Towards enhanced response: Integration of a flood alert system with road infrastructure performance models

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ABSTRACT

This paper presents a conceptual framework for improved situational awareness in severe rainfall events like hurricanes or tropical storms by coupling a Flood Alert System (FAS) with a model for transportation infrastructure performance assessment referred to as the Access to Critical Facilities (ACF) model. The FAS is a flood modeling and alert system that leverages state of the art flood modeling and rainfall radar data in an efficient manner. The ACF model comprises of a road network of the study area, census data, locations of critical facilities like hospitals and fire stations, and a spatial and network analysis toolbox written in Python. The proposed framework can be used to evaluate, in near real-time, system level performance such as accessibility to critical locations and component level performance such as potential impacts on roadways. As a proof of concept, the coupled framework is applied to the White Oak Bayou watershed, Houston, Texas. First, the hydrologic and hydraulic characteristics of the watershed are captured through inundation maps forming a Floodplain Map Library (FPML). Second, five accessibility measures quantifying mobility and accessibility are evaluated for each inundation map to develop the Accessibility Map Library (AML). During a storm event, real-time radar rainfall data is used to identify the pertinent scenario from the FPML and AML. The selected maps are then communicated to stakeholders to support emergency response and situational awareness. Further, the results from the framework can also be used for disaster mitigation planning. Although demonstrated on a single watershed, the methodology developed in this study is transferrable to other regions to develop an integrated flood alert system in support of emergency response and longer-term resilience goals.

INTRODUCTION

Hurricane Harvey made landfall as a Category 4 hurricane near Rockport, 50 km east of Corpus Christi, Texas on 25 August 2017. The slow-moving hurricane brought an unprecedented amount of rainfall—dropping about 72 trillion liters of rain on Texas (FEMA 2017). The ensuing flooding affected more than 270,000 homes necessitating the evacuation of more than 780,000 people (TCEQ 2018; FEMA 2017). Most of the major bayous (rivers) in Houston overflowed their banks inundating neighborhoods, overtopping bridges, and rendering key routes impassable. In addition to the flooding, road washouts and 12.1 million cubic meters of storm debris (TCEQ 2018) exacerbated mobility issues and severely limited the connectivity between impacted neighborhoods and critical facilities like hospitals, National Shelter System (NSS) facilities, and fire stations. While the rescue requests from the stranded communities overwhelmed the emergency response facilities, impassable roadways and the paucity of reliable information on the affected areas and their accessibility hampered emergency response operations, causing several detours and delays that put both the responders and evacuees at risk. Finally, over 122,300 people were rescued by the emergency responders with the assistance of volunteers with large vehicles and boats (TCEQ 2018; FEMA 2017). Further, while most of the hospitals in the Texas Medical Center were operational during Harvey, they were inaccessible to the impacted population due to the loss of transportation connectivity. In addition to exposing the vulnerabilities of transportation infrastructure, Hurricane Harvey demonstrated the necessity for tools that could facilitate improved situational awareness. Such tools should facilitate a) pre-event deployment of disaster response resources, b) identification of vulnerable population and affected communities, c) mitigation of potential flood-related connectivity issues between neighborhoods and critical facilities, and d) route identification for emergency response.

Past works have demonstrated the usefulness of flood alert systems in informing emergency response actions. For example, Fang et al. (2008) demonstrated the application of a flood alert system employing a new Floodplain Map Library (FPML) to provide near real-time visualization of flood inundation levels for the Texas Medical Center area, located in Houston, Texas. Further, several studies have used hydrologic and hydraulic analysis, spatial and network analysis to study flood impacts on accessibility and performance of emergency response services. For example, Chang et al. (2010) studied climate change impacts on travel disruptions in Portland, Oregon. Yin et al. (2017) also evaluated the impacts of sea level rise and resulting coastal flooding on the spatial accessibility for emergency response in Lower Manhattan, New York City. Further, Coles et al. (2017) coupled flood modeling with spatial network analysis for emergency response accessibility for services like ambulance and fire and rescue. Accessibility to care homes and sheltered accommodation were studied for two historical flooding events in the city of York, UK. This study observed a significant reduction in emergency services' spatial accessibility coverage and an increase in response time. Likewise, Green et al. (2017) used a network analysis-based framework to study the emergency responder accessibility during surface water and fluvial flood conditions in the city of Leicester, UK. While all these studies emphasized the detrimental effect of flooding on the emergency service accessibility, they primarily focused on scenario-based accessibility analyses to highlight the reduction in emergency accessibility without providing a framework for prospective real-time application. This paper presents a new framework extending the FAS framework proposed by Fang et al. (2011) by coupling it with accessibility and network performance models to evaluate, in near real-time, system level performance such as connectivity between critical facilities and census tracts, travel time for emergency response, and operability of major roads. Such a real-time framework can help improve the situational awareness during a flood event and aid emergency response. Additionally, the results from the framework can also be used to inform flood risk mitigation and siting of critical infrastructure facilities if used in a forward projection.

