Linking Risk to Resilience: A Quantitative Method for Communities to Prioritize Resilience Investments

Dr. Ellie Graeden, Dr. Justin Kerr, Ajmal Aziz

Talus Analytics, LLC; Boulder, CO; USA

Department of Homeland Security Science and Technology Directorate; Washington D.C.; USA

Abstract

Resilience is the ability of a community to respond to and recover from disaster. The characteristics of a community that impact resilience include demographic statistics, built infrastructure, the natural environment, economic robustness, and community planning efforts and can number in the hundreds. Critically, these characteristics are not often linked to the hazards to which a community is at risk, limiting the ability of a community to make risk-informed, targeted investment decisions. To help communities prioritize investments in resilience, we describe here a method to define hazard-specific risk based on hazard impacts, correlated with the resilience characteristics aligned with community priorities, and rank these investments based on their relative benefit. Using flood as the proof-of-principle hazard, we describe a method and corresponding decision support tool, in development through an effort funded by the US Department of Homeland Security Science and Technology Directorate (DHS S&T), to perform a rapid flood risk assessment to support data-driven investments in resilience enhancement. Flood impacts are described in either cost, or population common units, which are cross-referenced with a short list of resilience characteristics chosen by the community from an inventory collated from the resilience literature. This approach ensures the list of community resilience characteristics chosen for analysis are limited to those directly linked to flood risk, known to have a direct effect on resilience, and of priority to the community. The decision support tool provides communities support in defining investments to address and enhance resilience related to each community resilience characteristic, and evaluate these investments based on relative benefit as defined by the cumulative probabilistic impacts across a range of flooding scenarios. This proof-of-principle effort is designed specifically to support flood resilience, but is transferrable to other hazards so that a community can perform a rapid risk assessment. To our knowledge, this is the first of its kind to be specifically tailored to evaluating and communicating risk to community-level end users.

Keywords: flood risk, risk assessment, community, decision support, investment, resilience

1 Introduction

Resilience is defined as "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events" by the Committee on Increasing National Resilience to Hazards and Disasters at the US National Academies (National Research Council, 2012). Community characteristics related to resilience include demographic metrics (social factors), built infrastructure, and the natural environment as well as economic robustness and community planning efforts. Methods to measure resilience on the basis of these characteristics within communities have been developed (Cutter et al., 2010, 2003; Flanagan et al., 2011; and others), but principally provide a baseline assessment of community resilience and are not intended to be a framework for prioritizing actions to improve resilience. Indeed, communities tasked with improving resilience often have little practical guidance, and this limited guidance is rarely based on locally-relevant risk. Here, we present a method to support informed, risk-based decision making for flood resilience investments at the community level.

Community resilience is directly linked to hazard risk. Flooding is the most frequent, wide-spread, and costly natural hazard in the US. Estimates place 2016 flood-related financial losses in the tens of billions of dollars (Benfield, 2015; Bevere et al., 2011) and floods caused a significant number of fatalities each year both in the US and internationally. Therefore, enhancing community flood resilience is a central focus for resilience and flood risk mitigation investments to protect lives and reduce financial losses, whether caused by smaller, more frequent floods (e.g., 10-year return interval events), or large, catastrophic flooding (e.g., 500-year return interval events).

Here we present the framework for a decision support tool, including graphics developed to communicate results and provide context for community decision makers in choosing the most effective resilience investments. This method provides communities with a data-driven approach to focus investments in resilience enhancement to efforts that address flood risks that are a priority to the community.

2 Methods

2.1 Identification of resilience characteristics

Community resilience characteristics were identified through a review of published literature and other open source reports. Though hundreds of community resilience indicators have been reported in the literature, we found that resilience indicators are not directly linked to underlying hazard risk faced by the community (see results in Table 1 for selected examples). Community resilience indicators identified in this literature review formed the basis for a crosswalk from flood risk to community resilience to fill this gap in available tools for investment prioritization.

