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The hazard consequence prediction system: A Participatory Action Research approach to enhance emergency management

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Abstract

Emergency managers (EMs) need nuanced data that contextualize the local-scale risks and impacts posed by major storm events (e.g., hurricanes and nor'easters). Traditional tools available to EMs, such as weather forecasts or storm surge predictions, do not provide actionable data regarding specific local concerns, such as access by emergency vehicles and potential communication disruptions. However, new storm models now have sufficient resolution to make informed emergency management at the local scale. This paper presents a Participatory Action Research (PAR) approach to capture critical infrastructure managers concerns about hurricanes and nor'easters in Providence, Rhode Island (USA). Using this data collection approach, concerns can be integrated into numerical storm models and used in emergency management to flag potential consequences in real time during the advance of a storm. This paper presents the methodology and results from a pilot project conducted for emergency managers and highlights implications for practice and future academic research.

Highlights

1. A Participatory Action Research approach is used to capture subject matter expert concerns from major storm events that can be integrated into numerical storm models for emergency management.
2. This paper presents a standardized approach for capturing facility manager concerns that contains rich, actionable information that is relevant to the emergency management community.
3. This paper describes a process for working with facility and emergency managers across sectors and organizations to collaborate in the emergency management process for a major city.
4. The results of this study can be used to enhance emergency management and response by providing emergency managers with actionable information for local scale planning and response during a major storm event.

Introduction

Emergency managers (EMs) need nuanced data that contextualize the local-scale risks and impacts posed by major storm events (e.g., hurricanes and nor'easters). Traditional tools available to EMs, such as weather forecasts or flood mappers, do not provide actionable data regarding specific local concerns leading up to an emergency event (e.g., access by emergency vehicles and potential communication disruptions). Recent development of high-resolution storm models, such as developments in the ADvanced CIRCulation Model (ADCIRC) (Ullman et al. 2019), present new opportunities for emergency management tools that integrate subject matter expert (SME) concerns as outputs of numerical storm models (Stempel et al. 2018). Critical infrastructure facility managers, such as a wastewater treatment facility operator, possess an in-depth and holistic understanding of how storms may impact their facilities and the services they provide to the surrounding community. Using a Participatory Action Research (PAR) approach, this information can be solicited directly from SMEs to better inform EMs of the risk and impacts during a natural disaster, increasing the credibility and value of storm model outputs. PAR is grounded in the notion that addressing societal problems requires the knowledge and participation of persons affected by them (Brown and Rodríguez 2009), and has been used successfully to engage diverse stakeholders in Disaster Risk Reduction (Cadag and Gaillard 2012). This paper outlines a method for collecting subject matter experts' (SMEs) concerns, referred to as Consequence Thresholds (CTs), for later integration into numerical storm models. "Consequence" is defined here as the result of an impact to an infrastructure asset and the critical services it provides. "Threshold" is the point at which wind, waves, or flooding is likely to trigger a storm impact, according to an expert's opinion, design guideline, or other reliable source.

This research builds upon previous work that proposed and defined the CT datapoint, which contains geospatial and numerical data, such as surge height or wind speed at which the asset would be compromised, as well as a qualitative data regarding the results of damage to a particular asset (Witkop et al. 2019).[1] CTs can be integrated into outputs from a numerical storm model, such as ADCIRC, for use by EMs for decision-making (Stempel et al. 2018). The objective of this study is to use a Participatory Action Research (PAR) framework to capture CTs for incorporation into emergency management at the Emergency Operations Center (EOC). This study investigates the following research question: *How can a Participatory Action Research approach contribute to the collection of qualitative data from infrastructure facility managers for use in real-time numerical storm models used in emergency management?*

Background

This paper presents a mixed-methods approach underpinned by PAR theory, a key tenet of which is the convergence of multiple stakeholder perspectives as a means to guide academic inquiry (Bergold and Thomas 2012). PARs wide and varied history spans a continuum of practical and emancipatory practices (e.g., addressing social justice) (Littman et al. 2021). In an emergency management context, integrating local facility managers (FMs) perspectives adds a human dimension for detecting locations that are

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[1] More information on this project, including a video overview, can be found at www.richamp.org

both exposed to storm hazards and have value to communities. Minano et al (2018), for example, present findings that support the efficacy of participatory mapping to enhance geo-visualization tools for climate hazard (i.e., sea level rise (SLR) and storm surge) decision making (Minano, Johnson, and Wandel 2018). The team developed a Geoweb tool, "AdaptNS," which displays high-resolution, localized coastal flooding scenarios on an interactive web map and allows users to identify a location of concern, rank their level of concern (low to critical), and share the community value associated with that location – similar to the CT mapping technique of this study. These co-creative processes that facilitate the exchange of risk information and priorities among stakeholders (as opposed to unidirectional information distribution) enhance the perceived legitimacy and efficacy of process outputs such as visualizations and interactive dashboards (Stempel and Becker 2019; Olman and DeVasto 2020). Emergency managers currently use a variety of approaches to understand and communicate the risks and response options for natural hazards. This section discusses these approaches and sets the stage for the participatory mapping approach developed in this research.

