Sensing Flooded Roads to Support Roadway Mobility During Flooding: A Web-Based Tool and Insights from Needs Assessment Interviews

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ABSTRACT

Reliable sensing of roadway conditions during flooding is a long-standing, challenging problem with societal importance for roadway safety. Tools that provide real-time data on road conditions during floods can facilitate safer mobility, reduce vehicle-related drownings, enhance flood response efficiency, and support emergency response decision-making. Following the tenets of user-centered design, such tools should ideally address the needs of diverse stakeholders involved in flood response. Currently, existing literature lacks a thorough understanding of stakeholder needs to guide situational awareness tool development in the area of roadway mobility during flood events. This paper addresses this gap by studying the needs of stakeholders responsible for managing flood response in Houston, TX. Semi-structured one-on-one interviews were conducted with stakeholders from different Houston-based organizations responsible for managing and responding to flood hazard events in the downtown metropolitan area. Interview responses were systematically analyzed to identify: (a) data needs for facilitating efficient and safe emergency response; (b) most and least valuable information available during flooding; (c) communication and visualization strategies; (d) factors influencing stakeholder trust; and (e) factors influencing occupational stress during flood response. Finally, interview insights were used to develop a conceptual situational awareness framework and a prototype map-based tool that provides real-time road condition data during flood events. This study elucidates vital information for improving existing tools and providing preliminary guidance for future mobility-centric situational awareness tools that promote safer mobility and facilitate emergency response decision-making during flooding. While the study focused on Houston, insights gained may be useful for comparable flood-prone regions.

Keywords: Floods; Roads; Mobility; Situational awareness; Emergency response; Alert systems; User-centered design; Emergency communication; Psychological resilience.

PRACTICAL APPLICATIONS

In developed countries, 40–60% of flood fatalities are attributed to vehicle-related incidents. Flooded roads and lack of real-time road condition data pose safety risks to first responders and reduce emergency response efficiency. Understanding stakeholder needs and developing tools that address them are essential for improving the safety and efficiency of emergency response, especially considering a potential increase in flood risk to urban mobility due to climate change and other factors. Following the tenets of the user-centered design process, this study identified stakeholder needs, conceptualized a framework for sensing road conditions, and developed an open-source prototype tool in the context of flood response in Houston, Texas. Insights gained in this study can improve the efficacy of existing mobility-centric situational awareness tools and provide preliminary guidance for quick prototyping of new situational awareness tools. Further, organizations can use the insights presented here to help reduce work-related stress among emergency response personnel, thereby improving emergency response efficiency and organizational resilience.

INTRODUCTION

Houston, Texas, owes its growth partly to the 1900 Great Galveston hurricane—the deadliest natural disaster in American history. The 1900 storm caused many businesses and investments to shift focus inland from Galveston to Houston's safer shoreline (Sipes and Zeve 2012). The subsequent development in Houston, many in swampy areas, has since reduced the ability of nature to manage water and has increased its flood risk (Sipes and Zeve 2012; Sebastian et al. 2017; Zhang et al. 2018). The Bayou City has since weathered numerous floods, often at a high cost to its occupants. Hurricane Harvey (2017) (Blake and Zelinsky 2018) is the most recent of Houston's catastrophic floods. The slow-moving hurricane hovered near Houston producing record-breaking rainfall. The overflowing bayous, an overwhelmed stormwater network, and the release of water from reservoirs created widespread flooding that inundated roads and overtopped bridges. Flooded streets crippled the road transportation network leaving communities stranded without access to critical services, evacuation routes, or shelters. While rescue requests from the stranded communities overwhelmed the emergency response system (Fink 2018), flooded roads and scarcity of real-time information on roads hampered emergency response operations. As seen with Hurricane Harvey, limited knowledge about road conditions often caused delays and detours, putting responders and evacuees at risk and reduced emergency response efficiency.

During Hurricane Harvey, when the need to identify flooded roads was vital for flood response, existing tools (e.g., TxDOT DriveTexas; Texas Department of Transportation 2022), which often have limited availability, failed to deliver. The community responded by developing crowdsourcing tools to share information on flooded roads. Two example crowdsourcing efforts to identify flooded roads include U-Flood (McIntyre and Needham 2017) and a user-generated map (UGM) built using the Google My Maps tool (Dempsey et al. 2017). These tools allowed users to report roadway status using a map interface. While these ad hoc tools partially filled the information gap, they also led to information scattering and left people open to fraudulent reports from malicious or misinformed actors. U-Flood and UGM had more than 2,600 and 764 flood reports, respectively, and have been visited more than a million times. Experiences from Hurricane Harvey highlighted the need for situational awareness tools to sense flood impact on road transportation networks and its importance for emergency response and rescue missions. Developing such a tool is especially important considering the scale of emergency response in major cities such as Houston (first responders rescued more than 122,300 people and 5,200 pets during Harvey; FEMA 2017) and the potential future increase in the flood risk in many regions around the globe (Field et al. 2012; Jongman et al. 2012).

Past studies have proposed several tools for real-time sensing of flood conditions. These tools can be grouped into two categories: a) tools that use physical, social, or remote sensors to observe flooding directly, and b) tools that use mathematical models to infer potential flood conditions. Existing tools have advantages and limitations. Though highly accurate, physical sensors (e.g., water level sensors) (HCFCD 2022; Chang and Guo 2006; Islam et al. 2014; Arshad et al. 2019; Loftis et al. 2018) are expensive to deploy, operate and maintain at scale. Remote sensors (e.g., satellites and unmanned aerial vehicles) (Ahmad et al. 2019; Wieland and Martinis 2019; Matgen et al. 2020; Perks et al. 2016), though readily available for a large region, are often unsuitable for emergency response due to factors such as significant time lag between satellite revisits and occlusions. Unmanned aerial vehicles might not be operational during severe storms due to inclement weather conditions. Though ubiquitous in urban regions, social sensors (such as crowdsourcing (Google LLC 2022a) and social media (Twitter, Inc. 2022)) might be prone to bias (Fan et al. 2020a), noise (He et al. 2017), and misinformation (Praharaj et al. 2021; Jin et al. 2014). Authoritative sources (e.g., department of transportation alerts (Texas Department of Transportation 2022), official live camera feeds (Houston TranStar 2022)) are often available only for major roadways. Similarly, data availability is often limited to select watchpoints or roads adjacent to bayous for mathematical models that monitor flooding using real-time rainfall data and physics-based flood models (Versini et al. 2010; Naulin et al. 2013; Mioc et al. 2015; Morsy et al. 2018; Ming et al. 2020; Panakkal et al. 2019). Often trained on limited data, machine learning models (Mosavi et al. 2018; Zahura et al. 2020) though efficient may have unproven accuracy for unseen future storms. While existing tools provide acceptable results for their limited application, they fail to provide a comprehensive tool for facilitating safer mobility during adverse weather conditions (Dey et al. 2015). In addition, most existing tools focus on flood monitoring without directly reporting roadway conditions—thus requiring additional mental effort to infer roadway status. Due to the lack of reliable and complete information on road conditions, emergency responders often must rely on multiple tools, which adds to the work stress and reduces emergency response efficiency. In summary, comprehensive mobility-centric situational awareness tools are needed to provide accurate road condition data with high spatial and temporal availability and limited time lag.

Creating a tool that can address the mobility needs of a diverse group of stakeholders responsible for managing flood events is challenging. Stakeholders may represent institutions like hospitals, disaster response agencies, fire and police departments, or emergency rescue services—each of which has crucial but distinctive roles in emergency response resulting in varying needs for situational awareness data. To ensure that the developed framework meets the needs of target stakeholders, an iterative and responsive design cycle based on user-centered design tenets is essential. User-centered design (Robinson et al. 2005) is defined here as the process of developing tools with continuous and substantive user inputs. Several past studies have either developed or conceptualized tools for flood and related hazards using the user-centered design process: Lopez-Trujillo (2003) designed a tool for flash flood warning in Puerto Rico; Tsou and Curran (2008) presented an application to display U.S. Geological Survey hydrological data for water resource managers; Opach and Rød (2013) presented a tool to visualize vulnerability to natural hazards and support adaptation strategies in Norway; Stephens et al. (2015) developed an interactive sea-level rise viewer; Argyle et al. (2017) used user-centered design for weather forecasting and decision-support; Khamaj et al. (2019) tested the usability of smartphone weather applications; Gutierrez (2019) identified the important features of a digital volunteer platform for disaster response; and Retchless et al. (2021) developed an interactive web map to visualize local-to-national economic impacts of hurricane-driven storm surge events in Galveston Bay, Texas, US.

While current studies cover different aspects of flood response, existing literature lacks comprehensive guidance for designing situational awareness systems to support roadway mobility during flooding. Particularly, insights are required on three aspects: data needs for facilitating efficient and safe emergency response, strategies for effective communication and visualization of flood impacts, and factors influencing occupational stress (particularly given emphasis on emergency response during floods). On data needs, insights are required on: (a) existing tools adopted by stakeholders and their useful features; (b) adequacy of existing tools and need for new tools; (c) primary and supporting data required to support flood response; (d) most valuable and least valuable information for facilitating flood response; and (e) desired features of a situational awareness tool. On risk communication, insights are needed on: (a) factors influencing stakeholder trust; (b) preferred medium (website, mobile application, SMS, etc.) for communication; (c) appropriate ways to communicate uncertainty; and (d) the level of details required for informing decisions. On occupational stress, identifying factors that contribute to high stress during flood response and designing tools that can reduce stress could significantly improve emergency response efficiency and employee retention among response organizations. This paper addressed these needs and developed a prototype tool via a systemic user-centered design approach.

