JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

AMERICAN WATER RESOURCES ASSOCIATION

CHALLENGES AND OPPORTUNITIES FOR CREATING INTELLIGENT HAZARD ALERTS: THE “FLOODHIPPO” PROTOTYPE[1]

J. Michael Johnson, Jim M. Coll, Paul J. Ruess, and Jordan T. Hastings[2]

ABSTRACT: Disasters evolving from hazards are a persistent and deadly occurrence in the United States. Despite this, hazard alerts have remained spatially vague, temporally imprecise, and lack actionable information. These deficiencies indicate a divide between the status quo and what is possible given modern environmental models, geographic information systems (GIS), and smartphone capabilities. This work describes an alternative, prototype system, “FloodHippo,” which integrates operational model outputs, cloud-based GIS, and expanded communication channels to provide personal and interactive disaster alerts for floods. The precepts and methods underpinning FloodHippo apply equally to other disasters that evolve over space and time, presenting the opportunity for a more intelligent disaster response system. The development of such a system would not only minimize current shortcomings in disaster alerts but also improve resilience through individual action, along with community, academic, and federal cooperation.

(KEY TERMS: flooding; emergency response; geospatial analysis; public participation; hazard alerts; social media; National Water Model.)

Johnson, J. Michael, Jim M. Coll, Paul J. Ruess, and Jordan T. Hastings, 2018. Challenges and Opportunities for Creating Intelligent Hazard Alerts: The “FloodHippo” Prototype. *Journal of the American Water Resources Association* (JAWRA) 1–10. https://doi.org/10.1111/1752-1688.12645

BACKGROUND

Hazards become disasters once significant human life or property is lost. During the 20th Century, both the number of disasters and the population at risk dramatically increased in the United States (U.S.) (Figure 1) (EM-DAT 2017). Between 1995 and 2015, 90% of major disasters were caused by weather, and the U.S. has been one of the world’s most frequently hit countries (Guha-Sapir et al. 2016). Most recently, the 2017 floods in Texas, Florida, and Puerto Rico, and fires and mudslides in California, have demonstrated instances where people were unable to escape a hazard situation safely.

Increasingly dense populations faced with more frequent disasters will likely result in greater losses of both life and property. The enormous costs and resources needed to respond to these events can leave even national-level systems woefully inadequate, as seen with hurricanes Katrina in New Orleans (2005) and Maria in Puerto Rico (2017). This suggests current approaches to hazard alerts should be reexamined to unify individual-, community-, and federal-level efforts in building resiliency and minimizing response needs.

The essential purpose of an emergency alert is to communicate a threatening hazard to the public allowing them to make decisions and take action

[1]Paper No. JAWRA-17-0144-N of the *Journal of the American Water Resources Association* (JAWRA). Received April 18, 2017; accepted March 6, 2018. **Discussions are open until six months from issue publication**.

[2]Department of Geography (Johnson, Hastings), University of California Santa Barbara, Santa Barbara, California, USA; Department of Geography and Atmospheric Science (Coll), University of Kansas, Lawrence, Kansas, USA; and Department of Civil Engineering (Ruess), University of Illinois at Urbana-Champaign, Champaign, Illinois, USA (Correspondence to Johnson: mike.johnson@geog.ucsb.edu).

(Sorensen 2000; Linham and Nicholls 2010). These actions can help "... save lives, reduce losses, speed up responses, and reduce human suffering when they receive accurate warnings in a timely manner" (Working Group on Natural Disaster Information Systems 2000). When responding to disasters, human actions typically involve some form of movement in space, and hazards evolve over both space and time. Connecting spatial and temporal data, and communicating the results requires linking environmental models (EM) and geographic information systems (GIS) (Clarke et al. 2002). Therefore, when designing a new type of alert, one that provides both specific and actionable information, three concerns become apparent:

1. Forecasting the trajectory of the hazard
2. Notifying people at risk
3. Facilitating appropriate personal decisions

Substantial progress has been made over the past decade with improved hazard forecasting. With regard to flooding in particular, efforts to couple weather forecasting tools and hydrologic models have resulted in operational streamflow forecasting, mirroring existing capabilities for hurricane and fire prediction (Bauer et al. 2015; NOAA 2016b; Ogden et al. 2015). Ongoing collaboration between National Oceanic and Atmospheric Association's (NOAA) Office of Water Prediction, the National Center for Atmospheric Research (NCAR), and the academic community have created the National Water Model (NWM), which generates real-time streamflow forecasts for each of the 2.67 million reaches in the U.S. National Hydrography Dataset (NHD) for a range of time scales (Maidment 2015; Cosgrove and Klymmer 2016; Salas et al. 2018). Combined with active research into the development of synthetic rating curves, the potential for near-real-time flood mapping throughout the U.S. exists (Wang 2013; Liu et al. 2016; Johnson et al. 2017; Afshari et al. 2018).

The ability to notify people at risk has evolved alongside institutional and technological improvements in wireless communication capabilities. In response to the 2006 Warning, Alert, and Response Network (WARN) Act, the Federal Communication Commission (FCC) adopted the Commercial Mobile Alert System (CMAS) (Pascua 2008). WARN was initially focused on terrorist threats and child abductions but widened to natural hazards when CMAS was adapted to become Wireless Emergency Alerts (WEA). Since 2012, the National Weather Service (NWS) has used WEAs to provide weather-related warnings (NWS 2015). Current alerts appear as text messages showing the issuing agency, time, type of alert, and generic recommended action. Unfortunately, the actions recommended are underwhelmingly vague. For example, in times of flood, WEAs state: "Avoid flooded areas. Check local media" (NWS 2015). Owing to their broad distribution, WEAs also lose credibility as users become accustomed to false alarms (Blanford et al. 2014). In a 2015 study, the Department of Homeland Security (DHS) explored adding hyperlinks to external hazard applications within WEAs. Study participants specifically requested attention-grabbing

