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ORIGINAL PAPER

Environmental damage associated with severe hydrologic events: a LiDAR-based geospatial modeling approach

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Abstract
Increasingly, extreme hydrologic events are causing flooding and infrastructure damages in excess of one billion dollars per event. Hurricane storm surge is most frequently implicated; however, rainfall dominated events may have more damaging and costly impacts. Additionally, the environmental impacts and consequences of such events are not often considered in estimates of flood damage or in mitigation efforts. This paper integrates geographic information systems, floodplain analysis, observed flood level data, and public sources of pollutant releases to describe the environmental impacts of severe hydrologic events and identify infrastructure vulnerabilities with an emphasis on environmental facilities. Observed high water marks from recent significant flooding events, coupled with LiDAR data, were used to create high-resolution inundation maps. The degree of inundation of facilities with the potential to cause environmental impacts, such as wastewater treatment facilities, landfills, and Superfund sites, was modeled. The results indicated that rainfall-based flooding events could cause substantially more inundation of environmental facilities compared to surge-based flooding. Additionally, 100 and 500-year floodplain mapping was not sufficient to identify facilities at risk of inundation or spillage. The results from the study enable the determination of locations and facilities that are highly susceptible to environmental pollution due to flooding that would be candidates for increased resilience planning.

Keywords Chemical spill · Hurricanes · Satellite imagery · GIS · Superfund sites · Floodplains · Risk · Vulnerability · Resilience

1 Introduction

In the USA alone, 27 tropical cyclones (including hurricanes and tropical storms) have caused over one billion dollars of damages since the year 2000 (NCDC 2020). It is commonly believed that storm surge is responsible for the majority of the costs that can be

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attributed to a hurricane (Santella et al. 2010); however, hurricane-induced rainfall can cause more catastrophic damage than surge as evidenced in 2017. While Hurricane Ike (2008) with its 17.4 ft storm surge in Galveston Bay (Hope et al. 2013) caused $38 billion in damages (Smith and Matthews 2015), Hurricane Harvey only generated a storm surge of 6 ft in Corpus Christi, TX, but with its more than 50 inches of rainfall had close to $131.3 billion in damages (NCDC 2020). Severe storms not associated with hurricanes can also catastrophically damage urban and industrialized areas. The flooding that occurred on Memorial Day and Tax Day in Houston, TX on May 25, 2015, and April 16, 2016, respectively, is such an example; the two events had total damages of $0.55 billion (BBVA 2015) and $2.8 billion (NCDC 2020), respectively.

Most post-hurricane damage assessments focus on infrastructure (Abdulla et al. 2020), while little attention has been given to environmental consequences (Burleson et al. 2015). The effects of hurricanes and severe storms on the environment encompass a wide range of impacts including human exposure to chemicals and biological agents, changes in salinity, endangerment of aquatic biota, releases from hazardous waste sites and landfills, water column stratification, disruption in microbial communities, and acute and chronic changes in water quality (Pardue et al. 2005; Hagy et al. 2006; Amaral-Zettler et al. 2008; Engle et al. 2008). In particular, inland spills and pollutant discharges such as chemical releases from industrial, municipal, environmental, and hazardous materials infrastructure represent major sources of pollution that significantly affect water quality (Cao et al. 2012, 2013).

Numerous pollutant release incidents were reported during Hurricane Katrina (Santella et al. 2010; Pine 2006; Godoy 2007), Hurricane Rita (Godoy 2007), and several other severe storms (Mallin et al. 1997). Personna et al. (2015) observed elevated trace metal concentrations due to releases from the Raritan Bay Superfund site in Laurence Harbor, NJ, post-Hurricane Sandy (2012). Elevated bacterial concentrations were observed in floodwaters caused by the inundation of wastewater treatment facilities after Hurricane Floyd (1999) and Harvey (2017), in North Carolina (Bales 2003) and Texas (Yu et al. 2018), respectively. In addition, floods can cause erosion of landfills and lead to the release and transport of toxic material (Laner et al. 2009). Figure 1 shows a broad range of sources of chemical and pollutant releases from urban infrastructure, including industrialized facilities such as petrochemical plants, municipal facilities such as water and wastewater treatment

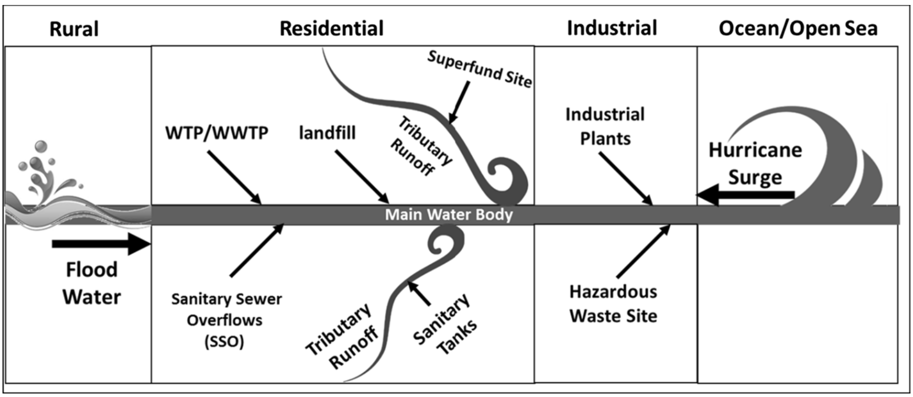

Fig. 1 Potential sources of pollutant releases and spills in an estuarine system due to storm surge and/or flooding

plants (WWTPs), Superfund sites, hazardous waste sites, and landfills (Li 2005; Pine 2006; Mallin et al. 1997; Ruckart et al. 2008).

The primary mechanism for exposure is initiated by land inundation due to storm surge and/or significant amounts of rainfall that occur before, during, and after hurricane landfall (Portela and Godoy 2005). According to the recommendations and guidelines, both at the national and state levels (see Code of Federal Regulation (CFR) 40 and 44, or Texas Administrative Code (TAC) 30), environmental facilities (e.g., WWTPs and landfills) should not be built inside the 100-year floodway, nor obstruct the flow of a 100-year flood, and should not be subjected to a wash-out of material by the flood. However, most of these building criteria did not come into effect until the mid-1990s. Moreover, the adoption of policies varies across states, the main emphasis of the regulations is on floodways, and there is a constant change in the 100-year floodplain maps from FEMA and other local agencies due to changing conditions in watersheds. As a result, many of the environmental facilities have been built within the 100-year floodplain, especially inside the flood fringe (the portion of the floodplain excluding the floodways). Finally, recent flooding events such as Hurricane Harvey caused the inundation of areas that were not located in either a 100-year or a 500-year floodplain, in some cases with rainfall amounts and intensities that were below a 100-year event. Thus, it is necessary to develop a tool (and methodology and approach) that could provide reliable estimates of historical inundation zones with relatively high spatial resolution to help decision-makers when issuing permits for the siting and construction of such facilities.

