Reviewer 1:

Fuchs:

Comment 1:

On page 2, lines 2 ff. the authors state that "Insured losses from natural disasters have been increasing globally (Munich Re, 2005), largely from the growing exposure and value of vulnerable assets (Bouwer, 2011)." – The authors should be aware that this is generally undoubtable, however, exposure (and associated vulnerability) is subject to considerable spatial (and temporal) variation, as for example shown for European mountain regions by Fuchs et al. (2015; 2017) [and please be aware that I am not providing these sources to press you for more citations, which would be against good scientific practice and is not in line with the rules of NHESS]. From my point of view it is just important to be a bit careful with these general statements since the question of growing exposure is a tricky one in areas with limited development space, and given certain political incentives for land development.

Author's Response:

Thank you for your perspective on the complex issue of growing losses from natural disasters. In the revised version, we acknowledge that the cause of growing exposure is not simple:

Authors' changes to manuscript:

Insured losses from natural disasters have increased globally \citep{re2005topics}, and while the causes of growing losses are complex and debatable, the increasing exposure and value of capital at risk has undoubtedly played a major role \citep{bouwer2011have}. Exposure to flooding is particularly acute in the United States (US), where a combination of subsidized flood insurance and homeowner tax incentive has actually encouraged risky development in floodplains and coastal zones \citep{bagstad2007taxes}.

Comment 2:

- The authors may wish to access the EU flood directive in more detail. As stated on page 2, lines 20 ff., they argue that "In the European Union (EU), member countries are under a mandate to develop national flood hazard maps, and general guidelines for meeting enduser needs have been developed based on participatory processes". In contrast, the EU Floods Directive explicitly focuses on flood RISK maps (on various scales and focusing on different hazard scenarios), leading finally to flood risk management plans. Therefore, it is not only the hazard information that should be communicated, but information on risk. The Directive is attached as a supplement.

Author's response:

Thank you for providing the Directive – we will address the purpose of the Directive more explicitly in the revised version:

Author's changes to manuscript:

Flood hazard maps are the most commonly used tool for flood risk communication and management. In the European Union (EU), member countries are under a mandate to develop national flood hazard maps, flood risk maps, and FRM plans based upon the mapped information \citep{directive}.

Comment 3

- Authors should carefully check their reference list; multiple-author sources are cited differently

Author's Response

Bibliography has been updated to remove multiple entries of " Flood maps in Europe- methods, availability, and use".

Reviewer 2:

Dotorri:

Comment 1

My only (moderate) remark is the lack of a discussion regarding the uncertainty of flood hazard maps and how uncertainty can be communicated to end-users. At page 20, lines 10-12, the Authors state that "... flood probabilities and corresponding frequency are inherently uncertain...". While I fully agree with such a statement, the same can be said for all the hazard variables included in flood hazard maps. To give an example: even if the use of historical flood events as reference may reduce uncertainty, not all the original boundary conditions may be determined with precision (e.g. river channel morphology or rainfall distribution). Please note that this is not a criticism to the methodology, which is in my opinion up to the current state of the art. However, it would be interesting to know how the accuracy (and the uncertainty) of the hazard maps is perceived by end-users: For instance, what is the precision assumed by end users for the numerical variables (e.g. +/- 10 cm for flood depths)? Does this value agree with the precision expected by the Authors? How did the Authors communicated the assumptions used for flood simulations? If these topics were not addressed within the focus groups, maybe the authors could still include them in the discussion.

