AGU100 ADVANCING EARTH AND SPACE SCIENCE

Water Resources Research

COMMENTARY

10.1029/2018WR022828

What Is Nuisance Flooding? Defining and Monitoring an Emerging Challenge

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Key Points:

- Focus on extreme events has led to less attention given to nuisance (minor) floods (NF)
- We propose a process-based threshold applicable to regions with short periods of flood monitoring records
- This threshold is useful for characterizing the spatial distributions of flood severity

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Citation:
Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M., & Matthew, R. A. (2018). What is nuisance flooding? Defining and monitoring an emerging challenge. *Water Resources Research*, *54*, 4218–4227. https://doi.org/10.1029/2018WR022828

Received 22 FEB 2018
Accepted 16 MAY 2018
Accepted article online 25 MAY 2018
Published online 10 JUL 2018

Abstract Nuisance flooding (NF) refers to low levels of inundation that do not pose significant threats to public safety or cause major property damage, but can disrupt routine day-to-day activities, put added strain on infrastructure systems such as roadways and sewers, and cause minor property damage. NF has received some attention in the context of low-lying coastal cities exposed to increasingly higher high tides, a consequence of sea level rise, which exceeds the heights of coastal topography. However, low levels of flooding are widespread and deserve greater attention. Here a simple, quantitative definition of NF is proposed based on established flood intensity thresholds for flood consequences (e.g., pedestrian safety, property damage, and health risks). Based on a wide range of literature including hydrology, transportation, public health risk, and safety impacts, we define NF based on depth >3 cm and <10 cm, regardless of the source. This definition of NF is not limited to high tide flooding but rather is inclusive of all possible flood drivers including pluvial, fluvial, and oceanic and can capture trends in NF resulting from trends in, and compounding effects of, flood drivers. Furthermore, we also distinguish between NF as a *process* and NF as an *event*, which is important for linking NF to societal impacts and developing effective policy interventions and mitigation strategies. Potential applications and implications of NF monitoring are also presented.

1. Introduction

Global exposure of population and assets to flooding has significantly increased over the last few decades (Intergovernmental Panel on Climate Change, 2012). Damages have been escalating for decades globally and in the United States (Cartwright, 2009; Hinkel et al., 2014; Jongman et al., 2012; Sundermann et al., 2014). Several trends including rising sea levels, urbanization, especially along coastlines, deforestation, aging infrastructure, and rural-to-urban population shifts will increase flood exposure in the future (Hallegatte et al., 2013; Jongman et al., 2012; Sundermann et al., 2014). While the primary driver of increased flood impacts over the past few decades has been an escalation in flood vulnerability, that is, the consequences of exposure to flooding, trends in hydrologic hazards raise additional concerns including more extreme precipitation (Donat et al., 2016), more frequent and higher extreme coastal ocean water levels (Muis et al., 2016; Wahl & Chambers, 2016), altered river hydrology (Hirabayashi et al., 2013; Ward et al., 2017), altered snowmelt regimes in cold regions (Coppola et al., 2016; Jennings et al., 2018), and combinations of these factors (Moftakhari, Salvadori, et al., 2017; Wahl et al., 2015). Jongman et al. (2012) estimate a twofold to threefold increase in exposure to river and coastal flooding between 2010 and 2050.

Studies of flood impacts have emphasized the occurrence of extreme events (infrequent, e.g., 100-year return period), and these are important for preparing for and responding to the possibility of disasters, that is, the *acute* impacts of flooding. However, what is also important is the increasing impacts of relatively frequent and small-magnitude events (e.g., annual or even monthly return periods) mainly due to relative sea level rise (Figure 1; Ezer & Atkinson, 2014; Karegar et al., 2017; Moftakhari et al., 2015; Ray & Foster, 2016; Vandenberg-Rodes et al., 2016) that present *chronic* flooding at low levels as seen in coastal cities such as Venice, Norfolk (VA), Miami (FL), and to a lesser degree San Francisco (CA; Moftakhari, Salvadori, et al., 2017). This is not, though, limited to coastal regions. In cold regions, for example, where the climate change-driven altered seasonality of rainfall and snowmelt runoff yield complex flood-generating processes (Coppola et al., 2016; Jennings et al., 2018), a time shift in runoff generation processes from melting accumulated snow pack during hot season to gradual contribution of precipitation in runoff generation during cold season may result in a

