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Principles for data management, visualization, and communication to improve disaster response management: Lessons from the Hurricane Maria response mission

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ABSTRACT

Data visualization and communication are important components in disaster response management. Data management should be a basic part of emergency preparation in the same way as prepositioning essential supplies. For this preparation to be effective, well-conceived data structures and data collection systems must be in place before disasters happen, and required hardware should be designed to operate in contingency environments. However, due to challenges in disaster complexities and data management, there is still a pressing need for improvement. This paper identifies key principles to assist practitioners and software developers in designing and implementing data collection and reporting systems that can be used for data visualization during a disaster response. The authors reviewed existing literature on data and disaster management and incorporated their personal experiences as first responders with the US Army Corps of Engineers Hurricane Maria response mission to develop principles for improving data management and visualization during a disaster response. These principles are illustrated by two case studies from the Task Force Power and Operation Blue Roof mission efforts in Puerto Rico during 2017-2018. Suggested principles include considering data management as part of disaster preparedness, having flexible data tools resilient to unprecedented disaster outcomes, eg, interruption of telecommunications networks, and using diverse graphics and tools that are appropriate to their communication purpose and audience.

Key words: Puerto Rico, temporary roofing, power restoration, geospatial analysis, Task Force Power, Operation Blue Roof, Hurricane Maria

INTRODUCTION

Natural disasters create complex problems due to their impacts, cascading effects, and the capacity of coupled social-ecological systems to anticipate, respond, and recover from disasters.[1] Response to natural disasters is becoming more challenging due to the increased intensity and magnitude of extreme weather events,[2] urbanization and population growth,[3] and the growing societal connectedness brought by globalization.[4] While the magnitude of the challenge is large, advances in technology and lessons learned from past natural disasters have helped protect human lives by improving disaster management, minimizing risks to hazardous events, and maximizing recovery efficiency.

A crucial component in the effectiveness of preparedness, response, and recovery of disasters is data visualization and communication it facilitates. Data visualization is, fundamentally, “the process of producing visual representations of data and the outputs of that work”[5] and can be a powerful tool that aids in disaster management because it “aims to enhance one’s ability to carry out a task by encoding often highly abstract information into a visual form.”[5] This visual form allows disaster management professionals to track performance concerns and make informed decisions to improve response and recovery. A key point is

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that data visualization will not replace the judgment required by disaster responders, but it can support these dedicated professionals in stressful situations by clearly and quickly providing organized information needed to carry out their mission. Harnessing powerful new datasets for disaster management has been a new focus area of research, and many new tools and technologies have been identified and employed during response efforts.[6] However, multiple challenges exist in the process of collecting, extracting, processing, and communicating data related to disaster management. These challenges have been summarized by others[7,8] as falling into four main types:

1. Structural and semantical heterogeneity of input data sources and the diverse needs of consumers.

2. The need for ad-hoc data collection and modeling due to the diversity and complexities of disasters themselves.

3. Time sensitivity of data exchange and the wide array of options available to illustrate data, eg, maps, graphs, and text summaries.

4. Data quality and reliability of data sources.

The unprecedented situation in the aftermath of Hurricane Maria illustrated the reality of these challenges. Hurricane Maria (Category 4) made landfall in Puerto Rico on September 20, 2017, causing catastrophic and historical damages.[9] It was the strongest hurricane to make landfall in Puerto Rico since San Felipe II (Category 5) 89 years ago. Only 2 weeks prior, Hurricane Irma had passed near Puerto Rico, and the combination of tropical-storm force winds, heavy rainfall, and storm surge flooding in coastal areas caused widespread power outages, damage to structures, uprooted trees, and at least three deaths.[10] When Hurricane Maria arrived, it crossed the main island of Puerto Rico diagonally from the southeast to the northwest for over 8 hours and caused damage to every municipality. The combination of storm surge inundation (up to 9 ft.), high winds, and rainfall (up to 38 in.) caused record breaking flooding, mud slides, and property damage. Maria was an extremely destructive hurricane causing at least 65 deaths[9,11,12] and approximately 90 billion dollars in estimated damages across Puerto Rico and the US Virgin islands.[9,13] These massive human, ecological, and economic impacts highlight the importance—and challenge—of accurate data collection before, during, and after a crisis.

During natural disasters and other emergencies, the US Army Corps of Engineers (USACE) can be involved in response and recovery activities through its own authority (Public Law 84-99) or in support of the Federal Emergency Management Agency (FEMA) as the lead agency for the "Public Works and Engineering" Emergency Support Function.[14] These support functions can include providing temporary power, temporary roofing, emergency water assistance, debris management, and other types of technical assistance.[14] In response to the 2017 hurricanes, FEMA tasked USACE with providing debris management, infrastructure assessments, temporary roofing, temporary power, and the additional and unprecedented role of coordinating and directly assisting with power grid restoration in Puerto Rico.[15]

This paper builds on the wide-ranging and large USACE emergency response effort to synthesize a set of recommendations, or principles, for data visualization during disaster response. These principles for data visualization are illustrated by two case studies that capture the federal response to a hurricane that caused both extensive network and patch-style impacts across the island of Puerto Rico: Task Force Power Restoration (TFP) and Operation Blue Roof. The TFP mission was tasked with managing reconstruction of a geographically expansive electrical generation and distribution network, while the Operation Blue Roof mission was tasked with providing assistance to (primarily) individual homeowners through the installation of temporary roofing materials. Our post hoc analyses of Hurricane Maria are, importantly, not intended as a critique of agency response and recovery, but instead benefit from the advantage of hindsight to look to future use of visualization and to suggest specific technical preparations to improve disaster response management.

METHODS

Identifying best practices for disaster data management and visualization

Three of the authors (MMK, KFC, and SKM) were directly involved in response activities of the USACE after Hurricane Maria, thus drew from personal experiences with on-site data management and visualization challenges. Collectively, these personal experiences included the following: (1) a deployment to the TFP as a Data Manager at the operations center; (2) a deployment with Operation Blue Roof as a Quality Assurance Inspector performing on-site assessments at residential structures; and (3) an extended deployment with Operation Blue Roof as a Data Manager at the main field operations office with responsibilities spanning data communication, process improvement, and error detection. These deployments provided a unique experience with a variety of data management practices as they evolved during the Hurricane Maria response. In addition to the authors' personal experience, peer-reviewed literature was surveyed at the intersection of disaster management and visual analytics, data management, and information systems, eg, NRC 2007.[8] The four principles described in this paper and the specific recommended practices are a synthesis of field experience and academic theory.

We present two case study examples drawn from personal experiences during the Hurricane Maria response and then a resulting set of principles alongside key peer-reviewed literature resources. These principles are not intended as a comprehensive review of data-driven disaster management,[8,16] information systems,[17,18] or visual analytics.[5,19-21] Instead, we provide disaster managers and those who design data collection systems, with a plain language translation of key data visualization principles to accelerate and facilitate better response in future.