This study first conducted semi-structured one-on-one needs assessment interviews. During the interviews, participants from different organizations responsible for managing flood response in Houston, Texas, were queried on their data needs, risk communication preferences, and factors influencing job stress during flood response. The interview responses were systematically analyzed to identify stakeholder needs. Finally, stakeholder input was used to create a conceptual situational awareness framework and a prototype tool that addressed essential stakeholder needs.

The remainder of the paper is arranged in five sections. A brief overview of the study area (Houston, Texas) is provided in the next section, followed by a section on the methodology adopted in this study. Next, key findings from the need assessment interviews are summarized before presenting a conceptual framework for situational awareness, as well as the prototype tool developed to meet these essential stakeholder needs. Finally, conclusions and recommendations for future work in the context of mobility-centric situational awareness tools are provided.

STUDY AREA

Houston, Texas, USA was selected as the study area to conduct stakeholder interviews to understand their situational awareness needs and develop a situational awareness tool that can facilitate safer mobility during flooding. Houston is located in the southeast of Texas near the Gulf of Mexico (Fig. 1). Several environmental and anthropogenic factors render Houston prone to repeated flooding (Gori et al. 2019; Sebastian et al. 2017; Zhang et al. 2018). Environmental factors include the proximity to the hurricane-prone Gulf of Mexico, flat topography, lack of relief features, and soil conditions. Anthropogenic factors include the lack of zoning laws, rapid urbanization and urban sprawl, limited storm drainage capacity, and land use changes leading to high percentage of impervious surfaces. Consequently, Houston has experienced significant flooding in recent years. Some notable examples include Memorial Day Flood (2015), Tax Day Flood (2016), Memorial Day Flood (2016), Hurricane Harvey (2017), July 4 Flood (2018), Tropical Storm Imelda (2019) and Tropical Storm Beta (2020).

Flooding in Houston has a particularly detrimental effect on its transportation system. Even minor rainfall events often overwhelm Houston's drainage system, which is designed to carry only 2- to 5-year recurrence period rainfall in many regions (Haddock and Kanwar 2021). The overflowing water then inundates roads, which act as natural drainage due to their lower elevation compared to the surrounding parcels in many regions. Flat topography and barriers further prevent rapid drainage of water. Consequently, flooded roads, often with stagnant water, pose threat to the safety and efficiency of emergency response during a flood event. For example, 21 of 57 flood deaths during Hurricane Harvey are attributed to roadway-related incidents (Jonkman et al. 2018). Further, the paucity of real-time information on road conditions results in delays and detours that pose a significant risk to emergency responders. Finally, the concentration of medical facilities in the Texas Medical Center region near downtown Houston exacerbates any impacts of roadway flooding on health care access in Houston.

Recurring flooding necessitated the establishment of specialized agencies, such as Harris County Flood Control District and Houston TranStar, to effectively manage flood risk and support emergency response mobility in Houston. Other organizations such as the National Weather Service Houston/Galveston Office, the City of Houston, and Harris County Office of Homeland Security & Emergency Management also play an active role in managing flood events in Houston. These agencies have a wealth of experience in responding to flood events in the area and are ideal resources for understanding the needs of a real-time situational awareness tool focused on urban mobility.

In short, the existing flood risk in Houston and the potential for future increase in flooding due to climate change and other factors necessitate the development of a real-time mobility-centric situational awareness tool to sense street flooding. Due to the need for a situational awareness tool and the availability of emergency response personnel expertise, Houston is an ideal test bed for understanding the needs of a situational awareness tool focused on mobility.

METHOD

This study adapted the user-centered design process from Robinson et al. (2005) to develop a mobility-centric tool. The design process used in this study (Fig. 2) consists of six stages: needs assessment, conceptual development, prototyping, interaction & usability testing, implementation, and debugging. During the needs assessment stage, the needs and challenges of the stakeholders are assessed. The stakeholder perspectives are then used in conceptual development (which identifies the core functionality of the tool) and prototyping (which creates a working model for interaction and usability testing). Multiple iterations of prototyping and usability testing lead to the implementation and continuous debugging of the tool. This study reports results from the first three stages of the user-centered design process: needs assessment, conceptual development, and prototyping. Our future research will address the remaining stages.

During the needs assessment stage, this study conducted twenty-four one-on-one semi-structured interviews to identify the needs of the stakeholders responsible for managing flood response in Houston. During the interviews, carefully crafted questions and visual aids elicited information on data needs and challenges during flood response, communication preferences, and other factors. Next, responses were analyzed to glean insights from the interviews. Results were then used to conceptualize a situational awareness tool. Following the conceptual design, a prototype interface that could provide real-time information on flooded roads was designed. The following subsections describe this methodology in detail.

Interview Procedure and Participants

This section describes the needs assessment conducted via semi-structured interviews and the characteristics of the participants. All semi-structured interviews were conducted between November 2020 and January 2021. Employees who respond to or manage flood hazard events in Houston, TX, were invited to participate in semi-structured interviews via Zoom (Zoom Video Communications 2022). Participants were identified through (a) publicly available directories for state and federal agencies; (b) working partnerships with the research team; and (c) snowball sampling. Upon agreeing to participate in the study, participants provided their consent and demographic information via a Qualtrics survey (Qualtrics International Inc. 2022). A member of the authorship team then scheduled and conducted all interviews; Zoom interviews were audio recorded. The interviews aimed to: (a) survey the situational awareness tools commonly used by the participants in past flood events; (b) identify the information needed to support safe and efficient emergency response and the tools' relative importance; (c) determine the factors that influence the trust in a situational awareness tool; (d) understand how to effectively communicate model uncertainty and lack of data; (e) obtain feedback on the mockup of the proposed situation awareness tool and insights on how to improve its usefulness to the community. See Table 1 for the full list of interview questions. On average, interviews lasted 26.66 minutes (standard deviation, $SD = 8.54$ minutes). All interview audio recordings were transcribed by Transcription Panda (SJM Ventures LLC 2021), a company that provides high-quality audio transcription services. Post-transcription, a member of the authorship team reviewed all transcriptions for errors and then began to synthesize themes and summarize findings.

Twenty-four employees ($n = 24$) participated in the semi-structured interviews. Participants were employed in occupations that entailed collecting and publicizing flooding information (29%; $n = 7$), making organizational decisions (42%; $n = 10$), and responding to flood-related emergencies (38%; $n = 9$) (Fig. 3a). Twenty-nine percent (29%) of participants worked as emergency responders (e.g., firefighters, policemen; $n = 7$), 46% as emergency services directors ($n = 11$) for public (e.g., university) or private (e.g., hospital) institutions, 17% as meteorologists for the state of Texas (e.g., Houston Mayor's Office; $n = 4$), and 8% for federal organizations (e.g., National Oceanic and Atmospheric Administration, NOAA; $n = 2$). Participants were employed at organizations including universities (e.g., Rice University, The University of Houston, and The University of Texas), hospitals (e.g., Texas Children's Hospital), health departments (e.g., Harris Health System), police and fire departments (e.g., Rice University Police Department), public agencies (e.g., Hatzalah of Houston, Westlake Fire Department), transportation departments (Houston TranStar), flood management agencies (Harris County Flood Control District), local emergency response organizations (e.g., Harris County Office of Homeland Security & Emergency Management), federal and state organizations (e.g., National Weather Service), and the City of Houston. The participants' organizational tenure ranges from 1 years to 29 years, with an average of 12.90 years ($SD = 8.19$).

Half of the of respondents (48%; Fig. 3b) reported that their jobs required them to travel during floods, while the remaining half (52%) said that they were either rarely (26%) or never required (26%) to travel for work during flooding. Among the participants, 92% ($n = 22$; Fig. 3c) of them stated that street flooding affected their capacity to perform their job duties to some degree; with street flooding directly impacting the ability to perform work-related tasks for 75% of participants ($n = 18$); staffing needs impacting 17% of participants ($n = 4$); and the commute to work impacting 8% of participants ($n = 2$). The proportionately high number of respondents who said that roadway flooding affected their ability to carry out their job duties emphasizes the significance of street flooding. In conclusion, the study's participants have a variety of job responsibilities, expertise, and experience in different facets of flood disaster response. The chosen participants also represented important organizations crucial to Houston's flood response. The insights generated by these needs assessment interviews provided a comprehensive understanding of the essential requirements for a situational awareness system addressing the needs of key stakeholders.

Conceptual Development and Prototype Design

The interview responses were analyzed to understand the characteristics desired in a mobility-centric situational awareness tool. Armed with this information, a conceptual design of a situational awareness tool was developed considering stakeholder needs. Creating a tool that could address all stakeholder requirements was prohibitively expensive. For example, significant investments are required to develop and test a mobile application or collect additional contextual data (such as information on building heights). Consequently, this study prioritizes the development of a mobility-centric tool that accommodates essential stakeholder requirements. Following the conceptual design, an example tool prototype with an interactive web-based user interface, interoperability components, and representative data was deployed. This developed prototype is currently undergoing usability testing before a wider deployment; such results are not provided here and will be presented in future work.

RESULTS FROM THE NEEDS ASSESSMENT INTERVIEWS AND DISCUSSIONS

Occupational Stress Findings

Near the start of the interview, we asked participants to describe the stressors and problems they most often faced when managing a flood event (Fig. 4a, b). In terms of occupational stressors, 62% of participants reported high concern for the safety of other respondents and evacuees while conducting their work (Fig. 4a). Other common stressors included flooded roads, access to limited information about street flooding, uncertainty of flood events, accuracy of information reflected on flood-related platforms, and prolonged flooding events. In the event of a power outage, participants also reported concerns related to redundancies in their communication systems (Fig. 4c) via personal cell phones, the government emergency telecommunication service, landlines, and the local news. When asked about the common emotions experienced during flood response, participants reported both positive (focused, adrenaline rush) and negative (overwhelmed, frustrated, and helplessness) emotions (Fig. 4b). These findings highlight the need to equip stakeholders with accurate real-time flood information. A dependable tool that can provide reliable real-time situational awareness data can reduce work-related stress. Any decrease in occupational stress could boost organizational efficiency in emergency response and increase employee retention (Ongori and Agolla 2008).