Author's response

Thank you for commenting on this important issue. While we did not explicitly address this issue in the focus groups, the discussion now includes a paragraph on uncertainty and the conclusion section has been updated as follows:

Author's Changes to Manuscript:

It is our opinion that least emphasis should be given to the probability when describing mapped flooding scenarios. Not only are concrete references preferred for describing flood risk \citep{bell2007efficient}, but flood probabilities and corresponding frequencies are highly uncertain \citep[e.g. Appendices \ref{RIVER_FFA} - \ref{RAIN_FFA},][]{di2010flood, kjeldsen2014uncertainty,merwade2008uncertainty,merz2008flood,stedinger2008flood}. Indeed, all hazard variables illustrated in flood maps are inherently uncertain, however it is remarkable that perhaps the most uncertain and complex characteristic of floods is also the primary descriptor.\par

Uncertainties associated with flood mapping products are rarely quantified let alone communicated, and in this study, we did not address the important issue of communicating uncertainty in flood maps to end-users. In one of the few studies that has explicitly addressed communicating uncertainty in the FEMA FIRMs' floodplain boundaries, \citet{soden2017thin} showed that providing end-users with contrasting information (i.e. the 1\% AEP flood extent versus an observed flooding extent) led to important flood hazard discourse and curiosity regarding flood mapping methodology. While it may seem counterproductive to purposefully expose the limitations of floodplain delineation, such innovative communication strategies force end-users to confront the deterministic standards that our institutions require for regulatory purposes. Confrontation with the limits of science promotes contemplation and is certainly worth further investigation in the context of flood hazard mapping and communication.\par

…

Online formats offer the opportunity for causal experiments - do different hazard variables make a user more (or less) likely to seek vulnerability reduction measures? How do different presentations of uncertainty in mapped data influence end-users' desire to seek further information? These questions could be answered with so called ``A/B'' testing, where subjects are presented different web pages and their interactions on the web site are recorded.

Comment 2

What is the extent of the two areas analyzed in the paper? Does the extent correspond to the areas shown in Figure 1A and 1C, or are these just a sample of the areas?

Author's Response:

The extent of the area analyzed in the paper includes the Los Laureles catchment in Figure 1A and the Tijuana River Valley shown in Figure 1C.

Comment 3

This is not completely correct. Even if pluvial flood hazard is not explicitly mentioned in the EU Floods Directive, several European countries did include pluvial floods in their national risk assessment, as it was considered a relevant component of the overall flood risk. For more details, please see the reports regarding the status of the implementation of the Floods Directive and available here: http://ec.europa.eu/environment/water/flood_risk/overview.htm

Author's Response:

Thank you for bringing this to our attention!

Author's Changes to Manuscript

Neither European, Australian, nor US flood mapping guidelines explicitly require or recommend maps characterizing pluvial flood hazard, which were of keen interest to both LL and TRV end-users. However, many EU member states have included pluvial flood hazard assessments in response to the Floods Directive \citep{directive_response}. The Australian technical guidelines for engineers allude to direct rainfall models that can be used to produce pluvial hazard maps \citep{aussie_RR}, but because these techniques are relatively new, guidance documents do not require the production of maps depicting the pluvial hazard or intense storm-water runoff. Since techniques for estimating pluvial hazards continue to advance, formal guidelines and requirements for mapping the pluvial hazard zone should be developed, especially in the US. As demonstrated by end-user requests in this study - and the largely pluvial nature of the flooding disaster caused by Hurricane Harvey in the US - pluvial flooding can dominate in urban areas and needs to be considered in future mapping efforts. \par

Going beyond the Flood Insurance Rate Map: insights from flood hazard map co-production

Adam Luke[1], Brett F Sanders[1,2], Kristen Goodrich[3], David L Feldman[2], Danielle Boudreau[4], Ana Eguiarte[4], Kimberly Serrano[5], Abigail Reyes[5], Jochen E Schubert[1], Amir AghaKouchak[1], Victoria Basolo[2], and Richard A Matthew[2]

[1]Department of Civil and Environmental Engineering, University of California, Irvine, CA, USA
[2]Department of Urban Planning and Public Policy, University of California, Irvine, CA, USA
[3]School of Social Ecology,University of California, Irvine, CA, USA
[4]Tijuana River National Estuarine Research Reserve, Imperial Beach, CA, USA
[5]Sustainability Initiative, University of California, Irvine, CA, USA

