



RESEARCH ARTICLE

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Key Points:

- Resident perception and awareness of flooding are enhanced more by fine-resolution depth contour maps than FEMA maps
- Viewing fine-resolution flood maps helps to minimize differences in flood perception across subgroups of a community
- Collaborative flood modeling is a transdisciplinary process to coproduce actionable flood information and knowledge

Supporting Information:

- Supporting Information S1

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Collaborative Modeling With Fine-Resolution Data Enhances Flood Awareness, Minimizes Differences in Flood Perception, and Produces Actionable Flood Maps

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Abstract Existing needs to manage flood risk in the United States are underserved by available flood hazard information. This contributes to an alarming escalation of flood impacts amounting to hundreds of billions of dollars per year and countless disrupted lives and affected communities. Making information about flood hazards useful for the range of decisions that dictate the consequences of flooding poses many challenges. Here, we describe collaborative flood modeling, whereby researchers and end-users at two coastal sites co-develop fine-resolution flood hazard models and maps responsive to decision-making needs. We find, first of all, that resident perception and awareness of flooding are enhanced more by fine-resolution depth contour maps than Federal Emergency Management Agency (FEMA) flood hazard classification maps and that viewing fine-resolution depth contour maps helps to minimize differences in flood perception across subgroups within the community, generating a shared understanding. We also find that collaborative flood modeling supports the engagement of a wide range of end-users in contemplating the risks of flooding and provides strong evidence that the co-produced knowledge can be readily adopted and applied for Flood Risk Management (FRM). Overall, collaborative flood modeling advances FRM by providing multiple points of entry for diverse groups of end-users to contemplate the spatial extent, intensity, timing, chance, and consequences of flooding, thus enabling the web of decision-making related to flooding to be better informed with the best available science. This transdisciplinary approach emphasizes vulnerability reduction and is complementary to FEMA Flood Insurance Rate Maps used for flood insurance administration.

Plain Language Summary This work demonstrates a new process for communities to build flood resilience: collaborative flood modeling. Development of fine-resolution flood models by scientists and engineers serves as a focal point for community stakeholders to build useful knowledge and tools to address flooding. A key issue shown here is that fine-resolution flood visualizations help diverse community stakeholders build a more shared awareness about flooding, which creates conditions favorable to improved flood management.

1. Introduction

Flooding is among the most significant natural hazards facing society (Hanson et al., 2011; Hinkel et al., 2014; Jongman et al., 2012; Kron, 2013). Damages have been escalating for decades (Cartwright, 2005; Hinkel et al., 2014; Jongman et al., 2012; Sundermann et al., 2014), and a U.S. record was set in 2017 with over \$300 billion in disaster losses, mainly from hurricanes and flooding (National Oceanic and

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Atmospheric Administration, 2018). Cities around the world (Hanson et al., 2011; Hinkel et al., 2014; Kron, 2013) and municipalities across the United States (Kulp & Strauss, 2017) are threatened by coastal flooding, and nearly 41 million Americans live within 100-year flood zones associated with fluvial and pluvial flooding (Wing et al., 2017). Gall et al. (2011) report that flood losses in the United States are not just growing in an absolute sense, after adjusting for inflation, but on a per capita basis and suggest that impacts are even greater than reported because of inadequate monitoring and assessment.

Future exposure to flooding in the United States will likely increase as a consequence of socio-economic growth (Wing et al., 2017) and sea level rise (Bilskie et al., 2016; Bilskie et al., 2019; Hallegatte et al., 2013; Hauer et al., 2016; Kulp & Strauss, 2017). Historic trends of increasing flood impacts have been primarily driven by increasing exposure and vulnerability (Davis, 2007; Gall et al., 2011; GFDRR, 2016; White et al., 2001). World population has more than doubled since 1960, from around 3 billion people to around 7 billion today (Wolsko & Marino, 2016). In the United States, some states have developed in high flood risk areas 2–3 times faster than in low flood hazard areas (Climate Central, 2019). Development also increases expectations of protection by hard infrastructure such as dams and levees that, upon failure, can lead to catastrophic consequences (Di Baldassarre et al., 2015; Hinkel et al., 2014; Kousky & Kunreuther, 2010). Indeed, when infrastructure fails, communities can be left vulnerable and underprepared to manage consequences (Blaikie et al., 1994; Lebel & Sinh, 2009; Vahedifard et al., 2017). Another factor contributing to the escalation of flood impacts is that the most vulnerable sectors of communities tend to live in more flood-prone areas and are often excluded from decision-making processes to prepare for and respond to flooding (Lebel et al., 2006). This is particularly important in disadvantaged communities where flooding amplifies inequalities and makes people more vulnerable to subsequent disasters (Brouwer et al., 2007; Dube et al., 2018; Eakin et al., 2016; Ratcliffe et al., 2019). Finally, a critical issue is that scientific knowledge about flood hazards and vulnerabilities is not effectively translated into actionable information for the web of decisions that alter flood risk (DeLorme et al., 2016; Morss et al., 2005; Spiekermann et al., 2015).

In the United States, flood policies have failed to curb the escalation of losses and environmental degradation of floodplains (Davis, 2007; Gall et al., 2011). The National Flood Insurance Program (NFIP) administered by Federal Emergency Management Agency (FEMA) and the U.S. Army Corps of Engineers Flood Damage Reduction (FDR) program have unintentionally incentivized high-risk floodplain development through subsidized insurance policies and allowances for protective infrastructure vulnerable to failure (Davis, 2007; Gall et al., 2011; Traver, 2014). In particular, underpricing of insurance policies, large subsidies for properties that repeatedly flood, and weak enforcement of mandatory insurance in the 100-year floodplain have contributed to an NFIP debt of over 20 billion USD, even after the cancelling of 16 billion USD of debt by Congress in 2017 (Horn, 2019; Horn & Webel, 2019; Traver, 2014). FEMA Flood Insurance Rate Maps (FIRMs) have also created an unintended consequence—a false sense of certainty that properties outside the flood hazard area are not at risk of flooding (Soden et al., 2017). Pinter et al. (2017) reported that two thirds of the inundated area in Harris County, Texas, from Hurricane Harvey was outside of the 100-year return period flood zone, and over half of the inundated area was outside of the 500-year return period flood zone. This contributed to 70% of flood damages experienced by properties without coverage (Guyton & Hayes, 2017). While infrastructure failure was not a major contributor to the damages from Harvey, levee failures from Hurricane Katrina exacerbated damages to New Orleans (Davis, 2007; Traver, 2014). The Natomas Basin near Sacramento, California, could suffer a similar catastrophe due to extensive development in high-risk areas “protected” by levees (Davis, 2007; Reid, 2005), and we note that homes with federally backed mortgages are not required to have flood insurance in areas “protected” by levees. Farther north in California, a flooding disaster nearly occurred at Lake Oroville when its two spillways were damaged during operation (Vahedifard et al., 2017). These incidents underscore the false confidence or “levee effect” that increases exposure and vulnerability to events beyond design levels (Di Baldassarre et al., 2015; Houston et al., 2019; Montz & Tobin, 2008; Myers & White, 1993). An expert panel convened by the American Society of Civil Engineers has called for Flood Risk Management (FRM) as the basis of a national strategy for the United States (Traver, 2014), as has been adopted within the European Union (Directive 2007/60/EC) and elsewhere (Sayers et al., 2013). FRM represents an important transformation in strategy from controlling floods to reducing flood consequences and managing or even avoiding flood risks. It is also aligned with the strategy of Disaster Risk Reduction (DRR) advocated by the Sendai Framework of the United Nations Office for Disaster Risk Reduction (UNISDR, 2015, p. 12).

A growing body of research is demonstrating that numerous dimensions of FRM can be supported through a process of collaborative flood modeling, whereby hydrological modeling serves as a focal point for engagement, dialogue, and deliberation among experts and local stakeholders (Steinführer et al., 2008; Pasche et al., 2009; Hagemeyer-Klose & Wagner, 2009; Dawson et al., 2011; Evers et al., 2012; Meyer et al., 2012; Maskrey et al., 2016; Luke et al., 2018). For example, Lane et al. (2011) show that urban flood models are effective at organizing stakeholders around the spatial dimensions of flood hazards. There is also strong evidence that collaborative flood modeling can build greater shared understanding about flood risks, facilitate the exchange of ideas, provide a framework for how to approach development, encourage interaction among scientists and end users, and provide a wealth of information that is accessible and understandable to end-users (Maskrey et al., 2016; Wilkinson et al., 2015). Hydrological modeling is inherently an iterative process involving building, testing and revising specific implementations. Hence, another key issue is that collaborative flood modeling can achieve what is critical for making any type of science useful: iterative interaction between researchers (modelers) and end-users (DeLorme et al., 2016; Dilling & Lemos, 2011). Finally, we note that fine-resolution urban flood modeling is rapidly advancing and now supports realistic, street-level flood visualizations (Bhola et al., 2019; Fewtrell et al., 2011; Kobayashi et al., 2015; Sanders, 2017; Sanders & Schubert, 2019; Xia et al., 2019).

Application of collaborative flood modeling in the United States presents enormous opportunities to reduce the consequences of flooding with (1) more accurate flood maps that benefit from the integration of local knowledge and expert knowledge and (2) increased flood risk awareness and risk-informed decision-making and social behavior. FEMA FIRMs were developed not to support FRM, per se, but rather to administer an insurance program and constrain development (National Research Council, 2009). Collaborative flood modeling is complementary to the NFIP based on the potential for improving communication and understanding of residual risks, and supporting a wide range of decision-making that bears on flood risk. The perceived certainty of FEMA FIRMs presently curtails dialogue and deliberation about flood risk within communities, which is critically important for translating knowledge into action that reduces flood exposure and vulnerability (Soden et al., 2017). More accurate mapping at the local level could be especially useful for planning, steering floodplain development away from the most hazardous areas so the consequences of flooding are less severe. Collaborative flood modeling is also aligned with strategic plans by FEMA to shift leadership of disaster management to the local level (FEMA, 2018), with recent calls for practical examples of stakeholder-engaged science to address growing flood risks (DeLorme et al., 2016), and with recent calls for a new generation of flood maps and visualizations across the United States that account for compound flood hazards that are changing in a warming climate (NASEM, 2019). Indeed, a number of cities with high vulnerability to flooding have in fact begun developing their own maps, and dedicating significant public funds to FRM (Morton, 2019). The use of collaborative flood modeling in the United States, however, remains limited and largely untested. We therefore ask the question: in what ways could FRM be enhanced in the United States with the application of collaborative flood modeling to produce actionable flood hazard maps? And more specifically, in the context of FRM, what are the benefits (if any) of innovative, fine-resolution, visualizations made possible by modern flood simulation technology?