The paper first presents and describes the framework; tools and methodologies used for coupling a FAS with network and spatial analysis tools are presented in detail. Next, the framework is applied to the White Oak Bayou watershed, Houston, Texas to demonstrate the methodological approach and application. Finally, conclusions are presented, and future research perspectives are discussed.

OVERVIEW OF THE FRAMEWORK

The coupled Flood Alert System (FAS) - Access to Critical Facilities (ACF) framework (FAS-ACF) integrates a Flood Alert System (FAS) with and a new Access to Critical Facilities (ACF) model for transportation infrastructure. The FAS is a conceptual flood modeling and alert system that leverages state of the art flood modeling, gauge measurements, and rainfall radar data. The ACF model comprises of a road network of the study area, census data, locations of critical facilities like hospitals and fire stations, and a spatial and network analysis toolbox written in Python. Figure 1 identifies the three major components of the FAS-ACF framework. The first component, the near real-time (NRT) data acquisition module, processes and feeds the incoming NEXRAD rainfall radar data to the FAS module at a regular interval. The interval between the following feeds depends on the data availability. Regular updating is preferred for maintaining the pertinence of the predictions for NRT emergency response. The second component, the FAS module, consists of a series of predefined inundation maps forming the Floodplain Map Library (FPML). The FPML is generated after considering the hydrologic and hydraulic characteristics of a watershed. Similarly, the third component, the ACF module, consists of pre-delineated accessibility measure (AM) maps forming the Accessibility Map Library (AML). The AMs quantify the impact of flooding on the spatial accessibility of emergency services. In the future, AMs could be generated for cases of interest beyond emergency services. During a storm event, real-time radar rainfall data is used to identify the pertinent scenario from the FPML and AML. The identified maps are then communicated to the stakeholders through a website or a mobile app to support emergency activities. Details on the generation of the FPML, AML, and AMs are detailed in the following paragraphs.

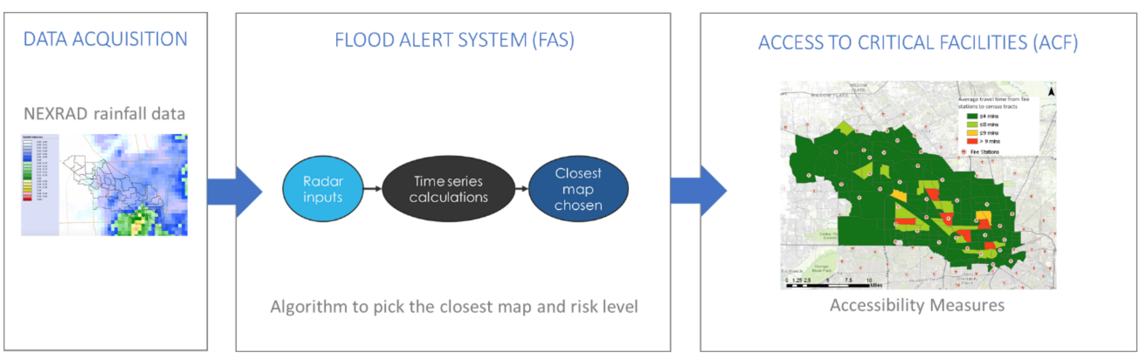


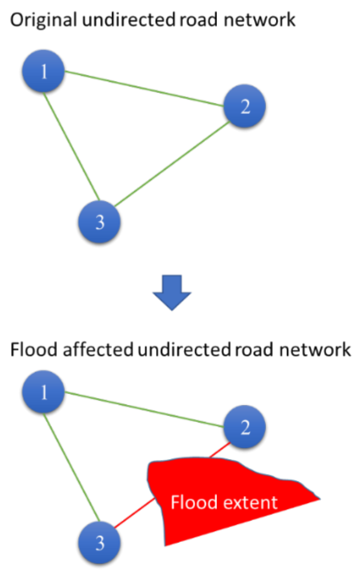
Figure 1. Coupled FAS-ACF framework (Source: Esri, NWS radar rainfall processed by Viex and Assosiates, Inc.)