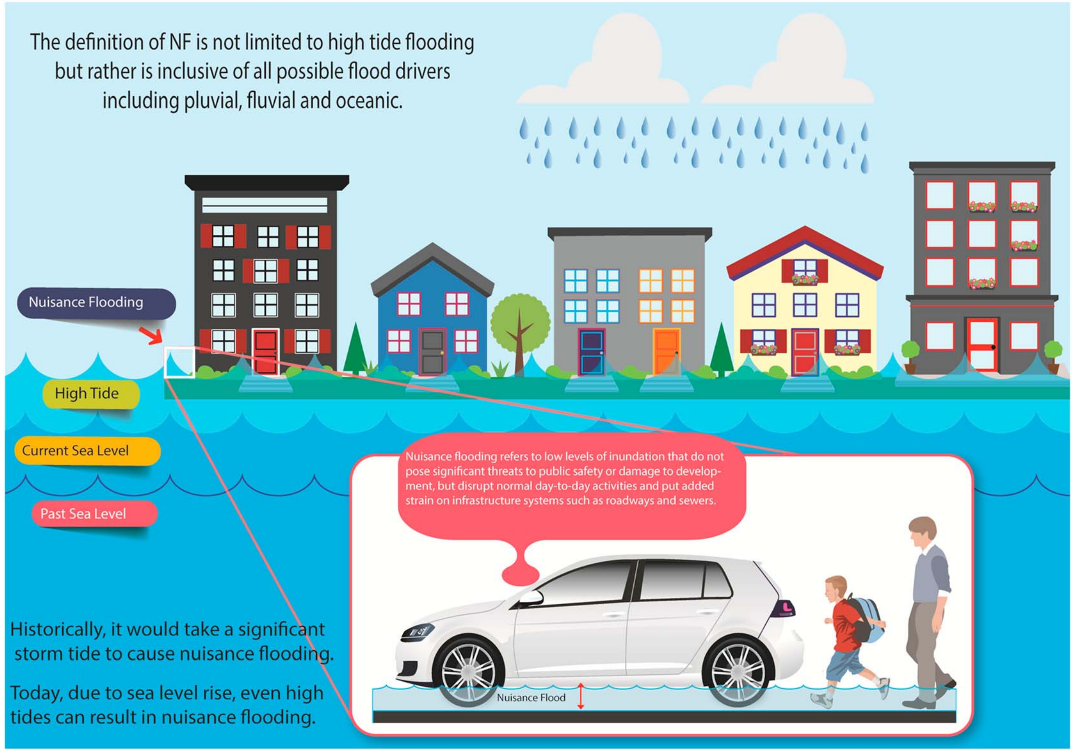

Figure 1. Nuisance flooding (NF) refers to low levels of inundation, mainly in urban areas, with socioeconomic impacts. NF may be associated with pluvial flooding, fluvial flooding, and/or coastal flooding.

secondary shift from major late spring flooding to nuisance winter/early-spring flooding dynamics (Hodgkins et al., 2017; Vormoor et al., 2015).