Correspondence to: Adam Luke (aluke1@uci.edu)

Abstract. Flood hazard mapping in the United States (US) is deeply tied to the National Flood Insurance Program (NFIP). Consequently, publicly available flood maps provide essential information for insurance purposes, but do not necessarily provide relevant information for non-insurance aspects of flood risk management (FRM) such as public education and emergency planning. Recent calls for flood hazard maps that support a wider variety of FRM tasks highlight the need to deepen our understanding about the factors that make flood maps useful and understandable for local end-users. In this study, social scientists and engineers explore opportunities for improving the utility and relevance of flood hazard maps through the co-production of maps responsive to end-users' FRM needs. Specifically, two-dimensional flood modeling produced a set of baseline hazard maps for stakeholders of the Tijuana River Valley, US, and Los Laureles Canyon in Tijuana, Mexico. Focus groups with natural resource managers, city planners, emergency managers, academia, non-profit, and community leaders refined the baseline hazard maps by triggering additional modeling scenarios and map revisions. Several important end-user preferences emerged, such as 1) legends that frame flood intensity both qualitatively and quantitatively, and 2) flood scenario descriptions that report flood magnitude in terms of rainfall, streamflow, and its relation to an historic event. Regarding desired hazard map content, end-users' requests revealed general consistency with mapping needs reported in European studies and guidelines published in Australia. However, requested map content that is not commonly produced included: 1) standing water depths following the flood, 2) the erosive potential of flowing water, and 3) *pluvial* flood hazards, or flooding caused directly by rainfall. We conclude that the relevance and utility of commonly produced flood hazard maps can be most improved by illustrating pluvial flood hazards and by using concrete reference points to describe flooding scenarios rather than exceedance probabilities or frequencies.

1 Introduction

Management of flooding is a major societal challenge that is only expected to worsen ~~in the future~~ due to several trends including population growth and urbanization (Sundermann et al., 2014), sea level rise (Hallegatte et al., 2013), intensification

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~~of precipitation~~ extremes (Lenderink and Van Meijgaard, 2008; Coumou and Rahmstorf, 2012), and the compounding effects of sea level rise and terrestrial flooding (Moftakhari et al., 2017). Insured losses from natural disasters have ~~been increasing globally (Munich Re, 2005), largely from the growing exposure and value of vulnerable assets (Bouwer, 2011). Losses from hurricanes and floods in the United States~~ (US) have tripled over the past fifty years (Gall et al., 2011), and the National Flood Insurance Program (NFIP) is operating at a deficit of about \$1 billion annually with a debt of over \$20 billion owed to the US treasury before considering insured losses from the 2017 hurricane season (Pasterick, 1998; Brown, 2016). In fact, properties insured by the NFIP represent the second largest liability of the US federal government after the Social Security program (Gall et al., 2011).

The American Society of Civil Engineers (ASCE) has called for a national strategy to address the escalation of flood losses and threats to public safety, but reports that the US public and policy makers have been unwilling to take action despite major hurricanes such as Katrina and Sandy (Traver, 2014). The ASCE directive aligns with a global paradigm shift in management philosophy away from *flood control* and towards *flood risk management*. Flood risk management (FRM) refers to a portfolio of approaches for reducing risk that is not limited to controlling flood waters with engineered structures, but also includes effective land use planning, emergency response, and personal preparedness. Importantly, FRM accepts that absolute protection is not possible. Comprehensive FRM reduces the reliance on engineered flood defenses, which is of paramount importance in the US due to the marginal condition of levees and lack of federal resources available for maintenance and necessary upgrades (Traver, 2014). Studies have shown that robust FRM does indeed lead to significant reductions in fatalities and monetary losses (Kreibich et al., 2017, 2005), however Traver (2014) and Merz et al. (2007) both report that effectively implementing FRM relies on stakeholders who understand their exposure and also have access to tools that are useful for managing personal, household, and community risks.