The FAS consists of two main components—the FPML and an algorithm to select, from the observed NEXRAD rainfall data, the pertinent scenario map from the FPML. The FPML (Fang et al. 2008) is a hydraulic prediction tool that provides NRT visual images of flooding conditions during a storm event. The FPML system consists of maps that were pre-delineated considering the hydraulic and hydrologic characteristics of the watershed. Depending on the spatial and temporal variability of the storm event, different parts of the watershed could receive a different amount of precipitation with varying magnitude, intensity, and duration. The watershed is divided into sub-sections to account for such variabilities. Also, the sub-sections are selected in such a way that each sub-section has at least one United States Geological Survey (USGS) gage (USCG 2018) that could be used for model validation and calibration. Next, a suite of synthetic storms representing a reasonable range of rainfall intensity and duration for the watershed that has the potential to cause riverine flooding is generated. The range of intensities and duration values are based on historical rainfall and gage data (HCFWS 2018). All intensity-duration combinations are identified for each sub-section and are then permuted among different sub-sections to arrive at a list of potential scenarios for the entire watershed. Further, only those combinations which are realistic and could potentially cause flooding are included in the final list of synthetic storm scenarios. Table 1 demonstrates the concept of combining rainfall duration and intensity for a watershed with two sub-sections, upstream and downstream, to generate synthetic storms scenarios for an entire watershed. The combination highlighted in grey in the table are removed either because they represent too low-risk events or are highly improbable events. Each synthetic storm scenario has a unique total rainfall value with annual exceedance probabilities ranging from 0.1 to 0.004. The inundation from each scenario is simulated using the hydrologic model in HEC-HMS (USACE 2018a) and hydraulic model in HEC-RAS (USACE 2018b). This study uses the latest HMS and RAS models obtained from the Harris County Flood Control District (HCFCD) Model and Map Management (M3) System (HCFCD 2018b) as reference. These official models were used as the basis for the generation of regulatory floodplain maps. Using both models, an inundation map that corresponds to a particular rainfall scenario is generated for the entire watershed. The collection of all inundation maps forms the FPML.

Table 1. Suite of synthetic storms representing a reasonable range of rainfall intensity and duration for the watershed that has the potential to cause riverine flooding.

Downstream	Upstream		
	…	20 cm in 3 hours	…
…	unrealistic		
35 cm in 6 hours			
20 cm in 3 hours			
…			unrealistic

The ACF model leverages spatial and network analysis to calculate flood impacts on emergency accessibility for each scenario in the FPML. First, a mathematical model of road transportation network of the study area is created using graph theory. A road network can be represented using a graph $G = (V, E)$, where $V = \{v_1, v_2 \ldots v_n\}$ is a set of vertices representing salient features such as road intersections or key origin/destinations like critical facilities and $E = \{e_1, e_2 \ldots e_m\}$ is a set of edges representing road links. Graphs could be directed or undirected. In an undirected road network, each road link provides two-way connectivity. Assuming an undirected road network significantly reduce the computational cost and data collection effort. Further, undirected road network models are justified in an emergency situation such as flooding where roads are sparsely occupied. Additionally, each edge can also be associated with different weights to capture characteristics or importance of that link. In the present framework, the edge weights selected are a) road condition ($W_{condition}$) representing operability of the link, b) travel time for traversing the original road link ($W_{TT\_NoFlood}$), and c) travel time for traversing the flood affected road link (W_{TT_Flood}). Due to unsafe condition during a flood, often emergency vehicles travel at speed lesser than the speed limit; W_{TT_Flood} captures this reduction in speed. Figure 2 illustrates the concept of network typology and edge list using a three-degree network. For road links in normal condition, $W_{condition}$ is set to one, and for flooded roads, $W_{condition}$ is set to zero. Road links inundated beyond a threshold water depth are assumed as inundated. The threshold water depth is chosen considering the characteristics of the emergency vehicles.