Low levels of flooding have been termed nuisance flooding (NF; aka *clear-sky* or *sunny-day* flooding) in a coastal context (Ruocco et al., 2011; Sweet & Marra, 2016; Sweet & Park, 2014; Sweet et al., 2014) and minor flooding (MF) in a fluvial context (Emergency Management Australia, 1999; Lumbroso, 2007; National Weather Service, NWS, 2012). With NF and MF, the intensity of flooding (e.g., depth, velocity, and discharge per unit width) is not large enough to cause significant property damage or threaten public safety, but it is capable of disrupting routine activities, putting added stress on infrastructure such as transportation systems (Jacobs et al., 2018; Suarez et al., 2005) and storm sewers (Cherqui et al., 2015; Flood & Cahoon, 2011), affecting real estate values, causing loss of income (Nabangchang et al., 2015), and heightening public health risks (ten Veldhuis et al., 2010). NF poses significant challenges in densely populated regions and threatens urban water security (Nazemi & Madani, 2017a, 2017b). Moftakhari, AghaKouchak, Sanders, Matthew, and Mazdiyasni (2017) showed that, over time, some areas will experience greater cumulative exposure of assets from the repeated occurrence of relatively small events, compared to the infrequent occurrence of extreme events and thus presented NF as a *cumulative hazard*. Overall, NF may represent a considerable burden for communities insofar as assets are impacted over time and Federal assistance is typically not available for events that are not declared disasters.

Compared to extreme flooding and disasters, the occurrence and impacts of NF are poorly understood. Systematic monitoring across coastal and inland sites is a starting point for advancing knowledge about NF and MF, and in turn, developing policy responses and management measures. However, it is unclear what exactly constitutes the occurrence of NF. An established severity classification used by governmental weather agencies including the Australian Bureau of Meteorology (ABM) and the U.S. National Weather Service (NWS) involves three categories of flooding: minor, moderate, and major. NWS (2012) presents concise categorical definitions based on impacts as follows:

Minor Flooding: Minimal or no property damage, but possibly some public threat.
Moderate Flooding: Some inundation of structures and roads near streams. Some evacuations of people and/or transfer of property to higher elevations.

10.1029/2018WR022828

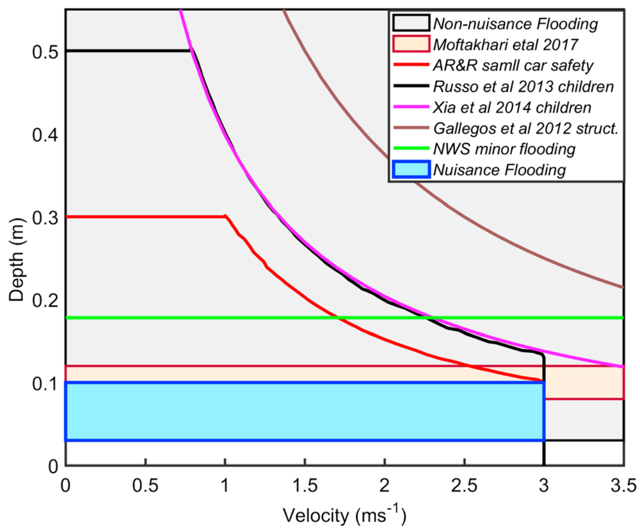

Figure 2. Curves representing thresholds of flooding intensity (depth and velocity) to acute impacts. NF is defined by the blue region corresponding to depths >3 cm and <10 cm and a velocity <3 m/s.

Major Flooding: Extensive inundation of structures and roads. Significant evacuations of people and/or transfer of property to higher elevations.

Furthermore, ABM and NWS link these flood categories to river stage at river forecast points, so forecasted river stage can be easily translated into likely impacts for emergency response. National Oceanic and Atmospheric Administration's National Ocean Service (NOS) also relies on gage readings to quantify NF, which is defined as "flooding that leads to public inconveniences such as road closures" (National Ocean Service, NOS, 2017). NF is measured as the number of hours that coastal water levels are above height thresholds that trigger the onset of flooding. Comparing the ABM/NWS flood classification with the NOS NF definition would suggest that NF and MF are similar types of flooding. However, room is left for interpretation. For example, Haigh et al. (2017) developed a flood database for coastal UK with six categories of flooding from lowest to highest severity as follows: (1) Nuisance Floods, (2) Minor Floods, (3) Moderate Floods, (4) Major Floods, (5) Severe Floods, and (6) Disasters. Thus, Haigh et al. (2017) viewed NF as being less severe than MF. Moreover, a fundamental problem with monitoring low levels of flooding based on impacts (e.g., economic losses, structural damage, and fatalities) is that impact reports are relatively scarce. Hence, a more promising approach to monitor NF is to combine use of traditional real-time monitoring data (e.g., stream gages, tide gages, wave gages, and precipitation gages) with flooding data harvested from social media (e.g., Smith et al., 2017). Gage data have successfully been used by NOS to document NF and by ABM and NWS to forecast flood severity, but gage measurements alone are far too scarce to capture the fine-scale spatial features of NF. Hence, the objective of this paper is to present a definition of NF based on hydrologic indicators, in accordance with established linkages between localized flood intensity and flood impacts. Moreover, we outline a vision for NF monitoring and discuss how the resulting data could improve flood policy and management.

