HSC-IC in Texas found a relationship between storm surge and the total area inundated at a given storm surge level and between storm surge and the total number of storage tanks affected at a given storm surge level. With additional storm surge events, this relationship can provide significant understanding in predicting the total area inundated in this region. As part of a potential economic analysis, a cost per inundated acre could be applied in order to predict or assess the total damage from inundation due to storm surge in the HSC-IC region. In addition, this relationship is consistent with previous work and shows that the 100-year FEMA floodplain may not be sufficient for considering significant storm surge impacts and consideration should be given to incorporating the vulnerability of areas that will experience economic and/or environmental losses at the storm surge level that is equivalent to the 100-year floodplain elevation.

The analysis done through this vulnerability framework demonstrated a methodology for evaluate environmental vulnerabilities for an industrial region and for specific facilities in the region by using releases from storage tanks, records of past historical releases, and risk management planning. By combining the results from the geospatial vulnerability analysis and the vulnerability analysis to environmental releases presented above, it is possible to categorize the facilities in the HSC-IC and rank them from most vulnerable to least vulnerable based on both storm surge and environmental releases. Additionally, and based on the findings presented above, it is noted that while there is variation in facility vulnerability between storm surge levels of approximately 4 and 7.7 m, this variation is almost nonexistent when storm surge exceeds 7 m. At storm surge levels of 7 and higher, almost every facility in the HSC-IC will experience significant economic and/or environmental losses. Plans for mitigation and protection whether at the individual facility level or regionally via berms and/or surge gates need to consider 7 m as a minimum level of protection for storm surge.

The limitation of this work lies in the availability of facility and tank data and understanding the failure risk associated with this infrastructure. The framework presented here does not account for failure modes or depth at the tank or facility level. A more detailed analysis of facility inundation and tank inundation is necessary to expand on this work and

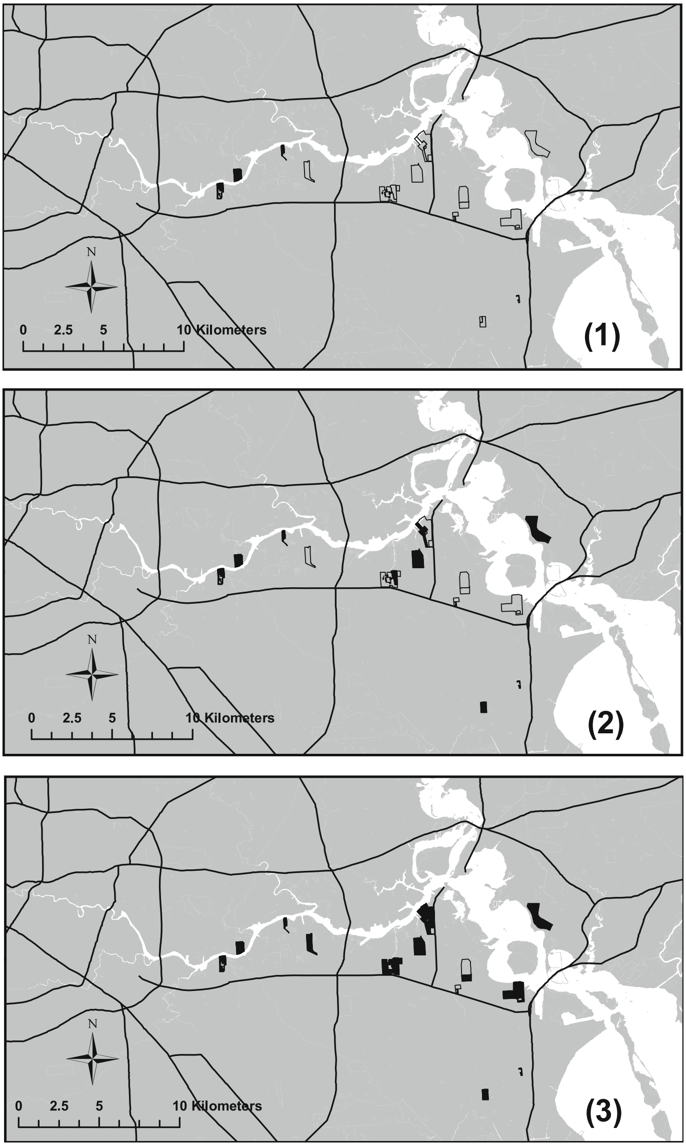


Fig. 10 RMP reporting facilities with relatively high environmental vulnerability due to stored toxic volumes and high geospatial vulnerability due to inundation. Facilities in solid black represent RMP reporting facilities that are the most vulnerable to releases to the environment due to storm surge for Hurricane Ike (*panel 1*), Hurricane Ike at point 7 (*panel 2*), and Hurricane Ike at point 7 with 30 % increase in wind speed (*panel 3*)

develop actual results of potential failures in an industrial region. In addition, this framework can be applied to present and future storm surge model predictions for the HSC-IC; however, additional scenarios should be analyzed to develop more reliable relationships for inundation and surge level. This unique framework is applied to three scenarios to demonstrate its usefulness and the potential worst-case scenario for the HSC-

IC based on Hurricane Ike. For future applications, it would be possible to associate the modeled storm surge levels from the various hurricane scenarios presented here with an "event risk" value based on ongoing FEMA studies that will categorize hurricanes using probabilities of occurrence. In this manner, the risk for facilities within an industrial region can be estimated based on their geospatial, environmental, and economic vulnerability and the event risk for each storm level.

The insights derived from the results of this analysis can be used to inform the general public about the potential impact of storm surge events on the HSC-IC and can be used to communicate to policymakers and facilities and port managers the need for mitigation strategies to protect this vital sector in the Houston–Galveston region. As mentioned previously, the framework uses surge level inputs that can be from hindcast or forecast models. Given real-time surge-level inputs, the developed framework can be used to identify regions of high environmental vulnerability, thereby informing emergency coordinators of regions that should be evacuated and that may require cleanup due to an environmental disaster. The information and results from the framework presented in this study provide a basis for assessing important economic factors related to impacts from storm surge that have yet to be fully addressed. This work addresses the limitations of current one-size-fit-all vulnerability approaches and brings to light the importance of having assessments that takes into account the unique and important aspects of a coastal region. Coastal communities are diverse along the Gulf Coast, and an appropriate understanding of the potential impact from severe storm surge events begins with including the infrastructure that would be most affected and that has a significant impact on the regional economy as this framework has done for the HSC-IC.

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