Post-event inventories of spills and other environmental pollutant releases are necessary to identify vulnerable locations of point and non-point source contamination and to assess human exposure and associated health effects. Land inundation and potential risks from spills and leaks can be evaluated using observed data, if available, or through modeling for areas with limited to no observed water surface elevation (WSE) data. Sources of data on spills and environmental releases before, during and after severe storms and hurricanes are sparse. In general, entities are responsible for notifying the National Response Center (NRC) at the earliest possible time after the release of any hazardous chemicals if the release is above reportable quantities (RQ) (Sengul et al. 2012). In addition to the NRC Incident Reporting Information System (IRIS) database, the Emergency Response Notification System (ERNS) of the United States Environmental Protection Agency (EPA) and the Agency for Toxic Substances and Disease Registry (ATSDR) Hazardous Substances Emergency Events Surveillance System (HSEES) have information on these releases and spills. However, and as of this writing, the ERNS database has been offline since 04/15/2018 and HSEES only has data for the period of 1996–2009. In addition, the HSEES database does not include the exact location, date, and time of the reported spills; and only contains state, county, season, the portion of the week when the event occurred (weekday or weekend), and the time band that the reported events occurred (day or night). The limited reported data, unreported releases and spills, and the relatively large number of facilities with high inundation risk motivate this research aimed at developing a geospatial model that can be used to estimate the inundation probability for different environmental facilities under different inundation scenarios.

High-resolution Digital Elevation Models (DEMs) compiled from data collected by Light Detection and Ranging (LiDAR) have been widely used to generate continuous flood risk maps for coastlines and wetlands to investigate flooding due to storm surge and sea-level rise (Webster 2010; Webster et al. 2004, 2006; Huang et al. 2014; Clinch et al. 2012; Demirkesen et al. 2007, 2008). Others have coupled ADvanced CIRCulation (ADCIRC) model results with LiDAR data to simulate flooding during Hurricane Sandy in New York

(Yin et al. 2016). Yet others have used 2-D hydrodynamic models to estimate the risk of landfills flooding in Australia (Neuhold 2013) or applied flood zone maps to identify the locations of affected landfills (Brand et al. 2018). Brody et al. (2014) used the SLOSH (Sea Lake and Overland Surges from Hurricane) model to simulate the inundation of the San Jacinto waste pit Superfund site, in Houston, Texas, during Hurricane Ike; while Burleson et al. (2015) used the results of ADCIRC and the Simulation Waves Nearshore (SWAN) models (Hope et al. 2013) to study the economic impacts of Hurricane Ike on industrial facilities under different surge-based hurricanes.

While hydrodynamic models are useful tools to predict storm surge, tides, and wind-driven circulation, most of the models lack the ability to model the effect of concurrent local runoff or rain-induced floods. Kiaghadi et al. (2017) developed the first of its kind hydrodynamic and water quality predictive model by coupling the Environmental Fluid Dynamics Code (EFDC) and ADCIRC + SWAN. Incorporating the effects of local flow and improved spatial resolution allowed the authors to predict land inundation both during surge and rainfall-based events. However, the model had some limitations in terms of geospatial coverage dictated by computational cost and lack of flow and tide data, as boundary condition inputs, during extreme events. To overcome such limitations, this research proposes a novel integration of a dataset of existing high water marks (HWMs) and high-resolution LiDAR elevation data to generate inundation maps for different types of severe hydrologic events. The resulting maps are used to investigate the environmental effects of flooding in an urban and industrialized metropolitan area; more specifically, the inundation of wastewater treatment plants, Superfund sites, hazardous waste sites, and landfills. The developed methodology demonstrates an alternate approach to hydrodynamic modeling to identify risks to human health and the environment using measured water level data. To the best knowledge of the authors, the approach presented in this paper has never been used to investigate environmental facility inundation from rainfall and surge. Importantly, the results from this research enable exploration of resilient mitigation strategies whereby risks of inundation are reduced or eliminated in advance of hurricanes and severe storms. The results using the presented approach are readily understood by decision-makers and laypersons with limited technical knowledge of the complexity of fate and transport under highly dynamic conditions.

2 Methods

The research approach in the study develops inundation maps for the study area based on LiDAR and HWM data for multiple storms. A geospatial database consisting of inventoried data for environmental facilities is cross-referenced with the results from the inundation mapping to develop estimates of inundation risks for the various storms and environmental facilities (wastewater treatment plants, landfills, Superfund sites, and hazardous waste sites) as described in more detail below.

2.1 Study area and severe storm history

Harris County (Fig. 2), with an area of 4596 km^2 inhabited by a population of 4.54 million, is the most populous county in Texas and the third most populous in the US. The combination of dense urban and industrial land cover in a hurricane-prone coastal region makes this area an ideal test bed for the study methodology. The research investigates five relatively