2. NF Definition

The definition of NF is conceived with a lower and upper threshold on local depth and velocity that are drawn from three categories of flood impacts: Transportation Impacts, Public Health and Safety Impacts, and Property Damage.

2.1. Transportation Impacts

Road closures have major impacts on communities by interrupting transportation and threatening the safety of motorists and emergency responders (Asadabadi & Miller-Hooks, 2017; Jaroszweski et al., 2010; United Nations, 2013). Around 13 cm of water reaches the undercarriage of most passenger cars (Gattis et al., 2010; Shand et al., 2011), at which point a door cannot be opened safely. Furthermore, as water levels and velocities increase, vehicles eventually lose their stability and may be washed away potentially causing injuries and fatalities (Martínez-Gomariz, Gómez, Russo, & Djordjević, 2016; Teo et al., 2012; Xia et al., 2014). According to the Australian Rainfall and Runoff (AR&R) criterion (Shand et al., 2011), which appears to be the best reference to date on the stability of passenger vehicles (Martínez-Gomariz, Gómez, Russo, & Djordjević, 2016), 10 cm and 30 cm are considered as limiting high velocity and still water depths for stationary vehicles, respectively (Figure 2).

2.2. Public Health Risk and Safety Impacts

Floods at any depth may threaten public health and safety. Ponded flood water of any depth can provide habitat for mosquitos and other disease vectors. Flood waters, especially sewage systems surcharges that are occasionally excluded from impact assessments (European Union, EU, 2007), may contain bacteria and contaminants such as toxic chemicals or wastes that may cause illness, especially in children. For example, ten Veldhuis et al. (2010) reported fecal indicator bacteria in flood water comparable to raw sewage. The contaminated runoff may dilute water bodies and so extend the impacts well beyond urban areas. Even a shallow layer of water is capable of transmitting electrical shock from downed power lines or bad electrical wiring.

10.1029/2018WR022828

However, public health and safety risks increase at greater depths (Abt et al., 1989; Cox et al., 2010; Martínez-Gomariz, Gómez, & Russo, 2016). In particular, fast-moving flood water is dangerous based on the potential to be hit by debris or be swept away (Figure 2).

2.3. Property Damage

Property damage from flooding includes impacts to structures, contents and facilities, and is strongly correlated with flood depth, in particular, flood elevations above the first finished floor (Scawthorn et al., 2006). NF is associated with flood heights below finished floor elevations, which are highly variable and regulated by local building codes in place at the time of construction. Commercial buildings are often constructed with doorways at ground level, and thus, building contents are exposed to flooding when flood levels overtop street curbs. Residences with first floor elevations on grade are similarly vulnerable to building content damage. Given that street curbs typically rise 10–20 cm above the crown of roadways (American Association of State Highway and Transportation Officials, 2001), this height is representative of the upper limit on NF from a damage perspective. We also note that damages can sometimes be avoided by flood resilient construction and adaptation measures (Holub et al., 2012; Proverbs & Lamond, 2017), especially at the nuisance level. For example, damage resistant building materials (e.g., tile, masonry) can be utilized and electric components (e.g., switches, sockets, circuit breakers, and wiring) can be raised (Insurance Institute for Business & Home Safety, 2018). Structural damage occurs from significant flood forces and erosion that are linked to a combination of depths and velocity far greater than what would be considered a nuisance (Gallegos et al., 2012; Kelman & Spence, 2004).