Table 1. Translating flood risk profile into resilience characteristics

Community characteristics at risk to flooding	**Resilience characteristics (risk-resilience crosswalk)**	
	Population impacted	**Financial losses**
Hospitals inundated	Number of patients to relocate	Cost to repair inundated hospital and replace contents
Inundated substations serving population using electricity-dependent medical equipment (EDME)	Population using EDME without power	Cost to repair inundated substation
Socioeconomically vulnerable population in inundation zone	Vulnerable population requiring evacuation and resource support	Cost of food and water support for 3 days
Schools inundated	Number of students likely to have education disrupted	Cost to repair inundated school
Residential building stock inundated	Population predicted to be displaced	Cost to replace residential buildings and contents

2.2 Converting flood impacts to common units

Using a rapid assessment flood risk modelling method, (Longenecker, et al, *in preparation*) community characteristics are prioritized. Characteristics that are at risk to the flooding events and also of greatest concern to the community, are included in the resilience characteristics defined in the literature. The relative impacts of flooding on these characteristics are defined by common units (i.e., population or cost) and calculated for a range of flooding events. For example, population impacts in the form of patient relocation from a hospital can be calculated by multiplying the number of beds by the percentage occupancy to define the number of people impacted. The cost of inundation to the same hospital can be calculated by multiplying the total cost to replace the interior of the basement and first floor by the depth damage function to determine a total cost of impact for each event type.

2.3 Investment benefits calculation

Investment benefits are calculated using a counterfactual approach that compares "before and after" flood risk for each investment. The method is designed to predict the difference in outcomes under two conditions (C versus C^*) where C is the factual (i.e., current reality) and the system operating with the hypothetical C^* is the counterfactual (i.e., the alternative reality reflecting a new resilience investment) (Bottou et al., 2013). Benefits are adjusted to account for the difference in likelihood between events using expected value decision analysis (Albright et al., 2010), a method designed specifically to assess aggregate benefit across a probabilistic range of scenarios used to inform decision-making in a wide range of fields.

The expected value of each decision D is equal to the probability-weighted sum of the outcomes' benefits. Here, decisions correspond to a specific investment, outcomes correspond to the benefits provided by the investment across a range of probabilistic flood events, and the expected value of the decision corresponds to the expected benefit of the investment across the cumulative risk of flood in the community. Mathematically, the expected value of decision D_i, denoted $E[D_i]$, is given by the equation

$$E[D_i] = \sum_{j=1}^{2} p_i \, b_{i,j}$$

where p_i is the probability of outcome O_j, and $b_{i,j}$ is the benefit of outcome O_j under decision D_i. Additional details of how this method is used to rank and prioritize resilience investments, using flood event probability, are described in the results section below.

3 Results

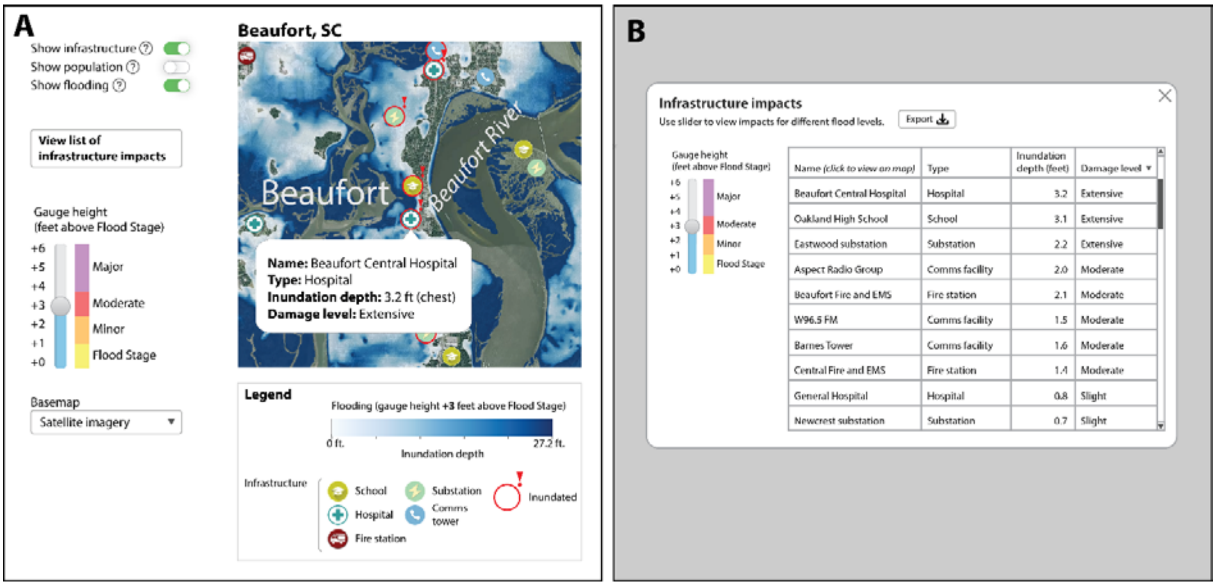
The list of community characteristics at risk to flooding can be extensive; likewise, the comprehensive list of characteristics associated with resilience is also large. In addition, communities have unique local priorities—some are focused on protecting a robust, small business community; some are specifically concerned about an economic hub – a factory, community college, or regional hospital; and some view themselves as a transportation hub primarily concerned with maintaining access to transportation infrastructure. By cross-referencing characteristics associated with resilience, to those at risk to flooding and aligned with community priorities, a list of target characteristics and corresponding investment strategies can be prioritized. Starting from a list of community resilience characteristics linked to the population and infrastructure at risk of flooding focuses community resilience investment efforts to where they best address flood risk.