Extant Platforms Used for Obtaining Real-Time Flood Information

Participants reported using a variety of platforms (Fig. 4d) to obtain information on flood events. Platforms used, in order from most to least often used, included: (a) internal organizational communication platforms (n = 13) (b) NOAA (n = 6); (c) Emergency Medical Services (EMS) dispatchers (n = 6); (d) Harris County Office of Homeland Security and Emergency Management (TDEM) (n = 5); (e) Houston TranStar (Houston TranStar 2022) (n = 5); (f) personal knowledge of roads (n = 4); (g) news media (n = 3); (h) Rice TMC Flood Alert System (Fang et al. 2011) (n = 3); (i) StormGEO (n = 2); (j) Google Maps (n = 2); (k) social media (n = 2); (l) Texas Department of Transportation (TxDOT) DriveTexas (n = 2), and (m) Everbridge (n = 1).

Half of the participants reported using internal organizational communications. Hence, interfacing with internal communication tools is necessary for the broader dissemination of real-time information; any new tools must be interoperable with existing internal tools using technologies such as Representational State Transfer (REST) Application Programming Interface (API). After internal organizational communication platforms, participants primarily relied on authoritative sources from federal, state, and city organizations.

Interestingly, very few participants relied on Google Maps or social media platforms such as Twitter. Recent literature (Zhang et al. 2019; Fan et al. 2020b) suggests that social media analytics can detect disaster, track its evolution, and sense community response and needs. This is especially true for urban regions, such as Houston, with active social media activity. Further, other crowdsourcing tools such as Waze (Google LLC 2022a) and U-Flood (McIntyre and Needham 2017) are absent from the sources mentioned by the participants. These citizen-led data collection or crowdsourcing efforts played a pivotal role in flood response during Hurricane Harvey (2017) in Houston. These results indicate a gap between the sources that emergency personnel and decision-makers rely on to make decisions and the platforms used by the public for data creation and communication. Although this study's small sample size and narrow focus preclude such conclusions, they highlight the need for additional research on communication between the public and responders during flood events. However, for the purpose of this study we focus on the situational awareness needs from employees in organizations responsible for managing and responding to flood related events and their mobility impacts.

Preferred Medium for Accessing Existing Data Sources

Seventy one percent of the participants ($n = 17$) accessed existing platforms online via websites, compared to 17% ($n = 4$) who used phone applications and 13% ($n = 3$) who accessed these platforms using news media (Fig. 4e). In comparison to phone applications or news media, interview results show that websites are the most popular way to access existing platforms.

Most and Least Valuable Information for Facilitating Situational Awareness

Interview participants provide nine suggestions on data requirements or algorithmic improvements. First, provide information on the spatial and temporal distribution of rainfall. Second, improve the predictive power of existing rainfall algorithms. Third, provide flood depth estimates that help identify flooded areas, isolated neighborhoods, and aid in equipment selection. Fourth, provide road closures that aid routing during emergency response and facilitate unavoidable travel during flood events. While existing tools predominantly provide road closure data for freeways, participants highlighted the need for flood information at feeder roads, residential streets, and other minor roads. Participants emphasized the lack of data for roads other than freeways as an area where current tools may be improved. Fifth, supply information on locations of utilities such as power lines and sewage lines to improve awareness of secondary hazards, especially in the context of high-water rescues during windstorms or hurricanes. Sixth, furnish information on topographic details such as ground elevation and general terrain data to aid in navigation during rescue operations. Seventh, enable visual confirmation of ground conditions using live camera feeds. Such camera feed should facilitate clear vision even at night using good lighting or infrared cameras for night vision. Eighth, improve the predictive power and accuracy of existing tools; participants find existing tools lack predictive power and accuracy. This opinion highlights the need for continued research in developing methods that can improve the prediction power of methods that estimate rainfall, flooding, and flood impact on communities. Finally, provide real-time information for situational awareness. Participants suggested the availability of real-time data from existing tools as a preferred feature, along with targeted information, predictive power, and informative data (Fig. 4g).

Interview participants provide five suggestions for improving visualization and communication of model results. First, use a simpler user interface that is more user-friendly and intuitive. This highlights the necessity for existing tools to improve their graphical user interface to accommodate the stakeholders' preferences. Second, use everyday language rather than domain-specific terms. The usability of existing tools could be greatly enhanced by using simpler language equivalents of domain-specific terms. Third, conduct public education initiatives to instruct people on how to interpret and use the information displayed in the tool. Fourth, use visual, rather than written, representations of situational awareness data. Finally, provide information targeted to their job duties.

Information that is not necessarily valuable includes light flooding, traffic information, and predictions based on just historical data. Light flooding may not cause widespread flood damages or mobility concerns. The ability to hide minor or nuisance flooding can declutter hazard visualization and enable stakeholders to focus on severely impacted communities. Many participants reported that real-time traffic data are less valuable. This is interesting since many flood events could result in road closures and traffic redistribution due to changes in travel demand and network capacity. Under such dynamic conditions, real-time traffic data are essential for routing and avoiding delays and detours during emergency response. Further investigation is required to gain additional context on the utility of real-time traffic data. Finally, participants suggested that predictions based on just historical data are not helpful. This suggestion shows a lack of trust in models based on just historical data and a belief that such models could fail to capture the dynamic nature of flooding and inter-event variability. Such a belief may be even more punctuated in other regions beyond Houston, with more limited historical rainfall records and even sparser flood records.

Factors Influencing Trust in Situational Awareness Tools

Trust in a tool is essential to facilitate its adoption in practice. Trust is especially important for high-risk scenarios like high-water rescue and emergency response. This section discusses the five key factors that influence stakeholder trust identified in this research (Fig. 4f). First, 42% of participants reported past tool reliability as the main reason for trusting a tool. This suggests that consistently providing reliable information is pivotal for gaining stakeholder trust. Second, 21% said they trusted mathematical predictions based on scientific reasoning. It might be helpful to communicate the methodology adopted to predict flooding and its advantages and limitations. Transparent communication on the mathematical models used could enhance community trust in the system. Third, 17% identified inter-organizational partnerships as the reason for their trust in the system. This further emphasizes the need to co-develop tools with stakeholders. Fourth, 16% attributed trust to the ability to visually confirm the data using cameras. Enabling stakeholders to verify the model prediction by providing corroborating sources of data such as live camera feed could enhance stakeholder trust. Finally, 4% of participants reported tool performance improvement over time as a reason for trusting the tool. These key insights offer information on the factors influencing stakeholder trust and steps tool developers can take to gain user trust and achieve wider adoption of the tool.

Perceived Usefulness of Mobility-Centric Situational Awareness Tools Using Mock-up Images

During the interview, participants reviewed mockup images (Fig. 5) of a situational awareness tool that would theoretically provide real-time information on road conditions. When asked about the perceived usefulness of the platform, based on the mockup, 64% of participants reported it as being useful, 32% said it was partially useful, and 4% stated that it was not useful. The participant who did not perceive the platform to be useful ($n = 1$) reported relying on personal knowledge of surface roads and their tendency to flood as more useful than flood awareness tools given 33 years of experience as an Emergency Management Services provider in the downtown Houston area.

Overall, participants confirmed the need for a mobility-centric situational awareness tool and attested to its usefulness. For example, one Director of Emergency Management stated: “I love [this tool]. I'm very excited and I hope that this is something that you guys can make happen. I think it's going to be very useful. We'd use it. It would eliminate me needing to go to three or four different outlets. I could just go right here because you're already doing it." Similarly, an Emergency Services Director remarked: "This [tool] would be great for emergency teams, such as the police team and firefighters. This [tool] can minimize so many problems, which can ultimately save money . . . and save lives." One Emergency Services Responder commented: "I think [developing this tool] is a very noble cause. I think it's very smart and I think it's very timely. I think it can help out not only in the greater Houston area, but definitely moving to a national platform." Finally, a dispatcher at a police department highlighted that the OpenSafe Fusion tool would be useful because "A lot of times we get calls from individuals asking us which roads open, which ones are closed, what's the best route for them to take from point A to point B without hitting floodwater, so [this tool] actually would help."

In addition to the previously identified recommendations, participants provided the following suggestions to improve the tool: (a) provide users with the ability to interact with map elements. Example interactions include zooming in and out of different map areas, clicking and expanding elements on the map to see additional information, and switching between representations of the same data with varying levels of detail; (b) provide exact flood depth information in addition to road condition. Conveying depth information will provide additional context during emergency response and could aid in equipment selection; (c) provide additional data such as building heights to assist with high water rescues; (d) provide additional communication channels such as chatrooms to facilitate information exchange and collaboration between users; and (e) provide time stamps on all data to indicate the recency of the observations. Further, participants encouraged the developers to consider (f) the color and design of map elements to make it more intuitive and avoid confusion. For example, using grey for conveying missing data is visually confusing because the color blends in with map's background. Similarly, the green and red colors used to represent open and flooded roads conflicts with the convention of using those colors to mark traffic conditions in apps such as Google Maps. Participants reported an interest in (g) the ability to overlay radar and radar-inferred precipitation information on the map along with camera views whenever possible. Finally, participants asked the developers to (h) communicate the limitations of the system and provide warning and disclaimers tied to liability.

Preferred Medium for Accessing the New Tool

When asked about the preferred medium for accessing the tool, 42% of participants preferred mobile device access only, 29% preferred website access only, 1% text alerts only, and 28% preferred accessing the tool through all three mediums (Fig. 4h). All participants responded "yes" when questioned separately about whether access via all three options would be preferred. Participants' feedback suggests a general preference for a mobile-first system that is complimented with a web dashboard. An intriguing finding in this context is the high preference for mobile access over website access, which contrasts sharply with the choice expressed for the available tools, where website access was chosen by 71% of participants. This result suggests that users favor mobile applications over websites. Both new and existing tools might focus on improving the experience on their mobile offerings to encourage more people to use them.