2.4. Definition of NF

Moftakhari, AghaKouchak, Sanders, Matthew, and Mazdiyasni (2017) analyzed measurements from 10 gages along the coasts of the United States and suggested that 10 ± 2 cm (mean ± std) above mean higher high water (MHHW) serves to distinguish between floods with minor (e.g., NF) and major impacts. This level corresponds to the 50th quantile of the observed hourly water level above MHHW. Figure 2 shows that the Moftakhari, AghaKouchak, Sanders, Matthew, and Mazdiyasni (2017) breakpoint in flood height compares well with the lower limits for flood damages associated with transportation impacts and property damage. Hence, we propose a simple depth-based threshold for the upper limit of NF as 10 cm, and a velocity threshold of 3 m/s to account for the potential for structural damage from shallow, fast-moving flooding, which is possible along steep roadways (e.g., Schubert et al., 2008). This is obviously a somewhat crude classification, and on a site-specific basis it can be adjusted to account for whatever local factors trigger the onset of a nuisance and the transition to more significant impacts that no longer constitute a nuisance. It is also necessary to establish a lower limit for NF; otherwise, every rainfall event that produces runoff would be considered NF, and hence, a 3 cm threshold is proposed. This height is chosen because it is large enough to constitute a nuisance to a pedestrian (e.g., wet shoes), and because it is comparable to the absolute vertical error in the best available digital elevation models (DEMs) of urban areas derived from a combination of terrestrial laser scanning (TLS) and differential Global Positioning System surveying (Lohr, 1998; Muir et al., 2017). Indeed, the accuracy of DEMs poses a significant challenge to high-resolution urban flood mapping (Dottori et al., 2013; Saksena & Merwade, 2015), and the upper and lower thresholds proposed here are at the order of magnitude of vertical errors of currently available LiDAR data (with vertical accuracy of 5 to 15 cm; de Almeida et al., 2016; Fewtrell et al., 2011; Sampson et al., 2012). Thus, regular LiDAR data may not be sufficient for accurate modeling/mapping of NFs and more advanced technology (e.g., real-time kinematic with a vertical root-mean-square error less than ~1 cm) is required to delineate NF from no-flood and non-NF situations (Gallien et al., 2011). We note that TLS is capable of millimetric precision for ground surveying, but the absolute vertical error accounts for uncertainty in ground control points and the TLS position at the time of data acquisition (Sampson et al., 2012; Schubert et al., 2015). Hence, while some impacts of NF (e.g. water quality issues) might occur at depths below 3 cm, with this definition, NF is established when flood depths exceed the vertical error in the DEM relied upon for flood depth mapping and are large enough to present a nuisance to pedestrians.

NF is defined as a process using depth and velocity at a point, as described above. Integral measures such as km^2-hr of NF are to enumerate NF and thus indicate the scale of the problem facing a community (NOS, 2017). But to improve the characterization of both the frequency and scale of NF, it would be advantageous to introduce an event-based definition. Thus, NF events are defined as contiguous episodes of NF (time) that

