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Empirical Estimation of the Conditional Probability of Natech Events Within the United States

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Natural disasters are the cause of a sizeable number of hazmat releases, referred to as "natechs." An enhanced understanding of natech probability, allowing for predictions of natech occurrence, is an important step in determining how industry and government should mitigate natech risk. This study quantifies the conditional probabilities of natechs at TRI/RMP and SICS 1311 facilities given the occurrence of hurricanes, earthquakes, tornadoes, and floods. During hurricanes, a higher probability of releases was observed due to storm surge (7.3 releases per 100 TRI/RMP facilities exposed vs. 6.2 for SIC 1311) compared to category 1–2 hurricane winds (5.6 TRI, 2.6 SIC 1311). Logistic regression confirms the statistical significance of the greater propensity for releases at RMP/TRI facilities, and during some hurricanes, when controlling for hazard zone. The probability of natechs at TRI/RMP facilities during earthquakes increased from 0.1 releases per 100 facilities at MMI V to 21.4 at MMI IX. The probability of a natech at TRI/RMP facilities within 25 miles of a tornado was small ($\sim$0.025 per 100 facilities), reflecting the limited area directly affected by tornadoes. Areas inundated during flood events had a probability of 1.1 releases per 100 facilities but demonstrated widely varying natech occurrence during individual events, indicating that factors not quantified in this study such as flood depth and speed are important for predicting flood natechs. These results can inform natech risk analysis, aid government agencies responsible for planning response and remediation after natural disasters, and should be useful in raising awareness of natech risk within industry.

KEY WORDS: Hazardous material; natech; natural disaster

1. INTRODUCTION

Hazardous material releases caused by natural disasters, or natechs,[(1)] have been documented by many researchers in the United States and worldwide.[(2–6)] These studies have established that natech events can pose significant risks to regions that are unprepared for them. Natechs present special challenges compared to other hazardous material releases because multiple releases may be initiated simultaneously, resources otherwise available for hazmat response may be diverted, and conditions may restrict site access and interrupt lifeline resources.[(3,5)] All these factors may lead to slower hazmat response and increased risk to exposed populations. A first step toward addressing this risk through mitigation or emergency response planning is a robust understanding of the causes and resulting likelihood of natechs.

Those interested in the natech risk associated with individual facilities have employed detailed engineering analyses to determine the vulnerability of facility components and operations to natural

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hazards. For example, Gupta[7] describes the methodology used in site-specific risk evaluations available as a commercial service to industry. By their nature, such studies are highly dependent on site-specific data such as the facility's construction, hazmat inventory, and on-site mitigation measures. For planning purposes at scales greater than an individual facility, a more generalized approach is needed that can provide assessment of the likelihood of natechs over a broad area, e.g., a city, county, river valley, seismic zone, etc. Most work on regional natech risk has focused on releases with earthquakes or floods as triggers. Lindell and Perry[5] were unique in quantifying the probability of hazmat releases at industrial facilities after the 1994 Northridge earthquake. Seligson *et al.*[8] presented a methodology for assessing seismic natech risk from chemical facilities using damage curves. In addition, Salzano *et al.*,[9] Fabbrocino *et al.*,[10] and Campedel *et al.*[11] have assessed seismically induced natech hazards, particularly from storage tanks, based on data from a number of prior studies of seismic vulnerability of storage tanks.

Similar to earthquake-based natech risks, methodologies for analysis of flood-related natech risk based on facility and flood characteristics have also been proposed.[12,13] Considering the limited data available, Krausmann and Mushtaq[14] proposed to characterize the flood natech probability on a qualitative scale based on flooding characteristics. Others have employed less detailed, GIS-based methodologies to screen for natech risk over regions with multiple facilities. For example, Laner *et al.*[15] assessed the risk of releases from landfills during flood events based on proximity to delineated flood zones and assuming worst-case emissions. In order to assist planning efforts by local governments Cruz and Okada[16] presented a method of screening for natech risk based on simple assessments of industrial site component vulnerability and consequences of failure. Along similar lines, Galderisi *et al.*[17] proposed a method of assessing natech risk that utilizes natural hazard maps and information from existing industrial site safety reports. Both of these studies note that a major limitation is the scarcity of data for assessing the likelihood of natech releases at industrial facilities, particularly for natural hazards other than earthquakes.

This study addresses this lack of probabilistic estimates of natech occurrences by analyzing large national databases that document natechs in the United States. Empirical data obtained from across the United States for many different types of industrial facilities are pooled to investigate the effects of a variety of hazards during natural disaster scenarios. The ensuing analysis provides estimates of the conditional probability of natech occurrence for broad classes of industrial facilities based on petroleum and hazardous material releases observed during recent U.S. hurricanes, earthquakes, tornadoes, and floods. For risk analysis purposes these natech probabilities can be combined with information about the probability and severity of natural hazards in order to predict the number of natechs expected within a particular region over a given period of time or under conditions expected during a future natural disaster.

2. METHODOLOGY

In this article, the "conditional probability of natechs" refers to the probable number of natechs that will occur as a result of the realization of a natural disaster. The conditional probability is reported as the number of hazmat releases per facility exposed to a specified type and intensity of hazard condition during a natural disaster. For example, the study estimates the number of releases that will occur per 100 RMP or TRI facilities, given that these facilities are exposed to MMI VII ground-shaking (see the Results and Discussion section for these analyses). Analysis was performed for a selection of natural disasters in the United States: eight hurricanes, three earthquakes, 10 flood events, and all F2 and higher tornadoes from 1990 to 2006.

Hurricanes were selected to include a range of various measures of intensity (size, wind speed, height, and extent of storm surge) and to include the four hurricanes during the period of interest with the largest monetary losses. The eight hurricanes considered make up 20% of the total population of 39 U.S. hurricanes that made landfall from 1990 to 2008 and account for 76% of the onshore hurricane natechs. All three recent U.S. earthquakes of large magnitude, occurring in a populated area, were analyzed (Loma Prieta, North Ridge, Nisqually). Flood events were selected based primarily on the availability of analysis delineating flood extent. All tornados F2 and higher were analyzed. F0–1 tornadoes were not analyzed because while very numerous (89% of all tornadoes) they are responsible for only about 25% of tornado-related releases, suggesting that their natech risk is quite low. These selection criteria result in an emphasis on large and damaging natural disasters, and those of most interest from the perspective of natech risk assessment.

For each individual natural disaster analyzed, analysis began with the delineation of the area impacted by the disaster using GIS tools. The impacted area was divided into one or more hazard zones based on the type and intensity of hazard conditions experienced (for example, storm surge inundation for hurricanes or MMI XI shake intensity for earthquakes). Next, the population of industrial facilities within each hazard zone was determined. The number of releases within each zone, aggregated by the type of facility from which the releases emanated, was then tabulated. Data describing releases were obtained primarily from the National Response Center (NRC) Incident Reporting Information System (IRIS). Results for each type of disaster and hazard zone were then pooled to estimate the conditional probability of a natech release under those natural hazard conditions. Details of the methodology and data sources for each step are described below.

2.1. Delineation of Hazard Zones

For hurricanes, one hazard zone was defined as the storm surge inundation zone; three others were defined based on maximum sustained wind speeds that corresponded to tropical storms, category 1–2 hurricanes, and category 3 hurricanes on the Saffir Simpson Scale. Storm surge inundation during Hurricane Ike was obtained from the Lake Charles National Weather Service Forecast Office.[18] The extent of storm surge zones for Hurricanes Katrina, Rita, and Ivan was obtained from the Federal Emergency Management Agency.[19] Inundation extent for Hurricane Isabel and Hurricane Gustav was defined based on data from simulations run using the ADCIRC model.[20,21] Hurricane Claudette inundation was approximated by the authors based on storm surge height data[22] and coastal topography. Storm surge for Hurricane Andrew in Florida was obtained from NOAA[23] and in Louisiana based on simulations by Westerink *et al.*[24] In addition, for a subset of three hurricanes, the storm surge zone was subdivided into four zones based on depth (0.0–0.5 m, 0.5–1.5 m, 1.5–3.0 m, and >3.0 m). The flood depth for Hurricane Ike was obtained from the same source as inundation extent,[18] while flood depths for Hurricanes Ivan and Andrew were calculated from the data used to define inundation extent and a digital elevation model. Only three events were analyzed in this way due to the additional time involved in producing the flood depth estimates. Data obtained as image files were geo-referenced and converted to shapefile zones for analysis. Surface wind speed estimates were obtained from the NOAA Atlantic Ocean and Meteorological Laboratory in the form of H∗Wind wind fields as described by Powell *et al.*[25] Maximum wind swaths or hourly data were downloaded[26] and used to define the three wind zones. In those areas where storm surge and wind zones overlapped, storm surge was given precedence as the majority of releases in these areas appeared to be consistent with storm surge effects.