Communicating Uncertainty in Model Prediction

Real-time sensing of flooding often involves mathematical predictions which contain uncertainty. Effective communication of uncertainties is essential to make risk-informed decisions. To test the best way to communicate uncertainty in model predictions this study created three mockups. In the first mockup (Fig. 5, Option 1), all roads were marked as either flooded (red) or open (green). Streets for which the model did not have data were also marked open. While tagging links without data as open might seem inappropriate, several existing tools only predict flooded roads, and the community implicitly assumes that roads without explicit flood tags are open; Option 1 simulates these conditions. In the second mockup (Fig. 5, Option 2), roads were marked in one of three ways: open (green), flooded (red), or no data (grey). In the third mockup (Fig. 5, Option 3), a linear scale was used to convey the probability of road flooding. The probability of flooding ranges from 0% to 100% and encodes the confidence of the model in its prediction.

Participants selected Option 1 only 2% of the time. Indicating that tools should acknowledge the availability of data. Sixty-five percentage (65%) of participants selected Option 2 and 33% selected Option 3. In general, participants preferred Option 2 (a simple three-color schema) over Option 3, which communicated uncertainty in model prediction. Interestingly participants in managerial positions were more likely to select Option 3 than emergency response personnel active in evacuation and high-water rescues. This indicates that a simplified categorization of flood conditions might be suitable for response personnel active on the field to reduce information overload and decision fatigue. Such categorization might be either 3-class (Open, flooded, and no data) or 5-class (no flood, minor flood, moderate flood, major flood and no data). A more detailed linear scale which can communicate prediction uncertainty might be more suitable for participants under lower stress conditions. Additionally, the participants recommended providing the ability to easily switch between Options 2 and 3. Finally, 76% of participants (and 80% of the EMTs) suggested including a navigations interface, similar to Google Maps, capable of suggesting routes that avoided flooded roads as a helpful tool to facilitate mobility during floods.

CONCEPTUAL DESIGN AND PROTOTYPE

Conceptual Design

Experiences from Hurricane Harvey and observations from the needs assessment interviews highlight the need to develop improved tools to sense flooded roads in real time. Many existing tools in Houston are primarily focused on flood monitoring. For example, the Rice-TMC flood alert system (Fang et al. 2011; SSPEED Center 2023) reports flood inundation in the Brays Bayou watershed and provides no information on roadway conditions. Similarly, services from NOAA (NOAA 2023), TDEM (TDEM 2023), and StormGEO (StormGeo AS 2023) often focus on general weather- and flood-related information with none to limited information on roadway status. While the information on flood conditions is essential, limited information on roadway status limits their usefulness for facilitating safer mobility. Both internal communication platforms (e.g., emails) and information from EMS dispatchers have limited ability to significantly enhance situational awareness or facilitate the inter-organizational cooperation necessary for effective emergency response. Though camera data from Houston TranStar (Houston TranStar 2022) and road flood reports from

News and social media (Twitter, Inc. 2022) could inform roadway status, they require additional manual processing to glean actionable inputs—further adding to the cognitive load under stressful conditions. Geolocated road condition data is available from crowdsourcing tools like Google Maps and Waze (Google LLC 2022a). However, their veracity is disputed (Praharaj et al. 2021), and only a few emergency response professionals presently use them (as indicated in the interviews). The TxDOT DriveTexas road condition data (Texas Department of Transportation 2022) offer trustworthy, verified information, but the data is only available for major highways. Due to the inability of existing tools to provide comprehensive and reliable road condition data, emergency responders are often forced to depend on multiple data sources and switch between them to track rapidly evolving flood conditions. A comprehensive situational awareness tool that can identify flooded roads and network-level impacts on flooding could improve emergency response safety and efficiency.

Deploying more sensors, such as cameras and water level sensors (as suggested during the needs assessment interviews), can improve data availability. However, these measures are often prohibitively expensive, even for affluent communities. While sources that can directly observe flooding are limited and deploying new sensing infrastructure is expensive, major urban centers such as Houston do possess data sources that could be leveraged to gain insights on flooding and, subsequently, road conditions. Some example sources include traffic cameras, social media, stream gages, and real-time flood models. These sources typically require additional manual processing (e.g., traffic cameras) to glean information on flooded roads, which is often impractical during flood events. A framework that can leverage all available sources in an automated way could significantly improve data availability and accuracy for real-time situational awareness.

This study conceptualizes a situational awareness framework (Fig.6) called Open-source Situational Awareness Framework for Mobility using Data Fusion (OpenSafe Fusion)(Panakkal 2022). Note that the technical underpinnings of OpenSafe Fusion are not a focus of this study, but rather its conceptual design to meet stakeholder identified needs for such a tool. Identifying reliable real-time data sources in the research area monitoring either flooding or road conditions is the first step in developing OpenSafe Fusion. Needs assessment interviews, literature review, and information on extant data sources used by stakeholders can help identify data sources in the study region. For example, Fig.4d shows some extant platforms and data sources used by emergency response agencies in Houston. In the conceptual design presented here, OpenSafe Fusion uses six real-time data sources—social media data from Twitter (Twitter, Inc. 2022), live camera feed from Houston TranStar (Houston TranStar 2022), water level sensor from USGS and Harris County Flood Control District (HCFCD) (USGS 2023; HCFCD 2022), a new crowdsourcing tool (Mapbox 2022), real-time flood models based on OpenSafe Mobility (Panakkal et al. 2022), and authoritative data (traffic alerts) from TxDOT DriveTexas (Texas Department of Transportation 2022). OpenSafe Fusion acquires real-time data from existing sources using Application Programming Interface calls (e.g., Texas Department of Transportation (2023)) or via web scraping at regular intervals.

OpenSafe Fusion can use data from sources that directly or indirectly observe roadway status. Information from sources that provide georeferenced road conditions data can be used by OpenSafe Fusion (e.g., TxDOT DriveTexas and OpenSafe Mobility) with little or no processing. For data sources that may not directly observe flooding on roads, OpenSafe Fusion leverages automated source-specific workflows using techniques such as deep learning and spatial analyses to infer road conditions. For example, flooded roads are identified from traffic cameras using a deep-learning image classification model (based on ResNet-34 (He et al. 2016)) and transfer learning. The classification model was fine-tuned using a new annotated image dataset (2300 images) to predict the road flood condition. Similarly, flooded entities can be identified from tweets using entity extraction and geocoding. First, CrisisMMD annotated Twitter dataset (Alam et al. 2018) is used to train a deep-learning-based natural language classifier (Sanh et al. 2019) to filter flood-related tweets. Entities from the filtered tweets are identified using Named-entity recognition (using Google entity extraction API (Google LLC 2023a)) and then geocoded using geocoding techniques (using Google Geocoding API (Google LLC 2023b)). Likewise, subtracting digital elevation data from real-time water-level data (HCFCD 2022) from sensors can provide flood depths at roads adjacent to the sensor locations. Finally, OpenSafe Fusion provides also provides an inbuilt crowdsourcing tool (Mapbox 2022) to facilitate information sharing between emergency response personnel (a need identified during the needs assessment interviews).

Once real-time data is collected and processed to extract road condition data, OpenSafe Fusion leverages Bayes Filter (Thrun et al. 2006) to fuse the observations while explicitly accounting for data type heterogeneity, spatial and temporal resolution mismatch, and varying accuracy and time lag. The combined road condition data are then used to quantify network-level impacts of flooding on roadway access (e.g., access to critical facilities such as hospitals) to provide a more holistic view of flood impacts to aid decision-making. Finally, model results are communicated to stakeholders via a website. Further, OpenSafe Fusion will also provide REST API access to model results; existing tools can leverage OpenSafe Fusion results to gain additional context on flooding. Further studies are underway to validate the proposed framework, and this paper limits its scope to the conceptual design as informed by the user-centered design process.

Prototype Development

This section describes the prototype web tool (Fig. 7a) developed to communicate the results from the OpenSafe Fusion framework for Houston, Texas. (Ideally, a mobile application would be subsequently prototyped per stakeholder input.) The web-based geovisualization interface is built using JavaScript, CSS, HTML, and Mapbox. The tool contains three main sections—a collapsible navigation pane on the left, the main map window, and the legend pane at the bottom right. The navigation pane contains buttons that control the visibility of map layers. For example, the “Flooded Roads” navigation button (Item 1) controls the visibility of the “Flooded roads” layer in the main map window. The navigation pane buttons enable stakeholders to filter only the information required for their job-related tasks—thus preventing cognitive overload during high-stress situations. Further, the legend pane provides information on the map symbols and will be automatically updated based on the layers available in the main map window.

The main outputs of the OpenSafe Fusion framework are information on flooded roads (Item 1 in Fig. 7a) and maps showing network-level impacts of road closures on access to select critical facilities, such as fire stations, hospitals, and dialysis centers (Items 2-4 in Fig. 7a). When the

"Flooded Roads" navigation button is toggled on (as indicated by the darker gray button color), the main window will display the map of flooded roads at the current time step. These flooded roads are identified by combining information from multiple sources.

The proposed web interface reports all processed observations used by the model to infer the current model predictions, thus addressing the stakeholder suggestion to supply corroborative evidence that enables them to verify the model predictions. Users can toggle the visibility of the reports from individual sources using buttons (Items 5 to 10) in Fig. 7a to verify model prediction and gain additional insights on the flood conditions. For example, Fig. 8a shows the flooded locations identified from tweets. Similar, Fig. 8b provide information on road condition inferred from traffic cameras. In both cases, the observations are color-coded to indicate the model predicted flood severity. Further, users can access more information such as links to the original Twitter post or current camera feed via pop-ups. Finally, the web tool also provides a crowdsourcing interface (Fig. 8c) where stakeholders can mark flooded roads using different shapes (Item 11 in Fig. 7a). This enables sharing of real-time information between stakeholders, thereby improving data availability.