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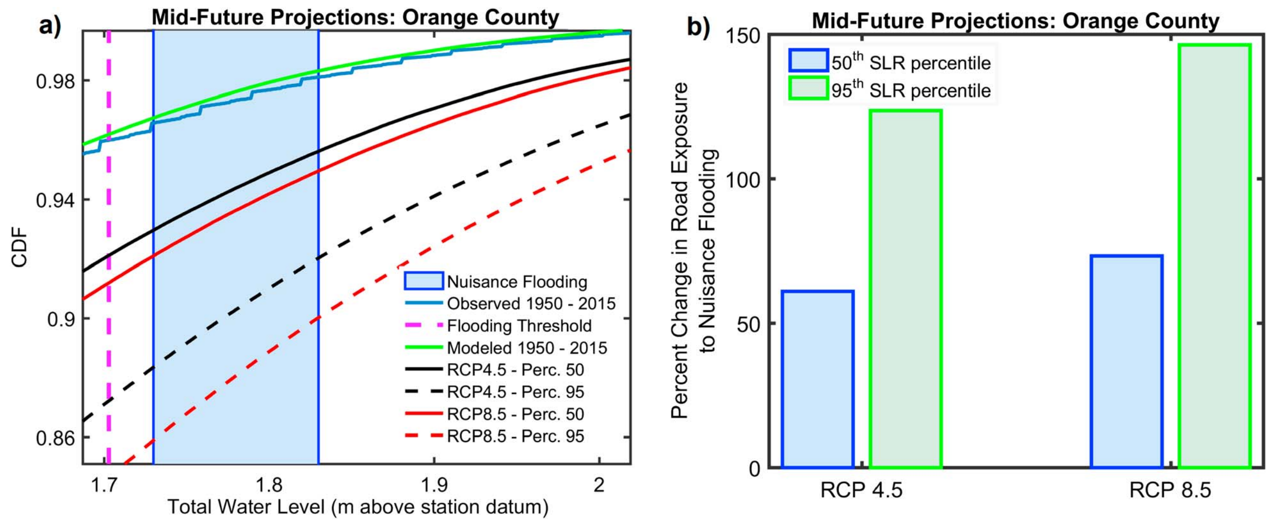

Figure 3. (a) Cumulative distribution function (CDF) of total water level above the station datum for the historical (1950–2015) observation/simulations and future projections in mid-future (2018–2083), and (b) estimated road exposure to nuisance flooding for simulated historic coastal ocean water dynamics and under the future Representative Concentration Pathway (RCP) scenarios and the given percentiles of mean sea level rise (SLR).

do not transition into more severe categories of flooding based on the process-based NF definition. Based on this definition, NF might not necessarily be spatially contiguous. For example, intense rainfall on a city often causes isolated areas of ponded water in roadways that disrupts traffic. Whether NF exists as several distinct flood zones or only one is not especially important from the perspective of impacts.

Integrals measures of NF such as km^2-hr of flooding will be important for monitoring the severity of a NF problem facing an area and projecting how it could change in the future. For example, Figure 3 shows the projected exposure of roads to NF (i.e., total water level between 3 and 10 cm above MHHW) in Orange County, California, based on analysis implemented by Moftakhari, Salvadori, et al. (2017; For further details about the materials and the methodology, please see Moftakhari, Salvadori, et al., 2017). As Figure 3 shows, the likelihood of coastal roads being inundated by coastal ocean water level in near future is expected to significantly increase relative to the past. Targeted projections such as this are extremely helpful for decision making by owners and managers of infrastructure systems such as roads and sewers (Forzieri et al., 2018).

3. NF Monitoring

NF monitoring poses significant challenges given the number of processes capable of generating localized flood depths in the 3–10 cm range, including precipitation, extreme high tides, high river stage, channel and culvert blockages, surcharging sewers, leaks in flood walls, and broken water supply pipes. Indeed, NF is strongly linked to the interaction of natural processes and civil infrastructure systems, which in turn are linked to human activity. As previously mentioned, monitoring of NF from high tide flooding and river flooding is possible with tide gages and river gages, respectively, but this captures only a fractional occurrence of NF. NF from pluvial flooding can potentially be monitored by precipitation data, and this would require localized precipitation data and an understanding of drainage patterns and potential for ponding within urban areas. Mechanistic models of urban flooding can be applied to simulate flooding in urban areas from numerous sources including precipitation (Luke et al., 2018), blockages of culverts (de Almeida et al., 2016; Schubert et al., 2008), and surcharging of sewers (Kim et al., 2006). The computational demands of mechanistic modeling are high at fine spatial resolutions (Fewtrell et al., 2011; Sanders et al., 2010), and factors that significantly influence urban flooding are not easily monitored (e.g., blockages, infrastructure failures) and thus it is difficult to imagine real-time pluvial NF data being generated by mechanistic models forced by real-time precipitation data. Accurately predicting low levels of flooding commensurate with NF is especially challenging given uncertainties in forcing data, such as rainfall rates (de Almeida et al., 2016). However, in areas that experience chronic flooding from systematic drainage problems, mechanistic models could help to develop

10.1029/2018WR022828

correlations between precipitation and NF that can be adopted as surrogate models for real-time monitoring (Bermúdez et al., 2018).