For earthquakes, five hazard zones were defined by Modified Mercalli Index (MMI) values from V to IX. MMI zones were based on Shakemaps obtained from the U.S. Geologic Survey (USGS) Earthquake Center.[27] These data provide instrumental estimates of shake intensity based on a combination of peak ground acceleration (pga) and velocity (pgv). Zones of lesser shake intensity were not analyzed because their full geographic extent was not delineated by the USGS data.

The hazard zone for tornadoes was defined as a 25-mile radius surrounding the track of all tornadoes equal or greater than class 2 on the Fujita Scale, in each year. While tornado paths are typically a fraction of a mile in width, this choice follows the methodology of NOAA as presented in its Severe Storm Laboratory tornado risk estimates. These estimates are in the form of maps that color-code the United States according to the expected number of days in a century with a tornado present within a 25-mile radius.[28] Tracks of tornadoes between 1990 and 2006 were obtained from the National Weather Service in a GIS format.[29]

For floods, the hazard zone was defined as the extent of flood inundation and was based on satellite estimates. Image files of maximum flood extent during eight floods between 2001 and 2008 were downloaded from the Dartmouth Flood Observatory website.[30] Images of flood extent were obtained for the 1993 Midwest flood from the U.S. Army Corps of Engineers (USACE) 1993 flood home page[31] and for 2007 flooding in Coffeyville KS based on estimates by the Kansas Biological Survey.[32] These image files were geo-referenced based on nearby rivers and converted to shapefile zones for analysis. Flooded areas defined by this method and satellite flood extent data obtained directly in GIS format for March 2008 in Indiana (personal communication, Jie Shan of Purdue University) and 1993 in Missouri[33] were in good agreement.

2.2. Identification of the Population of Facilities Exposed

Two broad classes of industrial facilities were considered in this analysis. One class contained those regulated under two Environmental Protection Agency (EPA) programs: the Toxic Release Inventory Program (TRI) (http://www.epa.gov/tri/), which includes manufacturing facilities, petroleum bulk storage terminals, power generation plants, and federal facilities, and the Risk Management Program (RMP) (http://data.rtknet.org/rmp), which regulates facilities handling large quantities of highly hazardous material. The second class was onshore facilities involved in oil and gas extraction designated by Standard Industrial Code (SIC) 1311 and identified from the EPA's Facility Registry System (FRS) (http://www.epa.gov/enviro/html/facility.html). While in many areas, TRI/RMP facilities far outnumber SIC 1311 facilities, in some parts of the country, notably the Gulf Coast region, SIC 1311 facilities are common and may result in many releases, as was notably the case during Hurricane Katrina. Determining the natech probability for these widely recognized classes of facilities allows for a straightforward use of results in future risk analysis. As some facilities report to both the TRI and RMP programs, RMP facilities were excluded from the set of TRI facilities based on location (latitude, longitude) before analysis. The location of facilities, based on latitude and longitude contained within the respective databases, was overlain on the hazard zones using GIS and the number of TRI/RMP and SIC 1311 facilities in each hazard zone tabulated.

2.3 Determination of Natech Occurrence

Data on natech occurrence were derived primarily from the IRIS database, which has previously been used to investigate the occurrence of natechs.[34] The NRC is the designated federal point of contact for reporting of chemical releases above reportable quantities (RQs), and for all oil spills potentially affecting water bodies. Other databases such at the Center for Disease Controls, Hazardous Substances Emergency Events Surveillance System (HSEES) have been demonstrated to record releases not captured by passive databases like the IRIS.[35] However, the IRIS database is better suited to the purposes of this study in that it covers the entire United States, has maintained fairly uniform data specifications over the past two decades, and records releases of both hazardous chemicals and petroleum. For events in the years from 1990 to 1999, reports of releases were also obtained from the EPA Emergency Response Notification System (ERNS), which largely duplicates IRIS but also contains a small number of unique events.

These records were filtered to identify natechs, based on the "incident cause" field and on keywords in the event descriptions (e.g. storm, rain, earthquake, flood, hurricane). Out of over 550,000 releases, 16,600 natechs were identified. Given limitations of the IRIS database, actual natech occurrence may be greater; in particular, smaller releases are likely to be underreported. However, given that RQs are set based on levels that might be expected to require an emergency response, this was not considered a major limitation. To supplement the IRIS record, natechs during earthquakes were also identified from releases recorded during the Loma Prieta earthquake (1989) by the Association of Bay Area Governments,[36] the Northridge Earthquake by the Los Angeles County Fire Department,[37] and the Nisqually Earthquake by McDonough,[38] each of which provided much additional data about smaller releases.

In all cases, the start and end dates of the event under analysis were first determined from written accounts. This period might vary from a single day for a tornado to several months for a long-lasting flood. All natechs that occurred in affected states from one week prior to two weeks after the event were then identified. This window served to capture releases due to shutdown in anticipation of, or which were not reported until some time after, the event. In addition, in the case of hurricanes, a search of the natech record for the hurricane name captured releases reported, sometimes years, after the event. These natechs were manually reviewed based on date and time, geographic location, and cause to identify those events caused by the natural disaster in question. From these releases, those occurring at RMP/TRI or SIC 1311 facilities were selected by a manual review of facility type, responsible party, event description, and material released. Approximately half of all releases during each natural disaster fell into these two categories. Other releases not considered in this analysis originated from offshore platforms, vessels, mobile sources, residences, and numerous small oil releases due to downed transformers in residential areas. Records selected for analysis were located by longitude and latitude by geocoding the address provided in the database. Some locations with

Table I. Definition of Spill Size Classifications

Release Scale	Petroleum (gal)	Chemical (lb or gal)	Natural Gas (cf)	Bulk Materials (lb or gal)	Aqueous Waste (gal)
Large					
5	100,001+	100,001+	100,000,001+		
4	10,001–100,000	10,001–100,000	1,000,000–1,000,000,000	1,000,000+	1,000,000+
3	1,001–10,000	1,001–10,000	10,001–1,000,000	10,001–1,000,000	10,001–1,000,000
Small					
2	101–1,000	101–1,000	1,001–10,000	1,001–10,000	1,001–10,000
1	0–100	0–100	0–1,000	0–1,000	0–1,000

incomplete addresses but other descriptive information such as company name were researched to obtain a complete address. For the small number of records for which no address could be obtained, the center of the relevant city was used and in the very small number of cases where city or town was not reported, the data point was excluded from the analysis.

In order to allow for simplified accounting of the size of releases, each was ranked on a scale from 1 to 5. The scale used for classification is shown in Table I. This classification was primarily intended to allow large (size 3+) and small (size 1 and 2) releases to be easily distinguished during analysis and interpretation of results. It also provides a qualitative indication of the potential magnitude of cleanup or environmental impact. Classification is not intended to rate the hazardousness of the release since much additional data, for example, toxicity, mode of release, and environmental conditions, would be needed for even a broad assessment. Natech events that did not include information about the size of the release were classified as consisting of unknown size.

