The Development of a Flash Flood Severity Index

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Revised Draft submitted to the Journal of Hydrology Special Issue: Flash floods, hydro-geomorphic response and risk management

22 March, 2016

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ABSTRACT

Flash flooding is a high impact weather event that requires clear communication regarding severity and potential hazards among forecasters, researchers, emergency managers, and the general public. Current standards used to communicate these characteristics include return periods and the United States (U.S.) National Weather Service (NWS) 4-tiered river flooding severity scale. Return periods are largely misunderstood, and the NWS scale is limited to flooding on gauged streams and rivers, often leaving out heavily populated urban corridors. To address these shortcomings, a student-led group of interdisciplinary researchers came together in a collaborative effort to develop an impact-based Flash Flood Severity Index (FFSI). The index was proposed as a damage-based, post-event assessment tool, and preliminary work toward the creation of this index has been completed and presented here. Numerous case studies were analyzed to develop the preliminary outline for the FFSI, and three examples of such cases are included in this paper. The scale includes five impact-based categories ranging from Category 1 very minor flooding to Category 5 catastrophic flooding. Along with the numerous case studies used to develop the initial outline of the scale, empirical data in the form of semi-structured interviews were conducted with multiple NWS forecasters across the country and their responses were analyzed to gain more perspective on the complicated nature of flash flood definitions and which tools were found to be most useful. The feedback from these interviews suggests the potential for acceptance of such an index if it can account for specific challenges.

Keywords: Flash flood, Severity scale, Extreme weather,

1. Introduction

The magnitude and severity of a flash flood is determined by a number of natural and human-influenced factors including: rainfall duration and intensity, antecedent soil moisture conditions, land cover and soil type, watershed characteristics, and land use. While land use impacts, particularly urban development, can increase the severity of a flash flooding event (Leopold, 1968), Martinez-Mena et al. (1998) and Castillo et al. (2003) suggested that rainfall intensity and antecedent soil moisture, respectively, play the most important roles. The complex and intertwined properties of these determining factors allude to the challenging nature of flash flood forecasting, warning, and classification. The complexity of the flash flood paradigm has been acknowledged for decades, and ample research endeavors focused on flash flood forecasting improvements have been undertaken worldwide (Doswell et al. 1996; Davis 2001; Alfieri et al. 2011; Alfieri and Thielen 2013; Alfieri et al. 2014). However, an easy-to-understand, universal method for classifying flash flood events has not been adopted by the scientific community as a whole, so the current study focused on the development of such an index.

The Intergovernmental Panel on Climate Change (IPCC) projects a higher frequency and greater magnitude of high intensity rainfall events for the remainder of the current century (IPCC, 2013). This projection combined with studies showing that recent climate change has caused an increase in extreme precipitation (Groisman et al., 2005; Gutowski et al., 2008; Min et al., 2011) suggested an increased likelihood of flash flood occurrence, which can lead to substantial societal impacts ranging from economic disaster to loss of life. According to NWS assessment reports (http://www.nws.noaa.gov/os/hazstats.shtml), flooding is one of the leading causes of weather-related fatalities in the U.S., with the majority of these fatalities resulting from flash flooding events (Ashley and Ashley, 2008). Flash flooding impacts are not problematic to the U.S. alone; they are a global natural hazard.

Current methods for classifying flood events include return period and the NWS four-tiered flood severity scale, among others. The return period, also known as average recurrence interval, is calculated using a statistical method based on frequency analysis of historical streamflow data ((http://water.usgs.gov/edu/100yearflood.html). Once a distribution (typically log Pearson III) is fit to the annual maximum or partial duration time series of streamflow observations, the return period is simply the inverse of the annual probability of exceeding the discharge level. The resulting value is typically reported in years, such as 2, 5, 10, 25, 50, 100, 500, or 1000. For example a 100-year flood indicates there is a 1 in 100 or 1% chance of exceedance in any given year. Because the return period is generally reported in years and not percent chance of occurrence, it is often misunderstood and mistaken to mean that a 100-year flood refers to a flood that will only happen once every 100 years, when in fact a 100-year flood could occur several years in a row, despite the probability of such an occurrence being very low (NRC 2006; Gruntfest et al., 2002). Although there are only a small number of studies that directly investigate the conceptual understanding of the return period, they emphasize that people prefer concrete descriptions of flood risk (Bell and Tobin, 2007) and that the presentation of the return period versus a probability (e.g. 100-year flood versus 1% likelihood of a particular flood magnitude per year) is problematic (Keller et al., 2006). Furthermore, work by Ludy and Kondolf (2012) showed that people living behind 100-year flood levees do not properly evaluate flood risk. These misunderstandings and complications potentially play a role in the fatality statistics mentioned earlier.