I. *Tools for emergency management*

A. Numerical Storm Models

Emergency managers assess risks during storms using outputs from real-time numerical storm models that forecast storm intensity and track, resulting in predictions for flooding, wave conditions, and wind, among other drivers. EMs may access the model outputs directly or through forecast products, such as those provided by the National Weather Service. High resolution storm models, such as Storm Surge Modeling Systems with Curvilinear-grid Hydrodynamics in 3D (CHS3D) model, and the ADvanced CIRCulation (ADCIRC) model coupled with wave models such as Simulating WAves Nearshore (SWAN) provide detailed predictions of wind speeds, wave height, and flooding in advance of major storm events. Recent advances in modeling capabilities have allowed for highly accurate storm model outputs. For example, the combination of the ADCIRC and SWAN allows researchers to model conditions during a storm down to a 20-meter resolution (Dietrich et al. 2012). The information provided by these storm models can play an important role in helping EMs identify and address the potential risk to infrastructure and the public during a major storm event. These high-resolution models also present an opportunity to make nuanced predictions about impacts and consequences of those impacts at the local scale (Stempel et al. 2018).

II. *Predicting storm consequences of concern to emergency managers*

Storm events pose significant risk to critical infrastructure – the assets, facilities, networks, and critical services provided – that maintains national security and supports economic development and prosperity within society. Major storm events can have direct, indirect, and intangible consequences to critical infrastructure and the services (Becker et al. 2015). Direct damages include damages to infrastructure, buildings, and property. Indirect costs refer to the potential economic losses that stem from severe storms, such as the loss of business for cement plant. Intangible consequences are broad, not easily quantifiable (e.g., the loss of life), and have long-range impacts (months to years), for which limited economic evaluation measures often exist (Becker et al. 2015). Tools available to emergency managers (Table 1), such as FEMA's Hazus, are commonly used to identify the risk and impacts of a natural hazard and assess the vulnerability of a system prior to a major storm event (Nastev and Todorov 2013; Remo, Pinter, and Mahgoub 2016). However, available tools are generally not well-suited to predict storm impacts and consequences during a real-time event.

Table 1: Examples of tools commonly used by emergency managers

Tool	Agency	Description	Link
HAZUS	FEMA	This nationally applicable, standardized method estimates potential losses from earthquakes, hurricane winds, and floods. State-of-the-art GIS software maps and displays hazard data and estimates of damage and economic losses to buildings and infrastructure. Detailed analysis requires the vetting and development of local data sets by experts.	https://www.fema.gov/flood-maps/products-tools/hazus
HURREVAC	NHC, FEMA	HURREVAC (short for Hurricane Evacuation) is a storm tracking and decision support tool of the National Hurricane Program, administered by the Federal Emergency Management Agency (FEMA), the U.S. Army Corps of Engineers, and the NOAA National Hurricane Center. The program combines live feeds of tropical cyclone forecast information with data from various state Hurricane Evacuation Studies to assist the local emergency manager in determining the most prudent evacuation decision time and the potential for significant storm effects, such as wind and storm surge.	https://www.hurrevac.com/
Flood Inundation Mapper	USGS	The FIM Mapper allows users to explore the full set of inundation maps that shows where flooding would occur given a selected stream condition. Users can also access historical flood information and potential loss estimates based on the severity of the flood. The FIM Mapper helps communities visualize potential flooding scenarios, identify areas and resources that may be at risk, and enhance their local response effort during a flooding event	https://fim.wim.usgs.gov/fim/
Coastal Change Hazards Portal	USGS	USGS coastal change hazards research produces data, knowledge, and tools about storms, shoreline change, and sea-level rise.	https://marine.usgs.gov/coastalchangehazardsportal/

III. *Participatory Action Research and Geographic Information Systems (GIS) for Emergency Management*

Emergency managers must determine the people, places, and infrastructure at greatest risk is during a major storm event (McCall and Peters-Guarin 2012). However, detailed storm impact information to infrastructure and communities is not easily accessible to emergency managers due to data quality, quantity, and challenges in its integration into emergency management operations (Cutter 2003). PAR supports co-creation of knowledge and bi-lateral sharing of information between researchers and stakeholders (Bergold and Thomas 2012). In the context of emergency management, PAR elicits local knowledge and experience used for determining risk and vulnerability, interventions, and for shaping emergency preparedness and response at the community level (McCall and Peters-Guarin 2012). Participatory mapping, an example of PAR, allows researchers to create cartographic maps based on the interests, experiences, and knowledge within a local community (Cochrane and Corbett 2020).

Researchers use Geographic Information Systems (GIS), a computer-based system used for creating, storing, displaying, and visualizing spatial data and geographic information, for participatory mapping exercises addressing flooding risk and vulnerability. GIS supports mitigation, preparedness, response, and recovery activities during a natural disaster, referred to as the four major stages of the "emergency management cycle" (Damjanović, Gigović, and Šprajc 2019; Haworth and Bruce 2015).

Until recently, the creation of geographic information required extensive technical knowledge (Damjanović, Gigović, and Šprajc 2019) and was subject to high costs. However, improvements in technology have simplified this process, spawning a number of applications for the creation of geographic information without needing expert training or knowledge, commonly referred to as Volunteered Geographic Information (VGI) (Elwood 2008). VGI, a component of the participatory mapping process for emergency management, can provide real-time and up to date information that can be used by emergency managers during a natural disaster (Tzavella, Fekete, and Fiedrich 2018). Web and mobile-based GIS applications have proven to be beneficial in providing critical information that enhanced emergency management during natural disasters events (Sharma, Misra, and Singh 2020; Lagmay et al. 2017). For example, during the 2007 to 2009 wildfires in California, VGI provided emergency managers with real-time on the ground situation reports that filled essential gaps in information that improved emergency response (Goodchild and Glennon 2010). In response to natural disasters, pre-planning activities and community engagement have also been shown to enhance emergency management, reducing stress and increasing disaster recovery time (Zukowski 2014).