2.4. Calculation of the Natech Conditional Probability

The results from analysis of individual natural disaster events were pooled to yield the total number of facilities and releases for each hazard zone. This pooled data set was then used to estimate the conditional probability of a natech occurring under the conditions associated with the given hazard zone. Logistic regression analysis, for testing of relationships within the data, was performed using SPSS. The conditional probability of a natech from TRI/RMP facilities was estimated for all natural disasters. The small number of SICS 1311 facilities exposed to earthquakes and floods did not result in a sufficient number of releases for the calculation of the probability of natechs for SICS 1311 facilities.

The results represent the probable number of natechs per facility exposed, given specific natural hazard conditions. This is not exactly equivalent to the probability that a facility will experience a natech under the same conditions, as individual facilities sometimes reported multiple releases during the events analyzed. The percentage of reports that were multiple releases from a single facility is approximately 1% for tornadoes and floods and 5% for hurricanes and earthquakes. Given that multiple reports from a single facility are not very common, the probabilities of natechs per facility exposed presented within this study are expected to be only slightly greater than the probability of an individual facility experiencing a natech under the same conditions.

3. RESULTS AND DISCUSSION

In this section, results showing the computed conditional probability of natechs from hurricanes, earthquakes, tornadoes, and floods are presented. To illustrate and clarify the procedures followed, the discussion of each hazard includes an example showing how the relevant data for computing the conditional probability were extracted from an individual natech event.

3.1. Conditional Probability of Natechs from Hurricanes

Fig. 1 shows the number of all onshore releases from fixed facilities or storage tanks during each hurricane that made landfall between 1990 and 2008. The hurricane bars are color-coded to indicate the number of releases in each class size for each hurricane. Eight hurricanes from this group were selected for analysis and are indicated with arrows in Fig. 1. The eight hurricanes chosen for analysis make up

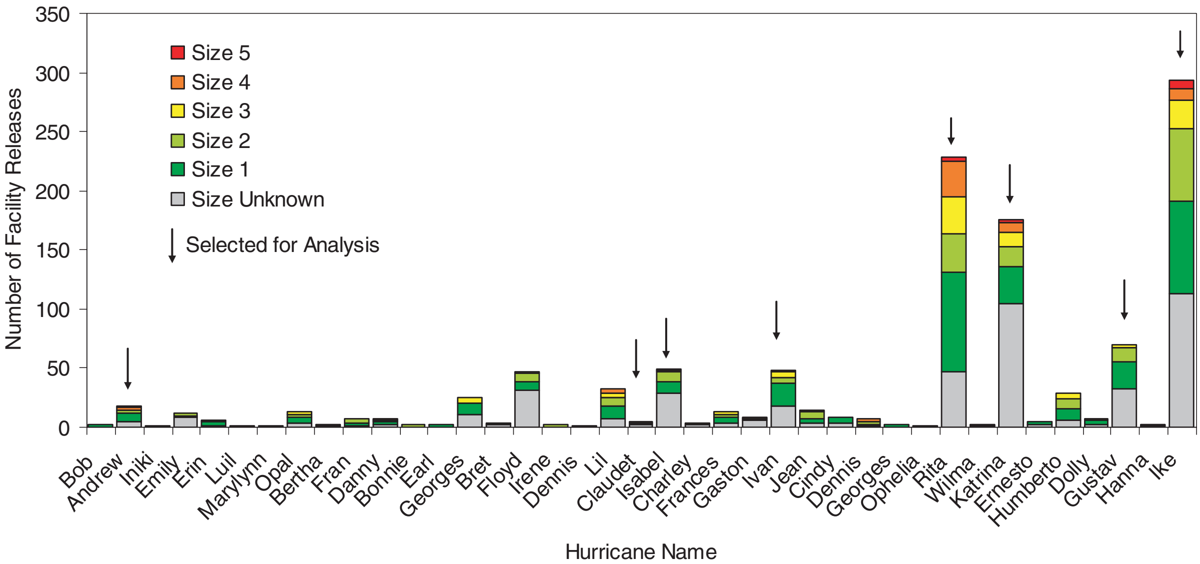

Fig. 1. Number and size of releases from industrial facilities during recent hurricanes.

79% of all hurricane-related releases from onshore industrial facilities in this period and encompass a variety of hurricane sizes, strengths, and geographic areas of landfall.

An example of the analysis performed for hurricanes is given in Fig. 2 showing Hurricane Ike. Hazard zones for tropical storm and category 1–2 winds and storm surge are illustrated, along with the two classes of facilities and releases (SIC 1311 facilities/releases and TRI/RMP facilities/releases). Most hurricanes analyzed demonstrated similar clustering of releases in areas with a high density of industry and within the storm surge zone. A number of releases also fall outside of the storm surge and wind zones analyzed. In the case of Ike, there were 15 such releases from TRI/RMP and SIC 1311 facilities, some as far away as Illinois. Such releases were generally due to power outages and flooding or overflows resulting from wind damage or heavy rains.

Results of the analysis of the eight selected hurricanes are summarized in Table II. Tabulated is the number of TRI/RMP and SIC 1311 facilities and associated releases in each hazard zone and the number of releases per 100 facilities exposed. Exposure to storm surge generally results in higher releases per facility exposed compared with exposure to tropical storm or category 1 and 2 hurricane winds. Releases per facility exposed are often, but not always, higher for RMP/TRI facilities compared to SIC 1311 facilities; this is particularly noticeable in tropical storm and hurricane wind zones. Only Hurricane Andrew exposed a measurable number of facilities to category 3 hurricane winds; in that instance a much higher frequency of releases and greater fraction of large releases was experienced than at lower wind speeds.

Logistic regression of presence of releases on the independent variables wind hazard zone and facility type provides a model that is a good fit to the data (Hosmer and Lemeshow test with significance > 0.95). The odds ratios for facility types and hazard zones are summarized in Table III. A greater propensity for releases to occur at RMP/TRI facilities is confirmed and the probability of a natech increases at higher wind speeds. The higher probability of releases at TRI/RMP facilities may represent greater complexity and physical vulnerability compared to SIC 1311 facilities. Adding the hurricane name as an ordinal variable to the logistic regression confirms that which hurricane a facility was exposed to, even controlling for facility type and hazard zone, is a significant determinant of natech occurrence (significance level of Wald statistics for the hurricane name variables < 0.05).

The increase in the probability of natechs with increased wind speed suggests that these data can be interpreted as an empirically derived system fragility curve. This is illustrated in Fig. 3 showing the number of releases per 100 TRI/RMP facilities exposed to varying wind speeds. Wind speed values shown in