Edge list for the original road network

Vertex	Vertex	$W_{condition}$	$W_{TT\_NoFlood}$	W_{TT_Flood}
1	2	1	O_{12}	F_{12}
1	3	1	O_{13}	F_{13}
2	3	1	O_{23}	F_{23}

Edge list for the flood affected road network

Vertex	Vertex	$W_{condition}$	$W_{TT\_NoFlood}$	W_{TT_Flood}
1	2	1	O_{12}	F_{12}
1	3	1	O_{13}	F_{13}
2	3	0	O_{23}	F_{23}

Figure 2. Network typology and edge list for undirected road links in the original and flooded conditions. Inundated road links are highlighted in red.

Accessibility measures (AMs) provide quantitative metrics to measure flood-related transportation accessibility disruptions between critical facilities and geographical units like census tracts. A detailed description of AMs used in this study and their potential applications are listed in Table 2. In the present study, the critical facilities selected are a) hospitals, b) fire stations, and c) NSS facilities. These facilities play an indispensable role in supporting the impacted population during a flood hazard. The geographical unit selected in this study is the census tract as socio-demographic data is readily available at census tract level. Thus, AMs evaluated in the present model include: 1) road link status; 2) connectivity loss to hospitals; 3) connectivity loss to national shelters; 4) connectivity loss to fire stations; and 5) travel time to fire stations.

Connectivity loss (CL) can be either measured in terms of travel time or travel distance. In the present study, CL in terms of travel time (CL_{TT}) is used as it could model the increase in travel time due to reduced speed in a flooded roadway in addition to the delay due to road closures and associated rerouting. The mathematical expression of CL in terms of travel time (CL_{TT}) is given in Equation 1. TT_{Normal} and $TT_{Flooded}$ are the quickest travel time between an origin-destination (OD) pair under normal and flood-affected road conditions respectively. Quickest travel time is calculated by solving the shortest-path problem for the weighted network using the Dijkstra's algorithm (Dijkstra 1959). CL_{TT} varies continuously between zero and one. $CL_{TT} \sim 0$ corresponds to no connectivity loss between the selected OD pair due to flood, whereas $CL_{TT} = 1$ corresponds to complete connectivity loss between the selected OD pair due to flood.

$$CL_{TT} = 1 - \frac{TT_{Normal}}{TT_{Flooded}};\ \ 0 < CL_{TT} \leq 1 \tag{1}$$

A network and spatial analysis toolbox written in Python using modules from NetworkX (Hagberg et al. 2008) and ArcGIS (ESRI 2016) is at the core of the ACF model. The ACF model evaluates AMs integrating data from FPML inundation maps, road network models, spatial locations of critical facilities, and census data. First, for each scenario in the FPML, road link status maps identifying flooded roadways are generated combining the information from inundation map and the road network using spatial analysis. Roads links inundated beyond a threshold depth are considered closed. Next, the network model is updated by removing the inundated roads. Travel time between nodes in the road network and the nearest critical facility is calculated for the normal and flood-affected road network to evaluate CL_{TT}. Average CL and travel time from a census tract to the nearest critical facility is calculated by averaging CL and travel time for all the nodes spatially located within the boundaries of the census tract. Finally, socio-demographic information in the census tract layer is used to summarize the characteristics of the population exposed to different risk levels. Figure 3 shows the workflow for generating accessibility measures for fire stations from a scenario in the FPML. Similarly, AMs are generated for all scenarios in the FPML to construct the AML.

Table 2. Descriptions of Accessibility Measures (AMs) and their potential applications

AMs	Description	Potential applications
Road link status	Provides information on the operability status of a road link. A road link is either closed due to inundation or open to traffic.	- Identify routes for emergency response. - Secure critical roadways for long-term accessibility.
Connectivity loss (CL)	CL measures the efficiency reduction in connectivity. CL ratio varies from 0 to 1, with 1 being completely inaccessible and 0 being no connectivity loss due to flood.	- Identify spatial distribution of vulnerable populations and prioritize emergency response. - Optimize the spatial distribution of critical facilities like hospitals and fire stations.
Travel time	The best estimate of travel time from a critical facility like fire station to a census tract.	- Evaluate the performance and efficacy of emergency response operations.