3.1 Applying flood to target resilience priorities

To assess flood risk, communities need to map predicted inundation for a range of flood event severities faced by the community, and overlay these maps with population distribution and infrastructure locations to determine predicted flood impacts across scenarios. The core requirements for inundation maps used in this method are inclusion of point-depth estimates at regular intervals (i.e., in a 10-meter by 10-meter grid) and include each of the recurrence intervals of concern to the community (e.g., 10-, 20-, 50-, 75-, 100-, 200-year floods). Potential sources of inundation maps in the US include the FEMA RiskMAP program (US National Flood Insurance Program), detailed flood studies previously conducted in the community, and local flood modelling subject matter experts using publicly available tools (e.g., models from the US Army Corps of Engineers Hydrologic Engineering Center). Population and infrastructure are available from national-level sources and by applying locally collected data. In a related effort, we are also developing a rapid flood risk model in collaboration with FEMA to directly support flood modelling required for the investment prioritization method, and improve access to flood risk information for communities that do not have ready access to flood risk assessment methods.

Figure 1 shows an example of flood modelling outputs – an inundation map with nationally-available infrastructure and population datasets. Impacts are described graphically on the map (Figure 1 A) and in a linked table (Figure 1 B) to provide additional detail. Essentially, the slider bar indicates the ability of the end user to evaluate a wide range of events, from frequent, less severe events to rare, but catastrophic events, including an overview of the impacts, as defined by the infrastructure and population affected by inundation. The primary goal of the visualization (illustraiting the risks with images) is to provide non-experts in flood modelling an intuitive sense for the severity and impacts both to infrastructure and population for flooding events defined both by water depth above flood height and annual exceedance probability (AEP).