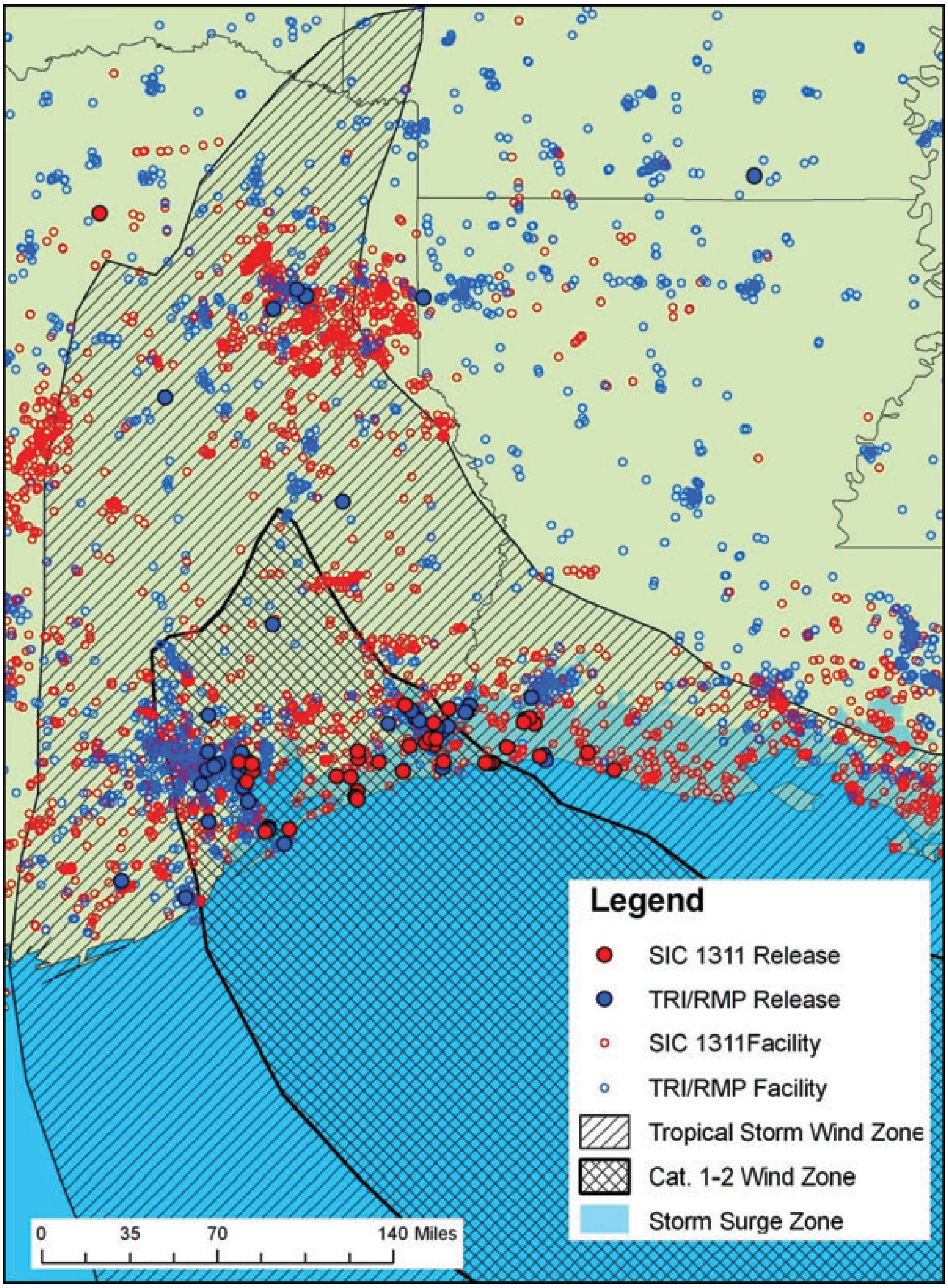

Fig. 2. Analysis of releases from Hurricane Ike.

Fig. 3 are approximations based on the center points of the ranges observed in the hazard zones analyzed (tropical storm wind speeds: 39–74 mph; category 1–2 wind speeds: 74–110 mph; and category 3 wind speeds 110–130 mph). With increased wind speed, the probability of a release increases in a nonlinear fashion. This is typical of fragility curves (for example, the damage state probability curves used for loss estimation within the Federal Emergency Management Agencies HAZUS software).[39] The ranges shown in Fig. 3 represent the maximum and minimum of values observed during the eight events, as summarized in Table II. As only a single event with category 3 wind speed was analyzed, a range could

Table II. Summary of Hurricane Analysis for TRI/RMP and SIC 1311 Facilities

	TRI/RMP					SIC1311				
Hurricane	Facilities	Releases (Small, Large, Unknown)			Releases per 100 Facilities	Facilities	Releases (Small, Large, Unknown)			Releases per 100 Facilities
Tropical storm winds										
Andrew	1,202	2	2	4	0.7	390	2	0	1	0.8
Claudette	525	3	0	2	1.0	610	0	0	0	0.0
Gustav	817	13	2	15	3.7	612	1	0	1	0.3
Ike	740	5	0	2	0.9	1,202	3	3	3	0.7
Isabell	999	5	3	2	1.0	0	0	0	0	0.0
Ivan	451	6	0	2	1.8	107	2	2	0	3.7
Katrina	1,047	6	2	4	1.1	457	2	3	1	1.3
Rita	748	37	9	10	7.5	573	5	2	5	2.1
Pooled data	6,529	77	18	41	2.1	3,951	15	10	11	0.9
Hurricane winds (cat 1–2)										
Andrew	337	1	1	3	1.5	181	1	0	1	1.1
Claudette	0	0	0	0	0.0	0	0	0	0	0.0
Gustav	63	0	0	0	0.0	160	1	0	0	0.6
Ike	903	63	10	13	9.5	333	3	3	5	3.3
Isabell	33	2	0	0	6.1	0	0	0	0	0.0
Ivan	75	0	1	0	1.3	24	0	0	0	0.0
Katrina	284	0	0	2	0.7	60	3	0	3	10.0
Rita	21	0	0	0	0.0	6	0	0	0	0.0
Pooled data	1,716	66	12	18	5.6	764	8	3	9	2.6
Hurricane winds (cat 3)										
Andrew	22	1	1	2	18.2	7	0	0	0	0.0
Storm surge inundation										
Andrew	81	2	0	0	2.5	446	3	2	6	2.5
Claudette	97	0	0	0	0.0	40	0	0	0	0.0
Gustav	193	4	1	8	6.7	287	4	0	2	2.1
Ike	226	10	6	12	12.4	422	8	9	17	8.1
Isabel	171	4	0	4	4.7	0	0	0	0	0.0
Ivan	21	0	1	0	4.8	2	0	0	0	0.0
Katrina	170	3	3	11	10.0	158	9	17	12	24.1
Rita	147	5	4	1	6.8	521	11	6	11	5.4
Pooled data	1,081	28	15	36	7.3	1,865	35	34	48	6.3

Table III. Odds Ratios for Logistic Regression of Hurricane Natechs

Variable	Odds Ratio	95% Confidence Interval	Significance
Facility			
SIC 1311	1.00	–	–
TRI/RMP	2.32	1.72–3.10	<0.001
Hazard zone			
Tropical storm winds	1.00	–	–
Hurricane winds (cat 1–2)	2.88	2.18–3.52	<0.001
Hurricane winds (cat 3)	8.7	2.97–25.41	<0.001

not be estimated and the reported probability can only be considered a preliminary estimate pending the availability of additional data. This study is only able to estimate the natech probability over the lower end of possible hurricane wind speeds because no substantial category 4 or higher wind speeds were observed onshore during the period considered.

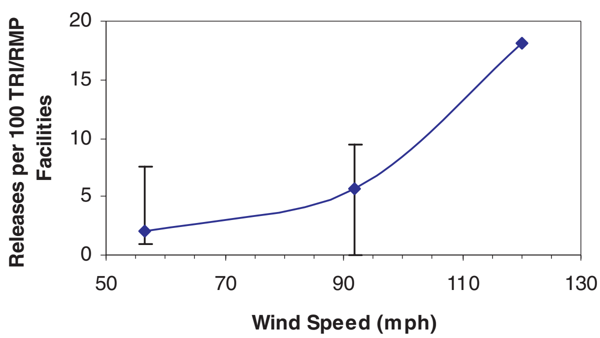

Fig. 3. Fragility curve describing the probability of natechs from TRI/RMP facilities due to hurricane winds.

Table IV. Analysis of Hurricane Storm Surge with Depth

	TRI/RMP					SIC1311				
Hurricane	Facilities	Releases (Small, Large, Unknown)			Releases per 100 Facilities	Facilities	Releases (Small, Large, Unknown)			Releases per 100 Facilities
0–0.5 m depth										
Andrew	4	0	0	0	0.0	16	1	0	0	6.3
Ivan	3	0	0	0	0.0	0	0	0	0	0.0
Ike	6	0	0	0	0.0	23	0	0	0	0.0
Pooled data	13	0	0	0	0.0	39	1	0	0	2.6
0.5–1.5 m depth										
Andrew	29	0	0	0	0.0	139	2	2	0	2.9
Ivan	4	0	1	0	25.0	1	0	0	0	0.0
Ike	60	3	2	3	13.3	93	2	1	1	4.3
Pooled data	93	3	3	3	9.7	233	4	3	1	3.4
1.5–3.0 m depth										
Andrew	32	1	0	0	3.1	230	0	0	5	2.2
Ivan	14	0	0	0	0.0	1	0	0	0	0.0
Ike	123	2	4	7	10.6	250	8	5	5	7.2
Pooled data	169	3	4	7	8.3	481	8	5	10	4.8
>3.0 m depth										
Ike	12	3	0	2	41.7	45	3	4	4	24.4
Pooled data all zones	287	9	7	12	9.8	798	16	12	15	5.4

As illustrated by the range of observed probabilities in Table II and Fig. 3, large variation exists from event to event in the number of releases per 100 facilities exposed within wind hazard zones. This variation may be related to releases that do not result from direct damage. Particularly in the tropical storm zone, many releases are due to indirect effects such as power loss or precautionary shutdown of facilities prior to hurricane landfall. Although shutdowns are a safety measure intended to prevent major accidents and allow for evacuation of workers, flaring or other releases often occur during shutdown or subsequent restart of the facility. By far the greatest number of releases per TRI/RMP facilities in the tropical storm wind zone was during Hurricane Rita and the majority of these occurred as a result of shutdown and startup. This may reflect extra precautions taken after the experiences of Hurricane Katrina that had the unintended consequence of increasing the total number of releases in moderately affected areas.