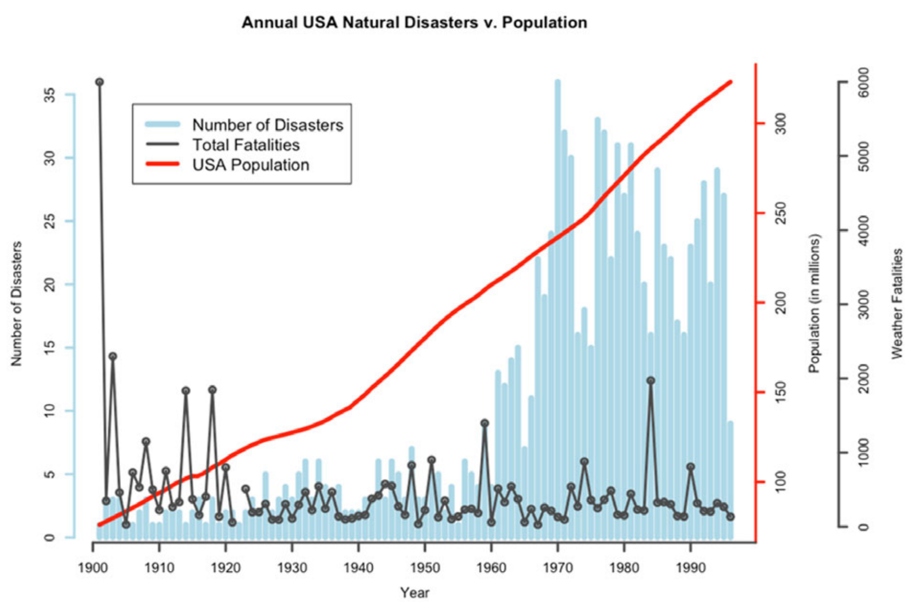

FIGURE 1. Trends in major disaster frequency, population growth, and total disaster deaths in the United States (U.S.): Emergency Events Database and census data.

alerts with a dynamic, real-time map capable of tracking disaster events (Wood et al. 2015). New mandates from the FCC will expand the system to include increased character limits, the capability to "Geo-Fence" an alert area, and URL integration (FCC 2016).

With improved forecasts and notifications, the challenge shifts to the third concern: how to analyze and share information in a way that helps individuals determine what actions they should (or should not) take. As such, an opportunity to reimagine the nation's alert system has emerged.

INTELLIGENT DISASTER ALERTS

Sorensen (2000) noted that effective hazard alerts should include information regarding the nature, location, time, and source of an event and stylistically emphasize specificity, consistency, accuracy, certainty, and clarity. Each of these indirectly speaks to the credibility of an alert's content. Advances in forecasting, GIS, and web mapping present the potential to supply hazard information at scales appropriate for individual action, i.e., providing flood risk at the street, not the county, level. Concurrently, advances in WEA infrastructure, smartphone capabilities, and open, cloud-based geospatial services facilitate the computation, analysis, visualization, and communication of datasets via URL-accessible web maps. If integrated, these services can provide instantaneous information and situational awareness at a personally relevant scale.

Alert systems could also better exploit modern digital relationships to accelerate the flow of information between those in geographic proximity (Schneider et al. 2012) and/or social proximity (connected via the Internet and/or telecommunications). These interconnections make it easier for individuals to actively engage in the refinement, distribution, and consumption of hazard alerts and information (Sutton et al. 2008; Lindsay 2011; Houston et al. 2015).

In light of advancements in knowledge, technology, and interaction, we offer four precepts for modern hazard alerts, building on Sorensen's original work:

1. *Credible*: Alerts and underlying data must be authoritative, consistent across broadcast outlets, and accessible to all demographic and economic groups.
2. *Actionable*: Alerts must be interactive and offer explicit instructions for staying safe throughout the duration of a hazard.
3. *Personal*: Alerts must be spatially and temporally relevant at an individual level.
4. *Socializable*: Alerts must be able to integrate with social media and the web, allowing users to receive, investigate, and share information rapidly on a range of communication devices.

Below we describe a prototype, intelligent alert for floods that offers both spatially and temporally relevant information based on NWM to inform individual action. Ongoing model development is critical, as is regular updates from the model, as these build credibility even if some information is in error.

THE FLOODHIPPO PROTOTYPE

The mascot for our prototype, FloodHippo, was inspired by a hippopotamus that escaped a Tbilisi, Georgia zoo during a flood (Schwartz 2015); it somewhat parallels the National Forest Service's Smokey the Bear Campaign. Over the last 80 years, Smokey has become one of the world's most recognizable characters, highlighting the impact of socializing hazards and making them conversational (About the Campaign 1944). Part of Smokey's success came from delivering content in the right way at the right time. In the 1940s, the right way included National Forest signage, stickers, posters, and stuffed animals. Today, information is consumed digitally. As such, FloodHippo lives on the web.

FloodHippo (http://disasterzoo.wixsite.com/floodhippo) incorporates two *portals* both implemented as web-based applications as opposed to dedicated mobile applications. Mobile applications are easily lost among the plethora of apps in the market and require proactive download, multi-platform development, and regular updates. By contrast, web-based URLs require minimal maintenance, are easily found, and integrate seamlessly across platforms. This continuity allows information to be distributed across both official and social networks from the same central source, invoking ease-of-use, consistency, equitable coverage, and technical support.