Case study: Task Force Power Restoration

In disaster management, often the only certainty is uncertainty, and decision-making tools need to be flexible enough to accommodate many scenarios. In short, tools should improvise alongside the mission. This principle is illustrated by the powerful (but drastically different) situational awareness methods that were utilized during TFP's mission. The power restoration mission was the first of its kind by the USACE, and the existing data templates, data management structures, and tools for collecting data in the field were overwhelmed by the scale of the mission, its unique requirements, and by the lack of cellular and internet connectivity during the first few months of the effort. At the start of the mission, the newly established TFP had to move quickly to identify the status of the system, its redundancies, key public service nodes, and critical population centers. Access to detailed maps of the system was slow to obtain as Puerto Rico Electric Power Authority (PREPA) employees were unable to return to work and access their computers and database storage systems. The initial map of the power system for the entire mission was a "ball and stick" representation of the 230 KV and 115 KV transmission lines and power distribution centers (Figure 1). The operational status of each line was manually updated within Microsoft PowerPoint to convey changes. This method was labor intensive, but the TFP ball-and-stick map was incredibly useful in orienting decision makers to the structure of the electrical grid and allowing them to strategize the location of USACE resources to coordinate repair and reconstruction activities and to focus on where to prioritize efforts. The map also became key to communication between the Unified Command Leadership (USACE, FEMA, Emergency Restoration Coordinator, and PREPA), the Governor of Puerto Rico, and executive leadership in Washington DC. It can be found within many public briefing materials that were produced during the first month of the mission (October to December 2017) as well as subsequent communication materials.[22]

The mission as directed by FEMA evolved to include not just the restoration of the transmission lines, but the comprehensive restoration of overall power generation, transmission, and distribution systems down to the last mile (consumer and residential consumers). The need to have consistent, reliable,

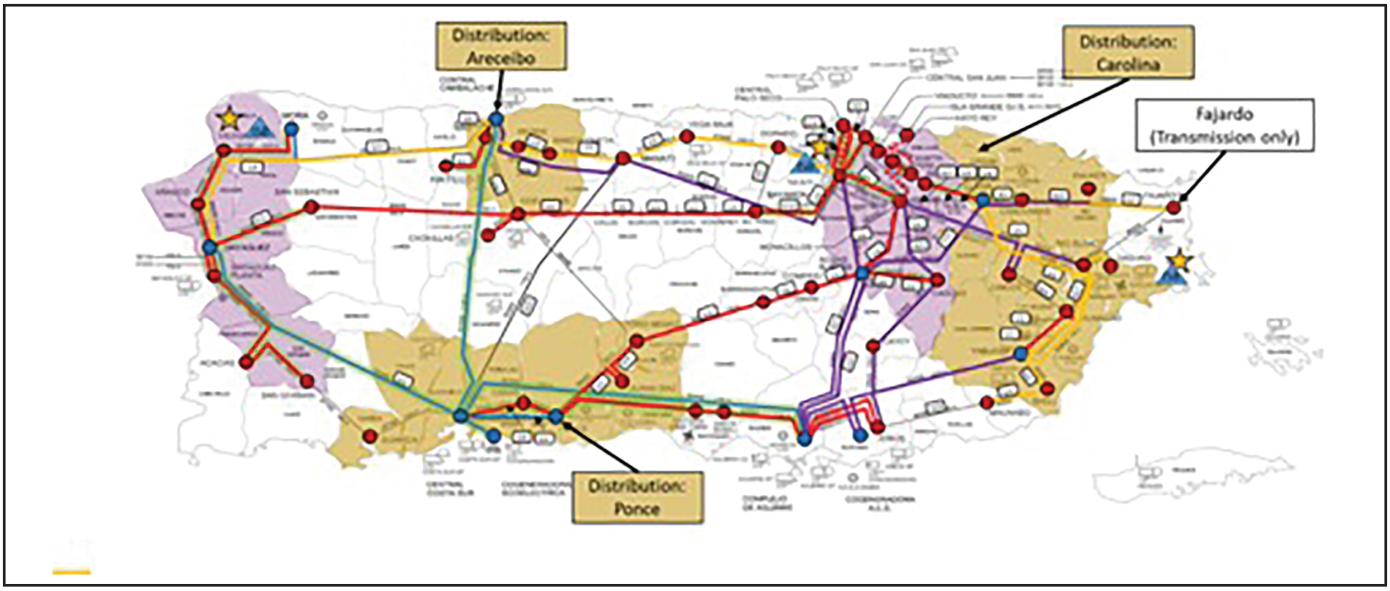

Figure 1. Electrical grid "ball and stick" representation, showing system redundancy and population centers across Puerto Rico.[22]

and up-to-date information on the entire system grew as the TFP leadership experienced a large increase in requests for status reports from USACE and FEMA leadership and national media. In addition, TFP volunteers would consistently rotate in and out of the mission (often on 30-day deployments) and need to be quickly brought up to speed on current procedures when they arrived. By December 2017, internet connectivity was stable, and ArcGIS analyst teams embedded at the TFP headquarters were able to deploy a customizable online portal to convey this necessary information (Figure 2). This portal was very well received, and the situational briefs quickly moved from paragraph and bulleted text updates to seamlessly generated graphs based on daily input from the field.

Overall findings from the TFP data management experience are as follows. (1) Tools and datasets for fast collaboration and communication are only as useful as the availability of the communication networks that support them. (2) When those networks are not available, first responders will resort to whatever existing tools they have on hand (including pen and paper, PDF, word documents, cell phone notes, etc.). (3) Tools for disaster management need to implement improvizational tactics by accommodating for a transition in the functions of supporting infrastructure without losing fidelity. (4) Data communication needs within a single mission will vary, eg, status reporting, prioritization for directing future resources. One dashboard will not satisfy every need.

Case study: Operation Blue Roof

Disaster management often requires juggling multiple objectives simultaneously, even within a single mission. The USACE maintains the Operation Blue Roof mission, whose purpose is to provide homeowners in disaster areas with fiber-reinforced plastic sheeting (colloquially known as "blue roofs") until permanent roofing repairs can be made.[23] The overarching mission objective is to provide temporary roofing as quickly as possible to prevent further damage to a home, thus allow people to shelter in their own home. The scale of assistance requested across Puerto Rico after Hurricane Maria was the third largest in the history of the Blue Roof program, which had already been active during the 2017 hurricane season in Florida and the US Virgin Islands in response to the storms preceding Hurricane Maria.[23] The challenge of accurately tracking thousands of cases was compounded by power outages and limited cellular or internet connectivity in many places. Eventually, over