These questions are addressed under the Flood Resilient Infrastructure and Sustainable Environments (FloodRISE) project funded by the National Science Foundation and carried out by an transdisciplinary team of researchers drawn from the fields of hydrology, civil engineering, urban planning, economics, policy, communications, and social psychology with experience in community-engaged sustainability scholarship. Our specific objectives include the following:

1. Measure the value of fine-resolution flood depth contours compared to FEMA maps with respect to developing perception and awareness of flooding.
2. Assess the potential for fine-resolution models, co-produced with end-users, to meet a wide range of decision-making needs related to flood risk management in the United States.

The remainder of the paper is organized into five sections: methods (2), results (3) discussion (4), and conclusions (5).

2. Materials and Methods

2.1. Site Descriptions

Collaborative flood modeling was applied at two sites in Southern California, Newport Bay, and Tijuana River Valley. Newport Bay is the second largest embayment in Southern California after San Diego Bay (Figure 1). Newport Bay is divided into two geographic regions: (1) the upper region of the bay is a nature preserve characterized by an intertidal marsh that provides habitat for several threatened and endangered species and (2) the lower region (Newport Harbor) falls within the City of Newport Beach and is developed with waterfront homes, marinas for boating and commercial areas; these areas support numerous recreational activities. Newport Harbor was developed over the first half of the 20th century on sand dunes and marshlands formed by the interaction of the Santa Ana River with the tides and waves of the Pacific Ocean. Hence, Newport Harbor development sits on low topography that is vulnerable to flooding from extreme high tides, waves, and precipitation. Along the shoreline of Newport Harbor, seawalls with heights <1 m above ground level guard development from flooding by extreme high tides and a wide sandy beach along the open coast guard the region from flooding from the combined effects of high tides and waves. Flooding has occurred on several occasions from overtopping of seawalls by extreme high tides, beach runoff and overwash of long period swell, and intense precipitation during high tides when storm sewers are closed to prevent back-flooding (Gallien et al., 2011; Gallien et al., 2014). The majority of runoff from the 394-km² watershed enters Newport Bay from San Diego Creek, with smaller contributions from the Santa Ana Delhi and Bonita Canyon channels. These tributaries enter the upper region of the bay consisting of channels and salt marsh habitat, and the system is periodically dredged to maintain water quality and ecosystem health. Flows exit Newport Bay at its Pacific Ocean outlet through a deep water channel protected by two jetties. Newport Bay experiences a warm dry summer and a cool wet winter. The City of Newport Beach is among the most affluent cities in California. In 2015, the median annual household income was \$113,071, compared with \$64,500 for California, and the community has a somewhat older population than California as a whole, with a median age of 46.8 compared to 36.2 years (United States Census Bureau, n.d.).

Tijuana River Valley is a rural coastal floodplain along the United States-Mexico border that encompasses the Tijuana River Valley Regional Park, Border Fields State Park, Tijuana Estuary National Estuarine Research Reserve, and a handful of privately owned properties dominated by equestrian activities (Figure 1). Tijuana River Valley receives runoff from a 1,380-km² watershed that is approximately 75% in Mexico, and flood hazard in the valley is dominated by Tijuana River discharge (Luke et al., 2018). However, smaller tributaries that feed laterally into the valley from the south (City of Tijuana) and the North (Otay Mesa-Nestor) also pose flood hazards and contribute sediment and debris affecting flood hazard (Luke et al., 2018). Additionally, extreme high tides and waves pose significant flood hazards along the coastline, notably at Imperial Beach (Gallien, 2016). While rural, Tijuana River Valley is surrounded by urban development including San Diego communities Otay Mesa-Nestor to the North and San Ysidro to the East, the City of Imperial Beach to the northwest, and the City of Tijuana, Mexico to the South. Due to the limited number of residences in Tijuana River Valley, demographic data are not available, but this region is among the least affluent stretches of the Southern California coastline. For example, in Imperial Beach, California, the median annual household income in 2015 was \$46,659 (United States Census Bureau, n.d.).

2.2. Flood Hazard Modeling

We define flood hazard information as the physical and probabilistic characteristics of the flood and do not address vulnerability of flooding related to loss, susceptibility, and damage potential (Merz et al. 2007). We restrict our analysis because flood hazard information alone has enormous potential to assist end-users in decision-making that reduces the consequences of flooding (Hagemeyer-Klose & Wagner, 2009; Martini & Loat, 2007; Meyer et al., 2012), and because producing vulnerability maps would require extensive survey data that were beyond the scope of the FloodRISE initiative.

A hydrodynamic urban flood model was applied to compute spatially distributed flood hazard information. In particular, BreZo (Kim et al., 2014; Sanders et al., 2010) was applied to simulate spatially and temporally varying flooding dynamics at spatial resolutions as fine as ~1 m, which aligns with the scales at which community members perceive the occurrence and impacts of flooding (Cheung et al., 2016). BreZo solves unsteady, two-dimensional shallow-water equations using a Godunov-type finite volume scheme, and

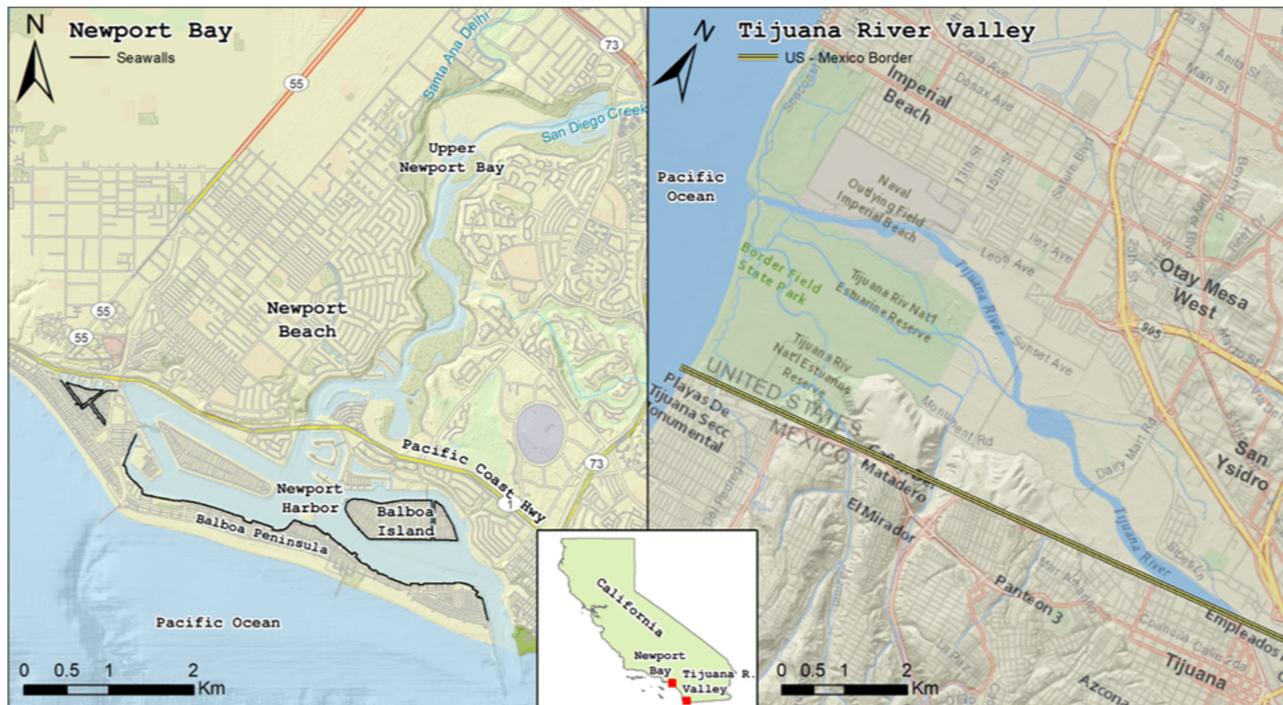


Figure 1. Collaborative modeling for flood risk management was implemented in Newport Bay (left), which is exposed to flooding by extreme high tides, waves, rainfall, and streamflow, and Tijuana River Valley (right), which is exposed to flooding by streamflow from watershed runoff, and by extreme high tides and waves along the coastline.

requires three key inputs: spatially distributed topographic data describing the land surface, which controls the pathways for water movement; a spatially distributed Manning coefficient representing the resistance of the land surface to horizontal flow; and boundary conditions that account for the causes of flooding such as extreme high tides, riverine inflow, and precipitation. Details about modeling methods are presented as Text S1 in the supporting information.

2.3. Co-production process

We will use the term “end-users” to refer to community members and authorities in a flood zone with governance, management, planning, design, and/or operations responsibilities. End-users may include residents, business owners, educators, developers, planners, regulators, resource managers, emergency management and public works personnel, and nongovernmental organizations. Previous research has clearly demonstrated that it is beneficial for end-users to be involved in the development of flood risk management tools (Martini & Loat, 2007; Steinführer et al., 2008; Pasche et al., 2009, Dawson et al., 2011, Evers et al., 2012, Maskrey et al., 2016, DeLorme et al., 2016, Aguilar-Barajas et al., 2019). Additionally, it is important to recognize that end-users not only include constituents whose behavior and actions will influence flood likelihood, exposure, and expected losses of flood events (for example, through preparedness and emergency response-related decisions and through the establishment and enforcement of policies that guide planning and mitigation) but also those in the community with local knowledge and experience about flooding who are aware of site-specific hazards and vulnerabilities and whose input into a co-production process can improve the quality of flood hazard models.