Awareness Portal

Emphasizing preparation, the interactive Awareness portal displays official government data and social media feeds through a web mapping interface implemented using Environmental Systems Research Institute's (ESRI) ArcGIS Online (AGO). The official data map allows users to explore near-real-time, government-produced data for any location down to the street-address level. In FloodHippo, this includes NWM 10-Day Anomaly Forecasts, NOAA Radar and

Short-Duration Hazard warnings, Federal Emergency Management Agency (FEMA) 100-year Flood Extents, and a rich collection of warnings and watches from the Department of the Interior. By contrast, the social data map offers on-the-ground reports that can be explored, and more importantly shared. Social data have proven enormously useful in emergency situations (Xiao et al. 2015) and results can be filtered by a user-specified text-string or hashtag to find images, videos, live camera feeds, hyperlinks, and commentaries for evolving hazards.

Screenshots from the Awareness portal were captured as a storm passed over the Mississippi River Basin and are shown in Figure 2. In the official map view, the storm radar can be seen, and the NWM reports the Ohio River is expected to exceed average flow by more than 200,000 cubic feet per second (panel a). Panel b zooms into this reach showing the surrounding area that falls within the FEMA 100-year flood zone and panel c shows the social data map filtered for the keyword "#flood" indicating a surge of geotagged tweets emerging along the river. Panel d again zooms into the impacted area, allowing users to interact with geotagged tweets, images, commentary, and local street cameras. The highlighted tweet in panel d links to a user's Instagram post of the flood waters (panel e) and the text from all tweets from the zoomed in area are shown in panel g, each linking to a video, photos, or external information. Images sourced from Flickr also highlight increased activity along this reach conveying video, imagery, and information relating to the event (panel f). Combined, the official and socially volunteered information paint a clear picture of the ongoing situation and can be used to inform citizens, verify and augment flood forecasts, advise emergency managers, and contribute to post-event archives.

Response Portal

Emphasizing action, the Response portal provides practical guidance. In contrast to WEAs, the portal is URL-based and designed for smartphone use. Because most flood-related deaths result from people attempting to circumvent water (Doocy et al. 2013; NOAA 2016a), the portal focuses on navigation, displaying near-real-time flood forecasts, derived from the NWM streamflow values, on a traditional road map. Routes and destinations within current or future flood boundaries are visible but excluded in route calculations.

To maximize utility, FloodHippo offers two distinct routing options: "Navigate" and "Evacuate." Navigate is intended for users who want to specify a destination, while "Evacuate" automatically selects a destination from a database of available and open shelters managed by first responders. From the 2015 DHS study, one noted criticism of the basic map used was, "... although it shows the area at risk, it doesn't show [me] where to go" (Wood et al. 2015). FloodHippo remedies this issue by providing the requested dynamic, real-time map capable of tracking disaster events.

Case Study

Figure 3 illustrates a case study for the 2009 flooding of Big Creek near Alpharetta, Georgia (panel a), contrasting a standard WEA (panel b) and an intelligent FloodHippo alert (panel c). Using NWM output, high streamflows could be anticipated before an actual event; these are continually updated at the top of each hour. If flood conditions were forecasted, an alert would be generated and distributed through official channels and could further disseminate across users' social networks (panel c.1). Upon opening the URL, a user would see a state-level map indicating impacted counties with an accompanying text-based list. If they believed they (or someone they know) might be impacted, they could elect to share the warning and/or investigate whether evacuation is necessary by clicking on the green icon (panel c.2). They would next see a local street map focused on their location and superimposed with a forecasted flood extent. Slider bars allow the user to "fast-forward" through the event to see its predicted trajectory, polygon by polygon. In this example, assuming the user wants to return home, they would select the "Navigate" option and enter that address (panel c.3). The route is calculated with respect to the flood boundaries and displayed (panel c.4). Once the user finishes their navigation (panel c.5), the system prompts the user to provide feedback and share the URL via their social networks (panel c.6).

Feedback

During the 2016 National Water Center Summer Institute, the FloodHippo prototype was demonstrated to a live audience (Johnson et al. 2016). In default of a real flood event, a FloodHippo alert was simulated for the 2015 "Christmas Day" flood in Tuscaloosa, Alabama generated from retrospective NWM version 1.0 output. The Response URL was distributed to audience members via a FloodHippo Twitter account and the "Evacuate" option directed users from the meeting location to local churches, which simulated community shelters. In near-real-time, these shelters were updated from active to full/inactive, altering the routes presented to users. This same prototype has