Flood hazard maps are the most commonly used tool for flood risk communication and management. In the European Union (EU), member countries are under a mandate to develop national flood hazard maps, ~~and general guidelines for meeting end-user~~ needs have been developed based on participatory processes (Meyer et al., 2012; Hagemeier-Klose ~~and Wagner, 2009; Martini and Loat, 2007). Guidelines~~ reflect the varying needs of different end-users for different types of information, as well as the need for context-sensitive information. For example, Meyer et al. (2012) present distinctions between the mapping needs for strategic planning personnel, emergency management personnel and the public, and show that geographical factors (e.g., mountains, polders) influence the need for velocity data.

In the US, flood mapping is tied to the NFIP and the resulting Flood Insurance Rate Maps (FIRMs) delineate the spatial extent of inundation with a 1% and 0.2% annual exceedance probability (AEP). As a vehicle designed to administer an insurance program, the FIRM provides essential information for insurance purposes. Properties with federally backed mortgages located within the 1% AEP floodplain are required to purchase flood insurance, while the flood elevations associated with the FIRM are used for insurance underwriting. However, the binary “in or out” floodplain designation by the FIRMs’ *thin grey lines* have been criticized for presenting flood risk as definitive and therefore discouraging important flood hazard discourse (Soden et al., 2017). Burby (2001) also suggests that the effectiveness of the NFIP is limited because FIRMs lack information necessary to integrate flood hazard considerations into local planning. The Federal Emergency Management Agency (FEMA) has recently extremes (Lenderink and Van Meijgaard, 2008; Coumou and Rahmstorf, 2012), and the compounding effects of sea level rise and terrestrial flooding (Moftakhari et al., 2017). Insured losses from natural disasters have increased globally (Munich Re, 2005), and while the causes of growing losses are complex and debatable, the increasing exposure and value of capital at risk has undoubtedly played a major role (Bouwer, 2011). Exposure to flooding is particularly acute in the United States (US), where a combination of subsidized flood insurance and homeowner tax incentive has actually encouraged risky development in floodplains and coastal zones (Bagstad et al., 2007). Losses from floods and hurricanes in the (US) have *tripled* over the past fifty years (Gall et al., 2011), and the National Flood Insurance Program (NFIP) is operating at a deficit of about $1 billion annually with a debt of over $20 billion owed to the US treasury before considering insured losses from the 2017 hurricane season (Pasterick, 1998; Brown, 2016). In fact, properties insured by the NFIP represent the second largest liability of the US federal government after the Social Security program (Gall et al., 2011).

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The European handbook (Martini and Loat, 2007) states the title of the map should include the hazard parameter and probability, while the FEMA FIRM describes hazard zones by AEPs only (i.e. Fig. 2). Yet there is increasing evidence that these descriptions are ineffective. Relatively little guidance is provided regarding the map legends as well, which is another important aspect of communicating the mapped hazard. Legends are either completely described by numerical values (i.e. depth of flooding in meters or feet) or a qualitative flood severity zone described by terms such as “low” to “severe” (FEMA, 2014). We recommend that future mapping guidance documents provide advice for different ways to communicate the mapped hazard scenario and more complete legend descriptors. Alternatives supported by this study include 1) providing qualitative and quantitative scales, and 2) describing flooding scenarios by the flood magnitude (in corresponding scientific units), the magnitude relative to an historic event, and finally the probability of the flood. The magnitude and probability of the flood provides relevant information for technical end-users, while the magnitude related to an historic event is a tangible reference point for lay-persons. It is our opinion that *least emphasis* should be given to the probability when describing mapped flooding scenarios. Not only are concrete references preferred for describing flood risk (Bell and Tobin, 2007), but *flood probabilities and corresponding* ~~*frequency* are inherently~~ uncertain (e.g. Appendices A1.1 - A1.3, Di Baldassarre et al., 2010; Kjeldsen et al., 2014; Merwade et al., 2008; Merz and Blöschl, 2008; Stedinger and Griffis, 2008).