During a storm event EMs need to understand the direct and indirect impacts of storms and their intangible consequences for emergency response decision-making. Yet, customary methods of risk assessment do not capture the level of detail necessary for local scale emergency management during an event. Critical infrastructure, such as hospitals or fire stations, provides key services during a natural disaster for emergency response and recovery. While traditional methods and tools can aid in identifying vulnerable critical infrastructure, they do not capture local, detailed, and actionable information that is qualitative in nature regarding the consequences of storm impacts to critical infrastructure facilities. Facility Managers (FMs) possess deep knowledge of how storms impact their facilities and operations. However, this knowledge is not normally incorporated in storm impact modeling tools commonly used by emergency managers. To increase usefulness of storm model outputs, a PAR process can leverage the use of GIS to integrate FMs knowledge of asset locations and vulnerabilities into high resolution storm models, increasing their utility and credibility for emergency management.

Methods

I. Steering committee

In applied projects such as this, buy-in from end-users and SMEs is essential. Without trust and credibility, as well as a clear purpose for data collection, facility managers are far less likely to participate. PAR frameworks address this by engaging stakeholders to take ownership of and direct research processes (Bergold and Thomas 2012). We partnered with the Rhode Island Emergency Management Agency (RIEMA), Rhode Island Department of Health (RIDOH), and Providence Emergency Management Agency (PEMA) to form a steering committee consisting of these and other local and state partners. The steering committee members identified critical infrastructure points of contacts, lent credibility to the project, and provided guidance to the researchers **(Table 2).**

Table 2: 15 steering committee members

Title	Agency	Sector
Public Property Coordinator	Providence Department of Public Works	Government
Principle Engineer	RI Department of Environmental Management	Water & Wastewater
Critical Infrastructure Key Resources Manager	RIEMA	Emergency Services
Deputy Director	PEMA	Emergency Services
Engineering Manager	Narragansett Bay Commission	Water & Wastewater
Chief of Sustainability, Autonomous Vehicles, and Innovation	RI Department of Transportation	Transportation
Director of Enterprise Business Continuity Planning	Lifespan	Health & Medical
Marine Transportation Recovery Specialist	United States Coast Guard	Port of Providence & Hurricane Barrier
Senior Coordinator of Investment & Economic Development	National Grid	Energy
Program Support Specialist	RIDOH	Health & Medical
Director of Engineering	Providence Water Supply Board	Water & Wastewater
Deputy Chief of Center for Emergency Preparedness &Response	RIDOH	Emergency Services
Chief Resilience Office	RI Infrastructure Bank	Government
Operations Section Chief	RIEMA	Emergency Services
Director of Security	City of Providence Capital Asset Management & Maintenance	Security

II. City of Providence Study Area

Situated at the confluence of the Woonasquatucket and Moshassuck Rivers and at the head of Narragansett Bay is Rhode Island's Capital, the City of Providence. Providence hosts a significant portion of the state's population and critical infrastructure, including nearly half of the state's hospitals and the Port of Providence, designating it as an important study site for storm risk in Rhode Island. We defined the study area (Figure 1) in Providence using the Federal Emergency Management Agency (FEMA) Flood Zones plus a 100-meter buffer to capture facilities located just outside of the historical floodplain.