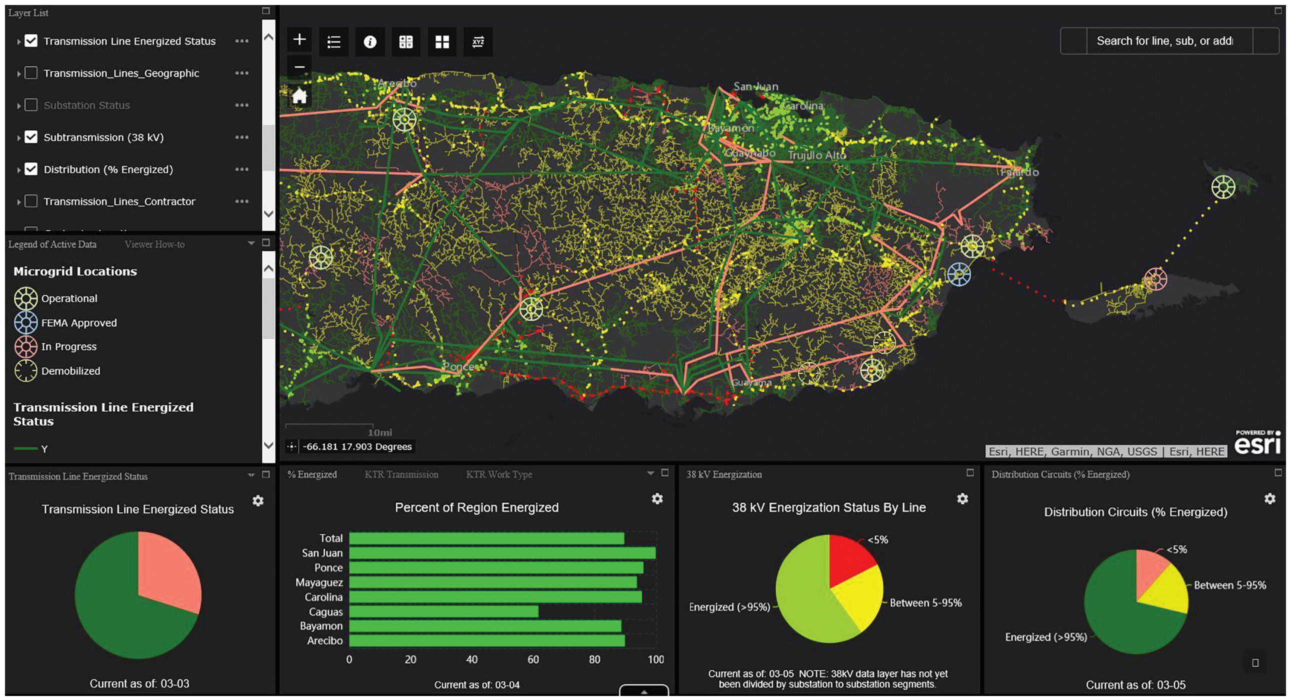

Figure 2. Screenshot of the USACE TFP web viewer. Image: USACE.

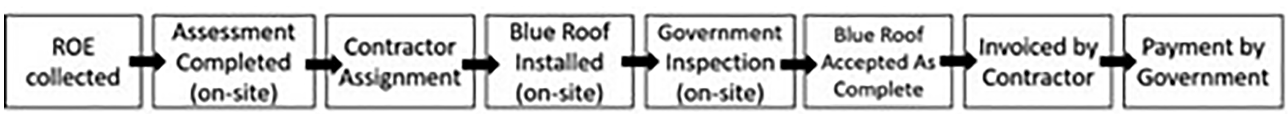

Figure 3. Idealized process for a structure participating in the Blue Roof program, with eight important steps. ROE: Right of Entry form (authorization form signed by homeowner allowing government officials and contractors to access the property).

60,000 blue roofs were installed throughout Puerto Rico across all 78 municipalities.[23]

As with any construction-based activity, the progress of a single home awaiting assistance from the Operation Blue Roof mission went through multiple phases. Figure 3 shows an idealized progression of a single property, from the initial creation of a Right of Entry (ROE) form signed by the homeowner, allowing access to the property by government inspectors and contractors, through Blue Roof installation on the structure, to the final step of payment by the government to the construction contractor. This idealized process includes eight steps, which required at least three on-site visits to a property for initial assessment, roof repair work, and final inspection. For any data management system designed to track construction progression, we strongly recommend that each step change event has a date-stamp associated with it. This would allow mission staff to see not just where in the process a property is at a single moment, but how long it took to move through each step.

This idealized progression shown in Figure 3 could be slowed for a variety of reasons, examples of which are shown in Figure 4. Each problem, whether incorrect location information or construction crew safety concerns, had to be resolved before the process could resume. For example, there were many instances of incomplete address information on an

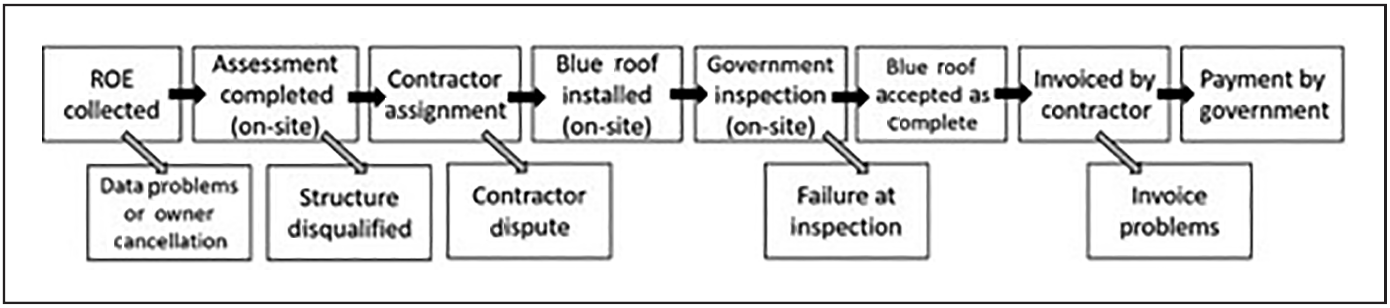

Figure 4. Blue Roof assistance progress with example problems that could delay delivery. ROE: Right of Entry form (authorization form signed by homeowner allowing government officials and contractors to access the property).