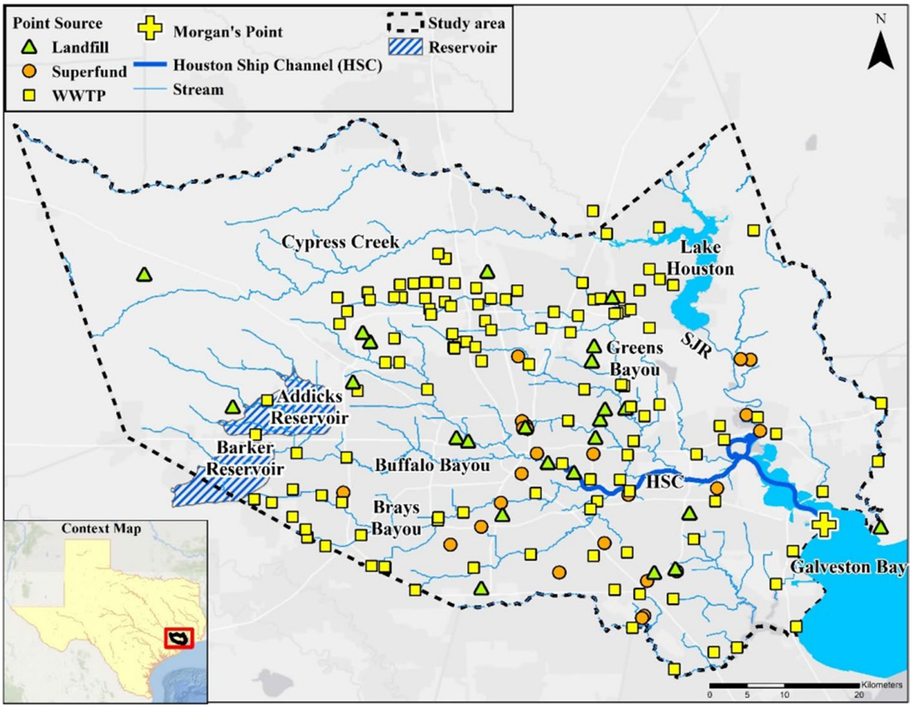

Fig. 2 Study area showing the waterways and environmental facilities in Harris County

recent severe hydrologic events that occurred since 2000, including four rain-based events (Flood-R1 through Flood-R4 in Table 1), and one surge-based event (Flood-S1 in Table 1). The rainfall distribution over the study area is shown in Fig. 3, and as can be seen in the figure, Flood-R4 received the highest rainfall followed by Flood-R1. Flood-S1, on the other hand, received the least amount of rainfall and was mainly a surge-based event. It should be noted that for the study area, the total daily rainfall associated with the 100-year and 500-year rainfall events is 33 and 48.3 cm, respectively (HCFCD 2017). Based on maximum 24-h rainfall values, only Flood-R1 and Flood-R4 received rainfall amounts that were greater than a 500-year rainfall.

2.2 Geospatial database development

A database was developed for the study that encompassed rainfall amounts, HWMs, LIDAR data, and a geospatial inventory of environmental facilities including wastewater treatment plants, hazardous waste sites, landfills, and Superfund sites.

Rainfall data from 150 rain gages were compiled from the Harris County Flood Control District (HCFCD) Flood Warning System (FWS) database (HCFCD-FWS 2017). For HWMs, the HCFCD Storm Center (HCFCD 2017) and the USGS Flood Event Viewer interface (USGS 2017) databases were used. Within Harris County boundaries, there were between 124 and 748 HWMs available for a given storm. Digital Elevation Map (DEM) blocks generated by LiDAR were downloaded from the Texas Natural Resources Information System (TNRIS) database (TNRIS 2017) at a one-meter resolution. The NRC's

Table 1 Study severe hydrologic events with associated rainfall and damages

Name	Storm event	Starting date	Rainfall (cm)**			Damage cost (billion $)
			Range	Average	Maximum 24-hr***	
Flood-R1	Tropical Storm Allison	5-Jun-01	11–1 - 100.1	38.3	72.4	11.9 (Smith and Matthews 2015)
Flood-S1	Hurricane Ike*	13-Sep-08	0.14–49.2	20.1	39.9	38 (Smith and Matthews 2015)
Flood-R2	Memorial Day Flood	25-May-15	12.1–40.9	25.6	27.9	0.55 (BBVA 2015)
Flood-R3	Tax Day Flood	16-Apr-16	12.0–52.3	27.1	44.7	2.8 (NCEI 2017)
Flood-R4	Hurricane Harvey	25-Aug-17	38.6–116.8	85.2	72.7	125 (Smith and Matthews 2015)

*Storm surge was 17.4 ft. in Galveston Bay

**All values are for Harris County

***Maximum 24-hr rainfall recorded among all gages

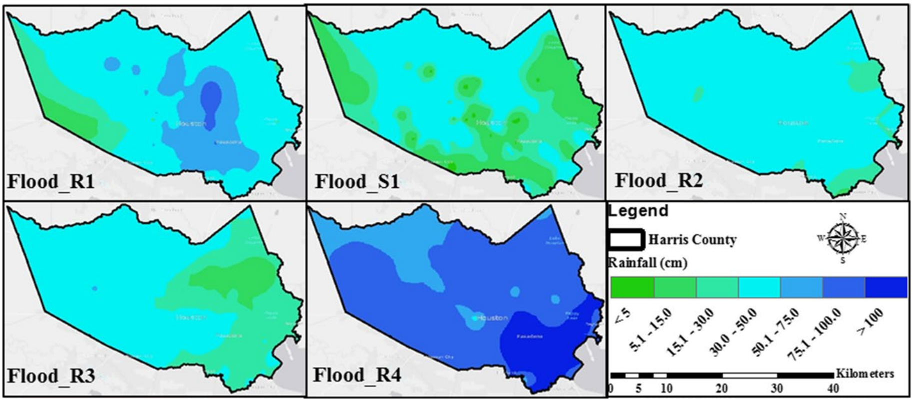

Fig. 3 Rainfall distribution in the study area during different severe hydrologic events

IRIS database, reports published by the US-EPA, the Texas Commission on Environmental Quality (TCEQ), and the media (the local newspaper: the Houston Chronicle and other media outlets) were all used to develop the data for pollutant releases and spills.

The locations of WWTPs were compiled from three different sources: TCEQ (TCEQ 2017), US-EPA Envirofacts (2017), and the City of Houston GIS Portal (COHGIS 2017) as point shapefiles. Overall, and based on the three databases, 121 WWTPs were identified; however, due to the lack of a unified database, it is possible that some WWTPs were missed using this approach. Landfill locations, including 24 landfills, were also obtained as a shapefile (TCEQ 2017). The polygon shapefile, including the boundaries of 24 Superfund sites, was directly downloaded from TCEQ (2017). While no data were available for the construction date of the WWTPs, and landfills, the permit date (extracted from the same source as the shapefile) was used as a surrogate to compare with the flood regulations and building codes. Permit status was available for 21 of the landfill facilities (out of 24) and 108 WWTPs (out of 121) considered in this study. Figure 2 shows the location of all identified environmental facilities in the study area.

Federal Emergency Management Agency (FEMA) 2015 National Flood Hazard Layers corresponding to storms with a probability of occurrence of 0.2% and 1% (500-year and 100-year floodplains) were downloaded from Houston–Galveston Area Council (H-GAC) database (H-GAC 2017). Boundaries of existing water features were also obtained from the H-GAC database as a polygon shapefile.