Within the storm surge hazard zone, a large variation in natech probability is also observed, as seen in Table II. This variation may reflect differences in the severity of storm surge effects (e.g., surge height, wave effects) between events. Large numbers of releases per facility exposed occurred during Hurricanes Ike and Katrina while fewer releases per facility exposed occurred during Hurricane Andrew. Greater storm surge height during Hurricanes Ike and Katrina is a probable explanation for this difference. For example, Katrina resulted in a storm surge of 12 to 19 ft in Louisiana[40] compared to maximums of 8 ft in Louisiana from Hurricane Andrew.[41]

In order to explore the theory that differences in storm surge height explain the different number of natechs observed, storm surge zones for Hurricanes Andrew, Ike, and Ivan were subdivided by depth and reanalyzed. Results are summarized in Table IV. No releases were recorded in the shallowest storm surge zone of 0.0–0.5 m depth and storm surge depth greater than 3 m was only observed during Hurricane Ike. Similar numbers of releases per facility exposed are observed at the two intermediate storm surge depths and a much higher number at depths >3 m. The greater numbers of releases per facility during Hurricane Ike compared to Hurricane Andrew, as seen in Table II, appear to be partially explained by greater storm surge. However, even in zones with the same storm surge depth, the number of releases per facility exposed was generally larger for Hurricane Ike than for Hurricane Andrew. This is presumably the result of other conditions that differed during Hurricane Ike and Hurricane Andrew such as wave effects or the design of facilities in the affected areas.

Table V. Odds Ratios for Logistic Regression of Storm Surge Natechs

Variable	Odds Ratio	95% Confidence Interval	Significance
Facility			
SIC 1311	1.00	–	–
TRI/RMP	2.07	1.24–3.46	< 0.01
Hazard zone			
0–0.5 m depth	1.00	–	–
0.5–1.5 m depth	2.74	0.36–21.08	0.33
1.5–3.0 m depth	3.06	0.41–22.79	0.28
>3.0 m depth	21.22	2.69–167.66	< 0.01

Logistic regression can be applied to the data in Table IV to provide an estimate of the effect that storm surge depth has on natech occurrence. Regression of presence of releases on categorical grouping of storm surge depth and facility type provides a model that is a very good fit to the data (Hosmer and Lemeshow Test of fit with significance > 0.95). The resulting odds ratios are given in Table V. A greater propensity to releases at RMP/TRI facilities is observed. The increase in natech probability relative to that observed during a 0–0.5 m depth storm surge can not be demonstrated within a 95% confidence interval for storm surge depth up to 3 m, but a significant increase is observed at depth >3 m. This finding may reflect a threshold in the storm surge depth at which the natech probability increases sharply or the limitations of a relatively small data set.

3.2. Conditional Probability of Natechs from Earthquakes

Three major earthquakes were analyzed in this study: Northridge (CA 1994), Loma Prieta (CA 1989), and Nisqually (WA 2001). Approximately 60% of all releases, and 99% of large releases, due to earthquakes, reported to the NRC, are attributable to these three earthquakes. Other seismic natechs reported in the United States were generally the result of less severe earthquakes, although still greater than magnitude 5.0. Events of this size were not analyzed. The low levels of ground shaking experienced during these events resulted in only one or two reported releases from industrial facilities during each event.

The analysis methodology for earthquakes is illustrated in Fig. 4 for the Northridge Earthquake.

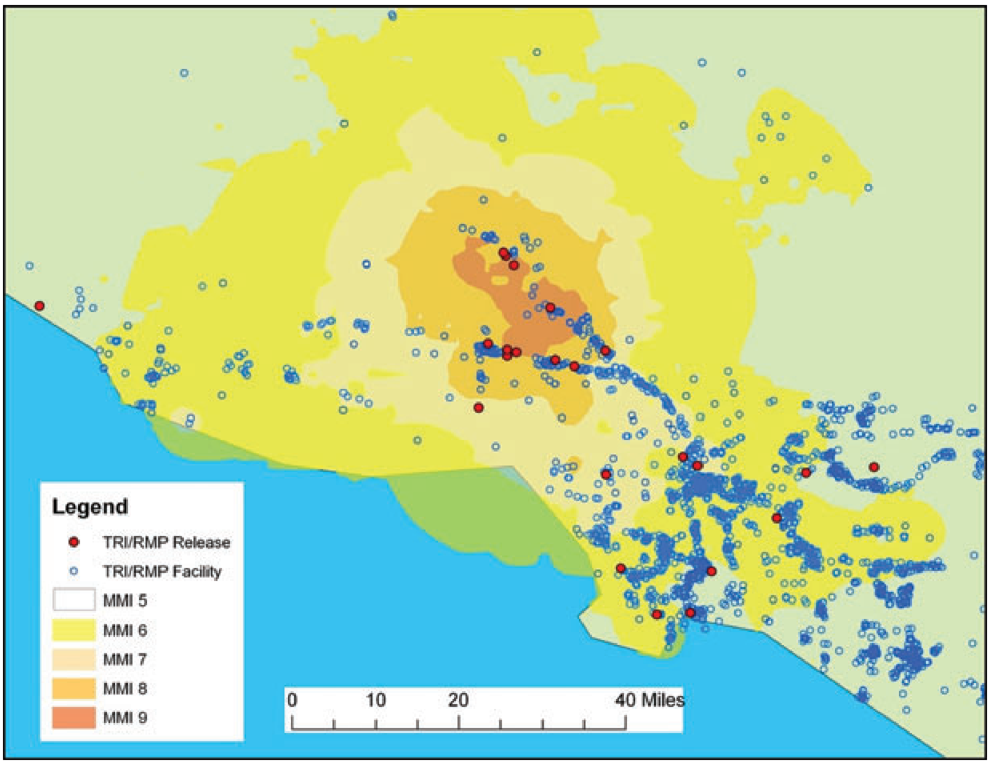

Fig. 4. Analysis of releases from the Northridge Earthquake.

Table VI. Summary of Earthquake Analysis for TRI/RMP Facilities

Earthquake	Facilities	Releases (Small, Large, Unknown)			Releases per 100 Facilities
MMI V					
Loma Pietra	178	0	0	0	0.0
Northridge	1029	1	0	1	0.2
Nisqually	179	0	0	0	0.0
Pooled data	1386	1	0	1	0.1
MMI VI					
Loma Pietra	407	4	2	0	1.5
Northridge	992	3	0	1	0.4
Nisqually	175	0	0	1	0.6
Pooled data	1574	7	2	2	0.7
MMI VII					
Loma Pietra	392	14	3	9	6.6
Northridge	257	0	0	3	1.2
Nisqually	146	2	0	2	2.7
Pooled data	795	16	3	14	4.2
MMI VIII					
Loma Pietra	202	9	2	9	9.9
Northridge	152	17	0	9	17.1
Pooled data	354	26	2	18	13.0
MMI IX					
Northridge	28	4	1	1	21.4

Shown are hazard zones from MMI V to IX along with TRI/RMP facilities and corresponding releases. During all three earthquakes, many releases clustered in areas with a high concentration of industrial facilities, such as Los Angeles in this example. Higher MMI values were also associated with a higher number of releases.