In addition to road conditions, OpenSafe Fusion quantifies network-level impacts of flooding on access to critical facilities to provide a holistic view of flood impacts and prioritize emergency response. OpenSafe Fusion quantifies access loss using the connectivity loss (CL) ratio. The CL ratio is defined as $1 - D_n/D_f$, where D_n is the shortest distance between an origin and destination pair under normal conditions, and D_f is the shortest distance between the exact origin and destination pair in the current flooded situation. The CL ratio ranges from 0 to 1, with 0 signifying no effect from flooding on network access and 1 representing a total loss of access. CL ration is estimated for each node in the road network, and the results are aggregated at census tracts for visualization. Please refer to Gori et al. (2020) for more details on the estimation of CL. In the current prototype, OpenSafe Fusion estimates network-level impacts of road closures on access to fire stations, hospitals, and dialysis centers. Fig. 7b shows an example map quantifying flood impact on hospital access for census tracts in the study region. Stakeholders can identify regions with limited access to hospitals and prioritize emergency response.

The features of the prototype as informed by and compared to essential requirements identified from stakeholder interviews are shown in Table 2. In this first iteration, this study focused on roadway mobility related application. Future versions will address other needs not addressed in this iteration. This web tool is currently undergoing interaction and usability testing using semi-structured interviews. Inputs from the interview participants will further aid in refining the tool before a wider deployment.

CONCLUSIONS

This paper presented the findings of an ongoing study to develop reliable mobility-centric situational awareness tools for emergency response applications during floods. It primarily presented findings from needs assessment interviews, conceptual design, and prototype development in the context of a user-centered design process. This study first conducted semi-structured one-on-one interviews with 24 participants representing different organizations responsible for managing flood response in Houston. Qualitative and quantitative analyses of interview responses provided insights on data requirements, communication preferences, and factors influencing occupational stress and trust in situational awareness tools. The insights gained during the interviews were then used to develop a conceptual framework that fuses observations from multiple real-time data sources to provide comprehensive and accurate information on road conditions. Finally, a prototype web tool was developed to provide real-time information on flooded roads and network level impacts of flooding on access to select critical facilities, such as hospitals. The conceptual framework and the prototype tool address several stakeholder needs identified during the interviews.

This study advanced our understanding of the situational awareness needs of stakeholders responsible for managing flood response in Houston. Notably, this is one of the first studies to provide a comprehensive outlook on data needs, as well as visualization and communication preferences for mobility-centric situational awareness during flooding. This contribution is significant and timely considering the potential increase in flood risk to roadway mobility due to climate change and other factors that necessitate better situational awareness tools to support emergency response. A lack of knowledge about and guidance around stakeholder needs could hinder timely and effective development of situational awareness tools. Insights from this research, such as data needs, visualization preferences, and communication strategies, may help with the quick prototyping of situational awareness tools in flood-prone areas. For example, ad hoc tools such as U-Flood can leverage the insights presented here to quickly deploy tools. Moreover, this study offers guidance on the user-centric design process of mobility-centric situational awareness tools. Finally, existing tools could also benefit from the insights presented here to improve their offering by addressing stakeholder needs. Similarly, organizations could make use of tools like OpenSafe Fusion to help reduce work-related stress among emergency response personnel, thereby improving emergency response efficiency and organizational resilience.

The proposed prototype tool is currently being tested for usability, and the OpenSafe Fusion methodology is undergoing extensive validation studies. Extensive and continued validation studies are required to ensure that the tool offers accurate data on flood impacts on the road transportation network, and the developed tool satisfies stakeholder requirements and usability. To test model accuracy, OpenSafe Fusion framework performance should be quantified under diverse rainfall scenarios, including flash flooding, nuisance flooding, and flooding due to tropical storms and hurricanes. The effectiveness of OpenSafe Fusion can be measured by simulating past storms and comparing them with observed ground truth. Furthermore, once deployed, the model's performance should be continuously monitored and improved. Similarly, focus groups and usability studies should be pursued to maintain stakeholder interaction and ensure that the tool continues to satisfy their needs. Any insights gained through the validation studies and usability testing should be used to improve the tool before a wider deployment. Since the study presented here is based in Houston, future studies should also perform similar user-driven tool development work in other regions to provide more generalizable insights on emergency response stakeholder requirements.

The insights this work offers should be considered in the context of its limitations. First, a generalization of the stakeholder requirements identified during the interviews should be approached with caution. The limited sample size (n = 24) and focus on Houston might preclude generalizing the observations to other regions. However, the insights could be used as preliminary guidance in the absence of region-specific insights. Second, the study limited the survey participants to employees from select organizations responsible for managing flood response in Houston. The insights may not represent the needs of the public or any organizations in different sectors. Third, user-driven design is an iterative process—additional insights during usability testing will update the prototype design of the tool. Finally, the prototype tools did not address all requirements identified during interviews due to technical challenges or limited resources. In the prototype presented, efforts were focused on developing an affordable open-source tool capable of providing reliable sensing of flooded roads and flood impacts on network accessibility. However, the tool could be easily extended by adding additional data sources or features in the future. Despite these shortcomings, this paper provides valuable insights into the needs of stakeholders responsible for managing flooding and actionable recommendations for improving situational awareness tools.

DATA AVAILABILITY STATEMENT

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions (e.g., anonymized data).

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List of Tables

TABLE 1. Interview questions used in the needs assessment interviews

		Questions
Q1	a.	Describe a typical day for you during a flood hazard event.
	b.	What are your roles, responsibilities, and goals?
Q2	a.	What are the main stressors you face and must overcome while working during such events?
Q3	a.	What are the emotional reactions you have to flood hazard events in Houston?
	b.	Why do you experience that reaction?
Q4	a.	Does your job require traveling (e.g., driving) during a flood hazard event?
Q5	a.	How does information about flood conditions, and in particular road flooding, influence your ability to work or the job functions you perform?
Q6	a.	Please list and describe the source(s) of information you use to track and maintain safety while working during flood hazard events in Houston, Texas.
	b.	What do you like best about this system (or these systems)?
	c.	How can these systems (or this system) be improved?
	d.	How do you access road closure information during flood events?
	e.	What information regarding flood levels and road closures is most valuable? Least valuable?
	f.	What makes you trust the systems you use?
	g.	If you lost power to your mobile device (or other electronic platform) during a flood event, what alternate communication methods do you use to perform you job safely and effectively?
Q7	a.	If a new flood awareness system was developed, what would you like to see available/included in that system (e.g., useful, and necessary information and components)?
	b.	What would you not want included in that system (e.g., unnecessary details or components)?
Q8	a.	Are there any other insights about this process or these systems you can share with us?
Q9	a.	We are working to develop a new flood-awareness system that will combine all the data sources you just reviewed (social media, traffic cameras, flood sensors, the flood alert system, the highway alert system, and crowdsourcing). By combining these systems, we hope to draw on all the pros and address all the cons.
	b.	What would be the most helpful way to present this combined data to you (and others)?
	c.	How would you like road closure information to be conveyed? What level of information would you need to perform your job effectively? For example, here are three options for our system; please indicate which you would prefer to use and why.
	d.	What would be most useful to you in order to perform your job?
	e.	How would you like to access this information (e.g., website, mobile device, through platforms you already use)?
	f.	What preferences can you share about this integrated system that you think we should consider

TABLE 2. Overview of select stakeholder requirements and prototype status

Stakeholder requirements	Status of implementation[a]	Comments
Data		
Hazard data		
Information on flooded roads	Implemented	Identifies flooded and open roads; estimates network level impacts of flooded roads (Fig. 7, Items 1 to 4).
Flood depth estimates	Implemented	Obtained from flood models when available (Fig. 7, Item 5).
Rainfall prediction	Partially implemented	No rainfall prediction. Observed rainfall from radar data available in the validation tab (Fig. 7).
Infrastructure data and topography		
Data on utilities (e.g., power lines)	Not implemented	Not implemented in this version. Infrastructure data are usually static and can be easily included in a future version.
Data on building heights	Not implemented	Not implemented in this version.
Topographic data	Not implemented	Not implemented in this version.
Trust and user validation related		
Access to corroborating data	Implemented	All information used by the model is accessible from the interface.
Communication		
Medium of communication		
Mobile application	Not implemented	No separate mobile application at this stage. The website design is optimized for touch screens and is mobile-friendly.
Website	Implemented	An open source website dashboard is available.
Text alerts	Not implemented	No text alerts at this point since text would require tailoring to specific user and their duties.
User interface design		
Interactivity	Implemented	Users have the ability to interact with map elements using a variety of elements.
Visual information	Implemented	All information are geolocated and contextualized on a map.
Simpler language	Implemented	Easily accessible language is used.[b]
User-friendly interface	Implemented	A simple, intuitive, and user-friendly interface is used.[b]
Targeted information	Implemented	The prototype enables users to filter only the data relevant to their duties.
Facilitate information exchange	Partially implemented	The prototype enables information exchange via crowdsourcing (Fig 7, item 8); no chatroom or direct messaging capability in the current version.
Factors influencing trust		
Reliability in the past	—	Not applicable.
Science-based predictions	Implemented	Model senses flooding by fusing observations from of reliable data sources.
Provides visual confirmation	Implemented	The tool enables users to validate all observations used by the model.
Partnership	Implemented	This tool is developed following a user-centered design process.
Targeted information	Implemented	The prototype enable users to filter only the data relevant to their duties.
Improvement over time	—	Not applicable.

Note: [a] Status of implementation in the current prototype. [b] Subjective opinion. Further studies are required to validate this statement.