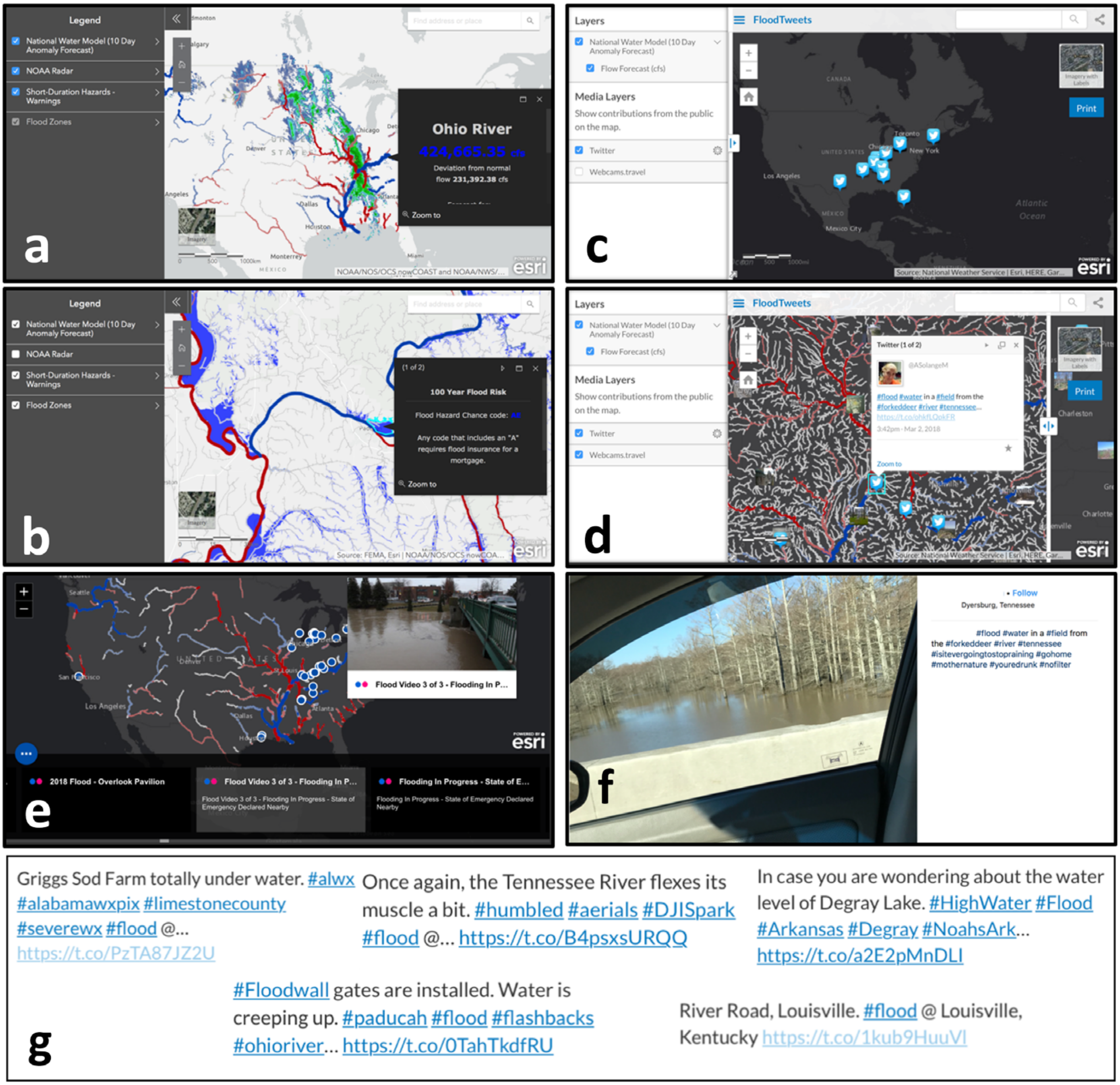

FIGURE 2. Awareness portal showing views of the official and social data maps: (a) National Oceanic and Atmospheric Administration (NOAA) storm radar and National Water Model 10-day anomalies; (b) FEMA 100-year floodplain extents; (c) examination of tweets and links to external sites; (d) localized street cameras and geotagged tweets; (e) Flickr images tagged by "flood"; (f) Instagram photo linked to tweet in panel d; (g) text from tweets linked to icons in panel d.

since been demonstrated four more times to industry experts and seasoned practitioners, using U.S. Geological Survey Flood Inundation Maps as pseudo-forecasts when available. These presentations included the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) biennial conference (July 24–27, 2016), the New Hampshire 911 Bureau of Emergency Communications (August 19, 2016), a NCAR working group (September 11, 2016), and the FEMA HAZUS Users Conference (November 7–9, 2016). In all cases, the implementation and methods employed by FloodHippo were well received.

Specific feedback has encouraged the development of a free-and-open-source FloodHippo to add flexibility and to remove reliance on proprietary software. Such an implementation requires linking inconsistent and