The results of the analysis of earthquakes are summarized in Table VI. Similar numbers of releases per 100 facilities exposed are observed for each MMI zone during all earthquakes. This is particularly true in the case of large releases. The highest shake intensities (IX) were observed only during the Northridge Earthquake and resulted in a high number of releases per facility exposed. No releases were recorded from SIC 1311 facilities during these three earthquakes in part because SIC 1311 facilities totaled less than one-tenth of the TRI/RMP facilities in each hazard zone. As releases from SIC 1311 facilities are often of petroleum, with different reporting requirements, they may also be underreported compared to those from TRI/RMP facilities, which are more frequently of hazardous chemicals.

Logistic regression of natech occurrence at facilities against ordinal classification of shake intensity produces a model with very good fit to the data (Hosmer and Lemeshow Test with significance > 0.95). The odds ratios for the probability of releases in the different hazard zones are summarized in Table VII. The statistically significant difference in natech probability between zones supports the use of these data to create a fragility curve. Unlike the case for hurricanes, logistic regression including earthquake event name as a nominal variable indicates that the earthquake involved is not a significant factor in natech occurrence (significance of Wald statistics for earthquake names >0.05).

Table VII. Odds Ratios for Logistic Regression of Earthquake Natechs

Hazard Zone	Odds Ratio	95% Confidence Interval	Significance
MMI V	1.00	–	–
MMI VI	4.87	1.08–22.01	0.04
MMI VII	29.89	7.15–124.90	<0.01
MMI VIII	103.35	24.95–428.04	<0.01
MMI IX	188.73	36.07–987.43	<0.01

As seismic fragility curves are often expressed in terms of pga, each MMI zone was translated into pga value based on the scale used in creation of the Shakemaps.[42] MMI zones V–VIII were assigned the mean value of their corresponding pga ranges, which were 3.2–9.2 for MMI V, 9.2–18 for MMI VI, and

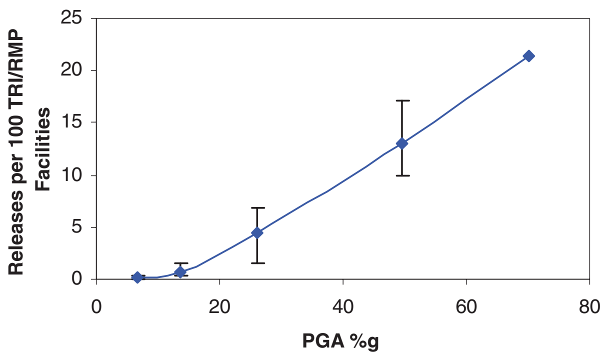

Fig. 5. Fragility curve describing the probability of natechs from TRI/RMP facilities due to peak ground acceleration.

34–65 for MMI VIII. The full range of pga values corresponding to intensity IX (pga 65–124) did not occur during the single earthquake (Northridge) that reached that intensity. Therefore, this zone was assigned a pga of 70 corresponding to the actual average pga experienced in the zone of analysis during the earthquake. This approximate conversion of MMI values to pga may result in the creation of additional, and unquantified, uncertainty in the pga values on the x axis of the fragility curve because of the empirical nature of the scale used by Wald *et al.*,[42] its dependence on both pga and pgv to determine MMI, and the simplification of translating a range to a point value.

Releases per 100 TRI/RMP facilities exposed are shown in Fig. 5. Bars represent the range of values observed across all three of the events analyzed as summarized in Table VI. It can be observed that the probability is relatively well known. A range is not presented for IX intensity because only a single event was analyzed. As with hurricane winds, natechs per 100 facilities exposed increase in a nonlinear fashion. Similar behavior is observed in fragility curves of risk of containment loss from atmospheric pressure tanks presented by Salzano *et al.*[9] The natech probability could not be estimated for earthquakes with pga values higher than those that occurred during the three earthquakes analyzed.

Particularly in the case of earthquake natechs, there is a possibility for changes in natech probability over time due to increased efforts at risk mitigation. The two severe earthquakes analyzed, Northridge and Loma Prieta, occurred over a dozen years ago and were the impetus for programs in California to decrease seismic risk for hazmat facilities. As a result, the probability of natechs during future earthquakes in California may be less than observed during these events.

3.3. Conditional Probability of Natechs from Tornadoes

Due to the small area affected by each tornado, releases are relatively rare. They average only 15 reports per year with a much smaller number from TRI/RMP and SIC 1311 facilities. Over half of facility releases (55%) are attributed to F2 or higher tornadoes. Of the remainder, approximately half are associated with tornadoes of magnitude F0 to 1 while the rest of the releases are not located near any known tornado and may result from strong winds misidentified by the reporter.

Fig. 6 provides an example of the analysis of tornado-related releases. It shows tornado tracks with intensity 2–5 on the Fujita Scale during 2006, the 25-mile buffer of these tracks, and all tornado-related releases reported in 2006. Although shown, the tracks of F0-1 tornadoes and associated releases were not included in the analysis. The locations of RMP, TRI, and SIC 131 facilities are not shown due to the large geographic domain of the figure. The spatial distributions of tornadoes and releases were similar to Fig. 6 for all years analyzed. Releases from SIC 1311 facilities were less common than from TRI/RMP facilities due in part to the smaller number of SIC 1311 facilities (about a third that of TRI/RMP facilities).

Results of analysis of F2–5 tornadoes from 1990 through 2006 are summarized in Table VIII. Releases per facility exposed are very low with a value of 0.025 releases per 100 TRI/RMP facilities and 0.009 releases per 100 SIC 1311 facilities exposed, when pooling all years. Release rates are low because of the large areas considered in calculating the number of facilities exposed compared to the very small area actually affected by tornadoes. Approximately 21% of the releases were large in size. The lower number of SIC 1311 natechs may be due in part to lesser vulnerability of SIC 1311 facilities. Almost all tornado-related SIC 1311 releases are from direct physical damage to the facility while about 13% of TRI/RMP releases are due to power interruption or other disruption. In addition, releases from SIC 1311 facilities, often of petroleum, may be underreported compared to releases form TRI/RMP faculties. Although these probabilities are small, it should be remembered that if a tornado does strike a facility, a release is very likely. For example, looking at the