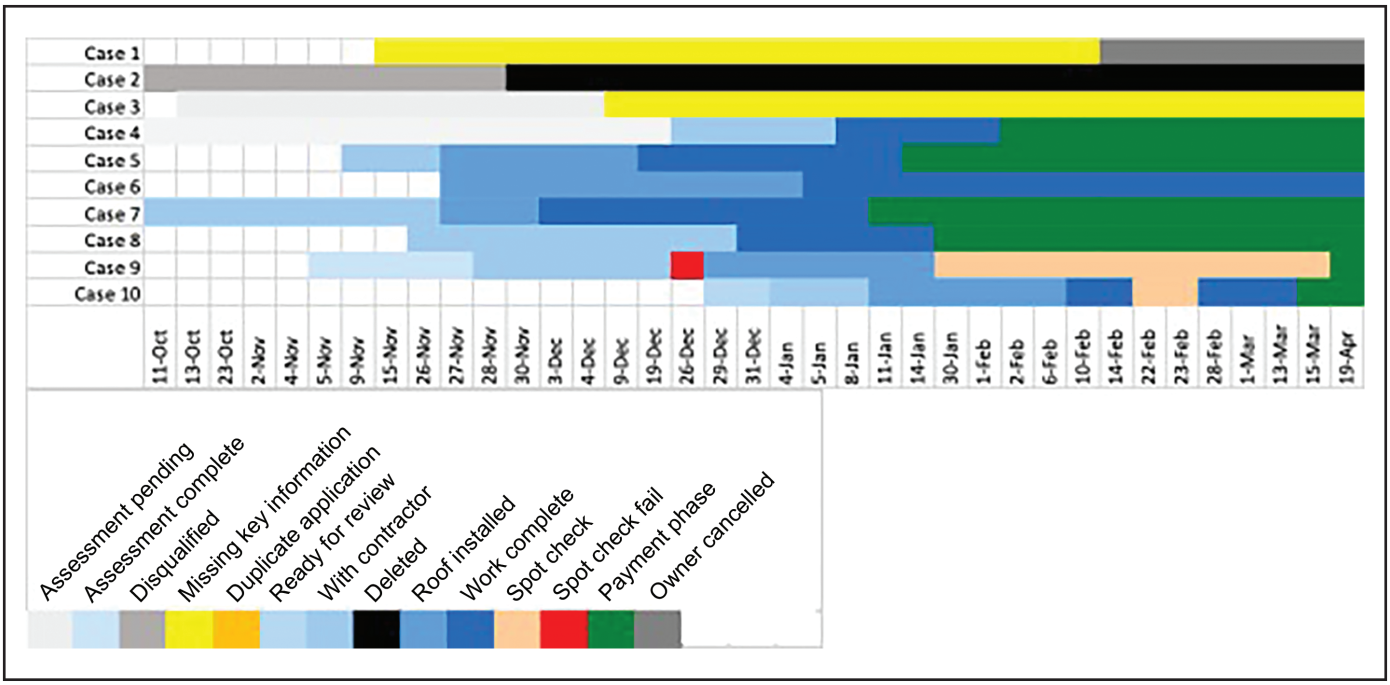

Figure 5. Example of pixel graph-style visualization to display progress tracking for hypothetical Blue Roof cases.

ROE form. Resolving this common problem required time and resulted in the practice of latitude and longitude information being added as a standard piece of address information even though ROE forms were not designed to capture this piece of information.

Tracking of each case at each step was essential for conveying mission progression at different levels of aggregation. For example, individual homeowners who called the Blue Roof helpline needed information about their case, local government liaisons needed information about specific municipalities to answer questions from mayors and community leaders while still respecting individual privacy, and mission leadership needed island-wide summary data to track progress and execute management actions. These data needs were in addition to the daily data needs of the mission staff distributed across the island in field offices. Field office managers needed to dispatch staff to different site visits every day, interface with contractors and suppliers, and respond to unique information requests. Figure 5 shows a pixel graph displaying a sample timeline of 10 hypothetical cases at irregular time intervals. An ideal progression would move from light blue (assessment) to dark blue (installation and inspection), then to green (paid), but other states were possible. Pixel graphs are especially useful for large data sets because the human eye is drawn to colors and patterns. For example, a sudden increase or cluster in inspection failures (red) could indicate the need for additional training or the discovery of a manufacturing defect in construction materials. The key function would be to present and preserve a history of each case progression, with the ability to group records by different attributes or subobjectives.

The Blue Roof mission provides a useful demonstration of how a single data set may need to be presented for multiple audiences, emphasizing different narratives based on information needs. The alternative presentations of data in Figure 6 are examples from the USACE briefing materials as of December 20, 2017 as a demonstration of interim status reporting 3 months after the Hurricane Maria. The plots in Figure 6 are not outputs from the mission database as it did not have that capability, but similar graphs were developed independently in response to mission needs. Mission leaders required information about two primary response tasks: field assessments of homes and installation of blue roofs. Figure 6A shows a simple line plot of these data relative to calendar date, but visual references have been added to contextualize decision-making. A horizontal line shows

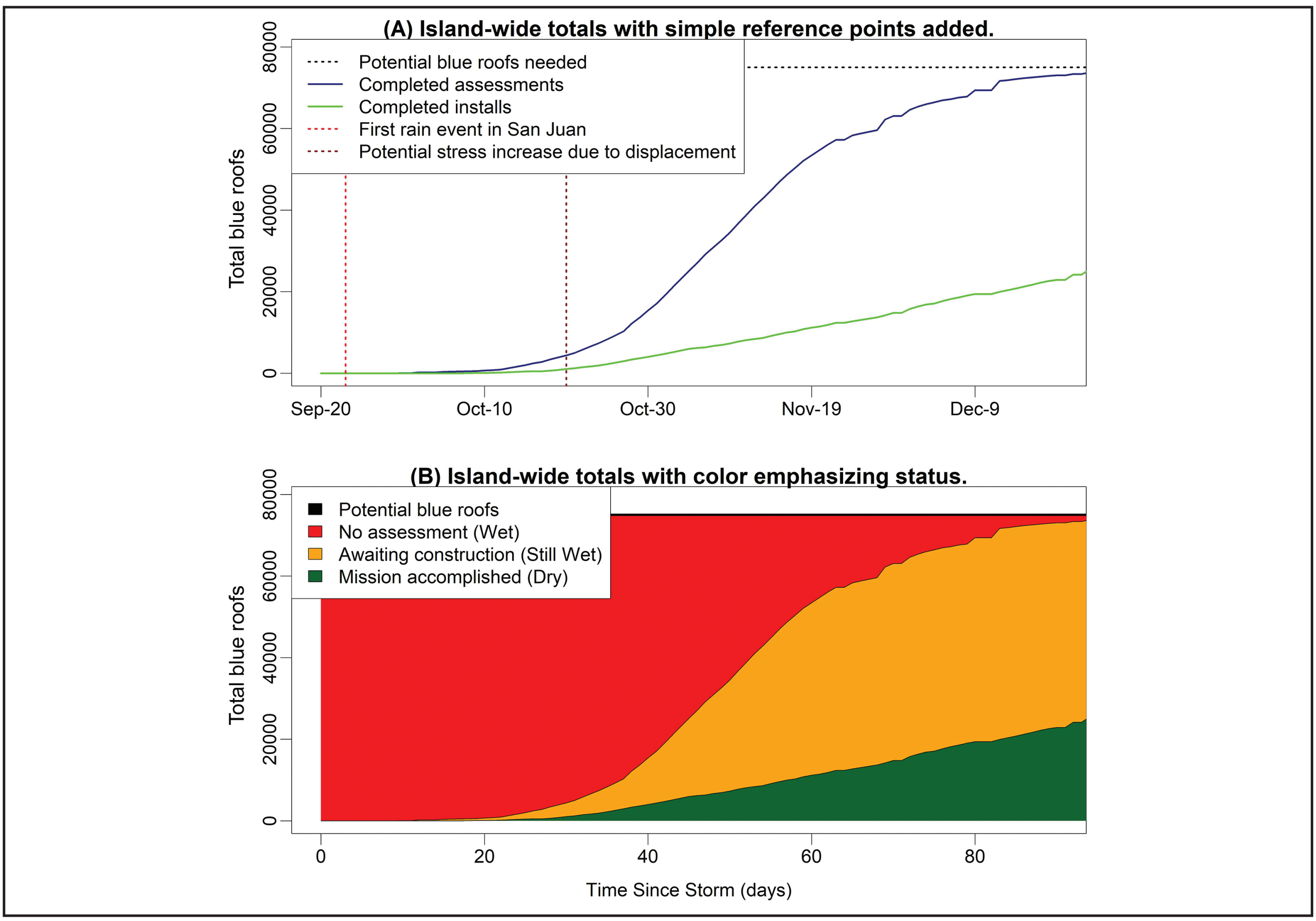

Figure 6. Alternative visual summaries of temporary roofing status during Hurricane Maria. (A) Island-wide blue roof summary with embedded reference points describing citizen effects. (B) Island-wide blue roof summary using color to emphasize status and trends.