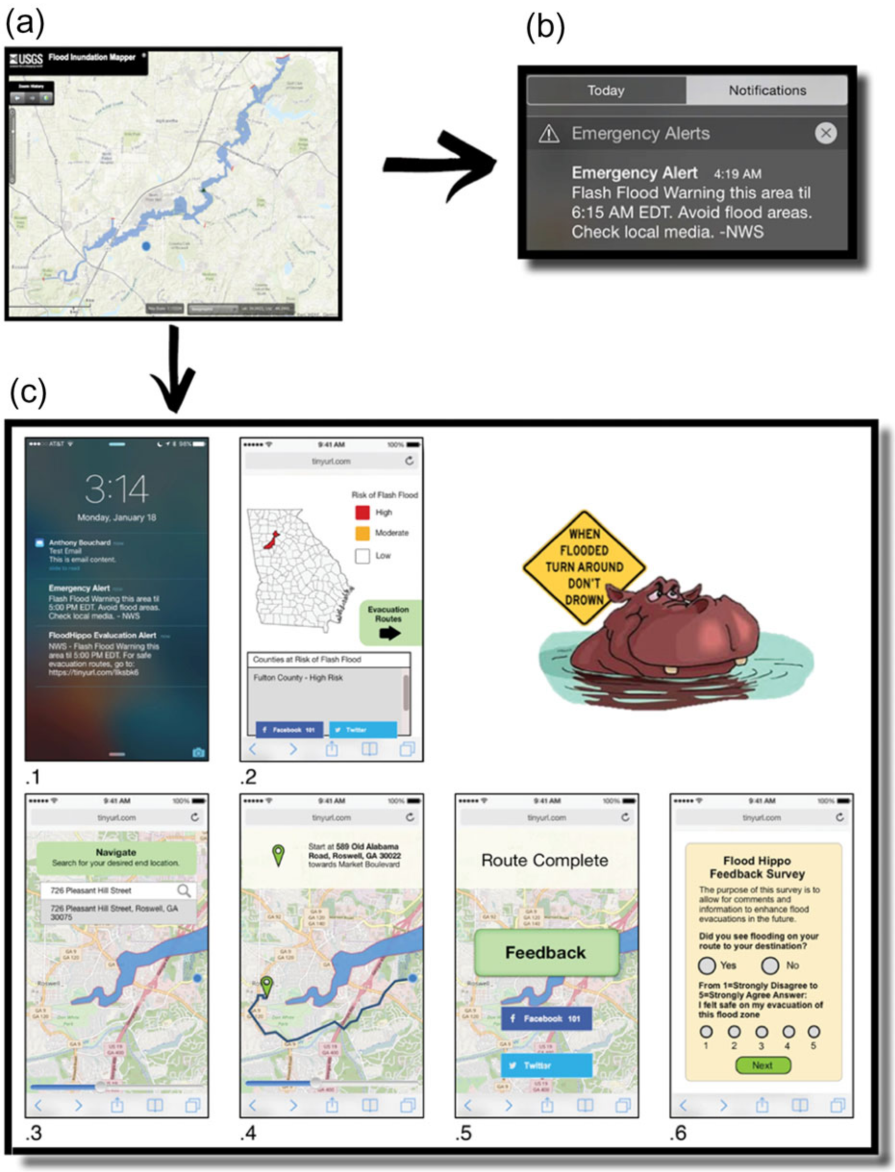

FIGURE 3. Response portal showing three panels: (a) inundation map from the U.S. Geological Survey (USGS) flood inundation mapper library; (b) standard Wireless Emergency Alert for flash floods; (c) FloodHippo alert demonstrating what a user might experience. NWS, National Weather Service.

complex data formats, map projections, and geographic scales, along with optimizing conversions between raster and vector data, and a litany of GIS functionalities, supporting both scalability (federal or state responsibility) and local customization (community or municipality responsibility). Preliminary results of this project using a combination of R, Leaflet, and RShiny are shown in Figure 4. Here, flood polygons are generated by linking (1) NHD flowlines, (2) Height Above Nearest Drainage (HAND) and catchment rasters (Liu et al. 2016), (3) NWM streamflow forecasts, and (4) synthetic rating curve files. Streamflow forecasts are related to stage values via the synthetic rating curves, and the stage values for each reach are assigned to each cell in the corresponding catchment. All cells with a HAND value less than the stage value are considered flooded and the indicated raster is converted to a polygon. These polygons are then intersected with the appropriate U.S. Census Topologically Integrated Geographic Encoding and Referencing (TIGER) road networks providing a shapefile of safe, and unsafe, roads for travel. Options for users to supply their own shapefiles of critical infrastructure are also available. Converting a shapefile of roads to a graph from which shortest paths can be determined quickly and robustly remains a challenge.

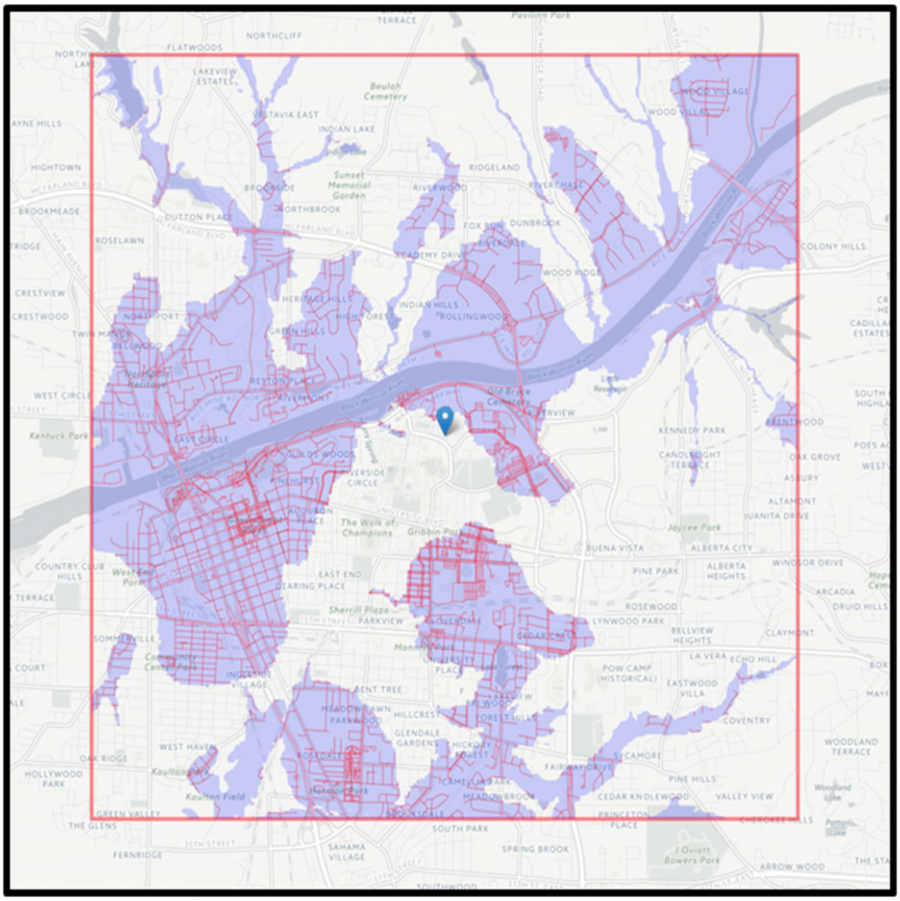

FIGURE 4. Proof of concept demonstrating the proposed work is possible. Image shows impacted roads for the Christmas Day flood for a defined area of interest in Tuscaloosa, Alabama.