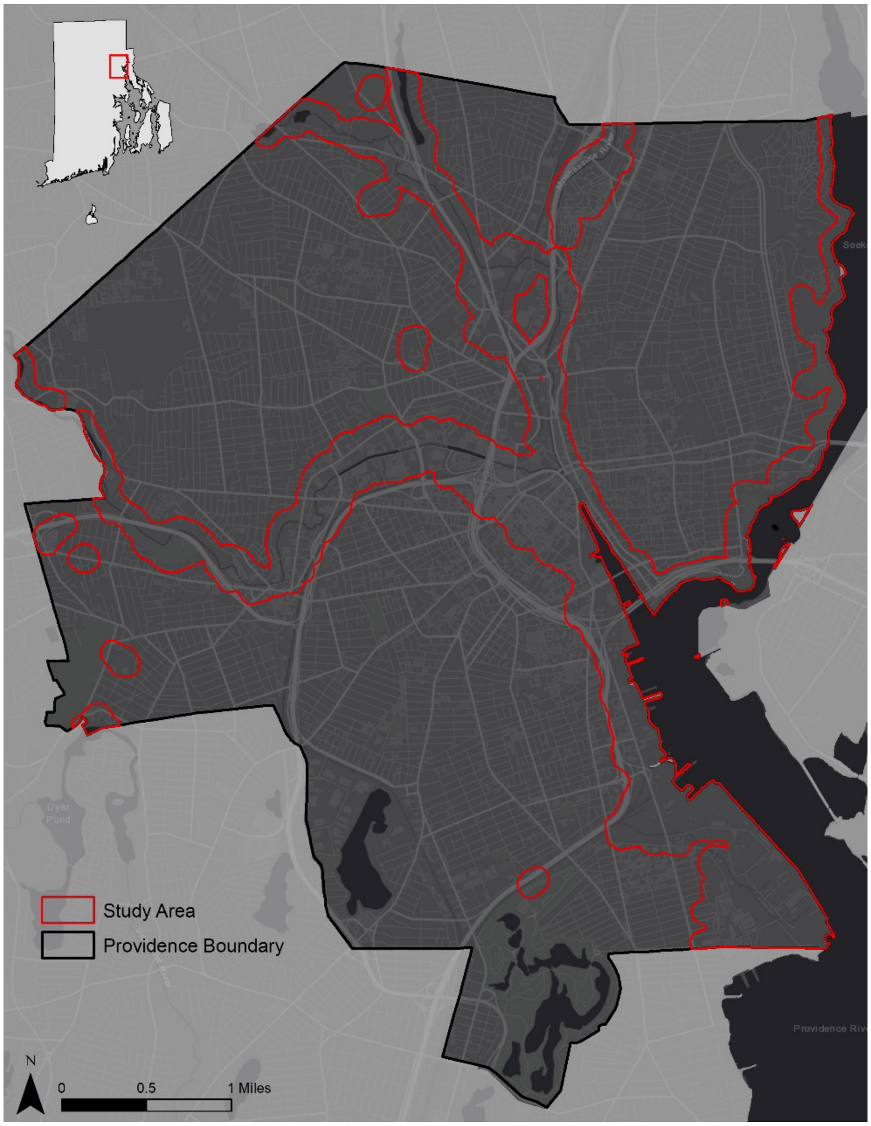


Figure 1: Study area boundary in Providence, Rhode Island, USA. The study area includes FEMA flood zones AE, AH, VE, and X, plus a 100 meter buffer.

III. Identifying facilities for data collection

Critical infrastructure facilities were first identified using the recently completed Providence Multi-Hazard Mitigation Plan (PEMA et al, 2019) and publicly available data from the Rhode Island Geographic Information System (RIGIS) (https://www.rigis.org/). Spatial data for Emergency Medical Services, Colleges and Universities, State Facilities, Fire Stations, Hospitals, and Law Enforcement were obtained from RIGIS and critical infrastructure within the study area were identified using geographic information systems (ArcMap, Version 10.5). In a focus group setting, the steering committee vetted the pre-identified facilities, providing additions and corrections (Figure 2). In addition, the steering committee added facilities not included in the publicly available database.

Figure 2: Steering committee members identifying and prioritizing vulnerable facilities in Providence (Photo: Authors)

These fell within seven DHS key infrastructure sectors, plus one sector that is unique to this study area (i.e., the Port of Providence & Hurricane Barrier) (Table 3). The steering committee assigned levels of importance (i.e., 1 = Most Important, 2 = Important, 3 = Least Important) to facilities based on the services they provided and identified additional facilities that were not identified from publicly available data. Level 1 facilities were considered high priority to the EM community and were included in the interview process. Level 2 facilities were considered important, but not of high priority, and included if practicable. Level 3 facilities were not engaged in the interview process. The focus group resulted in a final set of 33 critical infrastructure facilities located in our study area targeted for detailed data collection.

Table 3: Importance of critical infrastructure facilities for emergency management identified by sector

Sector	Most Important	Important	Least Important
Emergency Services	Providence Fire Dept. Providence Emergency Agency Providence Communications Dept.	N/A	Providence Animal Control
Energy	Manchester Street Power Station National Grid	N/A	N/A
Food, Water & Shelter	N/A	N/A	N/A

Government	Providence City Hall Division of Capital Asset Management & Maintenance Department of Children, Youth, and Families	RI Dept. of Environmental Management	N/A
Health & Medical	Rhode Island Blood Center Charlesgate Nursing Center	PCHC Randall Square PCHC Chafee Clinica Esperanza	Discovery House Rhode Island
Port of Providence & Hurricane Barrier	Fox Point Hurricane Barrier Hudson Liquid Asphalts Holcim Us Inc. Schnitzer Northeast ProvPort	N/A	Save The Bay
Security	RI Fusion Center	N/A	N/A
Transportation	Kennedy Plaza RIDOT	Amtrak Train Station FHWA	N/A
University	Roger Williams University of Rhode Island Providence Campus	RI School of Design Johnson & Wales Harborside Campus	N/A
Water & Wastewater	Providence Water Narragansett Bay Commission Fields Point Wastewater Treatment Facility	N/A	N/A

IV. Handling and communicating infrastructure data

Due to the proprietary and/or security-sensitive nature of Protected Critical Infrastructure Information (PCII), FMs are often reluctant to share information regarding their facilities and its operations. However, such sensitive information increases the credibility and value of storm model outputs at the local scale and regional scale. It also can enhance the capacity of emergency managers to prepare and respond appropriately (Zukowski 2014). Thus, strict procedures for collecting, storing, and sharing sensitive data is a significant hurdle in the development of a participatory approach. End-user input is essential to developing a data handling protocol that allows participants to

Components of a Consequence Threshold Data Point

Asset of concern: An asset the directly impacts by a storm hazard (waves, wind, flooding, surge)

Sensitivity of asset:

Level 1: Classified and available only to reporting facility

Level 2: Classified and available only to PEMA/RIEMA community

Level 3: Not sensitive, publicly available

The specific location of concern: The latitude and longitude of the specified asset

Hazard: The storm hazard (wind, flooding, wave, or surge)