the predicted number of blue roofs based on prior hurricanes, and vertical lines show key outcomes relative to citizens' experiences such as milestones related to household damages and psychological responses to displacement from other hurricanes. Figure 6B presents the same data using color and plain language to emphasize outcomes in plain language and evoke a more personal response. Additionally, calendar days were replaced with time since the hurricane to reduce memory required by users, ie, "Was the storm on September 15th or 25th?" These graphics demonstrate the value that could be added from alternative visualizations as well as the need to help users interpret and contextualize data by providing visual cues.

Overall findings from the Operation Blue Roof data management experience are as follows. (1) Visualization may need to be adapted for different purposes or audiences. (2) The same data visualized multiple ways may lead to different observations. (3) Plain language in visuals can potentially increase the breadth of audience understanding and reduce miscommunications. (4) Simple changes to figures can make them more accessible to decision-makers and nontechnical audiences.

Results and principles

Here, we outline principles for effectively using data visualization and communication to inform disaster response and recovery.

Principle 1: preparedness is more than people and supplies: it must include data collection systems designed for a full suite of mission needs

Resilience literature describes a cycle with the phases of prepare, absorb, recover, and adapt.[24-27] Often, the "prepare" phase focuses on the prepositioning of physical supplies, eg, potable water, nonperishable food, communications equipment, and power generators; establishment of relational networks between response groups, eg, first responders, local governments, and nonprofit aid organizations; and assessment of critical infrastructure, eg, hospitals, electrical grid components, and evacuation transportation routes. While these components remain critical, preparedness now needs to include considerations of data collection systems, data sets and data standards, and communication methods. Although this paper focuses on data communication within a response effort, an important component of data communication is sharing an information with outside entities such as news organizations. Groups in charge of data collection, processing, and visualization must be able to brief information clearly to agency leaders and the press that informs the public. The design of communication products destined for public consumption should include consultation with experienced communication professionals to ensure clarity and consistency with other communication products.

Data-collection systems that are likely to be used by volunteers or new staff (or where there will be frequent staff turnover such as during a response effort lasting more than 1 month) should be designed to minimize potential sources of error as much as possible. To avoid typographical or transcriptional errors with geospatial information, such as addresses, there should be as much prepopulated information as possible in any data collection system. For example, most parts of the United States have well-defined spatial units, such as towns, counties, municipalities, or ZIP code routes from the US Postal Service. On the whole, these do not change very much year to year and could be brought into (or activated within) data collection systems on a state-by-state basis depending on the extent of the disaster. Data-capture systems that will be used in dynamic environments where the risk of fatigue is high should minimize the burden of data entry as much as possible. To support this user-centric design, data-capture systems should auto-populate and error-check fields as much as possible. To continue with the ZIP code example, typical address capture follows the order of (1) house number, (2) street name, (3) city, (4) state, and then (5) ZIP code. A system with built in error-checking could start with (1) ZIP code, which then auto-populates fields for city, state, and county, then have the user continue entry for (2) street name and (3) house number, and compare typed results against a preloaded database of street names and house numbers and either disallow nonmatching entries or flag them for review before a record can be completed. Had this been available during the start of Operation Blue Roof, there would have been efficiency improvements in processing requests for assistance.

The Federal response and recovery efforts after the 2017 hurricane season exposed gaps in the completeness of housing address data infrastructure, especially in Puerto Rico. Subsequent efforts to improve residential address data collection are ongoing across multiple federal agencies,[28] with the US Census Bureau providing support to projects such as the nonprofit Initiative for Civic Address Systems Assessment in Puerto Rico[29,30] to support enhanced local residential address collection. The results of address infrastructure updates should be routinely reviewed and incorporated into geospatial databases, including for rural areas on the US mainland, which might have historically lacked traditional street address. Such data-maintenance protocols should be an integral part of any data-collection tool used for federal response and recovery.

Principle 2: identify commonly needed metrics beforehand

Disasters that are severe enough to involve federal assistance will often have recurring types of information requirements; this was the case during the extent of the Operation Blue Roof and TFP missions. Data collection systems should consider these recurring information needs, include nested units of measure, eg, neighborhood, city, or municipality, county, and state, and provide ways to aggregate and disaggregate data across disaster events. Unique numerical case identifiers assigned during one event should not be reused during another event. Each disaster response will have three general phases: (1) request for assistance and assessment phase; (2) intervention action or construction phase; and (3) close-out phase. Common metrics that should be readily available and extractable from relevant disaster management database include:

- Number of new requests for assistance received, or processed, per day.
- Number of requests for assistance relative to the population of the area, or relative to the number of homes in an area.
- Number of on-site assessments completed, relative to the number of requests.
- Number of construction actions or intervention actions, eg, debris removal, completed relative to the number of requests.
- Time elapsed between request for assistance and assistance provision, including observed minimum time, maximum time, average time, and median time, separable by spatial unit. (This feature has a special relevance for potential contract, financial management, and auditing actions after a mission is completed, which is beyond the scope of this paper but warrants mention because of the relevance to data capture system design.)
- Number of intervention actions completed (or end point reached), relative to the number of requests, relative to the population, or relative to a defined spatial unit.

These metrics are only a starting point; they represent a minimum that should be made readily available to decision-makers from day 1 of any natural disaster response mission. Any team designing data collection and management systems should be made aware of these high-frequency reporting needs, and the reality that different summaries and visualizations will be required. Common data types and structures also allow for pre-event development and testing of visual summaries with historical or hypothetical data.

Principle 3: tools should improvise alongside the mission

Emergency management incorporates a large amount of improvization and creativity. Improvization does not necessarily indicate the failure of a plan or the failure to make plans—instead, it is the ability of the mission to act during the disruptive event.[31] Miner, Bassoff, and Moorman define improvization as "the deliberate and substantive fusion of the design and execution of a novel production,"[32] which means that it allows room for conception and implementation of action when it is needed.[33] Improvization is a desirable quality in any emergency management mission, and therefore, any emergency data management and visualization system.