General guidelines exist for understanding and meeting end-user flood mapping needs through participatory processes (Hagemeier-Klose & Wagner, 2009; Martini & Loat, 2007; Meyer et al., 2012; Voinov & Bousquet, 2010; DeLorme et al., 2016) and reflect the varying needs of different end-users for different types of information, as well as the need for context-sensitive information. The co-production process used here was modeled on the concept of mixed methods (Creswell, 2011) and the principles of participatory research outlined and evaluated by Israel et al. (1998, 2008) including the following: (a) recognize the community as a unit of

identity, (b) build on strengths and resources in the community, (c) facilitate collaborative partnerships, (d) integrate knowledge and action for the mutual benefit of all parties, (e) promote a colearning and empowering process that attends to social inequalities, (f) involve a cyclical and iterative process, and (g) disseminate knowledge gained to all partners. However, fulfilling these principles is daunting because costs are high, time investment is great, constant requests for end-user participation by the research team can lead to fatigue, and “close interaction may be taxing or intimidating for both scientists and stakeholders, who may feel they do not have the training, personal inclination, understanding of each other’s contexts, or organizational support to participate in co-production” (Lemos et al., 2018, p. 722). With these concerns in mind, a streamlined co-production process was developed with four stages of engagement, as shown in Table 1. Here, each stage of co-production is linked to questions addressed, and the progression of flood hazard information toward actionable and accessible information. This reflects a transdisciplinary approach linking social sciences with hydrologic science and engineering, with similarities to work on the Gulf Coast of the United States addressing sea level rise adaptation (DeLorme et al., 2016, 2018). In more traditional models of flood hazard mapping, and increasingly with FEMA flood mapping, engineers may work in isolation from the site that they model and never interact with the end-users of the model, which results in significant shortcomings for effective use of this knowledge (Soden et al., 2017).

Our interpretation of community follows Mattessich and Monsey (1992, p.56), who define it as “people who live within a geographically defined area and who have social and psychological ties with each other and the place they live.” Hence, we approached both Newport Bay and Tijuana River Valley as distinct communities and developed flood hazard information in parallel at the two sites. Additionally, we engaged research site community liaisons. These individuals were not members of the community of identity but provided the partnership structure to help convene, and in some cases span boundaries by interpreting research goals to the community and creating a process that increased community participation and influence in the research.

2.3.1. Expert Consultation

Expert consultation occurred over numerous meetings as well as through in-person and phone and email exchanges directed at understanding where flooding occurs, what causes it, who are the potential end-users of flood hazard information, and whether there is interest in new information to manage it. Additionally, expert consultation was aimed at building a cooperative and productive relationship with the end-user community and communicating the goals of the FloodRISE project. Details and outcomes of expert consultation are reported in Text S2.

2.3.2. Household Surveys and Interviews

An in-person survey of residents along the Newport Beach Estuary supported collaborative flood modeling by assessing variations in the flood risk knowledge and mapping needs across population subgroups. The survey was designed using methods described in Dillman et al. (2009) and was conducted by field surveyors recruited and trained specifically for this research. Data were gathered using a door-to-door survey conducted from May–July 2014, in which 2,448 addresses within the target community were sampled to represent locations with different flooding experience and risk. Each survey took 30–45 min to complete and was conducted in English. Of the households sampled, 219 (9%) completed the survey. The survey methods and questionnaire were first reported by Feldman et al. (2016) and Houston et al. (2019) and were used to support collaborative flood modeling in three primary ways.

First, the survey identified how flood experience, knowledge, and preparation varied among residents. Demographic characteristics of respondents were collected to examine differences across population subgroups. Resident flood experience was measured by asking respondents how many times in their life they had been affected by a flood and how these events affected them. Residents were also asked if they thought flooding would occur more frequently in the next 5 years and to rate how prepared their household was for a flood event.

Second, as previously reported (Houston et al., 2019), the survey included a “map experiment” component that used a predesign-postdesign to test the hypothesis that flood visualizations from FloodRISE fine-resolution urban flood models could enhance public perception and response to flooding more than traditional FEMA flood maps. The study team hypothesized that the FEMA map could be more familiar to residents since it is utilized during real estate transactions and that the FloodRISE map could instill greater flood awareness because it displays greater spatial differentiation and estimated flood depth information.

Table 1

FloodRISE Collaborative Flood Modeling Process Supports Coordinated Iteration of End-User Engagement and Hydrologic Model and Flood Map Development

Iteration in engagement	Questions addressed by collaborative flood modeling	Iteration in hydrologic model and flood map development
1. Expert consultation	Where does flooding occur, what causes it, who are the potential end-users of flood hazard information, and is there interest in new information to manage it?	Establish model domain, identify flood drivers, collect data, and prepare first-generation models/maps.
2. Household surveys and interviews	How does flood experience and knowledge vary across subgroups, how does local knowledge of flood-prone areas agree/diverge from modeled estimates, and how do fine-resolution maps enhance awareness of flood-prone areas?	Refine models considering local knowledge and develop appropriate flood maps given local context.
3. Focus groups	What flooding scenarios, flooding attributes, and contextual information is useful for meeting end-user needs in each community?	Refine models based on local knowledge and refine maps based on end-user preferences.
4. Training and outreach	How can the co-produced flood hazard information be used in each community to advance FRM?	Create online information system for flood hazard maps and deepen understanding of user applications.

Abbreviations: FloodRISE: Flood Resilient Infrastructure and Sustainable Environments; FRM: Flood Risk Management.

Respondents were randomly assigned to view on a tablet device either a FloodRISE 1% annual chance flood depth map or a traditional FEMA map showing flood hazard classification areas (Figure 2). Residents were asked the following spatial flood awareness question before and after viewing the map: “How would you rate your awareness of where flooding could occur in your community?” on a 7-point Likert Scale from 1 (not aware) to 7 (very aware). We compared resident pre-map and post-map ratings to assess the impact each map had on spatial flood risk perception across resident subpopulations. In addition, respondents were asked to rate the usability and impressions of each map and to rate whether the map improved their understanding of the hazard. This survey component supported collaborative flood modeling by providing insights on the impact of the two flood hazard maps on resident spatial knowledge and by providing insights into the variables and map formats that end-users found useful and informative.

In contrast to the Newport Bay site, the Tijuana River Valley site hosts very few private properties and residents and was thus not suitable for a survey. Instead, semistructured in-depth interviews were conducted in Tijuana River Valley to support collaborative flood modeling by assessing resident awareness and perceptions of flooding. Due to the unique and rural field conditions, only 32 addresses were identified based on a windshield survey of private residences and business properties. Pre-notice letters were sent to notify residents/owners to provide information about the study and an invitation to schedule an interview. Fourteen addresses were classified as not viable for an interview after contact letters were returned and the study team confirmed the site was not viable (e.g., unoccupied or safety concerns). Of the remaining 18 viable addresses, there was a 100% completion rate. A referral approach was also employed to improve coverage of the population (e.g., a landowner might refer us to a worker on their property, whom would have otherwise been overlooked).

During the interview, residents were asked to review a digital map of the 1% annual chance flood depth using a laptop computer (Figure 3). The map spanned the entire valley and did not allow for magnification down to reveal street-level details, which could have an impact on resident perceptions of the map. The remainder of the interview discussed life/business ownership in the valley and flood preparedness and protection. The interviews lasted approximately 1 hr, and the interview transcripts and notes were organized, categorized, and analyzed through open coding (Saldaña, 2013; Feldman, 1995).

2.3.3. Focus Groups

Participants in the focus group consultations at each site were recruited through personal communication and referral sampling and included local government personnel, emergency response personnel, natural resource managers, nongovernmental organizations (NGOs), and community members. Each site had a limited number of personnel in leadership positions among the different invited stakeholders, and this was reflected in the total number of focus group participants. For the Newport Bay site, stakeholder representation primarily involved local government, NGOs, and community members, with 11 participants from those categories. There were also three participants representing natural resource managers and emergency

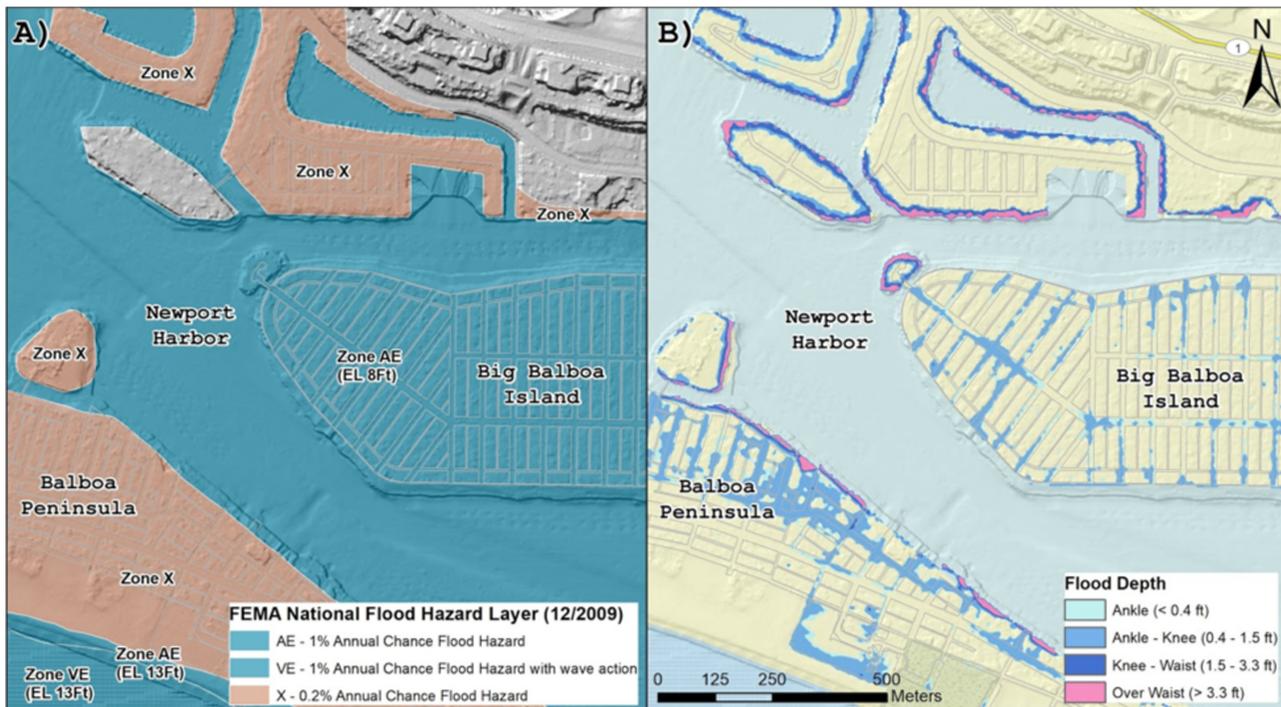


Figure 2. The Newport Bay household survey included a “map experiment” where respondents viewed either (A) Federal Emergency Management Agency (FEMA) map of flood hazard zones from 2009 or (B) a Flood Resilient Infrastructure and Sustainable Environments (FloodRISE) map of flood depth contours corresponding to a 1% annual exceedance probability. The maps encompassed the entire study area vulnerable to flooding; only a portion is shown here to emphasize the relative level of detail.