Perhaps the most promising direction for NF monitoring, irrespective of the causes of flooding, is harvesting of real-time flood information using social media (Smith et al., 2017) including Twitter feeds, Facebook posts, and Instagram photos/stories, as well as other sources such as security/traffic cameras. Previous research has shown that flood extent can be mapped from flood photos by consulting with a DEM (e.g., Gallien et al., 2011), and automation of this process in accordance with the location, orientation, and magnification of photos is needed for real-time NF monitoring based on photographs posted to social media. Social media has emerged as an important platform for two-way communication about flooding between authorities and community members (Feldman et al., 2016; Le Coz et al., 2016; Palen & Hughes, 2018) and can be used to gather information around the severity of floods (Fohringer et al., 2015; Smith et al., 2017; Wang et al., 2018). Flood monitoring efforts have also explored combining social media with remote sensing and unmanned aerial vehicle data (Rosser et al., 2017), although these efforts have been mainly focused on extreme events (Kogan et al., 2015; Middleton et al., 2014). In summary, there is presently no proven method to systematically monitor NF everywhere based on the definition defined above, but NF monitoring is possible now at sites where gages are predictive of urban flooding and information systems could be developed, on a site-specific basis, where chronic flooding occurs (e.g., Bermúdez et al., 2018). There is also an enormous opportunity for future research into the use of social media (e.g., Twitter, Facebook, and Instagram) to quantitatively monitor NF. Traffic/security cameras (if available) and drone imagery can also complement information harnessed from social media to improve/advance NF monitoring.

4. NF Characterization and its Policy Implications

NF poses challenges in densely populated regions, where attitudes and behavior of citizens become crucial in hazard perception and management (Spinks et al., 2014). In this section we consider how key stakeholders might perceive NF and how an event-based NF definition could improve outcomes:

4.1. Federal, State, and Local Governments

By appropriately defining NF, the Federal government could control growing burdens of disaster assistance. The Federal government is required under the Stafford Act to only provide assistance for disaster impacts that exceed a jurisdiction's capacity to respond and recover (United States Code, 2018). In practice, FEMA has historically focused on a damage threshold when deciding disaster declarations. The thresholds for public assistance funding are currently $1.46 per capita (state-level) and $3.68 per capita (county level; FEMA, 2018). Yet these values are unreasonably low since they have not been adjusted for increased income since 1986 or inflation from 1986 to 1999. The state level threshold would be more than double if appropriately updated for rising income and inflation (Government Accountability Office, GAO, 2012).

The low threshold has contributed to the increase in disaster declarations, which from 2004 to 2011 totaled 539 declarations with obligations of over $90 billion (GAO, 2012). Although individual NF events are not expected to lead to disaster declarations, defining NF offers the potential for providing Federal funding for major *cumulative* impacts resulting from chronic NF. Establishing quantitative measures of NF and local coping capacity could also limit the current practice in the United States of supplemental funding requests for minor, single-occurrence events. Quantification of NF could also improve flood risk assessment in Europe, where the legislation authorities focus on a specific (e.g., moderate to rare) event with "significant adverse consequences" (EU, 2007), and there is not an ongoing standard process to keep accounting for chronic impacts of NF.

In the United States, a jurisdiction's capacity to cope with disaster impacts is not adequately considered in public assistance decisions. As a result, state and local governments have been able to readily qualify for Federal assistance for events that do not necessarily represent major disasters. For example, in local jurisdictions with small populations, damage to a single facility could produce per capita damages that meet the threshold for public assistance (GAO, 2012). Generally, the large role of Federal government in disaster assistance can lead to moral hazard and perverse incentives that discourage risk mitigation actions. The current system is structured such that federal funding is provided to communities that have done little to reduce flood risk and thus incur damages that exceed the threshold for a disaster declaration. In addition, communities that wait to take action until after a major disaster might then benefit from additional Federal funds for risk mitigation. Nearly 90% of FEMA funding for flood risk reduction is allocated after major disasters (Kousky & Shabman, 2017). Defining and quantifying NF could limit Federal funding and reduce some of these perverse incentives because comparisons in NF levels could easily be made across states and cities to assess those areas where the burden is greatest. It might even enable a more risk-based approach to allocating flood risk reduction funding. By not allowing Federal funds to be allocated to NF, state and local governments would have greater incentive to undertake mitigation actions and reduce exposure, particularly to frequent flooding events.