Looking Forward

Essential to a successful implementation of the FloodHippo system is the ability to route around polygons. While ESRI AGO allows this capability, it is limited to networks of < 2,000 nodes, and it is not free. Of the 15 routing machines available for OpenStreetMap data, only two, bRouter and OpenRouteService, offer the ability to route around polygons. The former is a system for biking, ill-suited for vehicle routing, and the latter allows only digitizing polygons, not uploading them. Requests for dynamic routing around arbitrary polygons in OpenRouteService date back to January 2014; however, this capability has yet to be implemented (Padgham and Petutschnig 2017).

Also essential is research on routing around moving, rather than static, obstacles. Even though EM and GIS models can calculate and display temporal variation, the capacity for routing algorithms to generate graph networks on-the-fly is limited but urgently needed by dynamic hazard-routing algorithms.

Finally, the question of FloodHippo's broad applicability must be explored. Mileti and Sorensen (1990) suggested that a single warning concept could not equally serve the requirements of all hazards. Despite this, FloodHippo's basic geographic, organizational, and social components are applicable to any hazard evolving over space and time that requires movement (or explicit lack thereof) from people. Thus, we believe FloodHippo can be extrapolated to a multi-hazard platform.

We call this future framework the Operational Platform for Emergency Response and Awareness (OPERA), or more colloquially the “DisasterZoo.” Building on FloodHippo, each DisasterZoo module would involve a relevant mascot, an organized social media campaign, and dedicated Awareness and Response portals for each hazard type. Figure 5 shows how the pieces of GIS and EM come together in FloodHippo and outlines the organizational structure for a generic OPERA module.

For an actual implementation of OPERA, the agency and political aspects of multi-hazard mitigation and response organizations must be considered as the U.S. lacks a centralized emergency warning strategy. Currently, NOAA provides operational weather and flood forecasts, but FEMA and state emergency

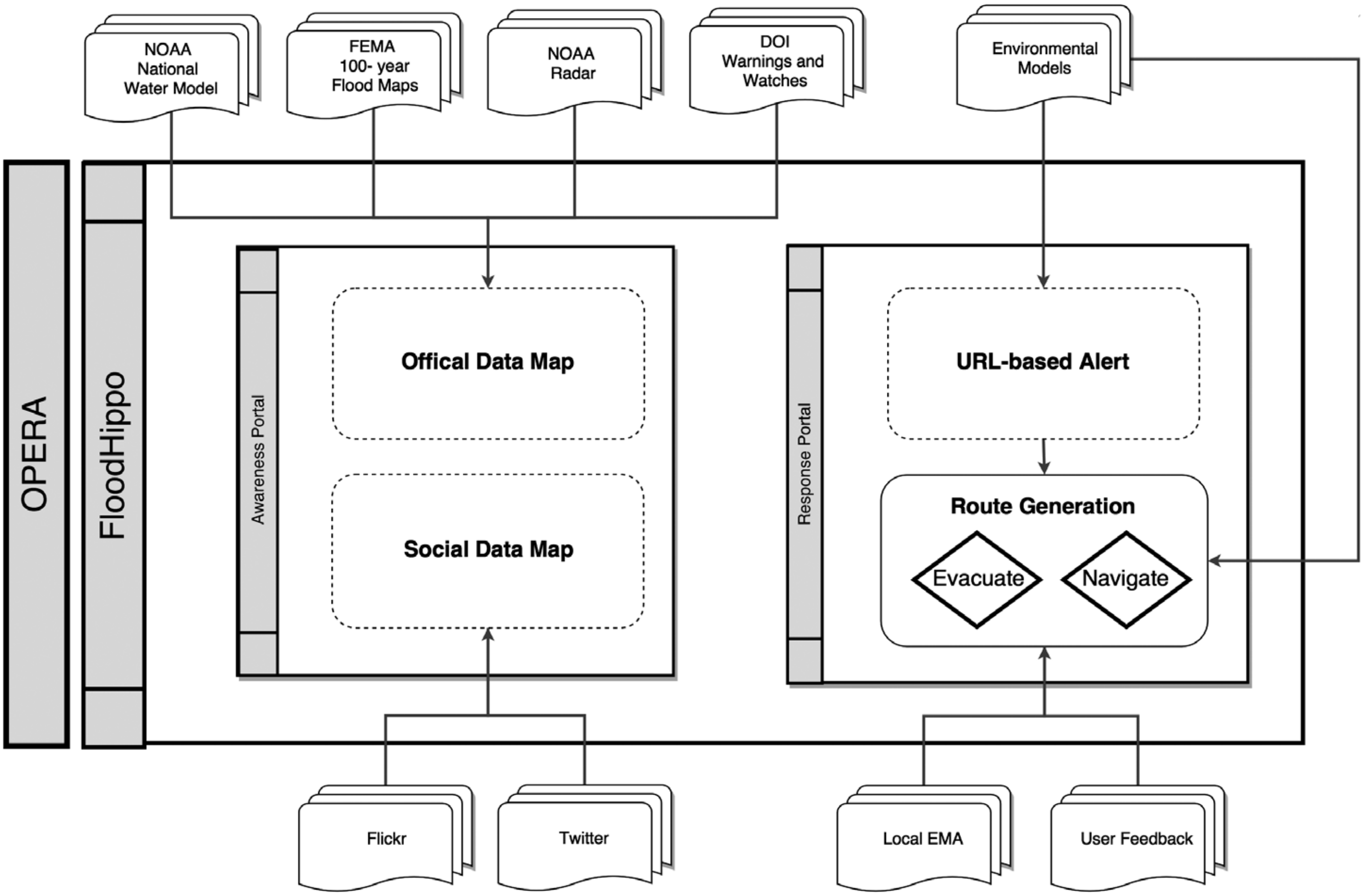

FIGURE 5. The FloodHippo organizational chart is used as a template to highlight the structure and relationship of the critical elements, and the overall framework of a generic Operational Platform for Emergency Response and Awareness (OPERA) module. EMA, Emergency Management Association.

management agencies are charged with managing disaster events. The Department of the Interior and the Department of Agriculture hold tenure over much of the land affected by floods and wildfire, and the National Science Foundation funds much of the academic research on hazard forecasting and response through organizations such as CUAHSI and NCAR. For an OPERA capability to emerge, it is imperative the platform be robust and intuitive for users and operators, and that all interested stakeholders are involved from the onset. If nothing else, this technical note hopes to convince readers that an OPERA platform *is* possible, has been advocated for, and should be pushed ahead.