Beyond public confusion regarding return periods, there are factors that affect the accuracy of the calculations themselves. Climatic stationarity is an underlying assumption used in return period methods, and when stationarity assumptions are not valid, these methods become less reliable (Sivapalan and Samuel, 2009). Changing climate and patterns of land use result in streamflow changes, making a stationarity assumption inaccurate (Milly et al., 2007; Villarini et al., 2009), which may lead to less accuracy in the return period. Another source of error comes from the inherent difficulty and danger of measuring large peak flows over short periods of time, leading to decreased accuracy in the measurement of flood peaks, particularly in watersheds prone to flash flooding (Potter and Walker, 1985). Additionally, for watersheds with frequent flash flooding, gauging ratios, i.e.: the largest measured streamflow divided by the largest estimated streamflow, are often as low as 10 percent (Smith and Smith, 2015), resulting in additional errors. These factors combined with the inherent lack of stream gauges, particularly in heavily populated urban corridors, suggest that even with a stationary streamflow record, accuracy in return periods may be difficult to properly estimate. Lastly, the return period applies to streamflow observations in channels. They do not readily apply to flash flood scenarios with significant inundation of streets and infrastructure in urban zones, without the associated high streamflow values.

Another flooding classification tool is the multi-tier, impact-based flood severity scale used by the NWS to evaluate river flooding at a select number of U.S. Geological Survey (USGS) stream gauge sites. The scale incorporates four levels: action, minor, moderate, and major flooding, and is available for 2,975 out of the total 8,833 stations in the contiguous United States (CONUS). However, because the scale was designed to evaluate river flooding only, many of the sites are located along large rivers that rarely experience flash flooding, which often occur in small ungauged streams or in urban areas separate from stream channels. Additionally, the scale for each respective stream gauge site is only applicable for areas within a certain distance from the site. As a result of these caveats, this flood severity scale is only applicable in regions where a stream gauge is available and local flooding reference points have been established.

While additional flash flood indices have been previously proposed, such as the Flash Flood (FF) Index from Davis (2002) (published in conference proceedings) and the Flash Flood Potential Index (FFPI) from Smith (2010), the foundation of such indices were developed despite the caveats listed above and therefore have some inherent complications. The FF Index was a quantitative index that incorporated calculated differences between the average basin rainfall and the predetermined Flash Flood Guidance (FFG) product produced by the NWS River Forecast Centers. As a result of the data assimilated into the FFG product, the FF Index is limited to areas containing relatively large gauged rivers. The FFPI accounts for watershed physiographic characteristics and combines them with forecast and observed rainfall to determine the likelihood of flash flood occurrence. The FFPI values scale from 1-10 corresponding to the hydrologic sensitivity of the basin from least to most. These scaling factors are used to adjust a 25.4 mm hr^{-1} rainfall rate threshold. This method is applied operationally for flash flood forecasting in the western U.S. but was shown to have poor skill in forecasting flash flooding (Clark et al., 2014).

The current paper outlines the preliminary study that focuses on the development of a Flash Flood Severity Index (FFSI), which was a student-led effort by a group of interdisciplinary collaborators from a diverse range of backgrounds including: atmospheric science/meteorology, hydrology, civil engineering, Geographic Information Systems (GIS), sociology, and science and technology studies. The group was formed as part of the Studies of Precipitation, flooding, and Rainfall Extremes Across Disciplines (SPREAD) workshop at Colorado State University in June

2013 and July 2014 (Schumacher, 2016). The interdisciplinary nature of the workshop led to complex negotiations arising from contrasting definitions, scientific methods, and analysis tools; however it allowed unique perspectives to be combined to evaluate flash flood characteristics, ranging from operational forecasting to societal impacts. During the two summer workshops, the group discussed challenges related to multiple aspects of extreme precipitation, ranging from precipitation modeling and prediction to return periods and weather warnings. Group discussions during the workshop about community vulnerability in light of field trips to visit historic sites, such as the Big Thompson Canyon flood of 1976, led the group to identify two potential areas of major improvement in future flash flood research: (1) the measurement of flash flood severity and (2) the communication of flash flood risk. Therefore, this paper addresses the former, with the goal of developing a different method for categorizing flash floods separate from the return period, which is the current standard. The index is designed to be (1) easy to understand and to communicate, (2) universally applicable to all geographic locations prone to flash flooding, and (3) a stand-alone product without the necessity of an associated stream gauge site.