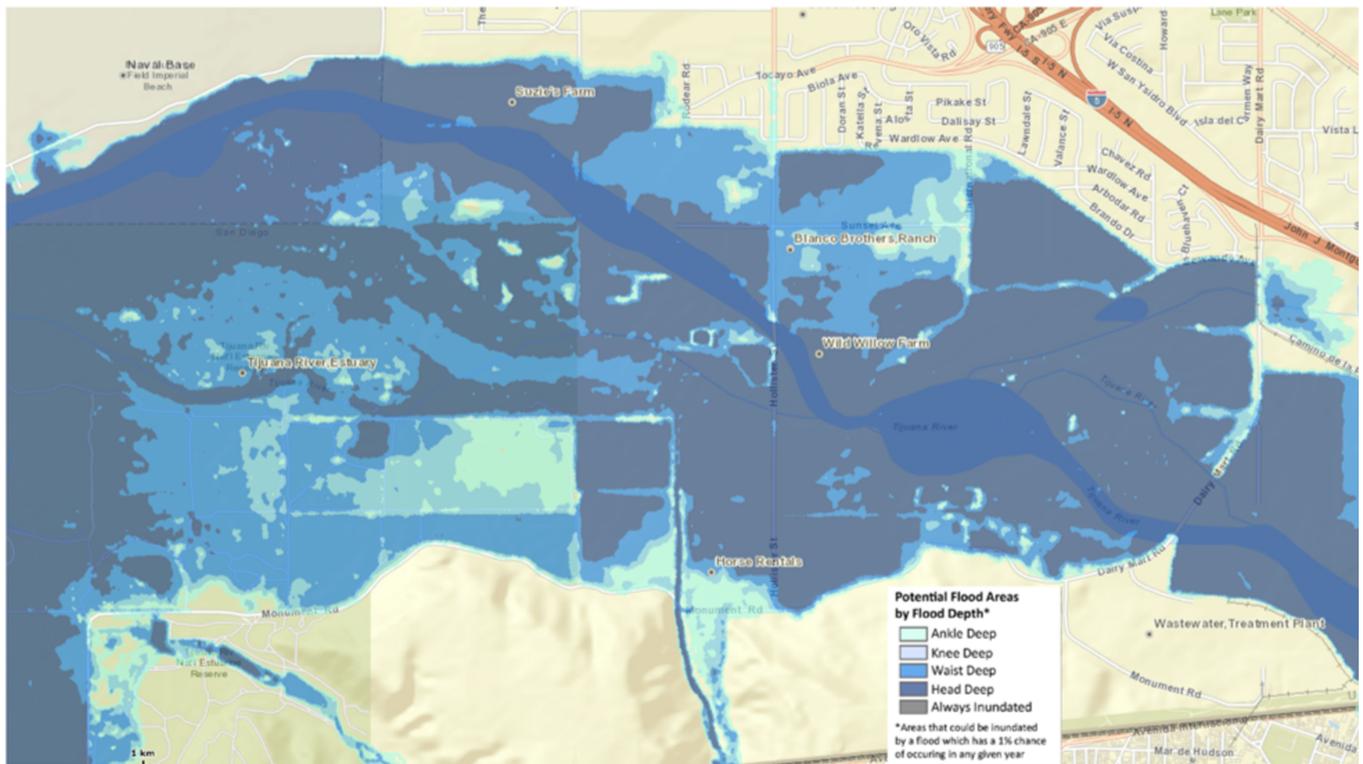


Figure 3. Map of the 1% annual chance flood depth presented on a laptop computer to Tijuana River Valley residents during interviews.

responders. For the Tijuana River Valley site, focus group participation included six participants representing public works professionals and city planners, eight participants representing emergency managers, five participants representing natural resource managers, and three participants categorized as community members or NGOs (Luke et al., 2018). The focus groups lasted 2.5 hours, during which a facilitator elicited information regarding participant perceptions of flood hazard maps that were developed by the research team in response to the mapping and information needs of potential stakeholders identified through the previous project stages (expert consultation, household surveys and interviews). The maps presented to each focus group are listed in Table 2 under the heading “Pre-consultation.” The rationale for selecting these maps is presented in Text S3.

Each participant received a copy of each map, which was printed in a large format (11×17”) with a glossary of terminology. After individually examining the map, the facilitator would ask the modeler who produced the map to explain the hazard map and establish a common understanding. Participants could ask the modeler questions, while the facilitator used a script with questions specific to each hazard map to lead discussion about the usability and accuracy of the maps. Focus group transcripts were prepared for all conversations based on audio recordings and key observations were reinforced by research team notes.

2.3.4. Training Sessions and Outreach

The research team revised flood maps and created new ones based on feedback from focus groups. The revised maps were organized into an interactive, online, and publicly accessible geographical information system (GIS) that served as a flood hazard viewer (ArcGIS Online, ESRI, Redlands CA). Price and Vojinovic (2008) propose GIS as a focal point for coordinating FRM; Wilkinson et al. (2015) present a cloud-based tool for information access and knowledge exchange on local flood risk; Mackay et al. (2015) suggest that GIS enhances opportunities for knowledge exchange between scientists, policy makers, and local communities regarding a broad range of environmental issues; Almoradie et al. (2015) present a web-based GIS to support stakeholder collaboration in FRM; and Stephens et al. (2014, 2015) report on the elements of sea level rise viewers for effective communication with stakeholders.

End-users were invited to participate in training sessions held in a nearby computer laboratory. Attendees included representatives of government agencies and community members with wide-ranging flood management responsibilities, some of whom also participated in the focus groups. During the training session, end-users were guided through a tutorial on the use of the online viewer. Participants learned to access different maps corresponding to different scenarios, to pan and zoom to different areas and also to identify conditions for specific sites (such as a street address). After becoming familiar with the flood hazard viewer, participants were asked about the potential applications for the system.

3. Results

3.1. Survey and Interview Results

3.1.1. Newport Bay Flood Experience and Preparedness

The first component of Newport Bay resident survey analysis that supported collaborative flood modeling focused on characterizing variations in resident flood experience and knowledge.

About 42% of Newport Bay survey respondents reported having experienced flooding; 44% of these respondents indicated the most severe flood event they had experienced occurred in the Newport Bay study community. On a scale of 1 (not affected) to 7 (greatly affected), respondents with flood experience reported an average ranking of 3.5 when asked how much they were affected by the most severe flood event they had experienced. The most frequently cited impacts included disruption to daily activities (76%), effects on personal or neighboring property (77%), and effects on public property (72%). About 37% of respondents expected flooding to become more frequent in the next 5 years. The most frequently cited reasons included climate change (95%), followed by aging infrastructure (68%) and land development (41%).

Respondents were asked to rank how prepared their household was to handle a flood with 1 indicating “not prepared” to 7 indicating “completely prepared.” The average ranking for household preparedness was 3.22, which suggests that many respondents did not feel their household was adequately prepared to handle a flood. On average, male respondents, homeowners, respondents age 65 years or older, longer term residents (over 10 years), and residents with higher household income (over \$100,000/year) reported higher preparedness than other respondents.

Table 2

Titles of Pre-consultation and Post-consultation Flood Hazard Maps Codeveloped for Newport Bay (NB) and Tijuana River Valley (TRV).

Timing	Site	
	Pre-consultation	Post-consultation
Newport Bay (NB)	FEMA FIRM 1% Annual Chance Flood Depth (2015/2050) Chance of Flooding (2015) Chance of Flooding (2015) accounting for statistical uncertainty Chance of Road Blockage (2015)	FEMA FIRM Historical Event Flood Depth (2005) 1% Annual Chance Flood Depth (2015/2035/2050) Chance of Flooding (2015/2035/2050) Chance of Road Blockage (2015/2035/2050) Causes of Flooding (2015/2035/2050) Hours of Inundation Per Day (2015/2035/2050) "King Tide with Rainfall" Flood Depth (1/2", 1") 1% Annual Chance Flood Depth with Proposed Flood Wall 1% Annual Chance Flood Depth with Flood Wall Failure
Tijuana River Valley (TRV)	FEMA FIRM 1% Annual Chance Flood Depth Chance of Flooding 1% Annual Chance Flood Force Chance of Flood Force Strong Enough to Move Cars. Causes of Flooding Hours of Inundation Per Day 2050	FEMA FIRM Historical Event Flood Depth (1983) 1% Annual Chance Flood Depth 20% Annual Chance Flood Depth Chance of Flooding Historical Event Flood Force (1983) 1% Annual Chance Flood Force 20% Annual Chance Flood Force Historical Event Shear Stress (1983) 1% Annual Chance Shear Stress 20% Annual Chance Shear Stress Change in Flood Depth from Channel Dredging (20% Annual Chance Event) Change in Flood Depth from Illegal Fill Removal (1983 Flood) Poorly Drained Areas

Abbreviations: FEMA: Federal Emergency Management Agency; FIRM: Flood Insurance Rate Map.