2.3 Modeling the vulnerability of environmental facilities

2.3.1 High-resolution inundation mapping

The coarse-resolution HWM datasets were enhanced to generate continuous WSE maps for the hydrologic events considered in the study. Such continuous maps are very valuable as they can be overlaid with DEM maps to generate higher resolution inundation maps. All calculations were undertaken at the watershed scale using the Tropical Strom Allison Recovery Project (TSARP) watershed delineations. The TSARP delineations were completed after Tropical Storm Allison in 2001 (Flood-R1 in this study) and divided the Greater Houston Metropolitan drainage area into 22 watersheds. As shown in Fig. 4,

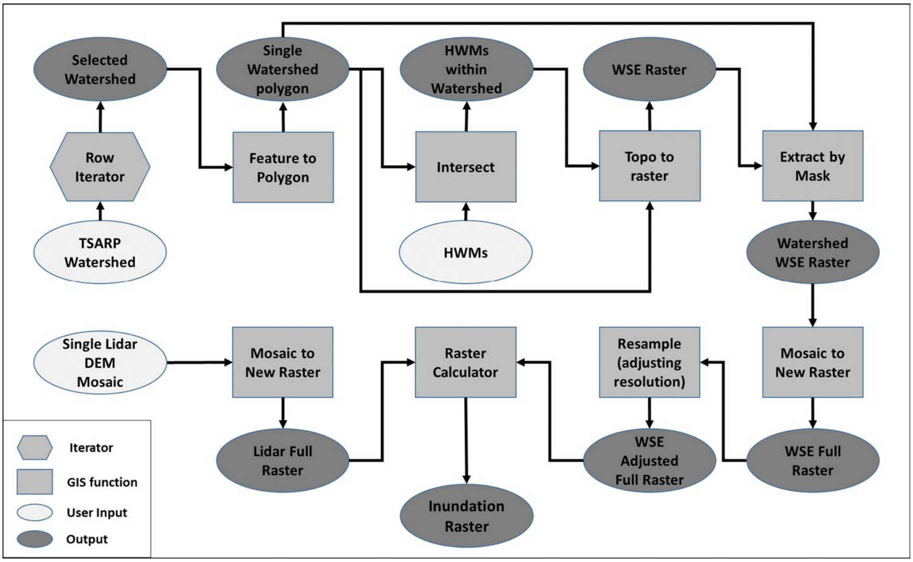

Fig. 4 Flowchart showing the various steps in the ArcMap model to develop continuous land inundation maps

a model was built in ArcMap to automate the process of generating continuous inundation maps for all 22 watersheds. Only watersheds with more than five HWMs within their boundaries were considered in the model. A total of 20 watersheds for Flood-R4, for example, were qualified using this criterion; the total number of watersheds was 11, 5, 9, and 19 for Flood-R3, R2, R1, and S1, respectively.

The developed ArcMap-based model used watershed boundaries, HWMs, and LiDAR DEMs as input, and with the many existing tools in ArcMap (see Fig. 4), WSE rasters were generated at the desired resolution of 1 m by 1 m for each event. “Subtracting” the LiDAR DEM raster (represents the ground level) from the WSE raster (represents the depth of water at a given location) generated inundation depth maps (standing depth of water at a given location for a given storm event). Eliminating existing waterbody surface areas from the inundation rasters yielded the inundation maps on land areas.

2.3.2 Spatial analyses

Using ArcMap (ESRI 2016) and applying world imagery base maps, the boundaries of WWTPs and landfills were drawn manually to create polygon shapefiles. Land inundation rasters were converted into binary maps, with 1 and 0 representing inundated pixel and dry land, respectively. The zonal statistics tool in ArcMap was applied to the land inundation raster using boundaries of environmental facilities as zones. For each facility (zone), the percent inundation was then calculated as:

$$\text{Percent inundation} = \frac{\text{Sum of pixel values(inundated)}}{\text{Total count of pixels}} \tag{1}$$

Three levels of inundation were defined to categorize the frequency of inundation for the five flood events. The number of facilities with inundation levels greater than 25, 50, and 75% were calculated for each event, in addition to the number of storms (out of 5) where inundation occurred.

The inherent potential for the inundation of environmental facilities was assessed using the 100 and 500-year floodplain delineations. The zonal statistics approach described above was used to calculate the percent inundation of each environmental facility for 1% and 0.2% floods. Facilities with more than 25% were categorized as having been built within the floodplain. However, and to put this categorization in perspective, and because of the significant magnitude of rainfall during Flood-R4 (Hurricane Harvey, see Table 1 and Fig. 3), the relative difference between R4 and a 500-year flood was further explored to understand how Hurricane Harvey inundation differed from that caused by a 500-year flood. The zonal statistics approach was used again to calculate the percent inundation at the catchment level (a smaller part of the watershed) for Flood-R4. Spatially joining the floodplain polygon to the catchments and then using the summary tool in ArcMap allowed calculating the 500-year percent inundation for each catchment. The inundation difference for each catchment was defined as:

$$\text{Inundation difference}\ (\%) = \text{Percent inundation}_{\text{Flood } R4} - \text{Percent inundation}_{500-\text{year}} \tag{2}$$

A positive or negative inundation difference meant that Flood-R4 caused more or less inundation than a 500-year flood, respectively.

2.3.3 Validating the geospatial model using actual pollutant release data

Due to a lack of information for the 5 events, validation was undertaken only for Flood-R4 (Hurricane Harvey) that had the most data. A comprehensive search of all Houston Chronicle articles published between August 25, 2017, and January 1, 2018, and of TCEQ and EPA data sources was undertaken using environmental and pollution-related keyword searches. Appropriate filtering was performed on the NRC database and search results to spatially limit the pollutant discharges and spill data to Harris County and to eliminate planned continuous releases (intentional releases prior to Hurricane Harvey were not considered in this study), leaks from vessels and observed sheens in the water without identified sources. The filtered data were exported to ArcMap to generate color-coded maps based on the type of spill (i.e., industrial, WWTP, Superfund, etc.). The developed pollutant discharge dataset was compared to the mapped percent inundation of environmental facilities mapping to develop a method for assessing risks of exposure and vulnerabilities in urban and coastal areas.