Resilience is the ability to manage uncertainties productively, and to do this, decisions must be made with the best available information. This flow of data into information for decision-making is critical to the success of a response and recovery effort. Technological advances have resulted in capabilities to create very powerful and mobile response and recovery tools. These tools can summarize information vertically within an organization—from the field to headquarters—and/or to coordinate across a wide variety of stakeholders, including nonprofits, individuals, and local, state, and federal government agencies. However, for such tools to be trusted, information must be accurate, up-to-date, and oriented in a form that makes it easy for decision makers to achieve situational awareness. Recent research has identified that there is a gap between the planned functions of disaster response tools and their performance during a disruption because of the failure of supporting infrastructure systems like power or communications.[34] Tools need to be developed with similar improvizational abilities as the missions they support—specifically reconfigurable and modular technologies.[35] By acknowledging potential restrictions to the toolsets and the need for improvization, data management professionals can better design adaptive technologies to improve decision-making when it counts the most.

Principle 4: data visualization is more than a single plot

Information visualization "aims to enhance one's ability to carry out a task,"[5] and thus, the type of visual summary is intimately linked to the disaster management decision being made.[19,20] Furthermore, visualization connects data to a narrative and an audience's analytical and emotional responses.[21] The scope of data visualization is typically driven by issues of purpose, data type and distribution, constraints of the visual media, logistical issues such as time and expertise, and other factors,[20,36] and many resources exist for comparing and contrasting methods.[37,38] Multiple visualizations are often needed to summarize complex data sets such as those encountered in disaster management, and critical thinking and trial-and-error may be required pre-emptively and in real-time to identify appropriate methods (Principles 1 and 3). For example, during Operation Blue Roof, there was a high demand for municipality-level data, both to inform local government leaders and to identify areas where construction activities were not proceeding at the expected pace.

A wide array of technical tools can facilitate the management, visualization, exploration, and communication of disaster response and recovery data. A number of context-specific tools have emerged for applications related to humanitarian relief coordination,[39] emergency incident management,[39] recovery of private businesses,[8,40] situation reporting,[41] and disaster cloud data management.[42] Additionally, data exploration and real-time report generation tools are emerging, which could be tailored to *ad hoc* needs and automate key parts of the response process. Notably, many methods are available as Free and Open Source Software (FOSS), which has been highlighted as particularly appropriate for disaster management applications.[43] Two groups of tools are highlighted here that are particularly germane to the role of visualization in informing a disaster response effort: data dashboards and open science methods.

"Data dashboards" generally describe a graphical user interface summarizing multiple data streams relevant to decision-makers typically in the form of a series of charts, infographics, and summary statistics. The public has gained broad awareness of these portals during the COVID-19 pandemic, during which many organizations established web services for conveying rapidly evolving data on case counts, mortality, hospital capacity, and local demography all across space and time.[44] Dashboards provide a powerful mechanism for different audiences to explore data through multiple summary figures as well as investigating outcomes at multiple scales, eg, municipality, county, state, or nation. From a software developer perspective, these tools provide the ability for dynamic update as data become available (rather than manually updated figures pasted into briefing books), capacity to control differential access on public and sensitive data, eg, through password protection, and easy mechanisms to "push" new visualizations or analytical results out to the audience.

"Open science" refers to an approach embracing transparency in all stages of the research process, including sharing of data, analytical code or software, published products, and other issues.[45] Disaster management often requires sensitive data such as personal information, health data, or financial outcomes, and thus, a complete embrace of data sharing may be inappropriate. However, the tools provided by the open science community could assist managers in transparently sharing outcomes with interested parties ranging from agency leaders and field practitioners to affected citizens and policy makers. One example of an open science application after Hurricane Maria came from a group of interdisciplinary scientists who responded to the health hazard of limited water treatment capacity due to power outages and subsequent concerns about the risk of leptospirosis. This group collected water samples from across the island and created an open-source cyber-infrastructure that connected communities, researchers, and practitioners to real-time water quality data and tools for analysis.[46] From a technical standpoint, real-time report generation tools like Markdown, Jupyter notebooks, and Sweave can facilitate rapid data sharing[45] and avoid duplication in preparation of situation reports and briefings. Furthermore, these methods can be used to share predictive modeling and allow decision-makers to interact with models by changing parameters related to policy options such as Stanford University's COVID-19 modeling toolkit.[47]

DISCUSSION

The need for assistance after natural disasters is unlikely to disappear. These events will vary in the type of damage they inflict but can include network impacts (electric, water, sewer, and internet) and patch-style impacts (individual structures and debris). The case studies described above illustrate the range of these issues—TFP mission engaged a centrally managed electrical generation and distribution network, and the Operation Blue Roof mission provided temporary roofing to individual homeowners. These two efforts were operating among other response and recovery efforts managed by other government, private, and nonprofit entities.

Although these missions varied in aim and scope, the need for accurate data collection, analysis, and communication was constant. During the TFP and the Operation Blue Roof mission, data communication evolved in response to increased technical capabilities and staff familiarity with data sources and communication needs. Based on the authors' experience, it is believed that if some of the suggested tools and technologies had been in place before the disaster, it could have improved the ability of field staff to perform data collection, database query processes, and speed of data communication and reporting, but it would not necessarily have sped up the overall response. Time is a precious commodity during disaster response, and it behooves agencies to have staff focusing on mission delivery and tactical goals, not chasing down typographical errors that could have been prevented. For example, switching from the labor-intensive ball-and-stick model of the electrical grid versus the later maps that were automatically generated (and much less prone to error) through ArcGIS allowed staff to focus on other aspects of data collection and reporting. Figures 5 and 6 display examples of different data visualization presentations, and how these could be used to understand different types of mission progression (subobjectives). In some cases, data aggregation is useful to display overall progress and discrete numbers to convey the total mission size. Conversely, disaggregation is essential to display individual case details that may be critical knowledge for field personnel. During the post-Hurricane Maria missions, there were subobjectives that required information on the overall trend in roof installation or power connectivity, ie, the central tendency, priority installations for residents with special needs, eg, health conditions exacerbated by group shelters, the installation of the "last" roof or last substation, ie, the extremes of the distribution, and the spatial distribution of installations across the island. A single visualization is unlikely to inform all aspects of a complex disaster-response mission; since purpose should drive the visualization, multiple figures will be needed for multipurpose disaster responses, and visuals must be interpreted and contextualized to effectively inform decisions.

The scale and type of response missions necessitates different specialty teams. Personnel deployed to the Blue Roof mission did not simultaneously serve within the TFP mission; data management was also separated. We suggest that future data collection, storage, and management efforts have the capability to be harmonized, so that multifaceted disaster response efforts can receive more complete situational awareness. In many places, coordinated tracking could be done by using a distinctive numerical identifier in addition to a geospatial feature such as an address, but this would harmonize better across different databases if data system architects agreed on an address structure in advance.

In this paper, we suggest a list of considerations for those building or managing a data collection system for use during disaster response and recovery operations; these include features related to data input and data outputs that can be used for management, reporting, and coordination with other stakeholders. In summary, we recommend the following elements to be considered in data management system design and maintenance:

- *Consult emergency management practitioners during software design and testing*. Practitioners who work in disaster response represent a variety of professions and have experience with different data sources and presentation styles. Their professional experience is required for identifying what pieces of information are used or desired during response management. Ongoing consultation between software developers and practitioners is critical because people who may be responsible for generating or capturing data, and downstream data consumers, are often neither information technology specialists nor have experience in data management.