3.1.2. Newport Bay Map Experiment

The map experiment resident survey component provided insights on the impact of the two flood hazard maps on resident spatial knowledge and insights into the variables and map formats that end-users found useful and informative. Respondents who viewed the FloodRISE map ($N=122$) ranked their agreement with the statement "I am able to get the information I need easily" higher on average than respondents who viewed the FEMA map ($n=88$; 5.86 vs. 5.31) on a scale of 1 (*strongly disagree*) to 7 (*strongly agree*; Figure 2). Those who viewed the FloodRISE map also had higher average agreement with the statement "I gained information from this image that will benefit my life" than those who viewed the FEMA map (4.98 vs. 4.08). Although there was no statistical difference by map type in respondent agreement with the statement "A person would need to learn a lot in order to understand this image," the average respondent ranking of 5.94 for this indicator suggests that many respondents felt unsure in their interpretation and would want further guidance interpreting and using the information presented on both maps. When asked whether their "understanding of risk changed as a result of seeing the map," most respondents (61%) indicated that their understanding stayed the same and over a third (35%) indicated their understanding had increased.

Before viewing a flood hazard map, the average respondent ranking for the question "How would you rate your awareness of where flooding could occur in your community?" on a scale of 1 (not aware) to 7 (very aware) was 5.16 and there was significant variation among respondent subgroups. Younger respondents, renters, lower-income respondents, and short-term residents had a lower overall average ranking compared to other respondents. The overall average flood hazard awareness increased to 6.03 after viewing either the FEMA or FloodRISE map, which suggests that respondents, regardless of the map viewed, felt more aware of flood prone areas in their communities. Viewing the map also seemed to have an equalizing effect in terms of self-rated spatial awareness. That is, differences in awareness observed across sociodemographic and geographic subgroups prior to viewing a flood hazard map were no longer present after viewing the map. In addition, viewing the FloodRISE map with estimated flood depth and greater spatial differentiation was associated with higher levels of postmap spatial hazard awareness (Houston et al., 2019).

3.1.3. Tijuana River Valley Interviews

Open coding of Tijuana River Valley interviews produced three prominent themes: (1) skepticism about initial mapped information, (2) experience with past flood events, and (3) desire for intervention.

3.1.3.1. Skepticism about Mapped Information

In 100% of the interviews, participants expressed some skepticism about mapped information. Participants had difficulty interpreting the map due to factors that created confusion and, in some cases, distraction in respondents' ability to interpret the map in response to interviewer questions. No participant felt that this initial map was completely accurate in various regards, including the extent and location of flooding displayed. Residents felt that the potential flood extent represented was exaggerated in some areas of the map and under-estimated in other areas, leading to expressions of "surprise." This reaction was often tied to place names and reference points on the map (Figure 3). Incorrect place names on the map led to immediate distrust and concern with the validity of other aspects of the map:

"I don't think it's accurate because a lot of things are wrong in it."

"I'm confused here because it says 'horse rentals', but 'horse rentals' are over here. They don't even know where the stables are, how are they going to know where the water is going to be?"

"Ok well that concerns me because what else is off?"

We note that the initial map (Figure 3) was generated using place names obtained through ArcGIS (ESRI, Redlands, California) and Google Maps (Google, Mountain View, CA), which are known to misrepresent neighborhood names or to approximate the location of place and street names in an automated way, centering them over a large area often resulting in geolocation errors (Bacchi, 2019; Nicas, 2018). Participants also had difficulty reconciling depth contours with their familiarity of site conditions:

"And why all of a sudden we're going to be fine and our neighbors are going to be flooded that doesn't make any sense."

"See here we're waist deep and then all of a sudden because there's a line there, the water didn't go any further and now all of a sudden we're knee deep and then to ankle deep with no gradation you know what I'm saying? That looks very strange to me."

These concerns prompted requests from participants for more fine scale information (i.e., access to a magnified perspective, which was not available at the time of the survey). Hence, flood information mapped at the scale of the entire valley was too coarse for participants to confidently reconcile their personal experience with the mapped information. The research team later addressed this concern in the development of the online hazard viewers, which allow users to zoom in and out on maps depicting various scenarios.

3.1.3.2. Experience with Past Flood Events

Participants drew upon past experience with flooding to reflect on the realism and magnitude of the mapped 1% annual chance flood:

"I know we have low spots but I've never seen it that deep. It looks a little exaggerated to me."

"I think it's a little more exaggerated than I've experienced it to be."

"Well, on the fringes it's not the worst I've ever seen. I've seen worse."

"You see this is what surprises me, they're showing a hundred a year event and they're not showing any water in the housing developments."

Generally, participants expressed a sophisticated and experientially grounded understanding of the causes of flooding and flow paths of flooding. As a participant described while pointing to the map, "Yes, so this is where the flow came the second time and it went through this way [pointing] so it created this drainage [pointing] and it use to come right up here, somewhere right up here [pointing]." Perhaps because it was an atypical flood event, many participants spoke about the 1993 flood with great detail and used it as a reference point to discuss the map (e.g., "compared to 1993 ...") considering the severe blockages of roadways and

evacuation routes from the River Valley, loss of property and death of livestock that occurred in 1993. As one participant described, “It was flooded ... all the streets were flooded [and] we couldn’t go in or out ... we had to go [back] in [to the Tijuana River Valley] through Mexico. I was pregnant ... I had to take a leave of absence because I couldn’t get to work ... and we all had to come through Mexico to get to our land.” Many participants offered to share photographs of flood events that were used by the modeling team to qualitatively validate models. Such detailed information about historical flood events from residents also deepened researcher appreciation for the human impacts of extreme events: “Cause we’ve seen it when it really does rain, we’ve been here, so people can tell you ‘oh my god, you know, based on the information that we see’ ... well, we’ve been there.”

3.1.3.3. Desire for Intervention

Some participants pointed to the strategy of construction of a concrete flood control channel to address flooding in Tijuana River Valley:

“They were supposed to sponsor a concrete-lined, a 100-year flood – it was supposed to be a 100-year flood controlled channel. All the way to the ocean and it was never built.”

“My concerns [about flooding] probably aren’t going to change unless they throw an unrestricted channel going all the way to the ocean.”

Indeed, except for the Tijuana River, nearly all other major rivers of southern California have been channelized on the coastal plain to provide flood protection, and these systems have been very successful at reducing flood losses from events below the design capacity (Brooks, 1982). On the other hand, channelization has well-known drawbacks including heightened vulnerability of populations to low-probability flood events (Di Baldassarre et al., 2019) and negative impacts to groundwater aquifer recharge, water quality, sediment flows, terrestrial and aquatic ecosystems, and stream health (Askarizadeh et al., 2015; Fletcher et al., 2013; Walsh et al., 2005). Resident interest in structural interventions later resulted in efforts to develop flood hazard maps depicting impacts of sediment removal from areas identified as “plugs” (e.g., Brown Fill identified by Tijuana River Valley end-users through expert consultation) designed to increase the capacity of the main channel in Tijuana River Valley and assess viable nonstructural solutions, like sediment removal from areas known to exacerbate the flooding condition (Table 2). Interventions can be illustrated and deliberated through a collaborative flood modeling framework, another benefit to the process, as we learned in this case.

Finally, in one case, the interviewer encountered a resident distressed over requirements for flood insurance under FEMA policy. The resident reported, “As far as I’m concerned, I’ve never been flooded here. So I don’t want to be included in a floodplain. If you’re going to do it, I’m gonna have to pay flood insurance. I don’t have the money. I’m on a fixed income.” Because our project was not associated with FEMA FIRM mapping, the interviewer was able to build trust and complete a valuable interview. This is an important consideration for the design of future collaborative flood modeling projects: having a research team which did not represent the regulatory agency helped to overcome distrust and set the stage for future engagements (e.g., focus groups) for the project’s multiphased iterative process (see Jagosh et al., 2015).

3.2. Co-production of Flood Hazard Maps

Table 2 shows the flood hazard maps finalized for each site (Post-consultation) compared with the initial set of maps presented to the focus groups (Pre-consultation). At both sites, the focus groups provided input used to transform the set of maps including (a) modifications of existing map types, (b) new maps that had not been contemplated by the research team, and (c) removal of maps found not to be effective at meeting end-user needs. The number of maps increased significantly from 6 to 21 at Newport Bay and from 6 to 12 at Tijuana River Valley. Several maps repeated the same type of information (e.g., flood depth) with changes to the flooding scenario. The scenarios for Newport Bay include a historical event and 1% annual chance flood in 2015, 2035, or 2050, while for Tijuana River Valley, scenarios include a historical event, 1% annual chance flood, and 20% annual chance flood. Consideration of multiple scenarios creates opportunities for end-users to “wrestle with uncertainty” about possible flooding (Soden et al., 2017), and to interpret the intensity and likelihood of probabilistic flood events using more familiar reference points such as the height of a high tide, the discharge of a flood, or an amount of rainfall recorded during an historical event (Luke et al., 2018).