Hazard threshold: The magnitude of the hazard at which the functioning of the specified asset would be compromised

Consequence(s): The outcomes if the storm force exceeds the threshold at the location of cent

Recovery period: The length of time until functionality can be restored

Short term - up to one week

Medium term - weeks or months

Long term - months or years

Text Box 1 - Components of a consequence threshold data point engage with the project in accordance with organizational mandates around data sharing. This may require training and use of standard protocols, such as the DHS Protected Critical Infrastructure Information standards used in this project or others, depending on the needs of participants. The study considered some data as protected critical infrastructure information (PCII), which is protected by law and requires formal training for its handling and storage (see https://www.cisa.gov/pcii-program). Accordingly, all researchers completed PCII Authorized Using Training offered by DHS. As an example, analysis software was tested using non-PCII data to eliminate the need for transmitting PCII data.

Protocols for the classification and sharing of sensitive information in this project were developed with input from the steering committee. Respondents were asked to classify their data as Level 1-3, depending on the sensitivity of the asset information or consequences reported. Level 1 (classified and available only to reporting facility) was deemed most sensitive and essentially would not be included in the database. Level 2 (Classified and available only to emergency management community) was deemed suitable for access only by emergency managers. Level 3 (Not sensitive, publicly available) was deemed appropriate for wider circulation. This system of classification was developed in close collaboration with the steering committee.

The University of Rhode Island (URI) Institutional Review Board (IRB) reviewed and approved all methodologies and procedures for conducting four focus groups and interviews. Prior to interviewing, researchers and steering committee collaborators engaged in email and telephone correspondence with identified critical infrastructure FMs to invite them to a focus group interview at PEMA or a one-on-one site visit at their location. We circulated a background information document to all participants so that an informed decision could be made about their participation. Participants reviewed and signed a Non-Disclosure Agreement (NDA) Consent Form for Research (URI Approval IRB1819-226). To maintain participant confidentiality, we present the findings by leaving all participants' facilities' names and specific job titles unspecified.

V. Consequence threshold data description

We collected FM concerns using a modified version of the CT framework from Witkop et al (2019). Our modifications include a sensitivity level classification scheme to ensure data security and a recovery period component that captures the amount of recovery time to restore services provided by critical infrastructure from storm damage. This approach parameterizes infrastructure vulnerabilities by mapping them to seven qualitative and quantitative CT components, as described in Text Box 1.

VI. Data collection and validity methods

Researchers held semi-structured interviews with key informants in focus groups and in individual site visits at FMs' respective facilities. This section describes each of these approaches, both of which follow the interviewing framework summarized in Figure 3 from Witkop et al (2019).

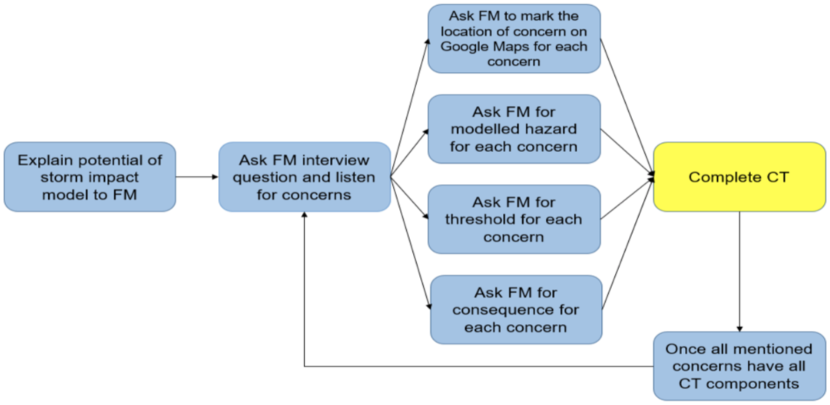


Figure 3: A framework for collecting consequence threshold data from facility managers (Witkop et al., 2019)

a. *Focus group interviews*

The research team began data collection through focus groups consisting of small groups of facility managers clustered by infrastructure sector. Researchers asked FMs to inventory critical assets (e.g., generators, servers, utilities, storage areas) at their facility. To aid FMs' identification of critical assets, researchers asked guiding questions such as, "What would keep you up at night if a major storm was forecast for the area?". Additionally, researchers shared visualizations of modeled historical flood events and flooding maps from STORMTOOLS (https://stormtools-mainpage-crc-uri.hub.arcgis.com/) to aid facility managers in identifying potential vulnerabilities at their facility. During focus groups, one researcher recorded the CT components on a CT Data Collection sheet and took notes while the other researcher(s) facilitated discussion. FMs pinpointed the location of the asset using Google Maps and provided the hazard (e.g., flooding) and hazard threshold (e.g., 6 inches) that would elicit a series of cascading consequences (e.g., flooding damages generator and facility loses backup power).

b. *Interview approach*

Researchers held individual site visits and interviews with participants that were unable to attend the focus group sessions or with previous focus group participants to collect additional CT information for facilities (Figure 4). Site visits were arranged with facility managers based on their availability. Researchers met with facility managers for 1-2 hours to tour the site and collect consequence thresholds data using a semi-structured interview instrument. Attendees were provided background similar information as described above.