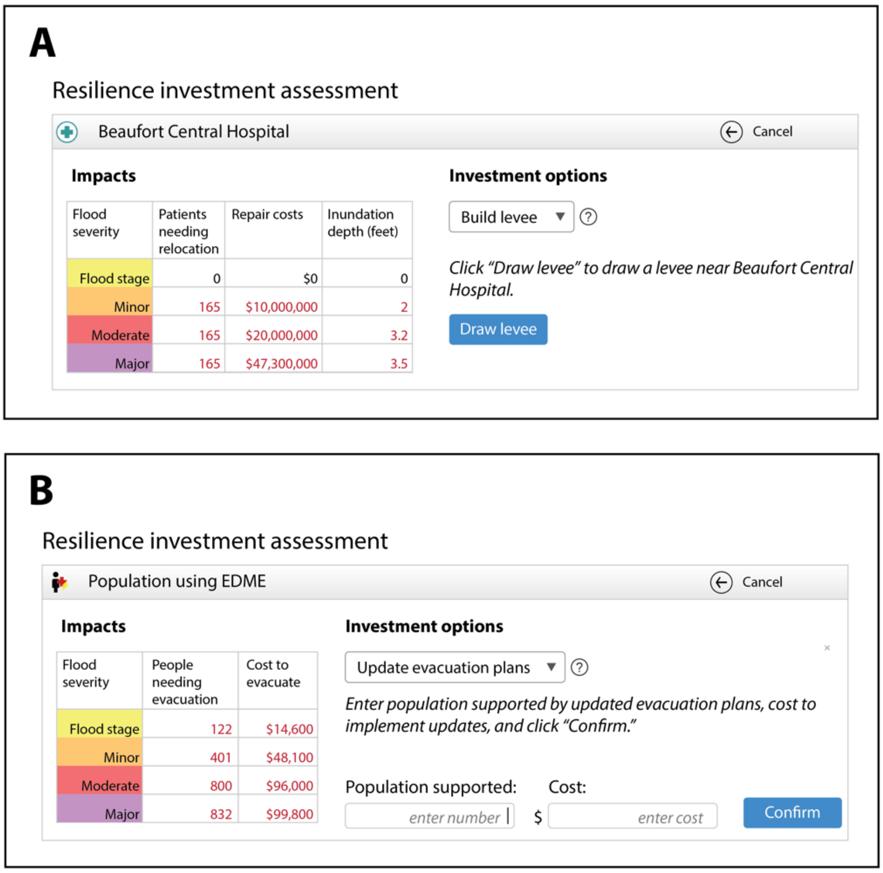
Figure 1. Modelled flood impacts to infrastructure. (A) Map of infrastructure inundated by a moderate flood (+3 feet above flood stage). Inundated infrastructure is circled in red. (B) Detailed infrastructure impacts table with inundation depths and damage to specific infrastructure.



3.2 Linking flood impacts to resilience in common units

Prioritizing investments in resilience first requires quantification of flood impacts in common terms. Impacts are described in two common unit types: financial loss and population impacts (see Methods) forming the quantitative basis to compare resilience investments to address flood impacts. Financial losses are calculated for both infrastructure and population impacts. In the case of infrastructure like a hospital, investment in sandbags, relocation, or drainage ditches can prevent inundation for smaller floods or lower local inundation depths. However, wider-scale protection from a levee may be the only effective investment to protect a hospital at risk of more significant flooding. In Figure 2A, an example is shown for a community concerned with protecting the local hospital during a flood. The inset table in the graphic shows the quantified resilience characteristics for an example hospital, calculated for each flood severity, for patients needing relocation (population impacted) and repair costs (financial loss). As shown in Figure 2, investment options can alternatively be targeted to address infrastructure or populations of concern. An option to build a levee to protect a hospital is shown in Figure 2A. As shown in Figure 2B, deploying generators or planning effective evacuation routes could significantly reduce impacts to the general population or sub-populations of special concern (e.g., elderly or those reliant on electricity-dependent medical equipment-EDME).

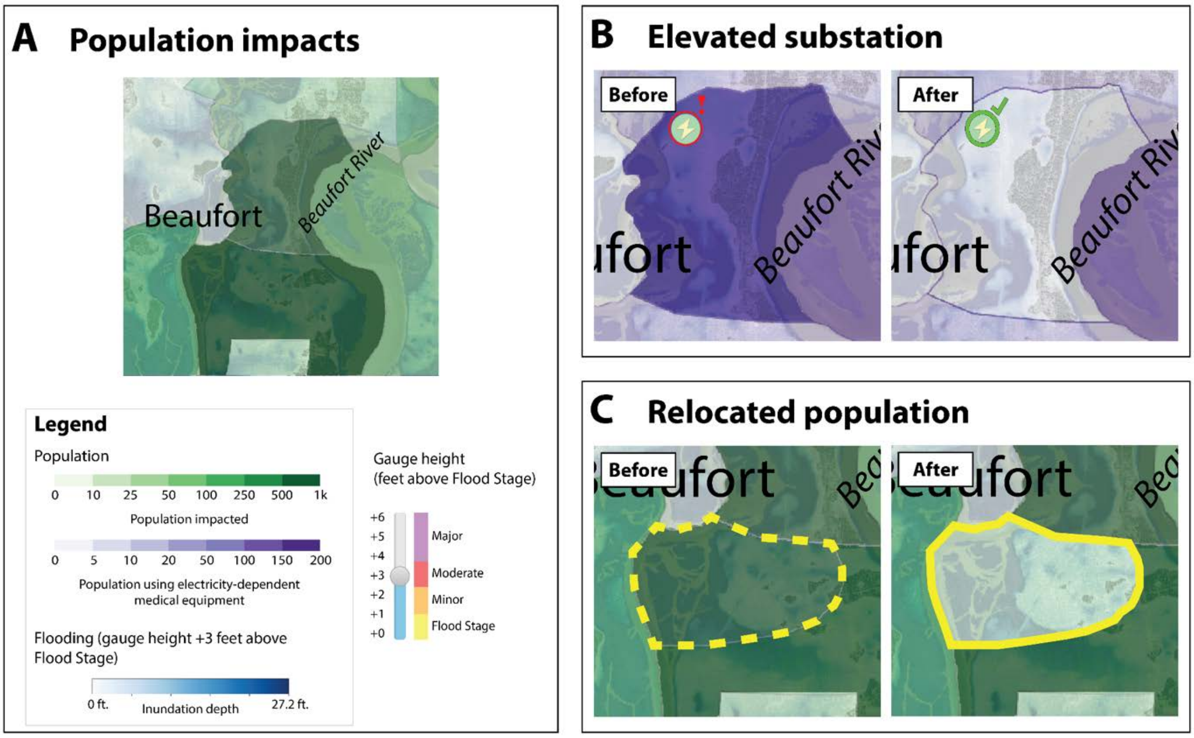
Figure 2. Defining target resilience investments for impacted infrastructure and population. (B) The impacts to the population using electricity-dependent medical equipment (EDME) for different flood levels, and potential investment options. The option "Update evacuation plans" is selected, and the interface guides users in defining how many people are supported by the updated plan and the cost to update it.



