EPiC Series in Engineering
Volume 3, 2018, Pages 1851–1858
HIC 2018. 13th International Conference on Hydroinformatics

Tapping the power of shallow-water models for flood hazard mapping

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Abstract. Advances in shallow-water modeling and high performance computing, combined with the increasing availability of fine scale geospatial data, now makes it possible to simulate flooding at spatial and temporal scales comparable to how people experience flooding. This poses enormous opportunities to improve the targeted communication of flood risks and accelerate adoption of vulnerability reduction measures. Here we present collaborative shallow-water modeling of flood hazards with end users, which results in hazard maps tailored to local decision-making needs and poised to reduce flood vulnerability within at risk communities.

Keywords: end users, flooding, flood map, shallow-water modeling

1 Introduction

Shallow-water flood models offer untapped potential to address the alarming escalation of flooding impacts [1]. Shallow-water models can resolve flooding at fine spatial scales of 1 to 5 m and account for obstructions [2] and formal drainage infrastructure [3]. Many numerical methods based on different forms of the shallow-water equations have been developed to describe the movement of flood water, each with different advantages and disadvantages that depend on flooding dynamics (e.g., unsteadiness, Froude number variability, wetting and drying), but none strong enough to produce one undeniably superior approach [1,4]. Recent research has focused on speeding up model execution through parallel computing [5-7] and upscaling with subgrid models (also called porosity models) that account for the bulk effect of fine-scale features with relatively coarse computational cells [8-12]. Upscaling is especially promising because computational costs decrease by a factor of 8, and memory costs by a factor of 4, with every factor of two increase in computational cell size [5, 9]. HEC-RAS 5.0 supported by the U.S. Army Corps of Engineers now makes the upscaling method of Casulli and Stelling [10] readily available for practical applications. However, caution is warranted because upscaling causes a loss of accuracy compared with models that resolve flow at DEM resolution or unstructured grid models that selectively refine important topographic features that control the spreading of flood water [13]. Hence, a key consideration is the level of accuracy that is needed and the significance of grid resolution uncertainty compared to other sources of uncertainty [14]. This motivates the following important question: what exactly are end-user needs for flood hazard information? Meyer et al. [15] describe the involvement of end-users in the development of useful flood hazard maps for European countries. Australian authorities have also issued guidelines for flood hazard mapping with 2D models [16]. In the U.S., however, flood hazard mapping guidelines mainly apply to creation of Flood Insurance Rate Maps (FIRMs) that delineate flood hazard zones for the National Flood Insurance Program (NFIP). There are no general guidelines in the U.S. for leveraging the power of 2D shallow-water models to produce detailed information about flood depths and velocities and, in turn, guide decision-making to reduce the consequences of flooding. Here, we present the results of the FloodRISE project whereby metric resolution shallow-water models were applied with stakeholder involvement to create flood hazard visualizations for tcommunities in Newport Beach, California, San Diego California, and Tijuana, Mexico.

2 Methods and Materials

Newport Beach (NB) is characterized by an urbanized embayment where development on lowland topography is vulnerable to flooding from a combination of extreme high tides, waves, and rainfall. The Tijuana River Valley (TRV) in San Diego California consists of a mix of open spaces that offer riparian and estuarine wetland habitat and residential properties on large lots that often include equestrian amenities. The TRV is vulnerable to flooding from high flows down the Tijuana River, from lateral inflows draining from local catchments, and from extreme high tides and waves. Los Laureles Canyon (LLC) in Tijuana, Mexico consists of steep topography that is densely developed. With limited oversight and control of construction practices and soil conservation, considerable erosion and flooding results from intense rainfall.