Regarding desirable content of flood hazard maps, stakeholder preferences from this study also align with previous work. Meyer et al. (2012) concluded that maps presenting flood hazards at different probabilities is required, velocity information should be provided when available, and the location of flood defenses and access routes should be integrated within the hazard map. All of these recommended contents were requested by the TRV and LL end-users. Hagemeier-Klose and Wagner (2009) also noted the importance of mapping more frequent events than the 1% AEP flood, which was strongly supported by the results of the survey (Fig. 6). Thus, this study demonstrates consistency between the desired map content of end-users studied in the US, Mexico, and Europe. Flood mapping guidelines in Europe (~~Van Alphen et al., 2009;~~ Martini and Loat, 2007) and Australia (AEMI, 2013) generally recommend producing this desired content. Guidelines either recommend or require the production of hazard maps associated with different probabilities and even infrastructure failure scenarios. Mapped data includes flooding extent, depths, velocities, and the depth-velocity product, while some studies even provide shear stresses ~~(Martini and Loat, 2007). Specific~~ guidance is also provided for producing maps that support the FRM activities of distinct European and Australian end-user groups.

Meanwhile in the US, flood mapping guidelines are fairly extensive and standardized for producing the FEMA FIRM only (FEMA, 2016). There is a lack of guidance and direction available for producing flood hazard maps that support non-insurance aspects of FRM, such as those specifically requested by end-users in this study. The required “non-regulatory” data products of recent FEMA Risk MAP studies (FEMA, 2014) have significant potential to support an expanded portfolio of actionable flood hazard maps in the US. For example, the required velocity grids in Risk MAP studies can be post-processed to produce erosion potential maps, while the required “flood severity grid” contains the depth-velocity data necessary for products designed to support emergency response. We recommend that future FEMA guidelines provide specific directives for producing ~~non-regulatory~~ flood hazard maps tailored to specific FRM objectives including land-use planning, emergency management, and public awareness. The content of flood hazard maps should also be expanded to include pluvial flood hazards when appropriate.

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Uncertainties associated with flood mapping products are rarely quantified let alone communicated, and in this study, we did not address the important issue of communicating uncertainty in flood maps to end-users. In one of the few studies that has explicitly addressed communicating uncertainty in the FEMA FIRMs’ floodplain boundaries, Soden et al. (2017) showed that providing end-users with contrasting information (i.e. the 1% AEP flood extent versus an observed flooding extent) led to important flood hazard discourse and curiosity regarding flood mapping methodology. While it may seem counterintuitive to purposefully expose the limitations of floodplain delineation, such innovative communication strategies force end-users to confront the deterministic standards that our institutions require for regulatory purposes. Explicit confrontation with the limits of science promotes contemplation and is certainly worth further investigation in the context of flood hazard mapping and communication.

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Neither European, Australian, nor US flood mapping guidelines require or recommend maps characterizing pluvial flood hazard, which were of keen interest to both LL and TRV end-users. ~~The Australian technical guidelines~~ for engineers allude to direct rainfall models that can be used to produce pluvial hazard maps (McCowan, 2016), but because these techniques are relatively new, guidance documents do not require the production of maps depicting the pluvial hazard or intense storm-water runoff. Since techniques for estimating pluvial hazards continue to advance, formal guidelines and requirements for mapping the pluvial hazard zone should be ~~developed.~~ As demonstrated by end-user requests in this study - and the largely pluvial nature of the flooding disaster caused by Hurricane Harvey in the US - pluvial flooding can dominate in urban areas and needs to be considered in future mapping efforts.

7 Conclusions and Future Directions

Two-dimensional (2D) flood hazard models developed for the Tijuana River Valley (TRV) and Los Laureles (LL) on both sides of the US-Mexico border supported the co-development of flood hazard maps responsive to end-user management needs. 2D modeling by engineers produced a set of baseline maps that were further refined through end-user focus groups that triggered additional modeling scenarios and map revisions.