List of Figures

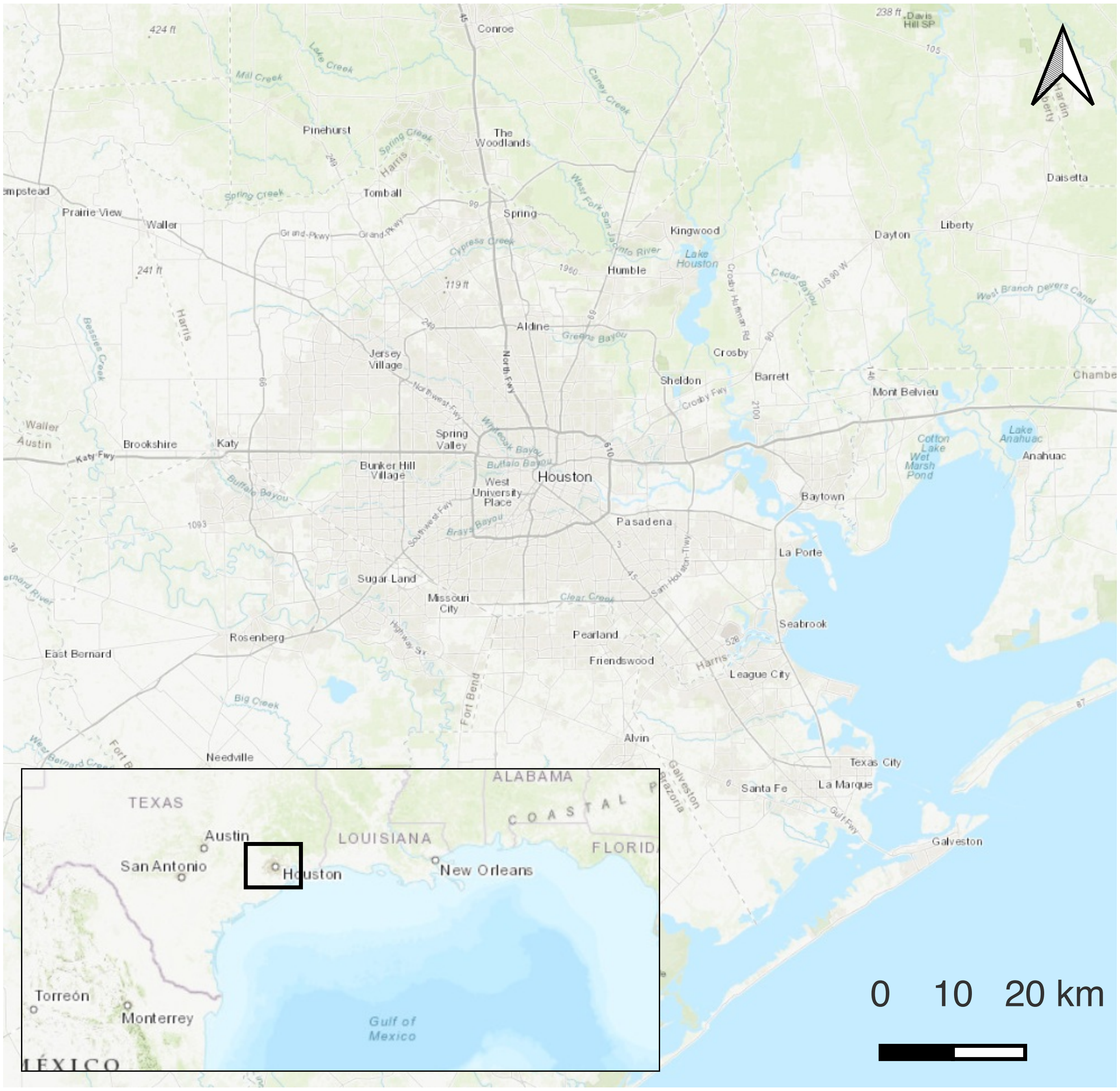


FIG. 1. Houston, Texas, US, is selected as the study area. Houston, located in Southeast Texas near the Gulf of Mexico, has historically experienced several flood events associated with hurricanes and severe storms. Source: ESRI (2022)

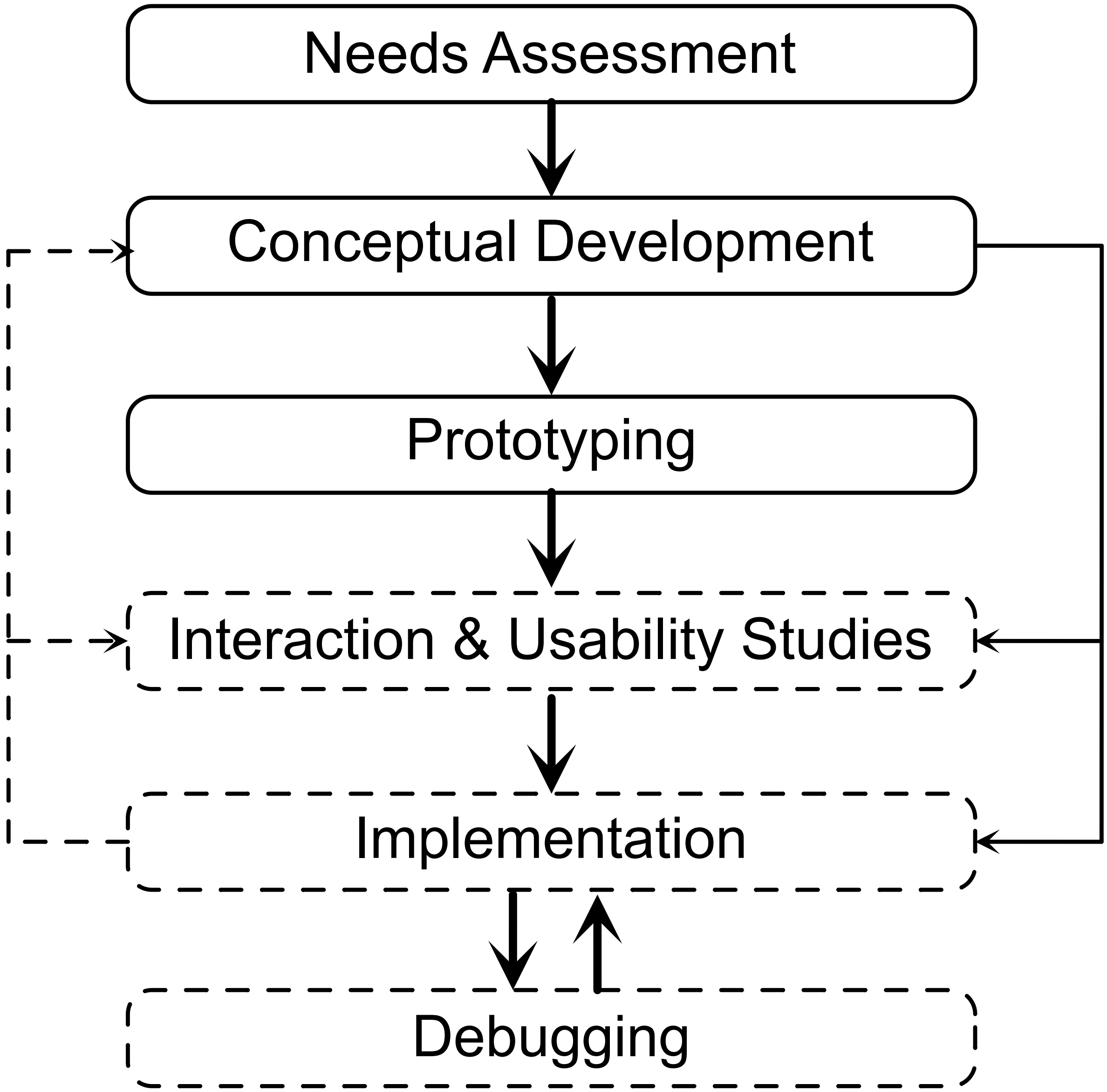


FIG. 2. Methodology used in this study to develop a mobility-centric situational awareness tool to sense flooded roads. This paper describes results from the first three stages (shapes with solid lines in the figure) following a user-centered design process (modified after Robinson et al. 2005). Shapes with dotted lines indicate stages that are either planned or underway. Lines indicate the non-linear relationships between the design steps.

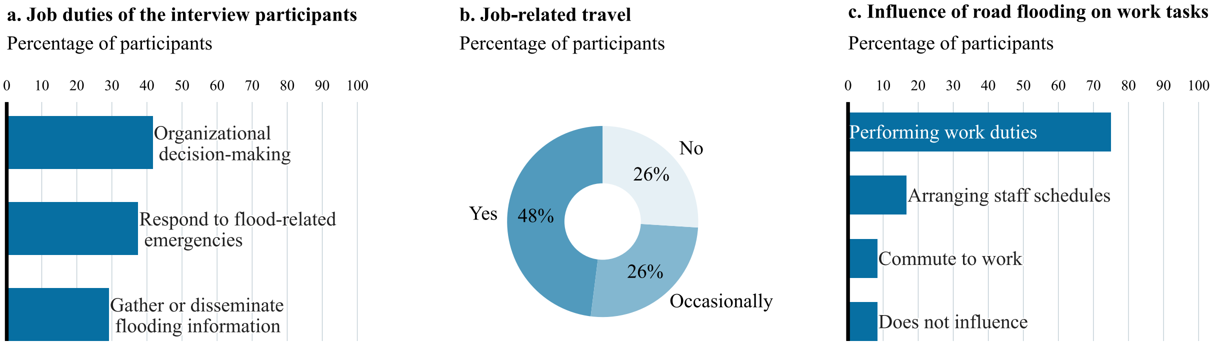


FIG. 3. Characteristics of the interview participants. The participants have a variety of job responsibilities in different facets of flood response. Further, 92% of the participants stated that street flooding affected their capacity to perform their job duties to some degree.