The ParBreZo hydrodynamic model [5] was used for flood hazard modeling at all three sites. ParBreZo solves the two-dimensional shallow-water equations on an unstructured grid of triangular and/or quadrilateral cells using a Godunov-type finite volume schemes capable of resolving sub-critical, super-critical and trans-critical flows with sharp fronts. At all three sites, the ParBreZo model was configured with a model domain that encompassed areas vulnerable to flooding, and ParBreZo internal and external boundary conditions were specified using data or models of the flood drivers. Hence, flooding is simulated as a time-dependent and spatially distributed process to realistically capture how one would experience flooding during an extreme event. Flooding can result from many different combinations of flood drivers (rainfall, streamflow, extreme high tides, waves), so there are countless ways in which flood model scenarios can be configured to inform and stimulate two-way dialogue about flooding. Two types of scenarios were utilized here: historical scenarios and probabilistic scenarios. To model historical scenarios, contemporaneous measurements or models of flood drivers were used as boundary conditions for the model including measurements from nearby tide gages, wave gages, stream gages and rainfall gages. Probabilistic modeling scenarios, on the other hand, required boundary conditions representative of a specific return period (e.g., 20 year event). This is challenging in the coastal zone where flooding can occur as the result of combinations of multiple extreme and non-extreme flood drivers that may or may not be independent [17]. Luke et al. [18] describe the approach that was developed and used in the FloodRISE project. Once simulations were completed for all important drivers, results were synthesized in a post-processing step to create a single flood hazard visualization representative of the chosen return level and to create a visualization of the annual probability of flooding of at least ankle depth water.

There were four phases of stakeholder engagement resulting in the evolution of flood hazard maps to meet end-user needs: (1) Meetings with Authorities – Resulting in Version 1 Flood Hazard Maps, (2) Household Surveys – Resulting in Version 2 Flood Hazard Maps, (3) Focus Group Meetings– Resulting in Version 3 Flood Hazard Maps and (4) Training Sessions and Outreach. The first phase of engagement focused on collecting system data (e.g., topography, flood defenses) and two-way communication between modelers and local authorities about flooding to establish a baseline flood hazard model that captured important flooding mechanisms and accounted for important flood drivers (e.g., rainfall, streamflow, extreme high tides). The second phase of engagement focused on testing the interest in, and usability of, metric resolution flood hazard visualizations among the general public. This provided useful feedback on details such as color schemes and legends, and the limitations of digital communications among segments of the population (e.g., elderly) who infrequently use computers. The third phase of engagement targeted end-users of flood hazard information including planners, public works officials, emergency response personnel, business owners, non governmental organizations, and residents and lead to changes in proposed flood hazard maps (e.g., legends, descriptions, flooding scenario) as well as the creation of new flood hazard maps had not previously been conceived by the modeling team. To facilitate access and allow users to toggle between maps, pan and zoom, an on-line flood hazard map viewer was prepared for each site using ArcGIS Online (ESRI, Redlands, California). In the fourth phase of engagement, training sessions were held at a computer laboratory where end-users were guided through available information on the flood hazard viewer.

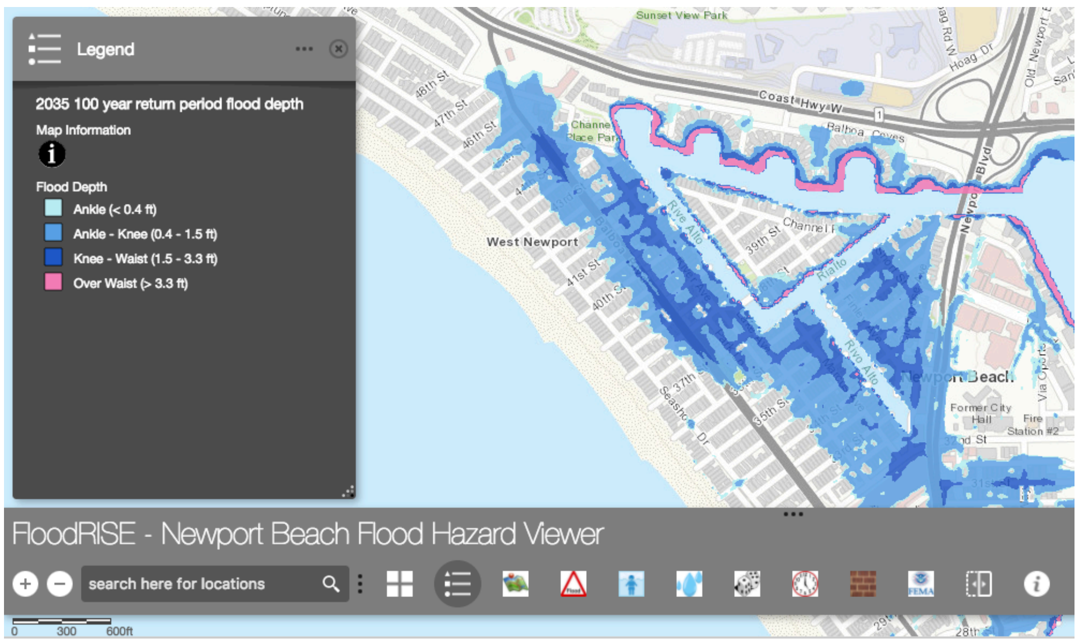

Figure 1 Newport Beach flood hazard viewer configured to show the 100-year return period flood depth with an intuitive body scale while accounting for multiple flood drivers (extreme high tides, waves, precipitation). Additional flood hazard maps for Newport Beach are available online (bit.ly/floodrisenb).