- *Design systems for use in environments with limited internet connectivity*. Natural disasters might interrupt critical communication elements such as internet cables and cellular towers. Satellite-based communications are not yet widely available and should not be expected to serve all potential communication needs.

- *Reduce the need for manual data entry as much as possible*. Preloading elements such as address fields are an important element of any system since so much disaster response and recovery is spatially based and may require coordination across multiple geographic entities by people who are unfamiliar with local names and spellings.

- *Include database fields for standard and nonstandard geospatial information*. Some communities may have limited road access or low-clearance bridges along certain routes, or hazards like mudslides might be present as a result of the disaster. This type of access-related information should be captured with geospatial information wherever possible.

- *Preload systems with relevant geospatial datasets*. Relevant datasets might include topographical maps, census-block datasets, street maps, flood risk maps, and other spatially based information such as social vulnerability maps.[48,49] Contingency environments may have limited or no internet connectivity, so any geospatial functions should not rely on internet-based connectivity to a remote server. These datasets should be reviewed and updated at least annually.

- *Design reporting systems that will be able to disaggregate and aggregate data in different ways to allow for the evolution of* *information needs during a mission*. The places or questions that are asked at the start of a response mission will evolve as more information becomes available and the recovery process progresses.

- *Include database outputs that can be quickly generated and exported into commonly used file types, eg, .CSV, .TXT*. If search and selection capabilities are not built into the database itself, sensitive data must be able to be removed before file dissemination.

- *Allow different levels of information access within the database*. Different response roles will require different levels of database access (permissions). Any dashboards within a data system should include relevant contextual data to promote accurate interpretation of any summary visualizations.

- *Regularly test software*. Computer operating systems go through regular updates, which may be incompatible with older software; this should be examined through regular testing of all functions and corrected as required.

We make these suggestions while cognizant of the fact that delays in assistance have very real impacts to those affected; every Blue Roof case number represented not just a structure, but a home. Every utility pole installed represented another step toward a community returning to their normal daily rhythms. Although valuable as tools, data visualizations, graphs, and charts can have the unintended side effect of obscuring the human element of a disaster behind numbers and maps. Aggregated progress bars can mislead or omit the nuance of which communities are still struggling to recover and why. Objectivity in disaster management cannot replace the original goal of providing humanitarian assistance. The best graphics in the world do not change the availability of plywood or utility poles, but they can communicate the urgency in a more visceral way. We hope that this paper will serve as a learning opportunity and guide for improved planning and collaboration across the multiple stakeholders involved in disaster response and recovery. A key message is that generic data management systems exist (long-term strategic goals) but are somewhat challenging to tailor in real-time (in the face of real-time, response-driven tactical goals). For organizations that regularly respond to disasters, we echo the recommendation that a data management specialist position should be embedded in early-response teams.[17] These data management specialist should be familiar with the data collection system(s) as well as the reporting needs commonly associated with emergency response, described in the next section. This position is critical in supporting the variety of action areas that contribute to a response mission, from logistical to legal, and might require skillsets, eg, database management, geospatial analysis, not normally emphasized in early-response teams.

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REFERENCES

1. Gunderson L: Ecological and human community resilience in response to natural disasters. *Ecol Soc*. 2010; 15(2): 18.
2. IPCC: Climate change 2014: Synthesis report. Contribution of working groups III and III to the fifth assessment report of the intergovernmental panel on climate change. 2014.