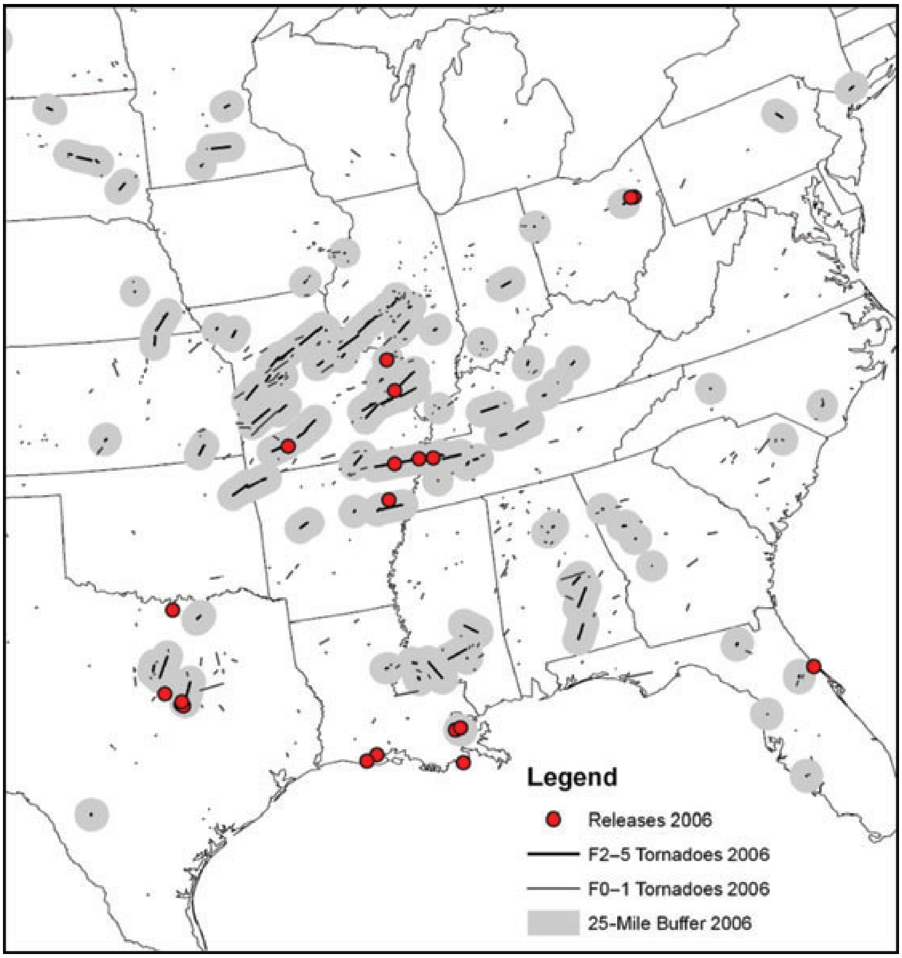

Fig. 6. Analysis of tornado natechs in 2006.

tracks of four randomly selected F4 tornadoes indicates that, of the six facilities in their direct path, five reported a release.

3.4. Conditional Probability of Natechs from Floods

The 10 flood events analyzed include a number of the most severe flooding events between 1990 and 2008. However, these events are a small fraction of the total number that occurred in this period. As a result, the releases associated with these events are only 10% of all flood-related natechs recorded in IRIS.

Analysis of a flood event is illustrated in Fig. 7 showing March 2008 flooding in the Midwest. In the case of this flood, 15 releases from facilities are recorded in IRIS but only six fall within the geographical domain of the satellite data used to define inundation. Of these six releases, only two occurred within the inundated zone. Events that fell outside the inundated zone were generally releases due to overflows from heavy rain rather than riverine flooding. Similarly, small numbers of releases were observed in all floods, and in many cases there were no releases recorded in the inundated zone analyzed, although releases were associated with the event in the database. The relatively low number of facilities and releases in the inundated areas may reflect in part broad awareness of flood threats in the United States and the effects of existing mitigation such as zoning laws. In many cases, high densities of facilities were observed along the course of rivers just *outside* of flooded areas, presumably having been deliberately constructed outside the flood plain.

A summary of the 10 flood events analyzed is shown in Table IX. These events are broken down

Table VIII. Summary of Tornado Analysis

	TRI/RMP			SIC 1311		
Year	Facilities	Releases	Releases per 100 Facilities	Facilities	Releases	Releases per 100 Facilities
1990	9,244	2	0.022	4,455	0	0.000
1991	7,364	2	0.027	3,113	0	0.000
1992	9,941	1	0.010	1,344	0	0.000
1993	6,116	1	0.016	2,988	0	0.000
1994	7,887	1	0.013	1,050	0	0.000
1995	5,469	1	0.018	2,143	0	0.000
1996	4,902	1	0.020	3,790	0	0.000
1997	5,415	0	0.000	490	0	0.000
1998	1,0536	1	0.009	1,289	0	0.000
1999	6,453	2	0.031	1,713	0	0.000
2000	4,744	2	0.042	858	1	0.117
2001	6,805	2	0.029	3,807	1	0.026
2002	6,706	6	0.089	2,403	1	0.042
2003	6,257	1	0.016	1,763	0	0.000
2004	7,008	1	0.014	1,335	0	0.000
2005	4,353	2	0.046	1,997	0	0.000
2006	7,953	3	0.038	680	0	0.000
All years	1,17153	29	0.025	3,5218	3	0.009

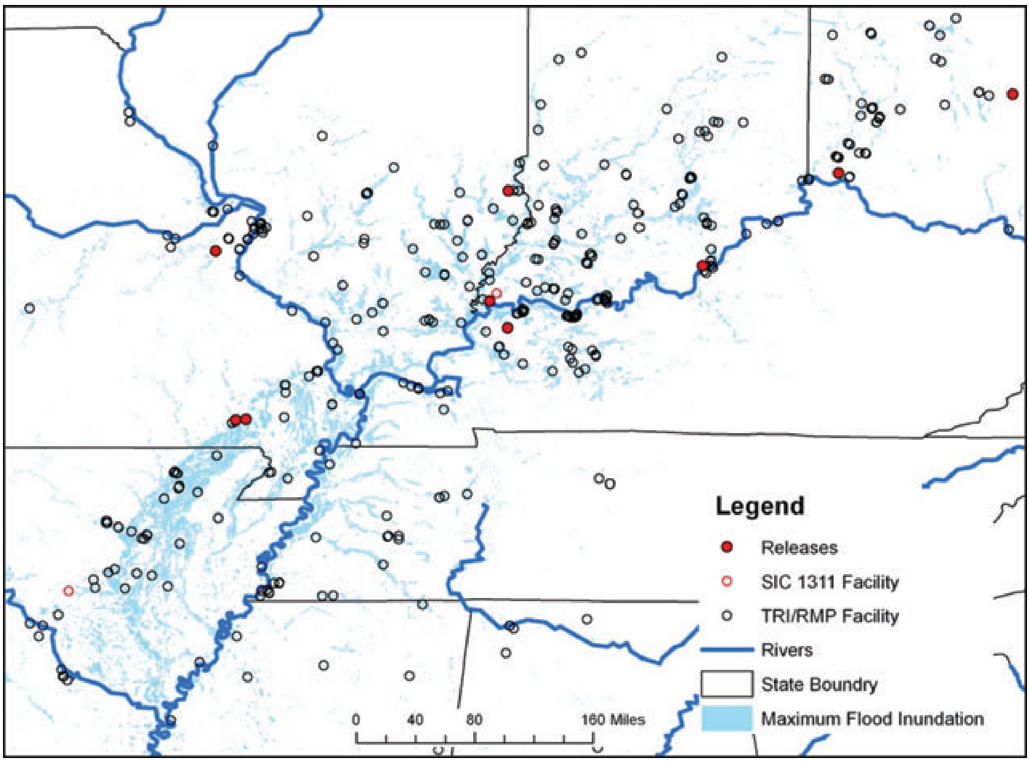

Fig. 7. Analysis of releases during March 2008 flooding.

Table IX. Summary of Flood Analysis for TRI/RMP Facilities

Date	Location	Facilities	Releases	Releases per 100 Facilities
Mar 2008	Midwest	624	2	0.3
Aug 2007	Near Findley, OH	18	0	0.0
	Near Oklahoma City, OK	26	0	0.0
Jun-Jul 2007	Near Coffeyville, KS	10	3	30.0
May 2007	East of Kansas City, MO	41	0	0.0
	South of Omaha, NB	47	0	0.0
	Near Aberdeen, SD	3	0	0.0
Jan-Feb 2007	East TX and West LA	36	0	0.0
	Mississippi River Valley, AK	9	0	0.0
	Wabash and White River IL, IN	38	0	0.0
Oct 2006	East TX and West LA	16	0	0.0
Jun 2006	Upper Susquehanna, NY	16	1	6.3
Apr 2005	Upper Susquehanna, NY	35	1	2.9
	Lower Hudson, NY	26	0	0.0
Jun 2001	East TX and West LA (T.S. Allison)	24	4	16.7
May-Aug 1993	Midwest	1410	14	1.0
Pooled data	–	2379	25	1.1

into 16 geographical domains defined by inundation data. Only a small number of releases are observed in inundated zones and there is a great deal of variability in the frequency of releases. No SIC 1311 releases were observed in inundated zones. This may be in large part due to the smaller number of SIC1311 facilities, which totaled only 5% of TRI/RMP facilities. Underreporting of releases from SIC 1311 facilities is expected to be less of an issue than during earthquakes or tornadoes as any releases of petroleum caused by flooding would most likely discharge to a water body and so require federal reporting. Approximately 45% of releases in Table IX were large compared to 16% of all flood-related natechs reported to the NRC. This may reflect selection of more severe flooding events for analysis.