3 Results and discussion

3.1 Continuous land inundation maps

Figure 5 shows the land inundation difference between Flood-R4 and the 500-year floodplain. In 316 out of 761 catchments with available data (41.5%), Flood-R4 caused more land inundation than the 500-year storm. The variability in the difference between Flood-R4 and the 500-year floodplain illustrates a very important point from this study: 500-year

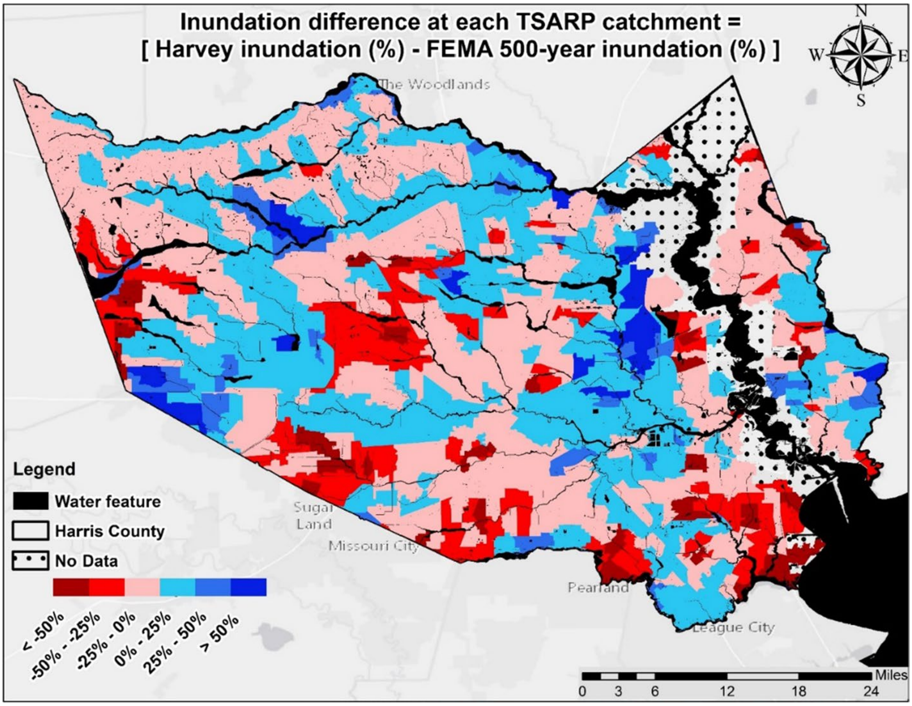

Fig. 5 Comparison of Hurricane Harvey (Flood-R4) inundation with the FEMA 500-year floodplain

floodplains are developed based on a uniform storm event whereas actual storms like Hurricane Harvey (Flood-R4) have significant variability in the amount and spatial distribution of precipitation (see Fig. 3) and can cause damage in unexpected areas within and outside 100- and 500-year floodplain delineations because of their extreme nature. Thus, a consideration of the acceptable risk level for environmental facility inundation is critical and may need to be much lower than that used for other infrastructure (residential flood insurance, for example) to protect human health and safety from further injuries or fatalities due to chemical or biological exposures.

While continuous inundation maps were generated for all TSARP watersheds where data were available; for illustration purposes in this paper, inundation in one watershed (Brays Bayou) with a long and severe flooding history is shown in Fig. 6. Flood-R1 through R4 and Flood-S1 caused total inundation areas of 13.56, 29.05, 14.70, 69.77, and 8.17 km^2, respectively. Flood-R4 with 83.7 cm total rainfall and Flood-S1 with 17.3 cm caused the maximum and minimum land inundation, respectively, in the Bayou.

3.2 Environmental facilities prone to flooding

Table 2 shows the number of each environmental facility type built within the 100- and 500-year floodplains. Approximately 55, 45, and 29 percent of facilities were built within 500-year floodplains for WWTPs, Superfund sites, and landfills, respectively. It should be noted that Table 2 only shows the number of facilities with 25 percent or more their area within the 100- and 500-year floodplains. The number of environmental

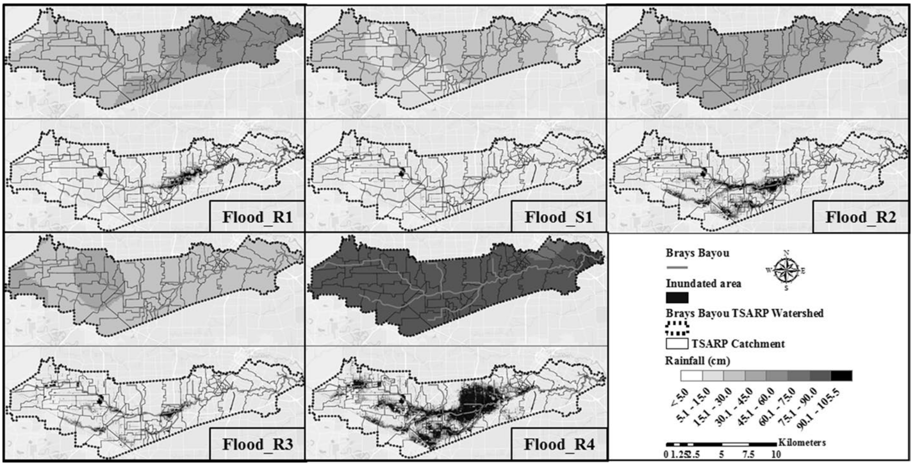

Fig. 6 Rainfall (top) and inundation maps (bottom) for Brays Bayou for various severe hydrologic events

Table 2 Distribution of facilities located in 100 and 500-year floodplains with at least 25% of their areas located in the floodplains

Type	Total # of sites	100-year floodplain		500-year floodplain	
		# of sites	Percent of sites (%)	# of sites	Percent of sites (%)
Landfill	24	3	12.5	7	29.2
Superfund	24	9	37.5	11	45.8
WWTP	121	45	37.2	67	55.4

facilities located in the 100- and 500-year floodplains would jump to 7 (~29%) and 12 (50%), 11 (~46%) and 11(~46%) and 66 (55%) and 78 (64%) for landfills, Superfund sites, and WWTPs, respectively, without the 25% threshold. The proximity of environmental facilities to floodplains increases the risk of their inundation and, consequently, the risk of pollutant discharges and spills.