4.2. Homeowners and Firms

Homeowners and firms tend to bear a large portion of costs due to NF, since these events do not tend to trigger government assistance. Nor would Small Business Administration loans be available to those affected by a NF event that is not a declared disaster. In addition, damages from NF might not exceed the deductible on a flood insurance policy. From the perspective of a single homeowner or business owner, flooding that causes damage to private property or contents can be a notable event. Owners bear the cost of uninsured repairs and may face lower resale prices of their assets (Bin & Polasky, 2004; Rambaldi et al., 2013; Skantz & Strickland, 1987). Furthermore, in the United States, policies under the National Flood Insurance Program do not cover a broad range of damages including vehicles, landscaping, septic systems, business interruption, and a variety of property located in basements. Reoccurring NF can especially be problematic for National Flood Insurance Program policyholders since four claims in excess of $5,000 can lead to a “severe repetitive loss property” classification.

4.3. Insurance Providers

In countries where flood insurance is privately provided, insurers might utilize NF data to inform premium setting and estimation of maximum probable loss. Insurers that provide incentives for policy holders to take mitigation actions could also use NF information to assess the effectiveness of various actions. Point scale NF data might also help insurance companies set deductibles corresponding to the upper limit of NF, and to thus avoid paying out repeating claims from high-frequency, low-level flooding.

4.4. Developers

New development or redevelopment projects pose an excellent opportunity to reduce future NF through grade raising (e.g., placing sediment to raise ground elevation) or the impacts of NF through flood resilient design. Point-scale NF data analyzed on a parcel by parcel basis within cities would help developers with resilient designs and help increase awareness of potential flooding hazards among the buyers and tenants of these developments.

5. Conclusions

This commentary presents a point-scale process-based definition of NF that draws from literature in hydrology, transportation, public health risk, and safety impacts. It is applicable to any possible cause of NF such as fluvial, pluvial, or coastal flooding, and confounding effects flood defenses and drainage infrastructure (e.g., culvert and channel blockages). NF events are introduced based on integral measures of NF measured at the point scale and are envisioned to be useful for trend analysis and projections of the severity of NF in the future. Moreover, this commentary is a call to action for experts to further evaluate trends and patterns in NF.

While the science community has mainly focused on extreme events with large acute impacts, the cumulative impacts of chronic NF may be greater in some areas than the acute impacts of a rare event. One of the main roadblocks in understanding NF and their impacts is lack of NF data. A promising direction for NF monitoring is mining real-time flood information from social media combined with traffic/security cameras and/or drone imagery. Data records of NF will encourage more research in this area and frame the likely benefits of protection/adaptation measures.

Acknowledgments
This research was made possible by a grant from the National Science Foundation (award DMS 1331611) which is gratefully acknowledged. The authors also thank the anonymous reviewers as well as Matthew Brand, Jochen Schubert, and Adam Luke at UCI for providing suggestions that improved the manuscript. All data sets used in this study are freely available to the public. The hourly water level data for the tide gauge in Los Angeles, CA (NOAA ID: 9410660) are available from the National Oceanic and Atmospheric Association (NOAA; http://tidesandcurrents.noaa.gov/). The sea level projections are provided by Daniel Cayan, David Pierce, and Julie Kalansky from Scripps Institution of Oceanography, University of California San Diego, and are available from Cal-Adapt (http://cal-adapt.org/). The estimated road lengths exposed to flooding under different sea level rise scenarios are retrieved from the risk finder tool developed by Climate Central (http://sealevel.climatecentral.org/).

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