Figure 4: The research team working with facility managers during a site visit interview (Photo: Authors)

c. Data conditioning and validation

Data were stored in a password protected Microsoft Excel Spreadsheet and were conditioned for input into a numerical storm model. Data conditioning included the removal of all commas in string data removal of space in column names, and removal of text in cells with numeric data. Whenever possible, syntax used for CT description was made consistent and depth hazard thresholds (e.g., 1 foot of flooding) were converted to meters and velocity thresholds (e.g., 70 mph winds) were converted to meters/second. Once all CTs were conditioned, the database of consequences was then converted to a shapefile using ArcMap Version 10.7 (ESRI, Redlands, CA). Next, researchers sent the data back the FMs for vetting and to ensure the information collected and recorded accurately captured their concerns.

Results

This section provides an overview of the results from the Providence data collection exercise.

1. Focus Groups

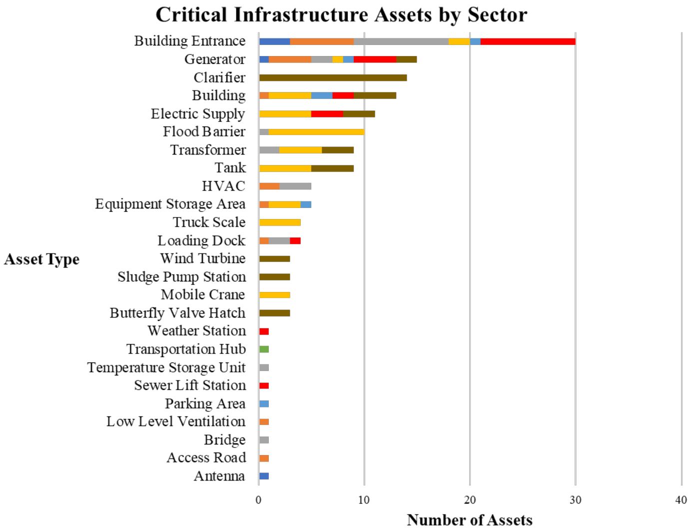
We hosted four focus group interviews, three at PEMA and one at the ProvPort facility for tenants at the Port of Providence. Nineteen facility managers among all CI sectors were in attendance for the focus group interviews, and a total of 134 CTs were collected from the four focus group sessions.

2. Individual Interviews & Site Visits

Through individual interviews and site visits with 15 facility managers, we collected an additional 173 CTs. CTs. Some participants provided information for multiple facilities overseen by their organization. We attempted site visits and individual interviews at three additional facilities but found that FMs were unable to participate in this study.

Assets of Concern

Through the focus groups and interviews, we collected location data for 150 assets from 29 facilities (**Figure 5**). Many of the assets identified had multiple potential consequences. The most common assets that were identified of concern at the facilities we interviewed included entrances to buildings, generators, wastewater clarifiers, buildings, and electrical supplies.



Sector	Facilities	Assets	Consequences
Port of Providence & Hurricane Barrier	6	41	51
Water & Wastewater	1	37	64
Medical & Health	4	22	77
University	4	21	42
Government	8	17	31
Security	3	6	31
Emergency	2	5	9
Transportation	1	1	2
Total	**29**	**150**	**307**

Figure 5: Number of assets identified by asset type and critical infrastructure sector

Consequence Thresholds

We collected a total of 307 CTs from 31 facility managers representing 29 critical infrastructure facilities in Providence. Many of the consequence thresholds collected were from the Port of Providence and Fox Point Hurricane Barrier, Water and Wastewater, and Health and Medical. Table 4 provides example consequence thresholds.

Table 4: Example Consequence Thresholds

Asset	Threshold	Consequence	Recovery Period
Truck Scale	2” flooding	Truck scale damaged, thus unable to distribute cement products in region	Medium Term

Server Room	6” flooding	Loss of access to secured systems of communication and classified files	Medium Term
Petroleum Storage Building	3” flooding	Potential release of hazardous materials stored in building	Medium Term
Emergency Vehicle Bay Entrance	2” flooding	Emergency personal are unable to access vehicles and equipment stored in building	Short Term
Communication Antenna Array	100 mph wind	Loss of communications between emergency responders	Medium Term

Of the 307 CTs, flooding triggered 86% (either storm surge or inland flooding), wind triggered 12%, and storm surge (only) triggered the remaining 2% (Figure 6). We did not collect any consequences for wave hazards due to the upriver setting of the study area, though this could be included in future research. Ground elevations were determined in a subsequent step using high-resolution Light Detection and Ranging (LIDAR) data, thus thresholds only needed to be reported as elevation above the ground at that particular location (For details on this aspect, refer to Stempel et al. 2018). Thresholds were determined by reviewing design manuals or by best estimate of the respondent, such as a facility manager that identified 6” flooding above the ground as the hazard threshold that would damage a generator at their facility. In some cases, we were able to use the design thresholds of assets as the hazard threshold. For example, a facility manager was concerned about several wind turbines at their facility being damaged by excessive wind during a major storm, but were unsure of the threshold for damage. For this asset, we used the design threshold for these winds turbines as the hazard threshold.

Data sensitivity remained an important element of the project throughout. Respondents identified 73% of the consequences as Level 2, 21% as Level 3, and 6% as Level 1 (Figure 6). The relatively low proportion of information provided that was categorized as Level 1 sensitivity suggests that FMs may not have been as willing to disclose highly sensitive information with the research team or emergency management community. 53% of the consequences had a medium-term recovery period, 37% had a short-term recovery period, and 10% had a long-term recovery period (Figure 6). This suggest that facility managers were most concerned about impacts to assets that could disrupt operations or critical services for several weeks to a month.