The remainder of the article is organized as follows. The next section describes the data collection methodologies needed for the development of the FFSI. Section 3 presents results from data collection methods that were conducted to understand potential challenges to implementing the new FFSI with those stakeholders responsible for issuing flash flood warnings, NWS forecasters. The preliminary FFSI is then provided in section 4, followed by a summary and conclusions in section 5.

2. Methods

There are numerous indices currently in use for a myriad of significant weather events including droughts, hurricanes, and tornadoes. The Palmer Drought Severity Index (PDSI) measures meteorological drought conditions based on departures from normal conditions (McKee et al., 1993; Palmer, 1965). The PDSI focuses on long-term drought conditions calculated from precipitation, temperature, and available soil moisture content, and uses a negative 5-point scale ranging from 0 being normal conditions to -4 being extreme drought conditions. Hurricane strength is quantified using the Saffir-Simpson scale, which classifies hurricanes based on the intensity of the sustained winds associated with the storm (Saffir, 1973). The scale defines intensity using five categories ranging from 1 associated with weakest winds to 5 associated with the strongest winds. Finally, there is the perhaps most well-known severe weather index, which serves as a damage-based post-event assessment tool. The Enhanced Fujita (EF) scale, formerly the Fujita (F) scale, uses 28 indicators of damage to estimate the probable wind speeds produced by a tornado (Fujita et al., 1971; McDonald and Mehta, 2006). The scale includes six categories that are used to infer estimated wind speeds from associated degrees of damage. As a well-known tool outside of the meteorological profession, tornado strength is often associated with the EF-scale categories, and as a result the categories are sometimes incorporated into impact-based statements included in tornado warnings issued by the NWS.

After analyzing the above severe weather indices, the group determined that the initial impetus for the FFSI is to serve as a post-event assessment tool as opposed to a warning tool. This determination was made largely because measuring flood severity and magnitude is not an exact science; flash flood forecasting and warning is complex and associated with many challenges and limitations (Norbiato et al., 2008; Reed et al., 2007). Further, the FFSI would need to be a damage-based post-event assessment tool with five categories ranging from 1 being the least damaging to 5 being the most destructive, similar to the other severe weather indices. There is an app called the mPING (meteorological Phenomena Identification Near the Ground) that enables volunteers to report flash flooding using a sliding scale from 1 to 4 (Elmore et al., 2014), which provides a starting point for the development of the FFSI. The aspiration of the group was to, after careful development and evaluation, have the FFSI eventually be widely used for flash flooding events and help to increase public awareness of flash flooding in a manner similar to how a Category 5 hurricane or EF-5 tornado rating does. Lastly, we decided to focus the development of the index on flash flooding alone, and not on cascading natural hazards such as landslides and debris flows. These events are often triggered by heavy rainfall and flash flooding, especially in complex terrain, but they introduce additional complications in the definitions of the impacts. As such, the index is developed specifically for flash flooding impacts, which is the same strategy undertaken with the other natural hazard indices.

Case Studies

In order to develop a preliminary scale for the FFSI, nearly 70 flash flood case studies of varying magnitudes were investigated to determine the flood severity and associated damage. These events were chosen based on data availability and the diversity of the case in terms of representing the full breadth of the FFSI (i.e., not just the biggest, well known events). Each investigation included researching NWS Local Storm Reports, relevant USGS and NWS stream gauge data, photos, news articles, books, peer reviewed articles, and other forms of online and print literature. Summaries for each event were created to document pertinent information, such as water depth, photos of damage, and reports of fatalities. These case studies served as the foundation for understanding the “typical” impacts associated with flash flooding events, as well as to what extent these impacts are documented. Following the analysis of the individual case studies, the summaries were compiled and associated damages were utilized to create the preliminary damage scale for the FFSI.

2.1. Interviews

Qualitative research offers a broad approach for studying human, cultural, and social phenomena, including those involving weather and climate risks. Through conceptual theoretical analysis and methodological rigor, research conducted across social science disciplines systematically investigates problems and issues relevant to populations affected by natural hazards and environmental risks (Cutter 2009; Few 2007; Blaikie 2014). Participant observations captured in rich, detailed fieldnotes; focus groups and interviews that are recorded, transcribed, and coded for patterns, relationships, and themes; and visual and textual media analyzed in terms of meaning and content—these encompass the main methods qualitative scholars employ in their research designs (Given 2008; Patton 2005). Semi-structured interviews, in particular, allow investigators to interrogate definitions, assumptions, experiences, and other salient features of social life as expressed by participants themselves (Boeije 2009). Transcribing interviews and coding such data through the lens of theoretical frames, such as risk communication, reveals analytic categories and themes that underpin and structure participant beliefs, motives, and behaviors.