3.3 Modelling investment benefits

Communities can effectively improve resilience by targeting investments that also reduce risk. Figure 4 shows examples of how the method developed here can be implemented to assess risk-weighted investment benefit by iteratively modelling the effects of each target investment under a range of flood conditions. In the example shown in Figure 3, power outages due to flooding impact a subset of the population in a community with EDME populations at particular risk. This method calculates the benefit of raising a substation as the reduction in power outage impacts the EDME population for a range of flood events (e.g., different flood depths). A three foot elevation of the substation protects against a 10-year, 50-year, and 100-year flood, but not against a 200-year or larger flood.

Figure 3. Population protected by investments. (A) Map of population inundated by a moderate flood (+3 feet above flood stage). US Census tracts inundated are darker. (B) Flood impacts to population using electricity-dependent medical equipment (EDME) before and after investment. (C) Flood impacts to general population before and after investment.



Investments may reduce flood impacts either by decreasing the likelihood of the event occurring (e.g., reinforcing a dam, building or raising a levee), or by targeting specific impacts (e.g., sandbagging a specific piece of infrastructure, writing and implementing evacuation plans). Evaluating the benefit of investment in flood control structures (e.g., levee or drainage ditch) that alter the flood event itself are calculated by comparing the results of event characterization and consequence modelling to compare inundation levels and corresponding impacts. Investments related to specific populations or infrastructure protections or enhancements are calculated by comparing impacts as determined by consequence modelling alone, as there is no change in the flood event itself.