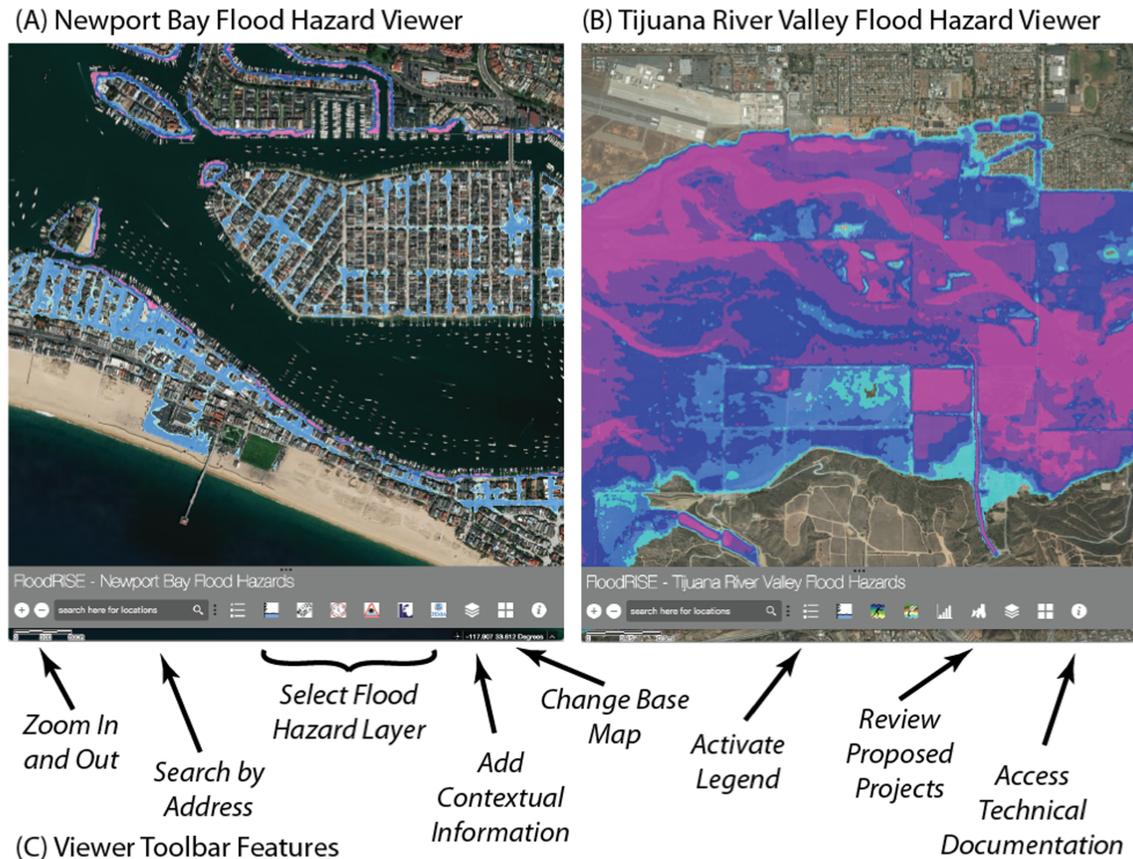


Figure 4. Online flood hazard viewer for (A) Newport Bay (bit.ly/floodrisenb) and (B) Tijuana River Valley (bit.ly/floodrise_TRV) displaying contours of the 1% annual probability flood depth with a basemap consisting of imagery. The hazard viewers include a toolbar (C) that allows users to pan, zoom, select between flood hazard layers, basemaps, contextual information, activate a legend, and access technical documentation.

Figure 4 presents the flood hazard viewers developed for each site, where anyone can access the post-consultation flood hazard maps listed in Table 3. A control bar at the bottom of the display allows users to pan and zoom, navigate to specific locations (e.g., street address), choose between available flood hazard maps (or layers), change base maps, add/remove relevant contextual information, review the impacts of proposed projects on flood hazards, and access technical documentation including data sources, modeling and mapping methodologies, and a glossary of terms. This functionality was developed in response to usability needs identified during end-user engagement. The titles of available flood hazard layers, base maps, and contextual information are not displayed in Figure 4, but when a user hovers the mouse/pointer over the icons in the menu bar, the title of the icon (e.g., “Flood Depth”) appears on the screen. The system was also developed with a floating “i” button that can be selected to access more technical information specific (e.g., modeling approach and model parameters) for the active flood hazard layer.

Several examples of flood hazard maps co-developed for Newport Bay are presented in Figure 5. A flood map configuration designed to orient end-users around present-day flooding hazards with minimal use of technical terminology is shown in Figure 5A. The flooding scenario corresponds to a historical event, photographs of flooding from the event are added for perspective, and the color scale provides both quantitative and qualitative information about the severity of flooding. The historical flooding scenario is a well-documented 2005 high tide flood event (Gallien et al., 2011).

During focus group meetings, significant time was spent clarifying the concepts of exceedance probabilities and return periods. This is consistent with findings elsewhere that technical terminology and statistical concepts present barriers to effective and useful risk communication (Burningham et al., 2008; Burton et al., 1968; Krinsky, 1982; Lundgren & McMakin, 2018). The flood map corresponding to flood drivers at the upper limit of the 95% confidence interval (Table 2) generated even greater discussion and created confusion among end-users, and thus, it was not included in the online flood hazard information system.

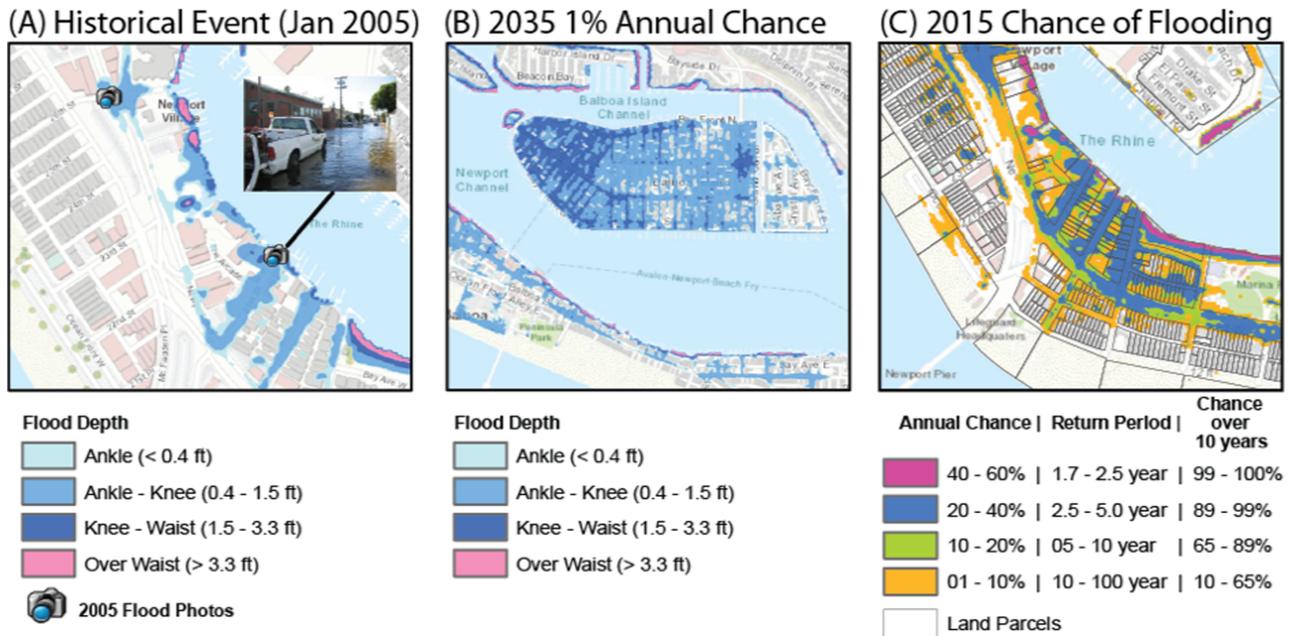


Figure 5. Examples of flood hazard maps for Newport Bay including: (A) flood depth for a historical event, ; (B) flood depth for the 2035 1% annual chance event accounting for all flood hazards such as rainfall, waves, extreme high tides, and streamflow, ; and (C) 2015 annual probability of future flooding accounting for all flood hazards with land parcel outlines added as a contextual layer.

The combined qualitative/quantitative intensity scale shown in Figure 5 is an output of iteration between researchers and end-users. This human-body scale, based on the height of an average human, was hypothesized to help end-users more easily contemplate the severity of flooding than quantitative information. Maps presented during focus group meetings only included a qualitative scale, which was received positively by many end-users. However, several requested quantitative information in addition to the qualitative information, which led to a combined qualitative/quantitative scale.

Figure 5B is a configuration that displays a near-future probabilistic flooding scenario (2035), and it also incorporates the terminology suggested by end-users to communicate the exceedance probability, “1% Annual Chance.” The preconsultation maps were limited to 2015 and 2050, but end-users expressed a desire for more near-term flood hazard information, which led to 2035 and 2050 maps, but not beyond. Projections of global mean sea level for 2050 at the 50% percentile (median value) differ by less than 3 cm (1 inch) across representative concentration pathways (RCPs) 4.5 and 8.5, but by 20 cm (8 inches) as of 2100; additionally, differences between the 95th and 5th percentiles for RCP 4.5 increase from 17 cm (7 in) to 57 cm (22 in) between 2050 and 2100 (Kopp et al., 2014). Hence, we suspect that end-users desire flood hazard assessment over a window of time when confidence in sea level rise projections is relatively high. Recognizing also that infrastructure will surely be adapted over time, end-users articulated the need for near-term flood hazard information to inform the modification and maintenance of present-day infrastructure.

We emphasize that probabilistic flood maps, such as the one shown in Figure 5B, mask a high degree of technical complexity stemming from the challenge of accounting for multiple flood drivers (i.e., compound flood hazards) through linkages of statistical and hydrodynamic modeling (Luke et al., 2018; Moftakhari et al., 2019) and the coupling of hydrodynamic models (Bilskie & Hagen, 2018; Santiago-Collazo et al., 2019). However, we avoid mentioning these details so as not to distract from the ability of end-users to contemplate the implications of flooding, and we make technical documentation available through the “i” button on the flood hazard viewer. Indeed, the goal of the technical modeling was to create a map that could be most easily explained to end-users *despite* the complexity of compound flood hazards.

Finally, Figure 5C is a configuration showing how the chance of flooding can be communicated using several different descriptors (annual chance, return period, and chance over 10 years) to help end-users reconcile terminology that is often used interchangeably and a source of confusion.