As with many physical science disciplines, the number of participants or cases analyzed is a function of research purpose and access to relevant populations. In qualitative interviews, purposive and snowball sampling techniques allow the researcher to directly target relevant populations or groups and to identify potential actors important to the research problem but unknown to investigators (Denzen and Lincoln 2008). As a result, the number of participants important to a valid qualitative approach varies from in-depth case studies of individuals or clusters of people that reveal important features of a unique demographic or issue, to a larger random sample of individuals from which surface though generalizable results might be claimed.

The NWS is the government organization in the U.S. that is solely responsible for issuing weather warnings in the U.S., which includes flash flood warnings. To better design a flash flood scale useful to this group, semi-structured telephone interviews were conducted with nineteen NWS forecasters to better understand their current definitions, warning challenges, and tools most useful to in their current warning practices. Appropriate to this particular research issue, participants for the interviews were selected using purposeful and snowball sampling (Noy 2008). NWS Weather Forecast Offices (WFOs) from across the U.S. were contacted based on a density map of flash flood warnings issued by each County Warning Area (CWA) (Fig. 1). In an effort to represent flash flood protocol from geographically diverse regions of the contiguous U.S., geographic location was also considered when contacting NWS staff.

Initially, 15 Warning Coordination Meteorologists (WCMs) associated with WFOs located in regions with the highest number of flash flood warnings were contacted via email. However, based on the recommendations of participants, another five offices were contacted resulting in a total of 20 WFOs from four NWS regions (Fig. 1). Future interviewees from River Forecast Centers may also be conducted based on recommendations from those involved with the first round of interviews.

Of those contacted, staff from 12 offices responded. Nineteen individuals were interviewed, including 13 men and six women (N=19). The interviewees represented varying levels of flash flood forecasting expertise, including three WCMs, one Science and Operations Officer (SOO), seven service hydrologists, and eight general and senior forecasters. Many of the general and senior forecasters also served as the hydrology focal point for their office, suggesting a greater knowledge of flash flood expertise. Interviews lasted an average of 49 minutes and were conducted by two graduate students affiliated with the FFSI research group. Interviews were audio recorded with participants' consent, transcribed, and checked for accuracy.

<<Insert Fig. 1 about here>>

3. Interview Results

Based on an interpretive analysis of interview transcripts using the mixed-method coding software Dedoose™ (http://www.dedoose.com/), forecasters were found to identify three significant overall challenges related to flash flooding: (1) the definition of a flash flood; (2) warning different public entities about the threat to life and property, both before and during an event; and (3) getting eyewitness accounts and ground truth reports about the progress of a flash flood in terms of timing, location, and severity. These challenges informed ongoing group discussions of those criteria that would constitute the FFSI.

In general, interviewees expressed mixed support for the FFSI, with the majority noting that it may be of use to forecasters, depending on the design of the scale (Fig. 2). Interviewees expressed greater interest in a warning tool that could help forecasters better alert and convey risks to the public, from emergency managers to citizens in their respective CWA. It wasn't clear from interviews that this tool should be in the form of a severity index. Of those interviewed who expressed support for the FFSI scale as a post-event tool, the most often cited reason was a desire to better document local flash flooding patterns in order to categorize the effects of flash flooding on their communities. Three main challenges emerged that related the need or desire for a FFSI as a post-event damage tool: (1) the possible criteria of the scale, (2) the ability to generalize the scale across different topographies and flash flood types, and (3) the challenges forecasters would face in evaluating every flash flood in their CWA. This next section explains the issue of defining flash flooding, and explicates the three challenges identified in the context of a post-event damage tool.

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3.1. Definition of a Flash Flood

Many of the concerns forecasters raised about the value of a post-event damage assessment tool were shaped by the definitional challenges inherent in the question, "What counts as a flash flood?". Officially, the NWS definition of a flash floods is the following: "A rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream or creek above a predetermined flood level, beginning within six hours of the causative event (e.g., intense rainfall, dam failure, ice jam). However, the actual time threshold may vary in different parts of the country. Ongoing flooding can intensify to flash flooding in cases where intense rainfall results in a rapid surge of rising flood waters." (from http://w1.weather.gov/glossary/index.php?letter=f). Yet several forecasters acknowledged that, in practice, their respective offices used different definitions, or even debated definitions, based on their unique challenges.

Philosophies about flash flood versus areal floods vary among meteorologists within the same office and between offices for how to interpret particular aspects of these official criteria, and they must be occasionally renegotiated as staff or flood patterns change. As one forecaster noted of this issue in her CWA, "…what constitutes a rapid rise or exactly what is a rapid rise, what depth does it have to be over the road, [these are] kind of … our worst enemy when it comes to trying to classify what a flash flood is, and we actually went to our neighboring offices and had this discussion with them." Other elements of flash flooding that affect how forecasters reinterpret official guidance include collaborative decisions with emergency managers, common flooding problems in particular areas where a smaller amount of water may have larger impacts, and flooding as it intersects with the built environment that is designed to mitigate flooding.