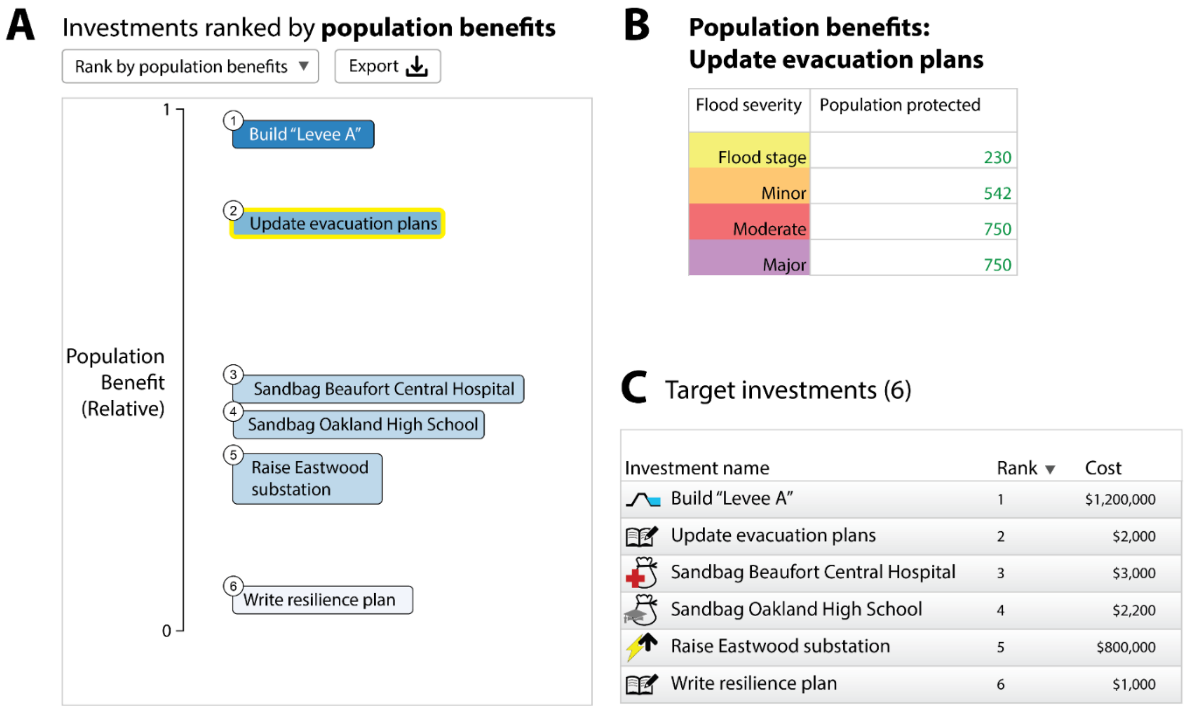
Investment benefits depend upon the severity of the flood and this method applies a risk-weighting approach to calculate the aggregate benefit across flood severities. Table 2 demonstrates the risk-weighting of benefits using flood event probability. Each event is assigned a probability weight equal to the difference in AEP between that event and next event of greater severity. To produce the results in Table 2, the first-order flood risk assessment method was used to model each flood recurrence interval shown, both in the absence of a levee and after construction of a levee that protects that hospital. The hospital was not inundated by the 10-, 20-, or 50-year flood events. It was inundated by the 75-, 100-, and 200-year events, with the levee providing protection for the 75- and 100-year events, but not the 200-year event. Benefits are shown for the 75- and 100-year floods as the financial loss prevented by the levee. The levee has no financial benefit for the hospital at less severe floods because they do not cause inundation, and no benefit for the 200-year event because the hospital was inundated despite the levee. The benefits for the 75-year and 100-year floods are weighted using their respective probability weights. By applying the same method to all target investments under consideration, the risk weighting step provides a common framework to compare disparate types of investments using a common, flood risk-based estimate of investment benefits.

Table 2. Calculating the mean weighted investment benefit (expected benefit) for a levee protecting a hospital.

Flood recurrence interval (years)	Flood annual exceedance probability	Cost to replace interior (no levee)	Cost to replace interior (with levee)	Investment benefits (losses prevented)	Probability weight	Weighted investment benefits
10	0.10	$0	$0	$0	0.050	$0
20	0.050	$0	$0	$0	0.030	$0
50	0.020	$0	$0	$0	0.0067	$0
75	0.013	$20.0M	$0	$20.0M	0.0033	$0.067M
100	0.010	$45.5M	$0	$45.5M	0.0050	$0.23M
200	0.0050	$47.3M	$47.3M	$0	0.0050	$0
				Expected investment benefit		**$0.30M**

Based on modelled flood impacts, this method provides the ability for communities to link flood risk with community resilience characteristics, and develop a short list of potential investments that reflect both an assessment of what drives local flood risk, and the selection of local priorities for resilience enhancement. Once the statistical method is applied to calculate a risk-weighted sum of benefits for each target investment (Table 2), these benefits are considered on a relative scale where the investment with the greatest benefit is set to 1 and all other investments are plotted as a relative comparison either based on population or cost (Figure 4A and 4B). This format supports best practices in risk communication identified in the research literature, including limiting quantitative information to only that most relevant to the decision, using clear terminology and plain language, and driving toward the end-goal – namely selecting resilience investments (Melkonyan, 2011; National Oceanic and Atmospheric Administration, 2016; Vaughan and Buss, 1998). These results can then be applied in the context of other factors important to the local investment decision making process, including budgetary constraints, or alignment with other ongoing resilience enhancement efforts (see Figure 4C).