3. Pelling M: *The Vulnerability of Cities: Natural Disasters and Social Resilience*. London: Earthscan Publications Ltd., 2003.
4. Brown T, Craddock S, Ingram A: Critical interventions in global health: Governmentality, risk, and assemblage. *Ann Assoc Am Geogr*. 2012; 102(5): 1182-1189. DOI: 10.1080/00045608.2012.659960.
5. McInerny GJ, Chen M, Freeman R, et al.: Information visualisation for science and policy: Engaging users and avoiding bias. *Trends Ecol Evol*. 2014; 29(3): 148-157. DOI: 10.1016/j.tree.2014.01.003.
6. Yu M, Yang C, Li Y: Big data in natural disaster management: A review. *Geosciences*. 2018; 8(5): 165. DOI: 10.3390/geosciences8050165.
7. Naumann F, Raschid L: Information integration and disaster data management (DISDM). 2006. Available at *http://db.cis.upenn.edu/iiworkshop/postworkshop/positionPapers/123.pdf.* Accessed January 11, 2020.
8. Hristidis V, Chen S-C, Li T, et al.: Survey of data management and analysis in disaster situations. *J Syst Softw*. 2010; 83(10): 1701-1714. DOI: 10.1016/j.jss.2010.04.065.
9. Pasch RJ, Penny AB, Berg R: National Hurricane Center tropical cyclone report: Hurricane Maria. Tropical cyclone report AL152017. National Hurricane Center, 2018.
10. Cangialosi JP, Latto AS, Berg R: National Hurricane Center tropical cyclone report: Hurricane Irma. National Hurricane Center. 2018.
11. Kishore N, Marqués D, Mahmud A, et al.: Mortality in Puerto Rico after Hurricane Maria. *N Engl J Med*. 2018; 379(2): 162-170. DOI: 10.1056/NEJMsa1803972.
12. Rivera R, Rolke W: Modeling excess deaths after a natural disaster with application to Hurricane Maria. *Stat Med*. 2019; 38(23): 4545-4554. DOI: 10.1002/sim.8314.
13. National Hurricane Center: Costliest US tropical cyclones table updated. 2018. Available at *https://www.nhc.noaa.gov/news/UpdatedCostliest.pdf.* Accessed January 11, 2020.
14. US Army Corps of Engineers: Emergency Response Fact Sheet. 2011, 1. Available at *www.usace.army.mil.* Accessed September 1, 2020.
15. US Government Accountability Office: 2017 Hurricane season: Federal support for electricity grid restoration in the US Virgin Islands and Puerto Rico (Gao-19-296), 2019.
16. Li T, Xie N, Zeng C, et al.: Data-driven techniques in disaster information management. *ACM Comput Surv*. 2017; 50(1): 1-45. DOI: 10.1145/3017678.
17. National Research Council: *Improving Disaster Management: The Role of IT in Mitigation, Preparedness, Response, and Recovery*. Washington, DC: National Academies Press, 2007.
18. Raschid L: Information integration and dissemination for disaster data management. In *Proceedings of the 8th Annual International Conference on Digital Government Research: Bridging Disciplines & Domains*. Los Angeles, CA: Digital Government Society of North America, 2007: 333-335. Available at *https://dl.acm.org/doi/abs/10.5555/1248460.1248543.* Accessed May 1, 2020.
19. Kelleher C, Wagener T: Ten guidelines for effective data visualization in scientific publications. *Environ Model Softw*. 2011; 26(6): 822-827. DOI: 10.1016/j.envsoft.2010.12.006.
20. Wang D, Guo D, Zhang H: Spatial temporal data visualization in emergency management. In *Proceedings of the 3rd ACM SIGSPATIAL Workshop on Emergency Management Using-EM-GIS'17*. New York: ACM Press, 2017: 1-7. DOI: 10.1145/3152465.3152473.
21. Engebretsen M, Kennedy H (eds.): *Data Visualization in Society*. Amsterdam: Amsterdam University Press, 2020. DOI: 10.5117/978946372290221.
22. Lloyd J: Department of Energy Project Management Workshop: Puerto Rico grid restoration presentation slides. 2018.
23. US Army Corps of Engineers: Emergency operations: National Response Framework: Temporary roofing. 2020. Available at *https://www.usace.army.mil/Missions/Emergency-Operations/National-Response-Framework/Temporary-Roofing/*. Accessed September 1, 2020.
24. Rosati JD, Touzinsky KF, Lillycrop WJ: Quantifying coastal system resilience for the US army corps of engineers. *Environ Syst Decis*. 2015; 35(2): 196-208. DOI: 10.1007/s10669-015-9548-3.
25. Sharifi A, Yamagata Y: A conceptual framework for assessment of urban energy resilience. *Energy Procedia*. 2015; 75: 2904-2909. DOI: 10.1016/j.egypro.2015.07.586.
26. Heinimann HR: A generic framework for resilience assessment. In *Resilience Resource Guide: An Edited Collection of Authored Pieces Comparing, Contrasting, and Integrating Risk and Resilience with an Emphasis on Ways to Measure Resilience*. Geneva: EPFL International Risk Governance Center, 2016: 90-95. DOI: 10.5075/epfl-irgc-228206.
27. Wardekker A, Wilk B, Brown V, et al.: A diagnostic tool for supporting policymaking on urban resilience. *Cities*. 2020; 101: 102691. DOI: 10.1016/j.cities.2020.102691.
28. Puerto Rico Address Data Working Group (PRADWG) of the Federal Geographic Data Committee Address Subcommittee: Phase 2 report: Federal agency challenges in the management of Puerto Rico Address Data. Report to the Federal Geographic Data Committee. 2020. Available at *https://communities.geoplatform.gov/ngda-address/wp-content/uploads/2020/05/PRADWG-Phase-2-Report-FINAL.pdf*.
29. iCASAPR: About iCASAPR. 2019. Available at *https://icasapr.com/*. Accessed September 1, 2020.
30. US Census Bureau: The opportunity project: Puerto Rico address database operations support (PRADOS). 2020. Available at *https://opportunity.census.gov/prados/*. Accessed September 1, 2020.
31. Kreps GA, Bosworth SL: Organizational adaptation to disaster. In *Handbook of Disaster Research*. Berlin: Springer, 2007: 297-315. DOI: 10.1007/978-0-387-32353-4_17.
32. Miner AS, Bassoff P, Moorman C: Organizational improvisation and learning: A field study. *Adm Sci Q*. 2001; 46(2): 304-337. DOI: 10.2307/2667089.
33. Kendra J, Wachtendorf T: Improvisation, creativity, and the art of emergency management. In Durmaz H, Sevinc B, Yayla AS, et al. (eds.): *Understanding and Responding to Terrorism*. Amsterdam: IOS Press, 2007: 324-335. Available at *https://books.google.com/books?id=jZjqavWoRfkC&lpg=PA324&ots=GzBgEUUcOq&dq=(Kendra and Wachtendorf 2007&lr&pg=PA324#v=onepage&q=(Kendra and Wachtendorf 2007&f=false*. Accessed September 1, 2019.
34. Tim Y, Pan SL, Ractham P, et al.: Digitally enabled disaster response: The emergence of social media as boundary objects in a flooding disaster. *Info Systems J*. 2017; 27(2): 197-232. DOI: 10.1111/isj.12114.
35. Singh JB, Sharma SK, Misra S: "Invented-on-the Fly" mobile application for disaster response: Construction of technological frames and impact. *EGOV-CeDEM-ePart 2019*. 2019: 99-108. Available at *https://biblio.ugent.be/publication/8626904/file/8626906.pdf#page=113*. Accessed January 11, 2022.
36. McKay SK: Visualization as a tool for ecological analysis. In *Encyclopedia of Ecology*. Amsterdam: Elsevier, 2019: 213-220. DOI: 10.1016/B978-0-12-409548-9.10566-4.
37. Tominski C, Aigner W: The TimeViz browser: A visual survey of visualization techniques for time-oriented data. 2015. Available at *http://survey.timeviz.net/*. Accessed September 1, 2020.
38. Lengler R, Eppler MJ: A periodic table of visualization methods. 2020. Available at *www.visual-literacy.org/periodic_table/periodic_table.htm*. Accessed September 1, 2020.
39. Sahana Software Foundation: Sahana foundation: Open source disaster management software. 2020. Available at *https://sahanafoundation.org*. Accessed September 1, 2020.

40. Florida International University: Business continuity information network. 2020. Available at *http://www.bizrecovery.org/*. Accessed September 1, 2020.
41. Zheng L, Shen C, Tang L, et al.: Disaster SitRep—A vertical search engine and information analysis tool in disaster management domain. In *2012 IEEE 13th International Conference on Information Reuse & Integration (IRI)*. Piscataway, NJ: IEEE, 2012: 457-465. DOI: 10.1109/IRI.2012.6303044.
42. Grolinger K, Capretz MAM, Mezghani E, et al.: Knowledge as a service framework for disaster data management. In *2013 Workshops on Enabling Technologies: Infrastructure for Collaborative Enterprises*. Piscataway, NJ: IEEE, 2013: 313-318. DOI: 10.1109/WETICE.2013.48.
43. Careem M, De Silva C, De Silva R, et al.: Sahana: Overview of a disaster management system. In *2006 International Conference on Information and Automation*. Piscataway, NJ: IEEE, 2006: 361-366. DOI: 10.1109/ICINFA.2006.374152.
44. Johns Hopkins University & Medicine: Coronavirus resource center. 2020. Available at *https://coronavirus.jhu.edu/us-map*. Accessed September 1, 2020.
45. Hampton SE, Anderson SS, Bagby SC, et al.: The tao of open science for ecology. *Ecosphere*. 2015; 6(7): art120. DOI: 10.1890/ES14-00402.1.
46. Hart J, Bandaragoda C, Ramirez-Toro G: Sharing data helps Puerto Ricans rebound after Hurricane Maria. *Eos (Washington DC)*. 2019; 100. DOI: 10.1029/2019EO121651.
47. Stanford University: Systems utilization research for Stanford medicine: COVID-19 tools. 2020. Available at *https://surf.stanford.edu/covid-19-tools/covid-19/*. Accessed September 1, 2020.
48. Cutter SL: Vulnerability to environmental hazards. *Prog Hum Geogr*. 1996; 20(4): 529-539. DOI: 10.1177/030913259602000407.
49. Cutter SL, Barnes L, Berry M, et al.: A place-based model for understanding community resilience to natural disasters. *Glob Environ Chang*. 2008; 18(4): 598-606. DOI: 10.1016/j.gloenvcha.2008.07.013.