During a storm, real-time rainfall radar data will be processed to identify and communicate the closest scenario from the FPML and AML. Figure 4 illustrates how the algorithm to identify the closest scenario form the FPML works. First, NEXRAD radar rainfall data is received and processed at regular interval. Second, radar rainfall information is consolidated into mean areal precipitation (MAP) values in real time for predefined sub-sections of the watershed. Third, the consolidated rainfall information is accumulated into duration bins. The duration bins are selected based on historical rainfall and gage information. For example, for lined channels historically prone to flash floods, intense rainfall in short durations will be governing. Finally, the algorithm compares the cumulative MAP values for the watershed sections against scenarios in the FPML. The scenario corresponding to the highest risk, together with the linked AM maps from the AML, are communicated to the stakeholders. Next section presents a case-study application of the FAS-ACF framework to the White Oak Bayou watershed, located in Houston, Texas.

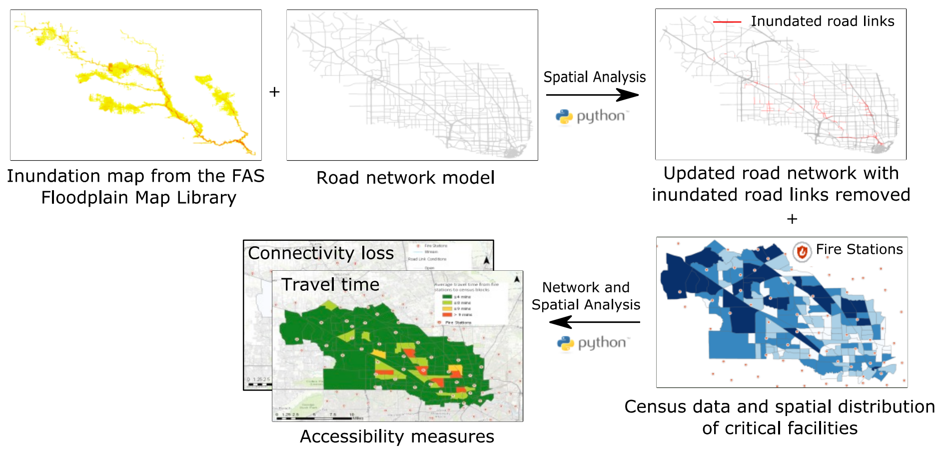


Figure 3. Workflow for generating accessibility measures for fire stations from inundation maps (Source: Esri)