This study revealed general consistency between the mapping needs of studied end-users in the US and Mexico with those reported in European studies and guidelines published in Australia. For example, mapping requests included scenarios with different probabilities and even infrastructure failure scenarios, and end-users also requested maps of hazard variables beyond traditional flood extent, such as velocities and standing water. This study also revealed several important flood hazard mapping requests relevant to other sites:

- Flood intensity scales (e.g., depth, force or shear stress) that frame the mapped information both quantitatively and qualitatively. The quantitative scale meets end-user needs for a technical reference point, while the qualitative scale meets end-user needs to easily interpret the mapped information.
- Flood scenario descriptions that report both the magnitude of the flood in terms of rainfall or streamflow amounts and also the flood magnitude relative to an historic event. Use of concrete scenario descriptions increases the utility and relevance of mapped information across different end-users of flood hazard maps.
- Flood hazard maps that depict the erosion potential of flood waters. Erosion potential maps support end-user needs for managing sediment.
- Flood hazard maps that depict standing water following the flood. Standing water maps support recovery planning and public health concerns.
- Flood hazard maps that depict storm-water runoff or pluvial flood hazards. Baseline flood hazard maps depicted *fluvial* flooding hazards only, and after end-user focus groups revealed a deficiency in usefulness, the need for a pluvial flood

guidance is also provided for producing maps that support the FRM activities of distinct European and Australian end-user groups.

Meanwhile in the US, flood mapping guidelines are fairly extensive and standardized for producing the FEMA FIRM only (FEMA, 2016). There is a lack of guidance and direction available for producing flood hazard maps that support non-insurance aspects of FRM, such as those specifically requested by end-users in this study. The required “non-regulatory” data products of recent FEMA Risk MAP studies (FEMA, 2014) have significant potential to support an expanded portfolio of actionable flood hazard maps in the US. For example, the required velocity grids in Risk MAP studies can be post-processed to produce erosion potential maps, while the required “flood severity grid” contains the depth-velocity data necessary for products designed to support emergency response. We recommend that future FEMA guidelines provide specific directives for producing non-regulatory flood hazard maps tailored to specific FRM objectives including land-use planning, emergency management, and public awareness. The content of flood hazard maps should also be expanded to include pluvial flood hazards when appropriate.

Neither European, Australian, nor US flood mapping guidelines explicitly require or recommend maps characterizing pluvial flood hazard, which were of keen interest to both LL and TRV end-users. However, many EU member states have included pluvial flood hazard assessments in response to the Floods Directive (Nixon et al., 2015). The Australian technical guidelines for engineers allude to direct rainfall models that can be used to produce pluvial hazard maps (McCowan, 2016), but because these techniques are relatively new, guidance documents do not require the production of maps depicting the pluvial hazard or intense storm-water runoff. Since techniques for estimating pluvial hazards continue to advance, formal guidelines and requirements for mapping the pluvial hazard zone should be developed, especially in the US. As demonstrated by end-user requests in this study - and the largely pluvial nature of the flooding disaster caused by Hurricane Harvey in the US - pluvial flooding can dominate in urban areas and needs to be considered in future mapping efforts.

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hazard modeling approach was recognized and implemented. Characterizing pluvial flood hazards is extremely important for urbanized sites with poor drainage.

Of course, the stakeholder preferences herein must be viewed cautiously, since focus group participants do not represent all end-users of flood hazard data. The primary limitation of this study is the limited number of focus group participants (55 total) and narrow geographic scope. Co-production efforts via focus groups acknowledge that community-level knowledge (and mapping preference) varies from locality-to-locality, underscoring how flood hazard knowledge should not be a "one-directional" process but an iterative learning approach that breaks down information gaps between experts and lay users in specific places - thus improving risk communication at the local level. They also produce actionable mapping information useful for reducing flood risks (Spiekermann et al., 2015; Moel et al., 2009). Indeed, restricted sample size and geographic scope is a common caveat of flood communication and mapping preference studies (e.g Hagemeier-Klose and Wagner (2009); Meyer et al. (2012)).