Another theme that emerged from focus group meetings was the need to relate a flooding scenario (such as the 1% annual chance event) to a more familiar reference point, such as the height of the tide or the amount of rainfall or a historical event that they have experienced. Luke et al. (2018) describe a similar experience based on focus group meetings to refine flood maps for Tijuana, Mexico. At Newport Bay, “King Tides” and “Rainfall” emerged as familiar reference points useful for orienting end-users around the severity of the 1% annual chance flood event. “King Tides” are a colloquialism referring to the highest high tides of each year, which pose the most serious threats in December and January when storm events with intense rainfall are also possible. The Newport Bay site is particularly vulnerable to flooding when rainfall is coincident with high tides because gravity-driven storm sewers are closed to prevent backflooding from high tides, and thus, this scenario is clearly grounded in local knowledge. Hence, the flood hazard viewer includes two different maps (Table 2) corresponding to flooding from ½” and 1” of rainfall (over 3 hr) and a typical king tide height (7 ft MLLW), and no attempt was made to estimate the likelihood of this event.

As another example of maps responsive to end-user needs, Newport Bay natural resource managers requested more information about the impacts of sea level rise on tidal wetland habitats. Information about *extreme* water levels was viewed as being useful, but natural resource managers sought information about the changing submergence times of intertidal habitats under sea level rise. The “Hours of Inundation Per Day” map was thus introduced to show how long different parts of the wetland system are submerged, on average, based on different sea levels and tidal dynamics of the embayment (Table 2). This map was created by running the hydrodynamic model over many tide cycles and integrating the time of submergence of each computational cell.

Planning, public outreach, and deliberation about a new sea wall to protect Balboa Island from flooding, led by the City of Newport Beach, preceded the focus group meetings and questions about the project were raised during the focus group meetings. Planning-oriented participants and natural resource managers were interested not only in the flood hazards that were being addressed on Balboa Island but also in the effect of the project elsewhere in the region. Indeed, in a public presentation of the Newport Bay flood hazard maps by the research team following the focus group meetings, a resident commented that the City’s plan for a flood wall only addressed the flood risk to Balboa Island—it did not address the flood risks facing other areas. Aside from planning-oriented decision-making, emergency management-oriented end-users were interested in the flooding that could occur if the seawall were to fail during an extreme event. Emergency responders reported that resources for flood management such as pumps and sand bags were housed in several different storage facilities on the island, and sought information about the vulnerability of these facilities to flooding as well as access to them. Hence, maps were prepared to show the 1% annual chance flood depth after construction of the seawall and the flood depth resulting from a hypothetical failure of the seawall during a 1% annual chance high tide (Table 2).

Luke et al. (2018) report the codevelopment of flood maps for Tijuana River Valley so only a brief synopsis is provided here. Like Newport Bay, the flood hazard viewer for Tijuana River Valley includes a mix of probabilistic and historical flooding scenarios (Table 2). A Tijuana River flood from the 1982–1983 “El Nino” storm season was used as a historical scenario based on the availability of data and the magnitude of the event (Luke et al., 2018), and two probabilistic scenarios (1% annual chance and 20% annual chance events) based on end-user interest in the regulatory standard and a more frequent event (Table 2).

Three examples of flood hazard maps that emerged from collaborative flood modeling at Tijuana River Valley and reported by Luke et al. (2018) are shown in Figure 6. A map of flood force useful for interpreting the danger of the flood is presented in Figure 6A (useful to residents and emergency managers), a map of flood shear stress useful for interpreting the erosive potential of a flood (useful to natural resource managers) is shown in Figure 6B, and a map of poorly drained areas (useful to public health managers) is shown in Figure 6C.

Table 2 also shows two-different flood force maps presented to the Tijuana River Valley focus group, one corresponding to the force associated with a specific event and the other corresponding to the probability of a force exceeding a threshold (similar to a probability map shown in Figure 5C). End-users found the second one more difficult to understand, and thus, it was not retained in the final set of flood hazard maps.

Finally, we note that end-users representing natural resource managers and local government (public works and city planners) sought information about the role of sediment management on flood risks. For example, a

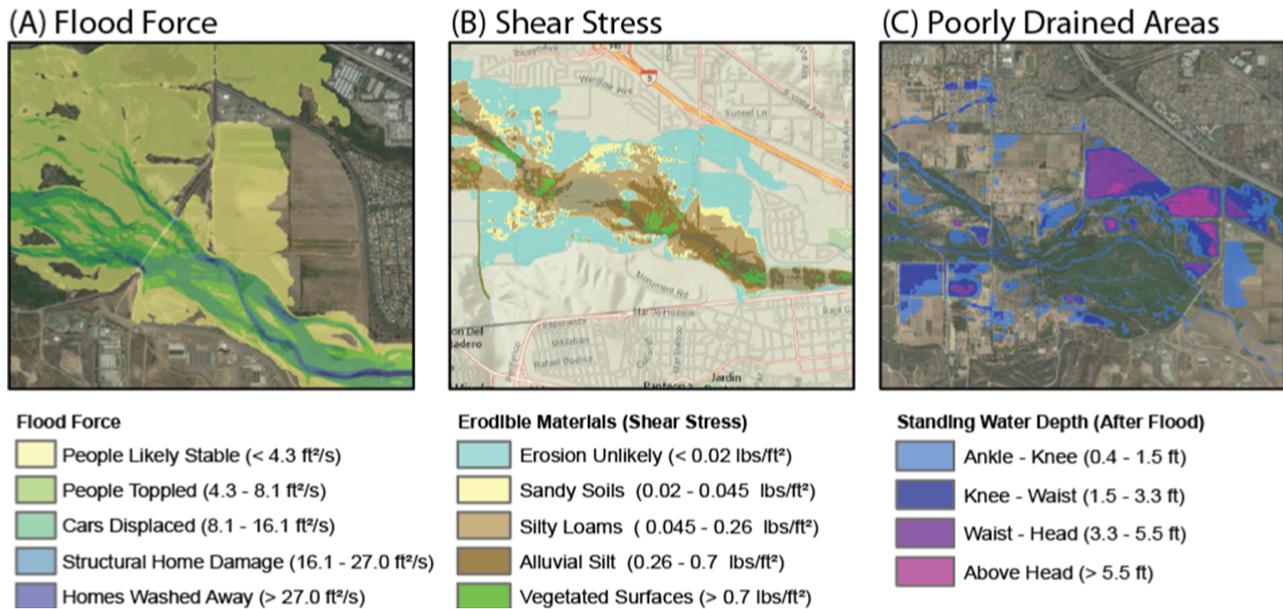


Figure 6. Configurations of the Tijuana River Valley flood hazard viewer showing (a) flood force relevant to safety of pedestrians, vehicles, and buildings; (B) shear stress relevant to potential erosion of soil and vegetation; and (C) poorly drained areas that pose public health hazards.

channel through the center of the valley (the so-called “pilot channel”) was dredged annually to enhance flood conveyance after sedimentation during the previous storm season, and local government was contemplating the removal of fill material (so-called “Brown Fill”) that had been illegally placed in the floodway by a property owner to reduce flood exposure. To address these interests, the flood hazard model was configured with revised topographic data representative of each management action and run to depict the influence on flood depths (Table 2).

Following focus group meetings, the research team was also approached by end-users in each community with specific management needs beyond what was met by the online system. For example, the City of Newport Beach requested flood elevation datasets for integration into its geographic information systems used by the planning department. In Tijuana River Valley, the County of San Diego requested additional flood hazard modeling related to proposed dredging, and the Tijuana River National Estuarine Research Reserve (TRNERR) requested flood hazard information related to a proposed road realignment and marsh restoration project. The research team supported these requests and integrated selected results into the online hazard viewers.

3.3. Adoption and Use of Flood Hazard Maps

Participants in training sessions reported potential and actual applications of the online flood hazard viewer for FRM. These involved individual, organization, and/or community decisions regarding flood risk include the following:

3.3.1. Planning and policy

Participants reported numerous examples of how the tool could and/or are being used to inform land use, natural resource management, community development, and flood control planning and policy. For example, at Newport Bay a local government representative reported that the tool was useful for assessing new legislation (California Assembly Bill 691) that makes accounting for the impacts of SLR on public lands a management priority of local trustees. A local developer reported that the tool was useful for understanding long term changes to flood risk. At Tijuana River Valley, a local government representative reported that the tool was useful for updating the City of Imperial Beach General Plan and Local Coastal Plan, and a federal government representative reported that the tool was useful for informing land use plans in Mexico based on a better understanding of the consequences of sediment and debris blockages.

3.3.2. Project scoping and design

Participants reported several ongoing projects currently being conceptualized where this tool provided timely information to help inform placement and design. At Newport Bay, a local government representative reported that the tool could aid the design of channel structures affected by sea level rise due to low lying and flat topography. At Tijuana River Valley, a federal government representative reported that the tool could aid conceptual design and a feasibility study for placement of trash traps and sediment basins in the main river channel. A local government representative reported that the tool was useful for assessing the proposed project to remove fill material (so-called “Brown Fill”) that had been illegally placed in the floodplain. A state government representative reported that the tool could be useful for realigning and regrading an access road through Border Field State Park in Tijuana River Valley. Lastly, a resource manager reported that the tool could be useful for planning upcoming restoration of a salt marsh in Tijuana River Valley.

3.3.3. Maintenance of existing flood control strategies

Participants reported there are several existing flood control strategies that are currently utilized at the different sites. The tool helps to ensure these strategies are effectively implemented, maintained and communicated to the public. At Newport Bay, a local government representative reported that the tool could be useful for providing justification for management actions such as beach nourishment, channel dredging, and vegetation clearing. At Tijuana River Valley, a local government official reported the tool could also be useful for informing channel maintenance and dredging.

3.3.4. Informing financial and economic decisions

There was also discussion of opportunities for the tool to inform economic decisions both at the project scale and within specific relevant industries (e.g., insurance). For example, at Newport Bay, a developer the indicated the tool could be useful for measuring the value of flood insurance, and at Tijuana River Valley, a consulting engineer reported that the tool could be useful for “walking decision-makers through the cost/benefits of projects.”

3.3.5. Leverage other modeling and research efforts

The tool has the opportunity to leverage other models to advance scientific and management applications. At Newport Bay, natural resource managers emphasized the importance of taking into account sea level rise projections from climate models in order to fully convey the risk that flooding poses to intertidal habitats. In Tijuana River Valley, the tool was cited by two federal government representatives and a scientific researcher working in the system as being valuable for informing sediment management studies.