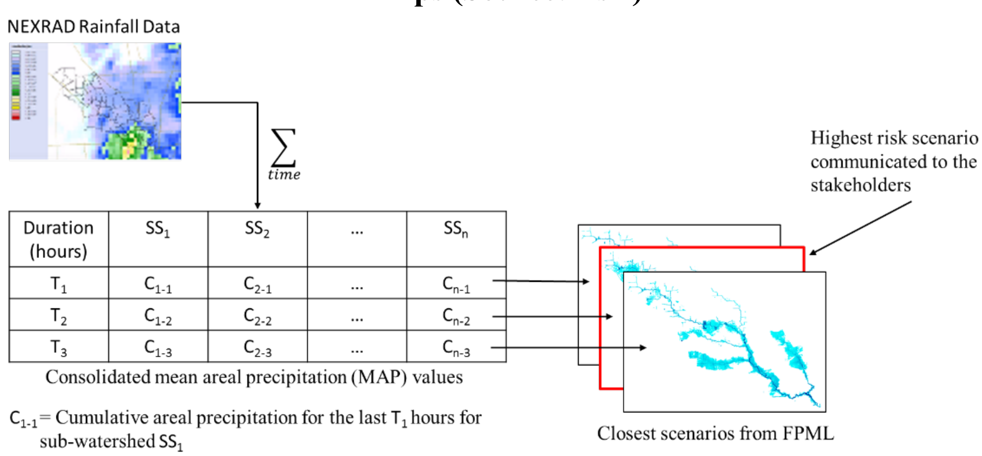


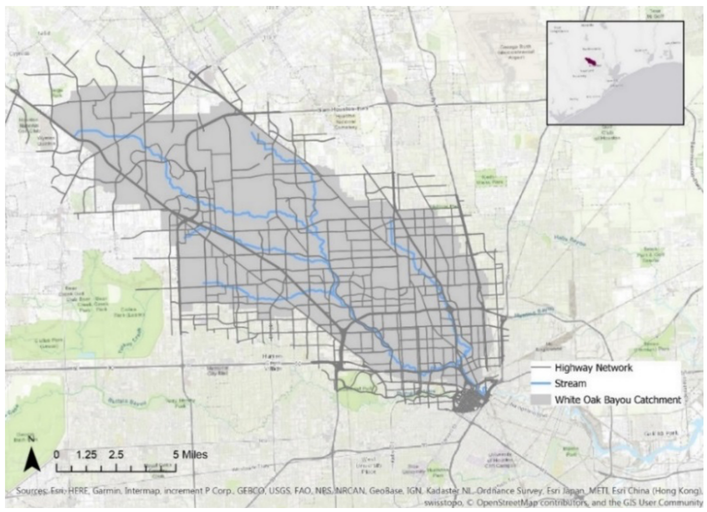
Figure 4. Algorithm for selecting pertinent map from the FPML (Source: Esri, NWS radar rainfall processed by Viex and Assosiates, Inc.)

EXAMPLE APPLICATION FOR WHITE OAK BAYOU

As a proof of concept, the coupled framework is applied to the White Oak Bayou watershed, located in northwest Houston (Figure 5), Texas. The White Oak (WO) Bayou watershed is highly urbanized with a population of 433,250 (HCFCD 2018a). The watershed has a drainage area of 287.5 km^2 and over 235 km of open streams (HCFCD 2018a). Though several active and completed projects such as White Oak Bayou Federal Flood Damage Reduction Project improved the flood resilience of the watershed, widespread flood damage and transportation accessibility issues were observed in the watershed during past major rainstorm events like Tropical Storm

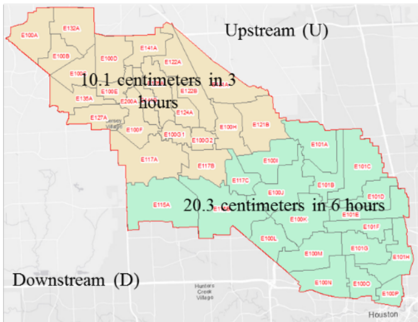
Allison (2001) and Hurricane Harvey (2017). More than 12,300 houses flooded in the White Oak Bayou and Little White Oak Bayou alone (Lindner and Fitzgerald 2018) during Hurricane Harvey. Moreover, several roads were inundated in the watershed causing severe accessibility issues. The existing flood vulnerability along with the presence of critical businesses and infrastructure downstream (i.e., downtown Houston) makes White Oak Bayou a good case study for the application of the coupled flood alert system.

Figure 5. Location of the White Oak Bayou watershed, northwest of Houston, Texas (Source: Esri)



For the White Oak Bayou application (FAS-ACF-WO), NRT NEXRAD rainfall data from Vieux & Associates, Inc. will be processed at an interval of 15 minutes to select the pertinent scenario from the FPML and AML. The chosen inundation and accessibility maps are communicated to the stakeholders for supporting emergency response decisions. For the FAS component, first the watershed is divided into two sub-sections—upstream and downstream. A suite of synthetic storms containing 32 scenarios that has the potential to cause riverine flooding was generated. For each scenario, inundation maps were generated using the latest HEC-HMS and HEC-RAS models for the WO watershed obtained from the Harris County Flood Control District's Model and Map Management (M3) system (HCFCD 2018b). Based on historical rainfall and gage info, the channel banks of WO were predominantly overtopped by relatively short duration but intense storm events. Therefore, 10.1, 20.3, and 35.6 centimeters rainfall scenarios in 3, 6, 12 hours are considered in this study. The list of 32 synthetic storms with their Scenario-ID (ID) and upstream and downstream intensity-duration (10.1 in 3 = 10.1 centimeters of rainfall in 3 hours) are shown in Figure 6.