The number of releases per 100 facilities inundated varies widely. Much of the variation is suspected to originate from variation in flood characteristics such as depth, force, and speed of onset.[14] For example, the July 2007 flooding in Coffeyville KS was both rapid in onset and exceptionally high and resulted in the highest probability of a release of any of the events analyzed. These results suggest that for prediction of flood-related natechs, a more detailed analysis is desirable that takes into account flood characteristics, particularly flood depth.

3.5. Summary of Conditional Probability Estimates

The analyses described above have provided estimates of the conditional probability of natechs under various natural hazard conditions experienced during hurricanes, earthquakes, tornadoes, and floods. Probabilities and the ranges observed during individual natural hazard events are summarized in Table X along with the fraction of large releases out of those with known size. These results allow comparisons to be made between the natech probabilities of various hazards.

Natech risk due to earthquakes has been more studied than other natural hazards, and is a hazard where organized efforts at risk reduction have been legislated.[43,16] Results of this study indicate that in areas of violent shaking, earthquakes *do* have among the highest probability of causing a natech release, and many of these releases are large in size. In areas of strong and very strong shaking during earthquakes, the probabilities of natechs remain high. However, hurricanes also have a high probability of causing natechs and the probability is greatest in the case of deep storm surge flooding. In the zone of storm surge greater than 3 m, observed during Hurricane Ike, the occurrence of releases was even greater than in the zone of violent shaking during the Northridge Earthquake and comparable rates were observed in the category 3 wind speed zone during Hurricane Andrew. Overall, considering the conditional probabilities of natech occurrence due to hurricanes and earthquakes it is fair to say that they are similar in magnitude.

In contrast to earthquake and hurricane natechs, this study demonstrates that the probability of tornado natechs in areas with tornado exposure is

Table X. Summary of the Natech Probability

	TRI/RMP				SIC 1311			
	Releases per 100 Facilities				Releases per 100 Facilities			
Hazard Zone	Min.	Mean	Max.	Large Releases	Min.	Mean	Max.	Large Releases
Hurricane								
Tropical storm winds	0.9	2.1	7.5	18%	0.0	0.9	3.6	34%
Hurricane winds (cat 1-2)	0.0	5.6	9.5	16%	0.0	2.6	10.0	21%
Hurricane winds (cat 3)	–	18.2	–	32%	–	0.0	–	–
Storm surge inundation all	0.0	7.3	12.4	34%	0.0	6.2	24.1	43%
Storm surge inundation 0.0–0.5 m	–	0.0	–	–	–	0.0	–	–
Storm surge inundation 0.5–1.5 m	0.0	9.7	25.0	60%	0.0	3.4	4.3	50%
Storm surge inundation 1.5–3.0 m	0.0	8.3	10.6	29%	0.0	4.8	7.2	38%
Storm surge inundation >3.0 m	–	41.7	–	0%	–	24.4	–	57%
Earthquake								
MMI V (light)	0.0	0.1	0.2	8%	–	–	–	–
MMI VI (moderate)	0.4	0.7	1.5	22%	–	–	–	–
MMI VII (strong)	1.2	4.2	6.6	15%	–	–	–	–
MMI VIII (very strong)	9.9	13.0	17.1	10%	–	–	–	–
MMI IX (violent)	–	21.4	–	19%	–	–	–	–
Tornado								
F2–5 tornado within 25 mi	0.0	0.02	0.09	21%	0.0	0.01	0.12	0%
Flood								
Flood inundation	0.0	1.1	30.0	45%	–	–	–	–

extremely low. Although this reflects the definition of the hazard zone used for analysis as an area much larger than that directly affected, these results also reflect the small footprint of tornadoes and the small number of releases they cause annually. With respect to floods, the study found that the probability of natechs in areas that experience inland flooding is quite small, although some particularly severe events resulted in a high frequency of releases. This low probability may reflect existing mitigation efforts such zoning restrictions and elevation of construction on floodplains. Storm surge flooding from hurricanes often results in a higher probability of natechs than inland flooding, perhaps due to the more energetic environment created by storm surge flooding where wind and wave action add to the hazard level.

Analysis of natech consequences, necessary for consideration of natech societal risk, is outside the scope of this work. Natechs with human impacts in the United States are too rare for their probability to be estimated with the type of methodology used in this study. However, the similarity of the conditional probability of natechs associated with hurricanes to that of earthquakes may suggest comparable levels of societal risk. In that case, similar levels of engineering and legislative attention would be warranted for mitigation of hurricane natech risk in vulnerable areas as have been dedicated to mitigation of seismic natech risk. However, other factors such as the early warning available for hurricanes will influence the level of societal risk posed by hurricane natechs. Early warnings allow the shutdown of potentially dangerous industrial processes and the evacuation of areas at risk from storm surge and high winds. Similarly, lower natech probabilities associated with floods and tornadoes, and availability of some warning, might suggest a lesser degree of societal risk associated with these events than for earthquakes. The potential for human and environmental impacts from natechs is an important area for further study.

4. CONCLUSION

Natechs are common in many parts of the United States and this study provides a methodology by which the natech probability can be quantified over broad areas for risk assessment and planning purposes. Conditional probabilities of natechs at TRI/RMP and SICS 1311 facilities during hurricanes, earthquakes, tornadoes, and floods were estimated through GIS analysis of a selection of recent natural disasters. During hurricanes, a higher probability of releases was observed for storm surge (7.3 and 6.2 releases per 100 TRI/RMP and SIC 1311 facilities exposed, respectively) compared to hurricane strength winds (5.6 and 2.6 releases per 100 TRI/RMP and SIC 1311 facilities exposed, respectively). Increased probability of natech occurrence was observed with increased storm surge depth and wind speed. At category 3 hurricane wind speeds, the probability of natechs due to winds approaches that due to storm surge. The natech probability at TRI/RMP facilities due to earthquakes increased from 0.1 releases per 100 facilities at a light shake intensity of MMI V to 21.4 during violent MMI IX shaking. The probabilities of natech occurrence during hurricanes and earthquakes are similar as are the fraction of the resulting natechs that fall within a large size class. This suggests that while less often being the focus of study, the natech risk associated with hurricanes can be comparable to that of moderately large earthquakes.

In contrast, the estimated probability of a natech at TRI/RMP facilities within 25 miles of a tornado was found to be very small (~0.025 per 100 facilities) reflecting the limited area directly affected by tornadoes. Areas inundated during flood events had an overall probability of 1.1 releases per 100 TRI/RMP facilities but showed much larger variation in natech probability from event to event than other phenomena investigated, indicating that additional factors not quantified in this study, such as depth and speed of onset, are important for predicting flood natech occurrence. Much higher natech probability was associated with storm surge verses flood inundation, attributed to the more energetic environment experienced during hurricanes. Overall, results suggest that, when the natech occurrence is normalized by the number of exposed facilities, many natechs are likely in vulnerable areas during hurricanes and earthquakes but fewer natechs occur from tornadoes or floods.

The most obvious extension of this work is to combine the conditional probabilities developed in this study with the probabilities of individual disasters (e.g., the probability of a category 2 hurricane striking a particular geographic region) to predict the marginal probability of natechs expected from hurricanes, earthquakes, tornadoes, and floods. The conditional probabilities themselves could be improved by expanding the population of historic events analyzed and extending the methodology to more specific hazard classes, such as the depth of inland flooding or finer gradations of wind speed. Such efforts should serve to reduce uncertainty in the probability estimates. In addition, the role of geography and spatial clustering of natechs could be examined. Natech risk associated with other natural hazards such as extreme rain events could also be quantified. Using the same methodologies, the conditional probability of natechs could also be derived for more specific types of equipment or facilities as other studies have been done for seismic risk to large storage tanks. The analyses presented here are only an important first step in understanding and quantifying natech risks.

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