Figure 4. Ranking target investments by population benefits. (A) Target investments are ranked by relative population benefit. Toggle to view relative benefits by population or cost not shown. (B) Detail of population benefits provided by updating evacuation plans for different flood levels. (C) The list of target investments ranked by relative population benefits, with user-provided implementation cost shown.



4 Discussion

Communities worldwide have been asked to improve their resilience. The method described here is a critical proof-of-principle effort demonstrating how rapid risk analysis for a single hazard can be applied to support risk-based investment prioritization at the community level. The method, and corresponding web-based tool in development, is specifically designed to inform decisions in the absence of more robust modelling, or local subject matter expertise, and is designed to inform more in-depth analysis once a community has established initial investment priorities. This community-focused approach presents the results of a complex flood risk modelling and statistical analysis in a way that communicates these priorities to support practical decision making by members of the community and stakeholders involved in resilience and disaster planning efforts. Developed as part of the DHS S&T Flood Apex program, this method is part of an emerging set of new technologies and analytical methods, including those supported by the Flood Apex program that will enhance flood resilience and support decision making for communities, first responders, and US Federal stakeholders for flood emergencies. Though flood was used here as a proof of principle hazard, the approach is broadly applicable for other hazards for which risk assessment models are available, including earthquakes, or disease outbreaks for which epidemiological models are available.

References

Albright, S.C., Winston, W., Zappe, C., 2010. Data Analysis and Decision Making. Cengage Learning.
American Hospital Directory, 2016. Individual Hospital Statistics for South Carolina [WWW Document]. URL https://www.ahd.com/states/hospital_SC.html (accessed 7.3.17).
Benfield, A., 2015. 2015 Annual Global Climate and Catastrophe Report.
Bevere, L., Rogers, B., Grollimund, B., 2011. Natural Catastrophes and Man-made Disasters in 2010: a Year of Devastating and Costly Events.
Bottou, L., Peters, J., Ch, P., Quiñonero-Candela, J., Charles, D.X., Chickering, D.M.,

Portugaly, E., Ray, D., Simard, P., Snelson, E., 2013. Counterfactual Reasoning and Learning Systems: The Example of Computational Advertising. J. Mach. Learn. Res. 14, 3207–3260.
Cutter, S.L., Boruff, B.J., Shirley, W.L., 2003. Social Vulnerability to Environmental Hazards n. Soc. Sci. Q. 84, 242–261. doi:10.1111/1540-6237.8402002
Cutter, S.L., Burton, C.G., Emrich, C.T., 2010a. Disaster Resilience Indicators for Benchmarking Baseline Conditions. J. Homel. Secur. Emerg. Manag. 7. doi:10.2202/1547-7355.1732
Cutter, S.L., Burton, C.G., Emrich, C.T., 2010b. Disaster Resilience Indicators for Benchmarking Baseline Conditions. J. Homel. Secur. Emerg. Manag. 7. doi:10.2202/1547-7355.1732
Federal Emergency Management Agency, 2017. FEMA Hazus [WWW Document]. URL https://msc.fema.gov/portal/resources/hazus (accessed 7.3.17).
Federal Emergency Management Agency, 2013. Hazus-MH 2.1 Multi-hazard Loss Estimation Methodology - Flood Model Technical Manual.
Flanagan, B.E., Gregory, E.W., Hallisey, E.J., Heitgerd, J.L., Lewis, B., 2011. A Social Vulnerability Index for Disaster Management. J. Homel. Secur. Emerg. Manag. 8. doi:10.2202/1547-7355.1792
Herman, B., 2014. 8 Statistics on Hospital Capacity [WWW Document]. Becker's Hosp. Rev. URL http://www.beckershospitalreview.com/patient-flow/8-statistics-on-hospital-capacity.html (accessed 7.3.17).
National Oceanic and Atmospheric Administration, 2017. 2016 Flash Flood Fatalities by State and Location.
National Research Council, 2012. Disaster Resilience: A National Imperative. The National Academies Press, Washington, D.C. doi:10.17226/13457