CONCLUSION

When Sorensen (2000) reviewed the previous 20 years of hazard alert progress, he suggested three foci to guide the next 20 years of development. As the end of this benchmark approaches, it is worth evaluating whether his focal ideas require updating. His first focus was on achieving more complete hazard detection. For floods specifically, the NWM offers complete coverage for streamflow forecasts, although it is not yet producing flood inundation polygons. This is not a significant hurdle, since personal computers can produce these polygons, as illustrated in Figure 4. Looking beyond floods, other services such as the Wildfire Assessment System, the NOAA/NWS Storm Prediction Center, and the European Center for Medium-Range Weather Forecasting (ECMWF) and Global Forecasting System (GFS) models offer spatially explicit warnings and forecasts for wildfires, tornadoes, and hurricanes, respectively.

Sorensen's second focus was on updating warning systems to take advantage of new hardware and technology and to provide rapid, low-cost information dissemination via telecommunications. The introduction of WEAs and their proposed changes address this issue by extending how communication infrastructure reaches people. However, alert content has yet to exploit the possibilities offered by EM, GIS routing, cloud-based mapping, smartphones, and social media.

Finally, Sorensen argued for a comprehensive national warning strategy that provides equitable protection and technical assistance regardless of location or demographic. An OPERA system that adheres to the four precepts of modern alert design — Credible, Actionable, Personable, and Socializable — would provide centralization as well a means for local agencies to “plug-in” their own databases, knowledge, and needs.

The number of disasters has increased 20-fold over the last 120 years, as a changing global environment presents more frequent and intense hazards. Today larger populations face greater exposure to risk, while federal level funds and response efforts are becoming less stable. Now is a critical time to evaluate the interdisciplinary, cross-agency challenges and opportunities associated with creating better disaster alerts and to promote increased individual response to those alerts. This note sketches a prototype system that has received positive attention and proposes guidelines for developing a larger multi-hazard system grounded in modern, free technologies. Looking to the future, we hope the precepts of OPERA become a baseline for intelligent disaster alerts, allowing individual involvement and interaction to become integral in warning the public, evoking appropriate actions, and ultimately preserving life and property.

ACKNOWLEDGMENTS

We gratefully acknowledge Benjamin Sterne for his assistance in creating Figure 3, and the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) for their support in bringing the authors together and funding this publication.

LITERATURE CITED

About the Campaign. 1944. “Smokey Bear.” https://smokeybear.com/en/smokeys-history/about-the-campaign.

Afshari, S., A.A. Tavakoly, M.A. Rajib, X. Zeng, M.L. Follum, E. Omaranian, and B.M. Fekete. 2018. “Comparison of New Generation Low-Complexity Flood Inundation Mapping Tools with a Hydrodynamic Model.” *Journal of Hydrology* 556: 539–56. https://doi.org/10.1016/j.jhydrol.2017.11.036.

Bauer, P., A. Thorpe, and G. Brunet. 2015. “The Quiet Revolution of Numerical Weather Prediction.” *Nature* 525 (7567): 47–55. https://doi.org/10.1038/nature14956.

Blanford, J.I., J. Bernhardt, A. Savalyev, G. Wong-Parodi, A.M. Carleton, D.W. Titley, and A.M. MacEachren. 2014. “Tweeting and Tornadoes.” *Proceedings of the 11th International ISCRAM Conference* — University Park, PA, May 2014, edited by S.R. Hiltz, M.S. Pfaff, L. Plotnick, and P.C. Shih. http://ww.w.iscram.org/legacy/ISCRAM2014/papers/p156.pdf.

Clarke, K.C., P.O. Parks, and M.P. Crane. 2002. *Geographic Information Systems and Environmental Modeling*. Upper Saddle River, NJ: Prentice Hall.

Cosgrove, B., and C. Klymmer. 2016. “The National Water Model.” http://water.noaa.gov/about/nwm.

Doocy, S., A. Daniels, S. Murray, and T.D. Kirsh. 2013. “The Human Impact of Floods: A Historical Review of Events 1980–2009 and Systematic Literature Review.” *PLOS Currents* 5: pii: ecurrents.dis.f4deb457904936b07c09daa98ee8171a. https://doi.org/0.1371/currents.dis.f4deb457904936b07c09daa98ee8171a.

EM-DAT. 2017. *The Emergency Events Database*. Brussels, Belgium: Université Catholique de Louvain (UCL) — CRED. www.emdat.be.

FCC (Federal Communication Commission). 2016. “Wireless Emergency Alerts; Amendments to Rules Regarding the Emergency Alert System.” *81 FR 75710*.

Guha-Sapir, D., P. Hoyois, and R. Below. 2016. *Annual Disaster Statistical Review 2015: The Numbers and Trends*. Brussels, Belgium: Centre for Research on the Epidemiology of Disasters (CRED) Institute of Health and Society (IRSS) Université catholique de Louvain.

Houston, J.B., J. Hawthorne, M.F. Perreault, E.H. Park, M.G. Hode, M.R. Halliwell, S.E.T. McGowen, R. Davis, S. Vaid, J.A. McElderry, and S.A. Griffith. 2015. “Social Media and Disasters: A Functional Framework for Social Media Use in Disaster Planning, Response, and Research.” *Disasters* 39: 1–22. https://doi.org/10.1111/disa.12092.