While there might not be much control over the location of Superfund sites, there are rules and building codes for WWTPs and landfills to protect them against flooding. The Texas Administrative Code (TAC) adopted the rule "30 Tex. Admin. Code § 330.547: no solid waste disposal operations shall be permitted in areas that are located in a 100-year floodway as defined by the Federal Emergency Management Administration" on March 27, 2006. The TAC also recommends the construction of levees to protect the aforementioned facilities against floods through rule "30 Tex. Admin. Code § 330.307" adopted on the same date as the § 330.547. As in the case with landfills, the construction of municipal and wastewater treatment plants should also be in accordance with the TAC (rule 30 Tex. Admin. Code §309.13 adopted on March 19, 1990). According to the code, domestic wastewater treatment plants need to be located outside a 100-year floodplain, unless the facility has flood protection structures.

As noted before, out of the 121 WWTPs considered in the present study, permit information was available for 108 plants. All permits were issued post the TAC rule (1990) regarding construction in a 100-year floodplain. For landfills, the permits of 9 out of 21 facilities with permit data were issued after 2006, when the corresponding TACs were adopted. While only one landfill site with 25% or more of its area is located in 500-year floodplain, 5 of them could be considered in the 500-year floodplain if the 25% threshold was not applied.

Due to the limited information available regarding flood protection structures in the WWTPs and landfills in the study area, it is unclear whether these facilities in the present study have any kind of protection against flooding. Despite the guidelines and codes in place, due to the nature of the permitting process, there are several facilities with active permits that may be located in a 100-year floodplain, and may not have the required flood protection (Keller 2020). In addition, the active facilities and even the closed ones, located within the flood-prone areas pose a potential risk of chemical release. Quantifying such risk is beyond the scope of this work but could be addressed in future studies.

3.3 Inundated environmental facilities during the studied hydrologic events

Figures 7 and 8 show the percent inundation of all three types of environmental facilities during Flood-R4 and Flood-S1, respectively. As expected, during a rain-based event, facilities located at the most upstream and farthest from the bayous had the least inundation and the ones located within the flood control Addicks and Barker reservoirs for Houston, just

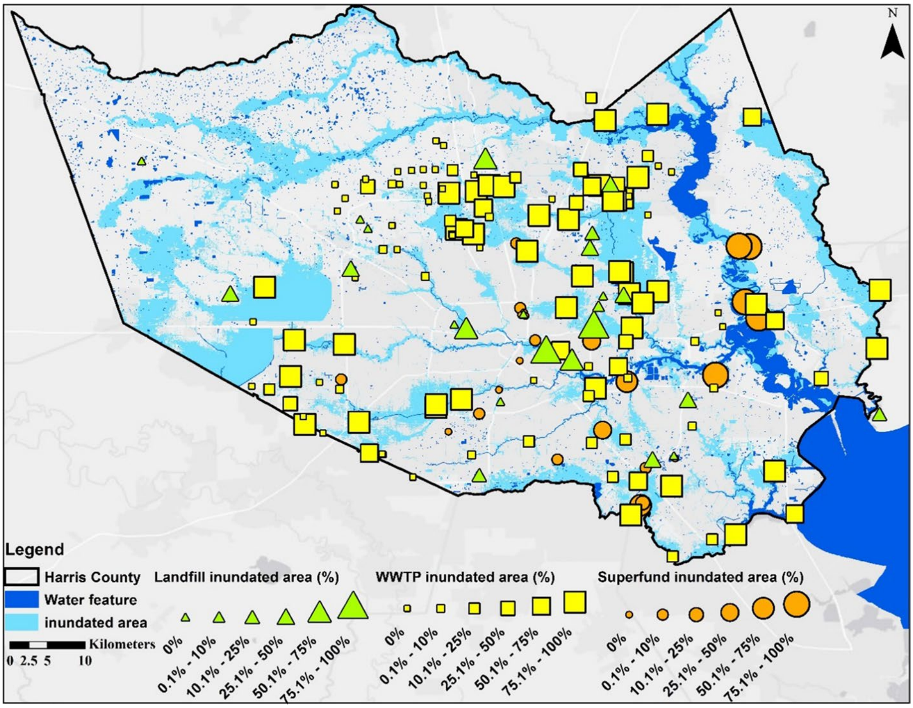

Fig. 7 Percentage of inundation of environmental facilities due to Hurricane Harvey (Flood-R4)

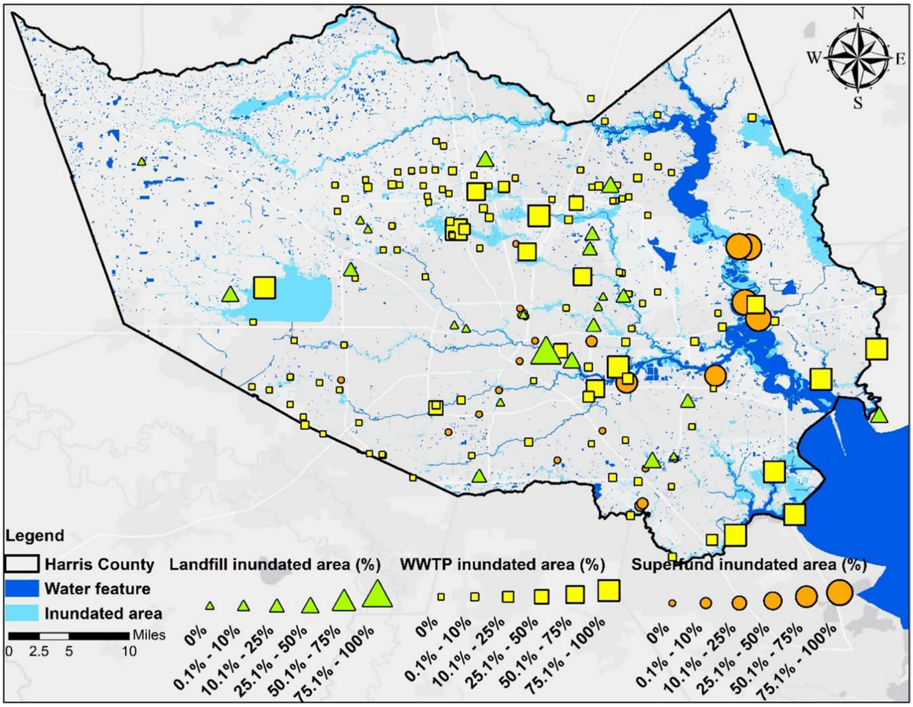

Fig. 8 Percentage of inundation of environmental facilities due to Flood-S1

downstream of the reservoirs, and very close to the waterbodies had the most inundation. During a surge-based event, on the other hand, facilities closer to the coastline were more vulnerable and showed more inundation. Even in the surge-based event Flood-S1 event, however, the rainfall accompanying the surge caused flooding in other areas that were farther from the coastline and inundated facilities in those areas (Fig. 8).