Next, street centerlines from the OpenStreetMap (OSM 2018) road layer were exported as an ArcGIS shapefile. All links were manually checked for completeness and connectivity. The developed road line shapefile was then used to generate an undirected road network graph in NetworkX. For arriving at the travel time for undisturbed network, an average speed limit of 88.5 km/h (55 mph) is assumed for highway road links, whereas for local roads an average speed limit of 48.2 km/h (30 mph) is assumed. Road links exposed to a water depth more than 60.96 cm (2 feet) are assumed as inundated (Gori et al. in review). To model a potential reduction in the travel speed for safe traverse of emergency vehicles under wet road condition a speed reduction of 16 km/h (10 mph) is applied to all road links for the disturbed network. Locations of hospitals, fire stations, and NSS facilities are obtained in the shapefile format from the Homeland Infrastructure Foundation-Level Data (HIFLD) database (HIFLD 2018a, HIFLD 2018b, HIFLD 2018c). Finally, corresponding to each map in the FPML, five AMs maps are generated forming a 160 maps AML.



10.1 in 3 = 10.1 centimeters of rainfall in 3 hours

ID	Upstream	Downstream
1	10.1 in 3	10.1 in 3
2	20.3 in 3	20.3 in 3
3	20.3 in 6	20.3 in 6
4	35.6 in 6	35.6 in 6
5	20.3 in 12	20.3 in 12
6	35.6 in 12	35.6 in 12
7	10.1 in 3	20.3 in 3
8	20.3 in 3	20.3 in 6
9	20.3 in 6	35.6 in 6
10	20.3 in 12	35.6 in 12
11	35.6 in 12	20.3 in 3

ID	Upstream	Downstream
12	35.6 in 12	35.6 in 6
13	20.3 in 3	10.1 in 3
14	20.3 in 6	20.3 in 3
15	35.6 in 6	20.3 in 6
16	35.6 in 12	20.3 in 12
17	20.3 in 12	10.1 in 3
18	35.6 in 6	35.6 in 12
19	10.1 in 3	20.3 in 6
20	20.3 in 3	35.6 in 6
21	20.3 in 6	20.3 in 12
22	10.1 in 3	20.3 in 12

ID	Upstream	Downstream
23	20.3 in 3	35.6 in 12
24	35.6 in 6	20.3 in 12
25	20.3 in 6	10.1 in 3
26	35.6 in 6	20.3 in 3
27	20.3 in 12	20.3 in 6
28	20.3 in 12	20.3 in 3
29	35.6 in 12	20.3 in 6
30	20.3 in 12	35.6 in 6
31	20.3 in 3	20.3 in 12
32	20.3 in 6	35.6 in 12

Figure 6. Sub-division of the White Oak Bayou watershed and the list of synthetic storms (Source: Esri, HCFCD)

Example AM maps are shown in Figures 7 and 8. Figure 7 shows road link conditions for a select scenario. This map could be used to identify routes for evacuation and emergency response. Also, roads frequently inundated could be identified and their resilience could be improved using measures such as elevated roadways. Figures 8a shows a map for average CL between census tracts and fire stations for a select scenario. The census tracts with high connectivity loss ratio are identified in red. Such information can inform pre-event planning regarding siting of facilities or infrastructure risk mitigation efforts, as well as emergency response activities by providing estimates of accessibility impacts in near real time. Figure 8b provides information on the minimum travel time between census tracts and fire stations. National Fire Protection Association's NFPA 1710 (NFPA 2016) recommends that all fire departments should complete full deployment within 8 minutes for 90 percent of the incidents. This map identifies census tracts for which the recommendations are not met. Thus, this paper outlines the key algorithm development and model integration for the coupled FAS-ACF-WO framework. One next step would be the implementation of the integrated FAS-ACF-WO model in the web application, along with future research that could aid in uncertainty characterization and propagation, physical damage and restoration modeling, among others.

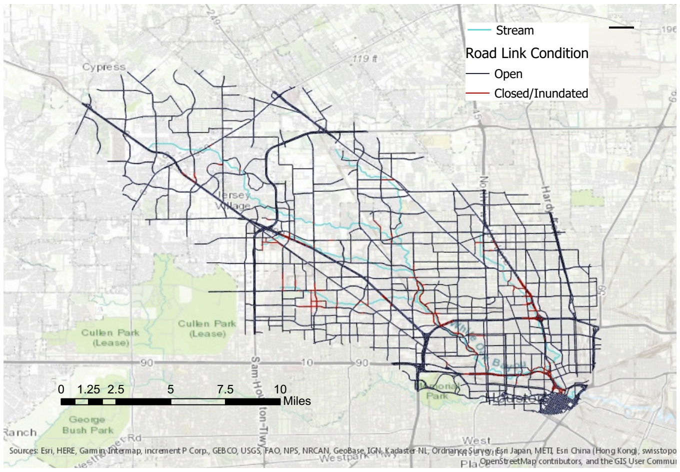


Figure 7. Map showing road link condition for a scenario. Closed roads are marked in red (Source: Esri, HCFCD)