3 Results

FloodRISE flood hazard viewers display flood hazard maps for NB (bit.ly/floodrisenb), TRV (bit.ly/floodrise_TRV) and LLC (bit.ly/floodrisell). Numerous flood hazard maps were produced including maps of flood depth, maps of the product of depth and velocity which serves as a proxy for flood force, maps of shear stress which bears on erosion potential, maps of flood duration, and maps of flood probability. The viewers for NB, TRV and LLC hosted a total of 27, 14, and 14 flood hazard maps, respectively, and one example is shown here. Figure 1 shows map of the Year 2035 flood depth corresponding to a 100-year return period. Note here the use of a body scale which was developed to communicate the flood hazard in an intuitive way, as well as a quantitative scale. An outcome of the focus group meetings was the need for both qualitative and quantitative scales of flood hazard information. Note also that the predicted flood depth accounts for multiple flood drivers (extreme high tides, waves, and precipitation), but the presentation is not unnecessarily complicated in response to the complexity of methods.

Management of erosion and sediment is a major challenge in TRV and this is reflected in the production of a flood hazard map depicting maximum shear stresses using both a quantitative scale and qualitative scale corresponding to the consequence of the shear. Figure 2 shows a map of shear stress corresponding to a historical flood event, one that occurred n 1983 amidst a strong El Nino. Use of a historical event to depict the hazard is one of several options provided by the viewer, in addition to two specific return periods (5-year and 100-year events). Interaction with stakeholders reinforced the fact that communication of probabilities and return periods, while common among engineers, poses challenges that can be overcome by presenting historical events that are often more easily relatable among diverse end users of flood hazard information.

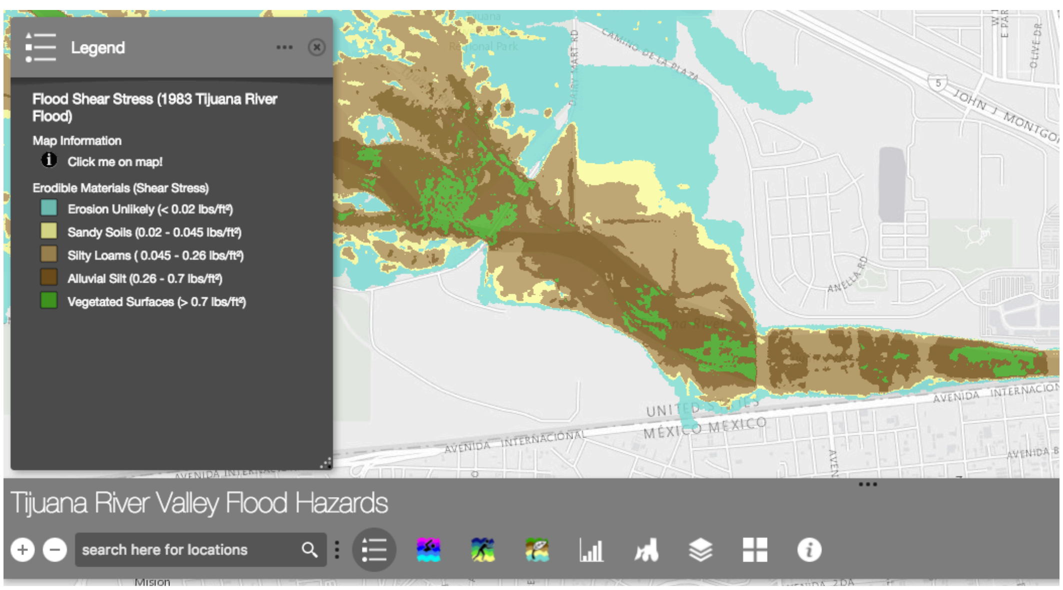

Figure 2. Tijuana River Valley flood hazard viewer configured to show shear stresses using both a quantitative scale and a qualitative scale that informs the susceptibility to erosion. The viewer displays both historical flood events and engineering design scenarios (e.g., 100-year return period) to make the information useful to multiple end-users. Additional flood hazard maps for Tijuana River Valley are available online (bit.ly/floodrise_TRV).