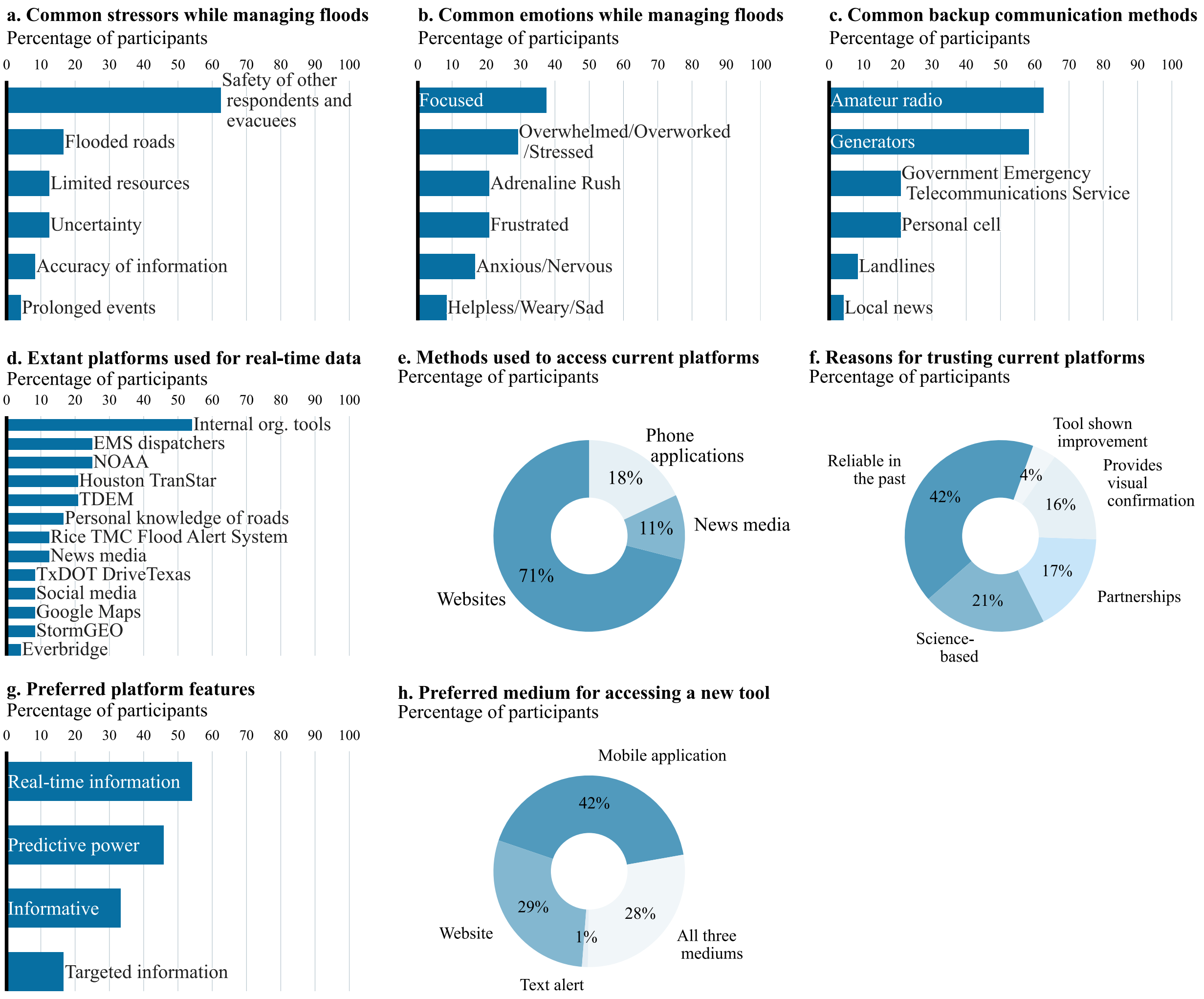
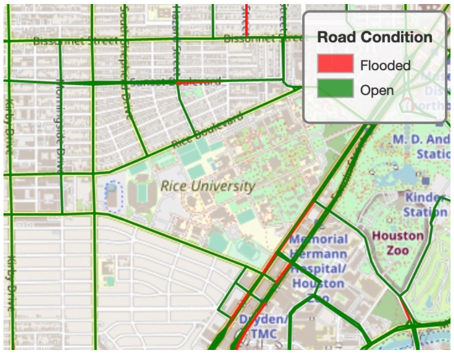


FIG. 4. Summary of insights from the needs assessment interviews.

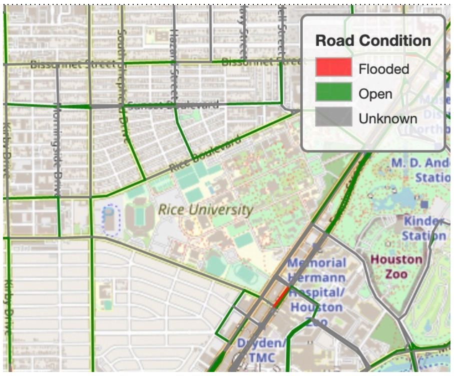
Option 1

- Flooded roads are marked in red.
- Open roads are marked in green.
- Roads with no data are marked in green.



Option 2

- Flooded roads are marked in red.
- Open roads are marked in green.
- Roads with no data are marked in grey.



Option 3

- Linear color map communicates the probability of roadway flooding.
- Grey color is used to mark roads without data.

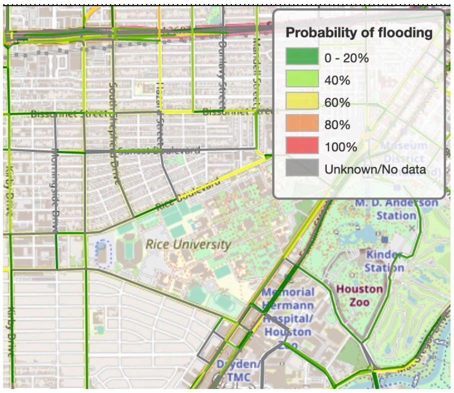


FIG. 5. Situational awareness tool mock-ups. Sources: OpenStreetMap contributors (2017)

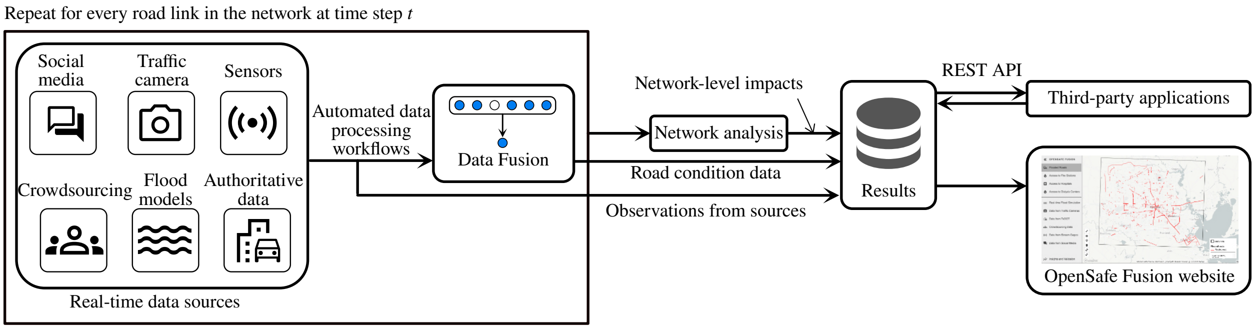
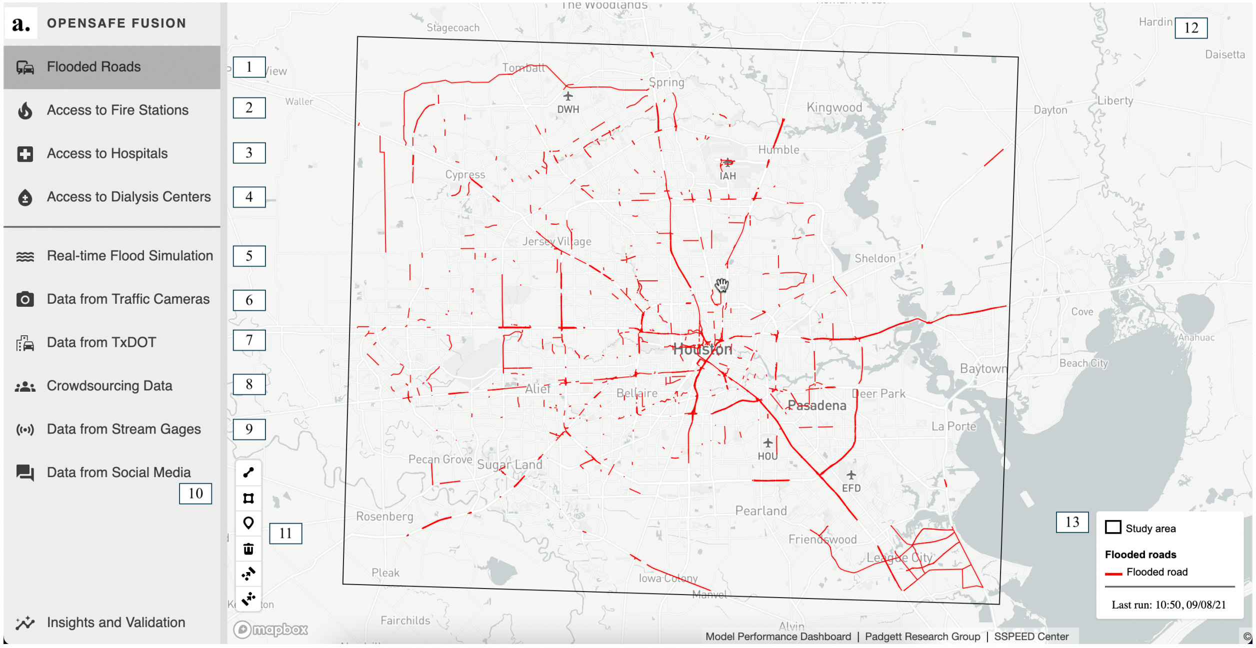