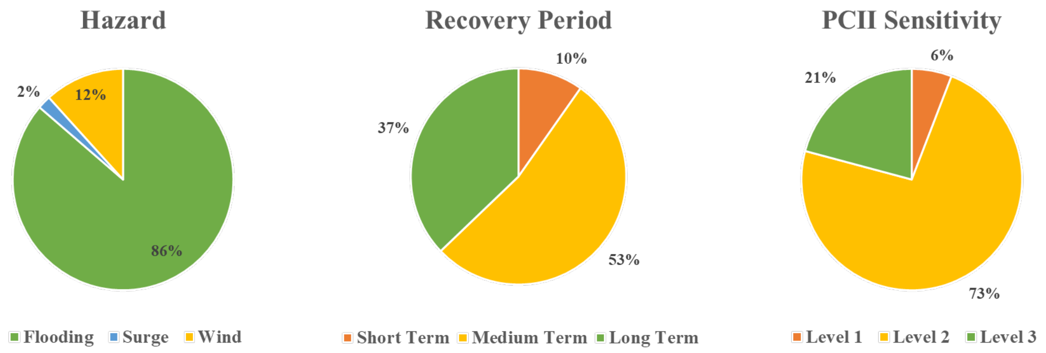


Figure 6: Proportion of CTs triggered by hazard, their recovery period, and the sensitivity of the information provided

Focus group interviews were more effective for encouraging group discussion around risk, but individual interviews and site visits allowed researchers to work one-on-one with participants, and tour their facility, which led to the discovery of more CTs at the site. The visits also aided in determining assets of concern and validating the hazard threshold visually. Both methods were effective for capturing consequence threshold, with slightly more CTs being collected during individual interviews and site visits (n= 173) as compared to focus group interviews (n =134).

Discussion

The work described in this paper builds on previous research and presents results from a pilot study conducted in Providence (RI). Through a PAR mapping approach, researchers and SMEs worked together in co-creation of knowledge and bilateral sharing of information, an important component of participatory research (Jull, Giles, and Graham 2017). Effective emergency management requires a holistic assessment of vulnerability that considers the direct and indirect impacts of storms, as well as their intangible consequences (Becker et al. 2015). Current weather reports and risk modeling techniques provide predictions of drivers (e.g., flooding or wind speed) and some generalization of storm impacts, but lack detailed and local impact information that is useful for emergency managers during a major storm event (Cutter 2003). The approach outlined in this research is valuable in that it serves a dual role, capturing both the quantifiable measure of a consequence (i.e., the hazard threshold) and the qualitative perception of risk (i.e., consequences) from stakeholders' experience and expertise. In the emergency planning and response process, stakeholder engagement and participation has been shown to increase emergency management by improving the understanding of risk, developing relationships between stakeholders and the emergency managers, and providing a medium for stakeholders to engage with the emergency management process (Haworth, Whittaker, and Bruce 2016).

This PAR used maps, storm hazard visualizations, and probing questions to elicit detailed information regarding the potential impacts of storm hazards at critical infrastructure facilities (McCall and Peters-Guarin 2012). This type of information is typically not provided through traditional storm models and approaches for risk assessment (Cutter 2003). Importantly, this approach allows for SMEs to identify the assets at their facility that they perceive of being at greatest risk and the potential impacts from storms, filling gaps in proprietary knowledge and information retained by emergency managers. Furthermore, the process of eliciting this knowledge in site visits and interviews helps FMs recognize potential hazards and vulnerabilities of which they may not have been aware. Integration of these concerns into numerical storm models can enhance capacity of emergency management during a major storm as it provides emergency managers with higher resolution and actionable information that can improve planning and response. This enhanced understanding not only allows emergency managers to better serve those impacted during a natural disaster, but also incorporates the concerns and needs of the community.

The elicitation of local spatial knowledge of vulnerable areas, people, and infrastructure is an important component in reducing risk to disasters (McCall and Peters-Guarin 2012). Given the spatial aspects of storm impacts, concerns can often be tied to the location of an asset, such as a generator. Numerical storm models predict conditions for flooding, include the extent and depth, surge, and wind speeds for both hypothetical and real-time storm events. Using the CT framework, SME concerns can be integrated into the numerical storm model to determine if and when storm hazards (e.g., flooding, surge, or wind) are predicted to impact critical infrastructure assets and trigger SME concerns. Within the CT framework, qualitative data from infrastructure managers must be linked to the location of an asset in order to increase the usefulness of numerical storm model outputs. To do so, the geographic location (latitude/longitude) of an asset must be captured in order to determine if the asset falls within the extent of the modellable hazard. Additionally, the height of the asset above the ground is an important component for determining if (and when) the hazard exceeds the “Hazard Threshold” identified by SMEs. The final component is the consequence, which provides actionable information for emergency managers.