Safety is a major concern in LLC due to the potential for erosion and fast moving flood waters. Figure 3 shows a map of flood force with both a quantitative and qualitative scale corresponding to consequences. This is a good example of the power of fine scale shallow-water models to depict hazardous conditions that can develop along streets as a result of intense rainfall, here equal to a rainfall depth of 100 mm which corresponds to a 100-year return period event. End-users stated a strong preference for naming these maps based on the amount of rainfall, and not the probability, because the former is much more easily understood during extreme events based on weather reports. More detail about the preferences of end-users in TRV and LLC for scenarios and mapping styles are reported in Luke et al. [18].

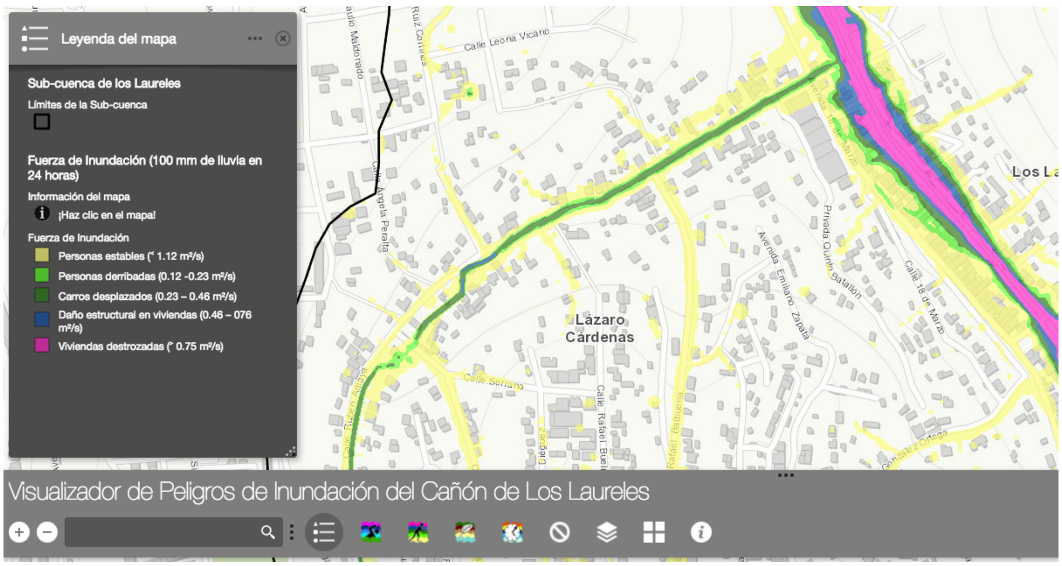

Figure 3. Los Laureles Canyon flood hazard viewer configured to show flood force using both a quantitative scale (product of depth and velocity) and a qualitative scale that indicates consequences. Additional flood hazard maps for Los Laureles Canyon are available online (bit.ly/floodrisell).

4 Conclusions

The FloodRISE project achieved two-way communication about flooding, between modeling experts and local stakeholders, through the process of shallow-water modeling and this resulted in flood hazard maps that meet end-user needs and preferences for information. Several examples of context-sensitive decision-support are shown herein, which validates the potential of the method to succeed under varied environmental and social conditions. The Godonov-based finite volume scheme used here to solve the shallow-water equations proved versatile based on its ability to resolve slow moving subcritical flow on relatively flat topography, supercritical and transcritical flows that occur on steep topography, and extensive wetting and drying associated with the rising and falling limbs of floods.

The Godonov-based finite volume scheme used here to solve the shallow-water equations proved highly versatile based on its ability to resolve slow moving subcritical flow on relatively flat topography, supercritical and transcritical flows that occur on steep topography, and extensive wetting and drying associated with the rising and falling limbs of floods. Furthermore, sub-grid models were not applied in this study because of: (a) interest in predicting localized velocities as accurately as possible (Guinot et al. 2016), (b) concern about flood extent over-prediction bias (Hodges 2015), and (c) sufficient computational resources to resolve important flow paths with a carefully constructed unstructured grid model.

Acknowledgements

This research was made possible by a grant from the National Science Foundation (Grant #DMS-1331611), who support is gratefully acknowledged. The research team is also indebted to many community stakeholders and support staff who contributed time and energy to this project.

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