3.3.6. Community awareness and outreach

There was widespread interest in utilizing this tool to raise awareness among end-users about flood risk and flood management decisions. In particular, at Newport Bay, the tool was cited by more than one local government official as being useful for communicating to the public about a project under consideration to raise the height of seawalls around Balboa Island.

In addition to opportunities reported by end-users for using the flood hazard viewer shown in Figure 4, several applications of the validated BreZo models in FRM are noted. Through a licensing agreement, the models were made freely available to engineering consultants to meet specific client needs. At Newport Bay, an engineering consultant used the BreZo model to help a client respond to FEMA map revision, which based on published FloodRISE maps, overestimated areas at risk of flooding by a 100-year event. FEMA subsequently revised the maps in consideration of this information. At Tijuana River Valley, one engineering consultant used the validated BreZo model to aid the design of a salt marsh restoration within the TRNERR, a second engineering consultant used the validated BreZo model to analyze the impacts of illegal grading/fill in the floodplain on flood extent, and a third engineering consultant used the BreZo model to develop a strategy for re-grading and possibly re-routing an access road that was experiencing chronic coastal flooding from extreme high tides. Based on discussions with engineering consultants who licensed the software from members of the research team, interest in using the model was based on a high level of credibility among clients, the ability of the model to capture narrow flow features through local refinements, and the cost-effectiveness stemming from use of a validated model. Conversely, engineering consultants also reported reservations about using the software for future flood-related projects because it is not FEMA-certified, which is due to the software being developed for scientific research applications and not commercial applications.

4. Discussion

The reported uses and the overall positive reception of the online flood hazard viewers by end-users reinforce previous findings by Cheung and Feldman (2019) and Wilkinson et al. (2015) that flood information tools codeveloped with end-users achieve several important outcomes such as (a) building greater shared understanding about flood risks, (b) facilitating the exchange of ideas, (c) providing a framework for how to approach development, (d) encouraging interaction among scientists and end users, and (e) providing a wealth of information that is accessible and understandable to end-users. Historically, flood hazard modeling in the United States has concentrated on supporting the FEMA Flood Insurance Rate Program (FIRP) through the preparation of FEMA FIRMs, yet our results point to extensive opportunities to support nonregulatory activities capable of reducing flood risks. Results indicate that the tool is especially valued for planning, based on the number of personnel citing planning-oriented uses and the total number of cited uses.

Collaborative flood modeling is consistent with the objectives of reforms to the NFIP, which seek to place greater responsibility for avoiding flood losses on property owners and communities and ensure that flood insurance rates more accurately reflect the real risk of flooding, and avoiding—where possible—the subsidizing of unnecessarily risky floodplain development. Collaborative flood modeling also supports more accurate flood mapping through synthesis of expert and local knowledge (e.g., Luke et al., 2018). Collaborative flood modeling is also well aligned with greater emphasis within FEMA on longer-term mitigation. Historically, the vast majority of risk mitigation funding from FEMA has been allocated only after major disasters. Only about 10% of FEMA funding for household and community risk reduction has been allocated pre-disaster (Kousky & Shabman, 2017). Yet the agency is now considering increased investment in risk mitigation before disasters occur. Collaborative flood modeling could provide an effective way to inform long-term risk reduction strategies and to prioritize strategies for support by FEMA mitigation grants. Long-term strategies would benefit from advanced understanding of pluvial, fluvial, and coastal flood hazards and potential erosion due to floodwaters. As shown here, urban flood models can be linked to statistical analysis techniques (e.g., Moftakhari et al., 2019) to map flood hazards from multiple flood drivers (e.g., precipitation, streamflow, high tides, storm surge, and waves), and 1% annual chance flood zones based only on riverine or coastal flood drivers will be expanded over more properties after accounting for all important drivers. This could help to address the problem of underinsurance (e.g., Michel-Kerjan & Kunreuther, 2011; Wing et al., 2017) if put into practice along with other measures to address low insurance uptake (Allaire, 2016). However, additional factors for underinsuring remain, such as anticipation of government aid, low-risk perception, and relying on heuristics to make insurance purchase decisions (Botzen & van den Bergh, 2008; Kunreuther et al., 2013).

We acknowledge that the study and practice of community-based research are much deeper and nuanced than this paper can address, and the collaborative flood modeling approach does not fully embody a participatory research model. For a community to participate as equal members and share control over all phases of the flood hazard mapping process (e.g., problem definition, data collection, interpretation of results, and application of the results to address community concerns), the collaborative flood modeling process would need to be adapted. Furthermore, asking end-users of information what they need before it is created in itself is not transformative. However, understanding the value of fine-resolution depictions of flood hazards in the context of end-user awareness, perceptions, and decision-making—that ultimately shapes exposure and vulnerability to flooding—should be valued as a major benefit of co-production. Finally, we acknowledge what has been reported elsewhere regarding stakeholder-engaged science (DeLorme et al., 2016), that collaborative flood modeling is costly and laborious due to the time required for multiple rounds of end-user engagement and model development/improvements. In fact, Dilling and Lemos (2011) and Lemos and Morehouse (2005) argue that sustained, regular interaction among participants shapes the ways that knowledge is produced as well as how the usefulness and value of the knowledge is perceived. This suggests that collaborative flood modeling needs to be sustained indefinitely to continuously shape planning, construction, resource management, and emergency planning/response across a site. However, it is not clear how this could be done in practice since flood hazard mapping is already underfunded (Burby, 2001; NRC, 2009). This points to the need for new institutional structures and funding mechanisms (e.g., Schaefer, 2017) to scale and sustain collaborative flood modeling.

5. Conclusions

Collaborative flood modeling is presented here as the coordination of two iterative processes, flood hazard modeling, and community engagement, leading to flood hazard knowledge, maps, and tools tailored to site-specific decision-making needs and adopted within communities for FRM. This stands as a departure from traditional flood hazard mapping in the United States in two critical ways: (1) At a time when flood hazard mapping is increasingly being performed by distant engineers with little familiarity of and connection to a site (Soden et al., 2017), collaborative flood modeling involves hazard modeling by engineers who are meaningfully engaged with and learn from local end-users. (2) In contrast to the FEMA flood hazard maps which depict flood hazard zones corresponding to 1% annual chance and 0.2% annual chance floods (and sometimes other information) in a single map, collaborative flood modeling leads to a menu of maps that contour different flood attributes (at fine resolution) to meet diverse decision-making needs that arise in communities from different end-user interests and responsibilities. Clearly, FEMA flood hazard maps were not designed to meet a wide-range of decision-making needs related to flooding, but rather to support the NFIP and to regulate floodplain development, and one could argue that the comparison is inappropriate. However, communities in the United States often have no other information to contemplate flooding than FEMA flood maps, and there is a pressing need to improve support for flood-related decision-making in the United States with mapped and actionable flood hazard information (NASEM 2019). This work provides insight on how this can be done, and what can be gained. In particular, we conclude the following:

1. Collaborative flood modeling, a transdisciplinary approach built upon principles of community-engaged research (e.g., Israel et al., 1998), resulted in high levels of participation among potential end-users of flood hazard information and revealed an eagerness for better information to address flood risks among planning, public works, natural resource managers, and emergency responders. This result is consistent with a report of high interest in several major U.S. cities for better information about urban flood hazards and risks (Morton, 2019, NASEM 2019). Herein, the technology itself, urban flood models that depict flood conditions with a resolution of several meters, also stimulated interest in collaborative flood modeling among end-users. But perhaps of greatest importance was the involvement of community liaisons, individuals who were not members of the community, but provided the partnership structure to help convene, and in some cases, span boundaries by interpreting research goals to the community and vice versa.
2. Perception and awareness of flooding are enhanced more by fine-resolution depth contour maps than the FEMA maps depicting flood hazard zones. Fine-resolution depth contour maps were also effective at minimizing differences in flood perception across subgroups. This result is consistent with previous research showing that flood visualizations are effective at building a shared knowledge about flooding (e.g., Lane et al., 2011; Maskrey et al., 2016; Wilkinson et al., 2015); however, it provides new evidence that fine details matter. In particular, we encountered skepticism about flood maps when residents were unable to magnify the map down to street-level details.
3. Actionable flood hazard information was produced by collaborative flood modeling. This builds on a limited number of previous studies that successfully apply this co-production paradigm with flood simulation tools and geographical information systems (e.g., Evers et al., 2012; Luke et al., 2018; Wilkinson et al., 2015). However, here we observe and report the adoption of maps and models for decision-making—strong evidence that the outcomes of collaborative flood modeling are actionable.
4. Both similarities and differences in mapping needs emerged from collaborative flood modeling at two coastal sites with different dominant flood drivers. At both sites, end-users valued flood depth maps corresponding to the 1% annual chance flood event, the regulatory standard in the United States. However, at the Newport Bay site dominated by high tide and wave-driven flooding, end-users requested maps depicting both present and future flood hazards (e.g., accounting for sea level rise). On the other hand, at the Tijuana River Valley site dominated by river flooding, end-users requested maps related to the velocity of flooding to assess flood forces (which bear on safety) and shear stresses (which bear on erosion management).
5. Use of technical terminology in collaborative flood modeling, and especially statistical concepts such as confidence levels, was disruptive of productive dialogue and discussion about flooding among end-users. Flood hazard maps can and should be presented to end-users with plain language such as “1% annual chance flood depth” even when the methods of statistical analysis and hydrodynamic modeling used

to make the map are far from simple (e.g., Moftakhari et al., 2019). Additionally, flood maps depicting historical flooding events are advantageous for productive, nontechnical dialogue aimed at reducing flood vulnerabilities.

6. Collaborative flood modeling aligns with the strategic plans of FEMA to support local leadership of FRM, creating a process for local stakeholders to contemplate flooding, map risks in ways that align with local decision-making needs, and enhance deliberations over strategies and projects to manage risks. It can be thought of as a bottom-up alternative to what has become a top-down process of flood hazard mapping that is limiting important dialogue about flooding (Soden et al., 2017) and prone to significant errors (NRC 2009, Wing et al., 2017, NASEM 2019).

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