FIG. 6. Overview of the OpenSafe Fusion framework concept. OpenSafe Fusion aims to improve data availability and accuracy by leveraging the collective intelligence of multiple real-time data sources. First, OpenSafe Fusion uses automated source-specific data processing pipelines to obtain road condition data from diverse sources for each road link. Observations at a road link are then combined using data fusion techniques. The road condition data are then used to estimate network-level impacts of flooding. The results are then published via a website as well as REST API. Sources: Google LLC (2022b)

[b]0.7



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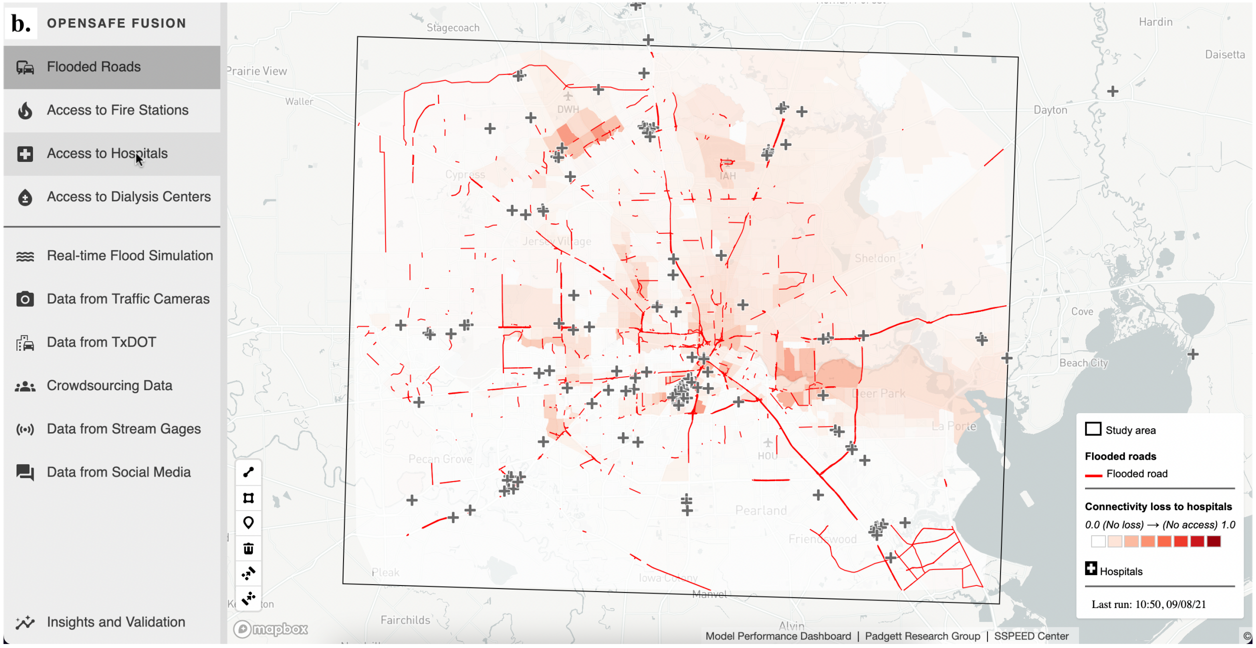
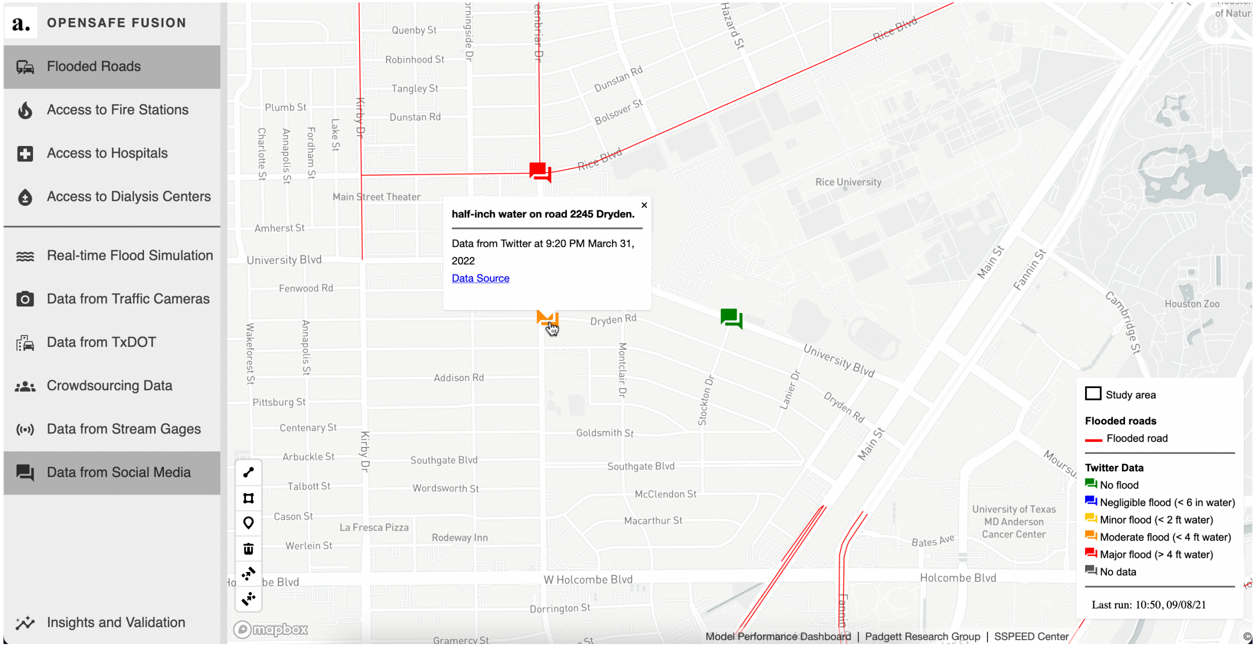


FIG. 7. Overview of the OpenSafe Fusion prototype. The top image shows the user interface with its different elements. Items 1-4 are buttons to toggle the visibility of results from the framework, and items 5-10 are buttons to toggle the visibility of observations from individual sources. Item 12 is the primary map window, and Item 13 is the legend. In the top image, flooded roads are shown in red and open roads in green (if present); roads without any data are not shown to improve website load time. The bottom image maps flood impact on access to hospitals for each census tract using connectivity loss ratio. Regions with a significant reduction in hospital access are marked with darker shades. Sources: OpenStreetMap contributors (2017), U.S. Department of Homeland Security (2021), Mapbox (2022).

[b]0.68

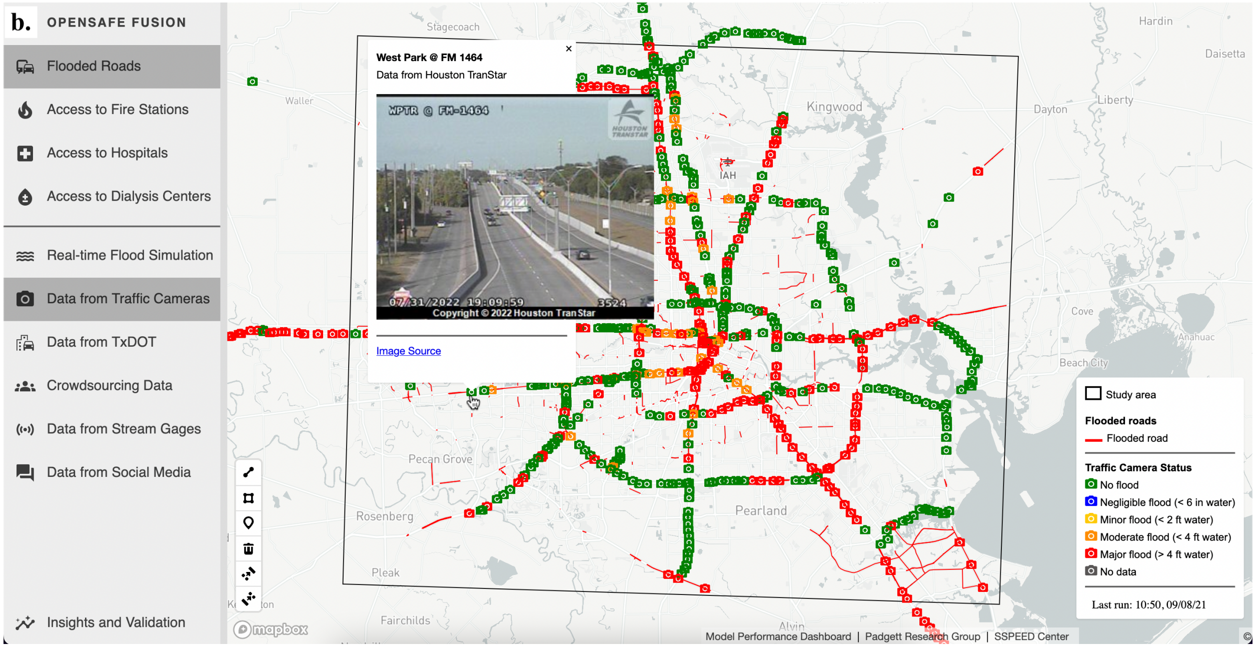


half-inch water on road 2245 Dryden.

Data from Twitter at 9:20 PM March 31, 2022

Data Source

[b]0.68



West Park @ FM 1464

Data from Houston TranStar

Image Source

[b]0.68