Johnson, J.M., J.M. Coll, D.R. Maidment, S. Cohen, J. Nelson, F. Ogden, S. Praskievicz, and E.P. Clark. 2017. “National Water Centers Innovators Program Summer Institute Report.” *Technical Report No 14*, Consortium of Universities for the Advancement of Hydrologic Science, Inc. https://doi.org/10.4211/technical.20171009.

Johnson, J.M., P.J. Ruess, and J.M. Coll. 2016. “OPERA — Operational Platform for Emergency Awareness: Reimagining Disaster Alerts.” *National Water Center Innovators Program Summer Institute Report* 4: 97. https://doi.org/10.4211/technical.20161019.

Lindsay, B.R. 2011. “Social Media and Disasters: Current Uses, Future Options, and Policy Considerations, Congressional Research Service.” *Report Number: R41987*

Linham, M., and R.J. Nicholls. 2010. “Technologies for Climate Change Adaptation: Coastal Erosion and Flooding.” In *TNA Guidebook Series*, edited by X. Zhu, p. 92. Roskilde, Denmark: UNEP/GEF.

Liu, Y.Y., D.R. Maidment, D.G. Tarboton, X. Zheng, A. Yildirim, N.S. Sazib, and S. Wang. 2016. “A CyberGIS Approach to Generating High-Resolution Height above Nearest Drainage (HAND) Raster for National Flood Mapping.” *CyberGIS 16, The Third International Conference on CyberGIS and Geospatial Data Science*, Urbana, IL, July 26–28. https://doi.org/10.13140/rg.2.2.24234.41925.

Maidment, D.R. 2015. “A Conceptual Framework for the National Flood Interoperability Experiment.” https://www.cuahsi.org/Files/Pages/documents/13623/nfieconceptualframework_revised_feb_9.pdf.

Mileti, D., and J. Sorensen. 1990. *Communication of Emergency Public Warnings*. ORNL 6609. Oak Ridge, TN: Oak Ridge National Laboratory.

NOAA (National Oceanic and Atmospheric Association). 2016a. “2015 Flash Flood/River Flood Fatalities 2015 Flood Fatalities by State and Location.” http://www.nws.noaa.gov/om/hazstats/flood15.pdf.

NOAA (National Oceanic and Atmospheric Association). 2016b. “NOAA Launches America’s First National Water Forecast Model.” http://www.noaa.gov/media-release/noaa-launches-america-s-first-national-water-forecast-model.

NWS (National Weather Service). 2015. “Wireless Emergency Alerts.” http://www.crh.noaa.gov/images/lbf/wxsafety/WEA/WEA_Update%2002052015.pdf.

Ogden, F.L., W. Lai, and R.C. Steinke. 2015. “ADHydro: Quasi-3D High Performance Hydrological Model.” *Proceedings of SEDHYD 2015, 10th Interagency Sedimentation Conference, 5th Federal Interagency Hydrologic Modeling Conference*, April 19–23, Reno, NV.

Padgham, M., and A. Petutschnig. 2017. “Osm-Router/Osm-Router.” GitHub. https://github.com/osm-router/osm-router.

Pascua, M. 2008. “Emergency Alerts Coming to Your Cellphone Via SMS.” Technology Tell. http://www.technologytell.com/gadgets/32386/emergency-alerts-coming-to-your-cellphone-via-sms/.

Salas, F.R., M.A. Somos-Valenzuela, A. Dugger, D.R. Maidment, D.J. Gochis, C.H. David, W. Yu, D. Ding, E.P. Clark, and N. Noman. 2018. “Towards Real-Time Continental Scale Streamflow Simulation in Continuous and Discrete Space.” *Journal of the American Water Resources Association* 54: 7–27. https://doi.org/10.1111/1752-1688.12586.

Schneider, F.W., J.A. Gruman, and L.M. Coutts. 2012. *Applied Social Psychology: Understanding and Addressing Social and Practical Problems*. London, United Kingdom: SAGE Publications.

Schwartz, N. 2015. “Hippopotamus Escapes Zoo and Wanders Streets in Tbilisi after Flash Flood.” *USA Today*, June 14. http://ftw.usatoday.com/2015/06/tbilisi-hippo-lion-tiger-zoo-animals-escape.

Sorensen, J.H. 2000. “Hazard Warning Systems: Review of 20 Years of Progress.” *Natural Hazards Review* 1 (2): 119–25.

Sutton, J., L. Palen, and I. Shklovski. 2008. “Backchannels on the Front Lines: Emergent Uses of Social Media in the 2007 Southern California Wildfires.” *5th International ISCRAM Conference*, Washington, D.C.

Wang, S. 2013. “CyberGIS: Blueprint for Integrated and Scalable Geospatial Software Ecosystems.” *International Journal of Geographical Information Science* 27 (11): 2119–21.

Wood, M., H. Bean, B. Liu, and M. Boyd. 2015. “Comprehensive Testing of Imminent Threat Public Messages for Mobile Devices: Updated Findings.” https://www.dhs.gov/sites/default/files/publications/WEA%20-%20Comprehensive%20Testing%20of%20Imminent%20Threat%20Public%20Messages%20for%20Mobile%20Devices%20Updated%20Findings.pdf.

Working Group on Natural Disaster Information Systems. 2000. “Effective Disaster Warnings.” http://tap.gallaudet.edu/emergency/nov05conference/EmergencyReports/EffectiveDisasterWarnings.pdf.

Xiao, Y., Q. Huang, and K. Wu. 2015. “Understanding Social Media Data for Disaster Management.” *Natural Hazards* 79 (3): 1663–79. https://doi.org/10.1007/s11069-015-1918-0.