In future studies, sample size limitations may be overcome by taking advantage of online information systems to present flood hazard data. Online formats ~~also offer the opportunity for causal experiments - does the presentation of mapped hazard data~~ make a user more (or less) likely to seek vulnerability reduction measures? ~~This question could be answered with so called "A/B" testing, where~~ subjects are presented different web pages and their interactions on the web site are recorded. Our current knowledge of flood mapping preferences and hazard perceptions is based upon empirical studies with relatively small samples (Kellens et al., 2013). What can "big data" tell us about how end-users respond to, and interact with, flood hazard ~~maps?~~

While online information systems offer avenues for new research, they also provide a medium for presenting an expanded portfolio of hazard maps. Relative to the EU and Australia, flood mapping practice in the US has the greatest opportunity for expansion. Funding for flood mapping in the US remains limited (Traver, 2014), however it is relatively inexpensive to produce additional mapping products from models that are already used to produce Flood Insurance Rate Maps. Furthermore, the availability of free 2D hydraulic modeling software (HEC-RAS 5.0) and increasing abundance of metric resolution topographic data provides practitioners with the means to produce flood hazard data that was previously cost-prohibitive (Sanders, 2017). While flood mapping methods and data continue to improve - additional criteria must also be addressed to provide ~~decision-~~makers and citizens with actionable information. To be actionable, map information must help decision-makers: 1) ~~discern~~ vulnerability of properties from flooding; and, 2) select actions that mitigate or reduce this vulnerability (Demeritt and Nobert, 2014; McNutt, 2016; Feldman et al., 2008). By fully utilizing flood modeling technologies and ~~mechanisms for incorporating local knowledge in the mapping process, flood hazard maps can~~ support first responders, natural resource managers, and local residents with the information necessary to manage and respond to flood hazards.

Data availability. The University of California's guidelines for maintaining the privacy and confidentiality of human subjects state that data obtained from human subjects should only be accessible on a "need to know" and "minimum necessary" standard. Thus, the transcripts of focus groups conducted in this study are not publicly available. If an interested researcher wishes to review transcripts, please contact the corresponding author with 1) data requests and 2) reasoning for requesting the data.

- Flood scenario descriptions that report both the magnitude of the flood in terms of rainfall or streamflow amounts and also the flood magnitude relative to an historic event. Use of concrete scenario descriptions increases the utility and relevance of mapped information across different end-users of flood hazard maps.

- Flood hazard maps that depict the erosion potential of flood waters. Erosion potential maps support end-user needs for managing sediment.

- Flood hazard maps that depict standing water following the flood. Standing water maps support recovery planning and public health concerns.

- Flood hazard maps that depict storm-water runoff or pluvial flood hazards. Baseline flood hazard maps depicted *fluvial* flooding hazards only, and after end-user focus groups revealed a deficiency in usefulness, the need for a pluvial flood hazard modeling approach was recognized and implemented. Characterizing pluvial flood hazards is extremely important for urbanized sites with poor drainage.

Of course, the stakeholder preferences herein must be viewed cautiously, since focus group participants do not represent all end-users of flood hazard data. The primary limitation of this study is the limited number of focus group participants (55 total) and narrow geographic scope. Co-production efforts via focus groups acknowledge that community-level knowledge (and mapping preference) varies from locality-to-locality, underscoring how flood hazard knowledge should not be a "one-directional" process but an iterative learning approach that breaks down information gaps between experts and lay users in specific places - thus improving risk communication at the local level. They also produce actionable mapping information useful for reducing flood risks (Spiekermann et al., 2015; Moel et al., 2009). Indeed, restricted sample size and geographic scope is a common caveat of flood communication and mapping preference studies (e.g Hagemeier-Klose and Wagner (2009); Meyer et al. (2012)).