A total of 41 out of 121 WWTPs were estimated to have been flooded in more than 75% of their area during Flood-R4. The count increases to 58 out of 121 for the percent inundation greater than 50%. As can be seen from Fig. 9, Flood-R4 inundated the largest number of environmental facilities, followed by Flood-R1 and Flood-S4. Flood-R2 and Flood-R3 showed the lowest inundation rates. It should be noted that this latter finding could be mainly because of the smaller number of watersheds with enough number of HWMs (more than 5 HWMs) and the fact that R2 and R3 were localized and only flooded a limited part of the study area.

Table 3 shows the frequency of inundation during the five investigated flooding events. Two WWTPs and one landfill site experienced greater than 75% inundation in 4 out of 5 events. The two WWTPs (both built after 1990) are located within the 100-year floodplain, are close to the coast, and as illustrated in the findings, may be affected by both storm surge and rainfall. The landfill, on the other hand, while outside the 100-year floodplain, was still inundated in most of the severe storms. Three out of nine landfills, built after 2006, had more than 25% of their area flooded at least once during the five studied events. These results demonstrate that the study approach is instrumental in identifying facilities that should be targeted for risk reduction measures. For the same

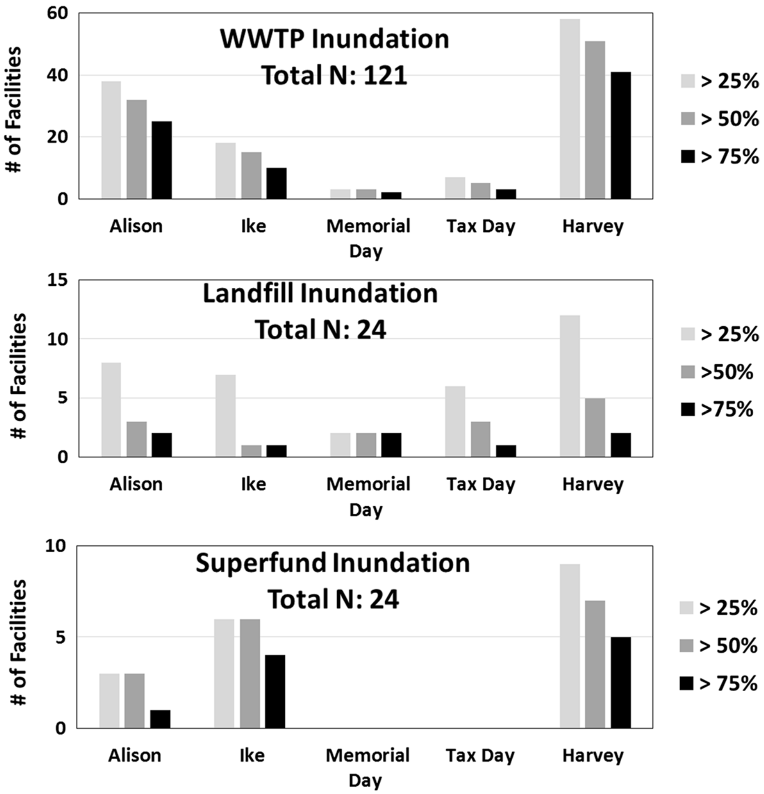

Fig. 9 Numbers and extent of inundation of environmental facilities during various severe events

Table 3 Frequency of percent inudation for environmental facilities

Percent inundation	Inundation frequency*	WWTP	Landfill	Superfund
> 25%	5	1 (1)**	0	0
	4	5 (3)	4 (1)	0
	3	8 (7)	3 (0)	1 (1)
> 50%	5	0	0	0
	4	4 (4)	1 (0)	0
	3	8 (7)	2 (1)	1 (1)
> 75%	5	0	0	0
	4	2 (2)	1 (0)	0
	3	5 (4)	0	0

*Number of storms where inundation occurred (out of 5)

**Numbers in parenthesis are number of facilities located in 100-year floodplain level of inundation (75%), five additional WWTPs (located in the 100-year floodplain) were inundated during three of the events.

The results presented in Table 3 demonstrate that not only the facilities located in the flood zones are at risk of flooding during severe storms, but also the facilities located outside these zones may be vulnerable. This points to the need to consider severe events and hurricanes in addition to the causes of localized flooding and/or the accuracy with which the 100-year and 500-year floodplains are drawn. Recent consecutive severe hydrologic events in a region deserve consideration as data that could be used for refinement of defined 100-year and 500-year rainfall zones and delineated floodplains when the risks of environmental failure are assessed. Equally important, with the prospect of climate change and sea-level rise, and their potential effects on the magnitude and frequency of extreme hydrologic events (Bates et al. 2008), the risk of toxic dispersion from environmental facilities would significantly increase (Marcantonio et al. 2019). As a result, public health, which is already affected by such releases from environmental facilities, will be at a higher risk of exposure if this is not addressed (Howard et al. 2016). Thus, resiliency measures for environmental infrastructure are essential to adapt to climate change and to attenuate and mitigate potential environmental risks (Kirchhoff and Watson 2019).