Implications of this research for emergency management

The methods outlined in this paper develop a framework for collecting and integrating qualitative concerns of facility managers into numerical storm model outputs that are useful for emergency management and response. In particular, the work supports the preparedness and response phases of the Emergency Management Cycle by providing emergency managers with access to information regarding the potential impacts of a storm event prior to landfall and for response during and immediately following a disaster. This research enhances traditional tools used by emergency managers by integrating qualitative information regarding the impacts that major storm events pose to critical infrastructure, providing emergency managers with access to high-resolution, actionable information. Next steps for this research include working with state and local emergency managers to refine a web-based GIS dashboard that can be used in EOCs for visualizing storm impacts for both real-time and scenario-based emergency response exercises (see also www.richamp.org). To automate the data collection process, a survey tool will be developed using pre-existing data collection applications, such as ESRI’s Survey123.

Future inquiries could investigate how EMs interact with the CT viewer through participant observation sessions in the EM EOC as well as further developing the CT framework to capture cascading consequences and interdependencies between critical infrastructure. Insights from hypothetical hurricane simulations could provide insight into the tool's capacity for use in planning exercises as well as long-term resilience planning. .

Implications for Academic Research

This work fits into an emerging Convergence Research approach in the field of Natural Disasters Research (Peek et al. 2020). Convergence research integrates methods, knowledge, and expertise, often multidisciplinary, to address and solve complex societal needs and challenges (see www.nsf.gov/od/oia/convergence/index.jsp). In an academic context, the goal of this paper is to address the inherent challenges in conducting applied research across disciplines. The work has social dimensions—such as getting stakeholder buy in, the handling and transfer of sensitive information across multiple agencies—and must result in research products that are useful to end-users. Our research team comprised social and natural scientists and outreach extension specialists, which required the development of a research space conducive to a diverse team of expertise (Nash 2008). The social science team needed to be able to communicate complex numerical storm models to non-scientists. The natural/physical scientists worked with the social science team to better understand the real-world application of their modeling for emergency management use. Together, the full team needed to match the research agenda with the needs of the end users (in this case, the emergency managers). These outcomes track with other PAR processes, and demonstrate that such processes have utility when used with primarily expert stakeholders such as FMs and EMs.

A few benefits of the PAR approach in particular are worth noting. First, we learned that endorsement and active engagement from local and state agencies, such as RIEMA, was critical for building relationships and trust between the research team and facility managers. Without this "buy-in", we would have met with a great deal of resistance from participants in the field and been unable to collect important data. Second, the development of data management protocols is time consuming and complicated, but critical to participants. We worked with our steering committee to develop our data collection and management protocols, through several rounds of iteration, approval, and training. Third, it can be difficult to elicit facility manager concerns that directly align with emergency manager priorities. For example, a facility manager may be concerned about potential revenue losses resulting from an impact, but emergency managers would need to know how services might be impacted within a larger system (e.g., hazardous materials spilled or loss of a communications network). PAR approaches facilitated iterative interactions between researchers, FMs and EMs that aided in addressing this.

Challenges & Limitation of this approach

Thus far, we are unable to meaningfully measure the utility of the CT framework for emergency response and planning. Through ongoing interactions with emergency managers, facility managers, and the project steering committee, we infer that this participatory approach generates a high level of detailed and actionable information as compared to traditional hazard impacts models previously in use by participants. Further research and implementation of the tool is needed to investigate how the information collected from participants actually improves emergency planning and response.

Due to the nature of PCII, there were concerns among participants regarding information privacy and security. This highlights the importance of developing a procedure for the secure handling and transfer of PCII in this context. This is also a limiting factor in capturing potential storm impacts as facility managers may not be willing to share information that is highly sensitivity to a facility and its operations. Concerns surrounding the sharing and handling of sensitive information has been noted as a major limitation of the use of volunteered information by emergency managers (Haworth 2016).

The process of collecting information that is qualitative in nature requires a standardized framework to ensure consistency and correctness to be integrated into numerical storm models. Due to the number of researchers collecting and synthesizing information, as well as participants, data standardization was challenging. To address this, a data conditioning protocol was developed to ensure syntax and semantics were consistent. During the data collection process, researchers experienced difficulties with quantifying thresholds for certain assets. For example, facility managers were unable to determine the exact wind magnitude required to damage a wind turbine. Instead, design thresholds were used for each individual asset were used. All data were vetted for accuracy with participants, but aligning the needs of the audience (e.g., emergency managers) with the information the respondents provided required researchers to use probing questions to help respondents “think like an emergency manager.” While our interview approach was effective for capturing FMs concerns, it required significant time to interview each stakeholder. To address these challenges, we plan to develop a web- and app-based tools through which responds can record their concerns without needing a researcher leading them through the process. Migrating to such an approach will also allow for regular edits and updates to the data, which will be essential for the tool to remain relevant and up to date.

Conclusion

Building upon the CT collection methodology from the Witkop et al. (2019) pilot study, we use Participatory Action Research to capture facility managers concerns from facility managers that can be utilized in conjunction with high-resolution storm impact models as a tool to support real-time decision making and develop adaptive capacity in emergency response. The methodology outlined in the paper develops a framework for capturing stakeholder concerns from a major storm event that provides actionable information that can be used by emergency managers for real-time or scenario-based decision making and response. This methodology advances traditional predictive tools by capturing both the quantitative (e.g., amount of flooding) and qualitative (e.g., loss of services provided by a hospital) hazard posed by major storm events. A participatory mapping exercise is coupled with a PAR approach for collecting actionable storm impact data that can capture measured and perceived risk to a storm event, thereby increasing the relevance of storm model outputs for emergency management. Finally, the CT framework has developed a standardized and uniform approach for the integration of qualitative data into high resolution storm models.

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