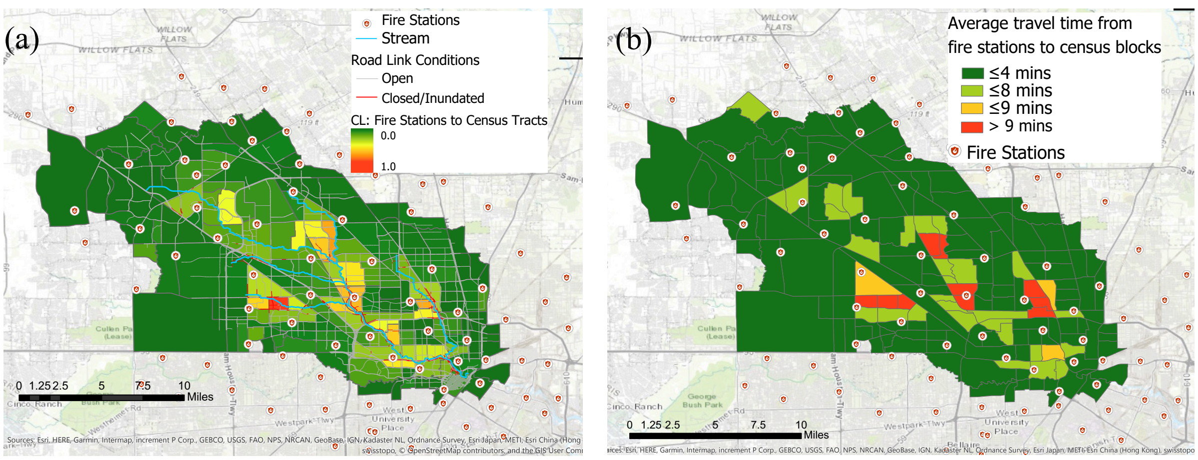


Figure 8. a) Average CL between fire stations and census tracts and b) average travel time between fire stations and census tracts for a select scenario from the FPML (Source: Esri, HCFCD, HIFLD)

CONCLUSION

This study developed a framework for improved situational awareness during a flood event with near real-time predictions of flood impacts on transportation accessibility. FAS-ACF framework leverages state of the art flood modeling, near real-time NEXRAD rainfall radar data, spatial and network analysis, and census data to generate metrics quantifying flood-related transportation accessibility disruptions between critical facilities and geographical units like census tracts. In addition to supporting near real-time emergency response activities, the results from the framework can also be used to inform flood risk mitigation and siting of critical facilities. The coupled framework is applied to the White Oak Bayou watershed, located in Houston, Texas to demonstrate the methodological approach and application. During a storm, the framework facilitates identification of inundated road links. This information can be used to identify routes for evacuation and emergency response. Further, in addition to identifying census tracts with high connectivity loss to critical facilities, the framework also estimates the average travel time for emergency response. Such information can inform pre-event planning regarding siting of facilities or infrastructure risk mitigation efforts, as well as emergency response activities. Finally, since the framework employs pre-delineated map libraries, it is computationally inexpensive and robust for real-time application.

Although demonstrated on a single watershed, the methodology developed in this study can be extended to other regions to develop an integrated flood alert system in support of emergency response as well as longer-term resilience aims. Besides, the framework could be tailored to address specific stakeholder interests such as the accessibility to fire stations and dialysis centers. Further, the framework could be enhanced by considering additional failure modes such as debris impacts on roadway functionality, road washout, and structural vulnerability of infrastructure. Furthermore, the methodology can be transitioned into a probabilistic framework by considering and propagating uncertainties associated with hazard quantification, infrastructure performance, and route selection and availability. Such a probabilistic framework will provide key insights and confidence levels to aid risk-informed decision making.

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