3.4 Pollutant releases and spills from environmental facilities

Actual pollutant releases and spills from 15 industrial facilities, 10 storage tanks (four caused by roof failure), seven WWTPs, and two Superfund sites were identified during

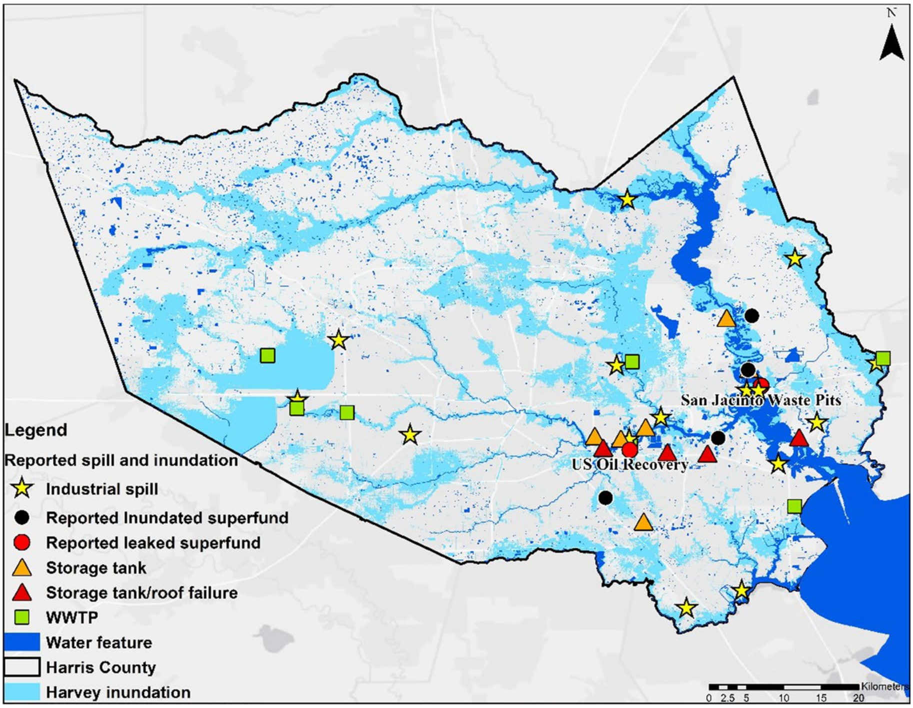

Fig. 10 Facilities with reported pollutant discharges and spills during Hurricane Harvey (Flood-R4)

Flood-R4. In addition to pollutant discharges from Superfund sites, four other Superfund sites were affected by unknown spill conditions. Figure 10 shows the locations of all identified pollutant releases and actual land inundation. It should be noted that while there were more facilities inundated during Flood-R4 as discussed in the previous section, the focus of Fig. 10 is mainly on facilities with reported pollutant discharges. Out of the seven WWTPs with reported spills, five exhibited a percent inundation greater than 95% based on the developed geospatial model. For six reportedly inundated Superfund sites, the developed land inundation map showed complete inundation for four sites, and 55% and 36% inundation for the other two sites. Due to their different modes of failure, storage tanks were excluded from the validation study; storage tank failure can occur not only due to uplifting of the tank and loss of integrity when breached but also due to roof failure for storage tanks with floating roofs as was demonstrated during Hurricane Harvey (Flood-R4).

Raw sewage, benzene, dioxins, trace metals, and petroleum by-products were some of the chemicals that were reportedly discharged from the various sources during Hurricane Havey (Kapoor et al. 2018; Yu et al. 2018; Kiaghadi and Rifai 2019). The raw sewage discharges were observed in floodwaters post-Hurricane Harvey in the Greater Houston Area (Yu et al. 2018), similar to other locations during extreme events (Divakaran et al. 2019). Local media and public health sources, for instance, reported the release of ~ 21 million gallons of raw sewage into the floodwater and bayous through 65 separate releases in Harris County and Fort Bend County during the weeks after the storm (Stuckey 2017). Such releases could cause an increase in the bacterial profile in the water, representing widespread health risks (Yu et al. 2018; Divakaran et al. 2019). The extent of damage to some of the WWTPs made them inoperable or completely destructed, suggesting the need for better flood protection strategies and more careful consideration of extreme events during the design phase. For landfills, the mixture of floodwaters with the leachate from landfills could contain inorganic and organic pollutants that pose risks to environmental health (Curtis and Whitney 2003). However, the extent of contamination released from landfills during the studied flood events has not been quantified. Hazardous heavy metals such as arsenic have been observed in landfill releases during floods in prior studies (Neuhold 2013). Finally, the potential release of carcinogenic compounds such as heavy metals, polychlorinated biphenyls (PCBs), and dioxins from the inundated Superfund sites (Personna et al. 2015) that occurred during Hurricane Harvey (Flood-R4), could threaten public health both in the short term (via direct exposure) and long term (consumption of contaminated fish, for example, caught in the Houston Ship Channel and Galveston Bay).

Using the NRC data, there were 125 reported WWTPs incidents (spills) in Harris County from 2000 to 2020; 18 of them (14.4%) were due to overflow caused by generated runoff during heavy rain or hurricanes. Most of the other incidents were minor and related to equipment failure (37.6%). Such a significant footprint in the cause of release emphasizes the importance of considering generated runoff in designing and locating new environmental facilities. The changing nature of floodplains over the years has led to these facilities being located within flood-prone areas that might not have been prone to flooding prior to the construction of the facility. The new precipitation-Frequency Atlas (Atlas 14) provided by the National Oceanic Atmospheric Administration (NOAA) in 2018 will likely alter significantly the 100-year and 500-year floodplains (Perica et al. 2018) highlighting the importance of the points being made in this study regarding consideration of extreme events in siting of environmental facilities and utility services such as wastewater treatment plants. Lastly, another lesson learned from the research in this paper is the need for all environmental facilities to have natural disaster risk assessment plans to mitigate the risks and be prepared to remediate and mitigate the damage and ensure recovery and resilience after a natural disaster.

3.5 Conclusions

The research in this study demonstrated that environmental facilities are vulnerable to flooding by not only extreme floods like Hurricane Harvey (Flood-R4), but also by events of a relatively smaller magnitude. Some of the facilities in the study were built within the 100-year and 500-year floodplains and were susceptible to inundation that was further exacerbated during the 5 studied events. Developing a rigorous and accurate database focused on pollutant discharges and spills in a specific region can not only be used to better understand the environmental impacts of hurricanes and severe storms but also to reduce vulnerabilities and improve the resilience of resource infrastructure, chemical storage, and management. Furthermore, the developed methodology allows the identification of urban pollutant sources that have an elevated risk of negative environmental impacts when flooded. In such cases, the identified facilities can be specifically targeted for enhanced resiliency planning, such as moving or retrofitting them. The methodology also enables more rigorous risk evaluation prior to the siting of a new facility and a holistic consideration of the risk level that might be experienced in terms of human health and the environment. While delineating floodplains using design storms and hydrologic modeling is important and necessary, approaches such as the method presented in this study can reduce the uncertainties in delineation and enable a comparison of real-time behavior to the simulated hypothetical scenarios.

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