In future studies, sample size limitations may be overcome by taking advantage of online information systems to present flood hazard data. Online formats offer the opportunity for causal experiments - do different hazard variables make a user more (or less) likely to seek vulnerability reduction measures? How do different presentations of uncertainty in mapped data influence end-users' desire to seek further information? These questions could be answered with so called "A/B" testing, where subjects are presented different web pages and their interactions on the web site are recorded. Our current knowledge of flood mapping preferences and hazard perceptions is based upon empirical studies with relatively small samples (Kellens et al., 2013). What can "big data" tell us about how end-users respond to, and interact with, flood hazard data?

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All of the hazard maps (and several not presented herein) are available to view on an interactive system found here:

FloodRISE (2017). Tijuana River Valley Flood Hazards. University of California, Irvine. https://bit.ly/floodrise_TRV

FloodRISE (2017). Los Laureles Flood Hazards. University of California, Irvine. https://bit.ly/floodrise_GC

Data that was used to create the hazard maps includes elevation, streamflow, ocean water level, and precipitation data. The elevation data is held by the County of San Diego and could be made available via requests to the corresponding author. The streamflow, water level, and precipitation data is available here:

International Boundary and Water Commission (1960 - 2006). Flow of the Colorado River and other Western Boundary Streams and Related Data. Department of State, USA. https://ibwc.gov/Water_Data/water_bulletins.html

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Appendix A: Flood Hazard Mapping Methodology

The flood hazard maps presented in this study resulted from three distinct tasks: flood frequency analysis (FFA), hydrologic and hydraulic modeling, and post-processing of model output. Generally speaking, FFA estimates the recurrence interval of rare flooding events, while hydrologic and hydraulic modeling predicts the hazards associated with simulated floods (depths, velocities, extents, etc.). In this study, post-processing methods are used to combine the results of multiple simulations onto a single map. The following sections outline our FFA, hydraulic modeling, and post-processing methods so that the interested modeler can produce the hazard maps presented herein.

A1 Flood Frequency Analysis

FFA is complicated in the coastal zone due to the multiple causes or “drivers” of flooding. In this study, we mapped flooding caused by extreme ocean levels, streamflow from the Tijuana (TJ) River, and precipitation over Los Laureles and Smuggler’s gulch watersheds (Fig. 1). The presence of multiple flood drivers often warrants a multivariate approach for FFA (Salvadori and De Michele, 2013). Under this approach, multivariate extreme value analysis (EVA) is used to estimate the probability of scenarios where multiple extremes occur simultaneously. However, we did not conduct multivariate EVA in this study because of the low correlation between flood drivers and the lack of emergent flood hazards caused by the joint occurrence of extremes.

Table 1 presents the Pearson’s correlation coefficient matrix between the flood drivers considered herein. The relatively low correlation is somewhat surprising but understandable. Extended periods of above average rainfall in the upper TJ River Watershed cause large streamflow events, whereas relatively short-lived coastal storm systems can elevate ocean water levels and lead to intense precipitation. The low correlation between flood drivers demonstrates that the simultaneous occurrence of extreme events would be especially rare. Perhaps more importantly, hydraulic model sensitivity analysis revealed that predicted flood depths, extents, and velocities are insensitive to the joint-occurrence of extremes in this system. For example, flood depths predicted by the hydraulic model are not sensitive to the downstream ocean level during large TJ River floods. The lack of flood mapping methods and data continue to improve - additional criteria must also be addressed to provide decision-makers and citizens with actionable information. To be actionable, map information must help decision-makers: 1) understand vulnerability of properties from flooding; and, 2) select actions that mitigate or reduce this vulnerability (Demeritt and Nobert, 2014; McNutt, 2016; Feldman et al., 2008). By fully utilizing flood modeling technologies and developing innovative communication strategies, flood hazard maps can more effectively support first responders, natural resource managers, and local residents with the information necessary to manage and respond to flood hazards.

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