Another issue that shapes forecaster issues with flash flood definitions stems from the tool that the NWS primarily relies upon for alerting the public about impending flash floods, FFG or Flash Flood Guidance. FFG is defined as the amount of rain required in a given time and area to produce bank full conditions on small streams (Clark et al., 2014). Like the definition of flash flood itself, FFG doesn't account for impacts to life or property as a result of the material environment and landscape (e.g. flooding caused by clogged gutters in urban areas) or other topographical considerations (e.g. engineered structures and their relative vulnerabilities). Thus definitional issues correspond to which factors are included or not included in creating official guidance. One forecaster pointed out this challenge specifically: "We don't put a whole lot of credence into [guidance] because it's kind of generalized I think…The River Forecast Centers have tweaked a lot of them for local areas, but in our southeast counties, our more coastal areas, our coastal areas they're…sandier soil. It's a sandy loam kind of soil. So four or five inches of rain is not a huge problem but then when you get further to the west and you get where it's more rocky and that flash flood guidance may say three inches – you know it's been dry for a long time – it may say three inches in one hour but then you've got a hillside and the rain falls on the hillside and rushes down and you get a flash flood a lot quicker than three hours."

While FFG offers some definitional clarity in terms of the scientific underpinnings of flash flooding, the practical application of that guidance poses challenges. Forecasters noted that radar estimates of rainfall can underestimate or overestimate precipitation amounts; areas may not have access to sufficient gauges, which are often purchased and maintained by entities other than the NWS; and forecasters new to a location may not have sufficient experience with flash flooding to quickly identify its potential. These all can complicate local definitions and detection of flash flooding. Additionally, forecasters also revealed that many individual offices have developed protocols or tools to supplement official guidance, and they have become useful in warning for and verifying events. One office, for example, uses Google Earth to overlay historical instances of flash flooding within their CWA with current radar images of storms to help identify vulnerable places in their area. Other forecasters mentioned building close relationships with emergency managers and other stakeholders in their respective areas so that they can monitor more directly locations that have already started to flood through phone calls or emails.

One potential benefit of an FFSI scale, then, could be to offer clarity of specific definitions of flash flooding across individual CWAs. That is, by categorizing and comparing those flooding events that occur most often or affect the most people in a particular area, forecasters might develop a clearer local definition of flash flooding from an impacts-based point of view. How a flood is defined as a hydrometeorological event based on guidance could be paired with its common, local appearance via the FFSI as an “impact,” or affect of flash flooding on people’s lives, to create a more robust and realistic picture of flash flooding for a given area.

3.2. Criteria of the Scale

The challenge of creating an FFSI scale most often mentioned by forecasters was related to the criteria of the scale itself. While the interviews demonstrate a consensus among forecasters that the most important criterion for flash flooding is its impact on people, just which impacts would be most useful or realistic to include in a scale was not obvious. For example, the number of fatalities in a flash flood is often used as a measure of its severity, as is damage to property measured in dollar amounts. However, as one forecaster noted, comparisons of these criteria across different demographics can be difficult to make since the context of the flash flood dictates its severity to those impacted: "…just recently [we] went through a project where we went to find the top five flooding events in the state. We've looked at say 20, 30 flooding events…. but it was like okay, how do you rank these? Because most of them were along the main stem of [a big river] and that's where you got the most impacts, the most dollars worth of damage, the most fatalities. And then you have maybe a small river out in western [part of the state] where it had some major flooding, there were several fatalities, some damage, but how do you really rank that compared to a major event on the [big river]?"

In this excerpt, which represents several forecaster concerns, the issue is one of how the scope of an event translates across different topographies, flash flood types, and population densities. Thus, including dollar amounts in the scale breakdown does not work because the significance of the cost of these damages for a population depends on their baseline and available resources. Nor do fatalities work as a criterion, given that these can occur over a broad range of flash flood severities, and depend on individual behaviors. To minimize the subjective nature of the scale, a post-event damage scale, like one modeled on the Enhanced Fujita Scale (EF-Scale), could be based on damage to or effect on material structures alone. This eliminates issues of damage costs or fatalities from the categorical ranking of the event. However, an assumption about common building codes is a potential weakness to this approach, as is the assumption that each office would use a consistent methodology in their evaluation.

3.3. Generalization

Given that flash flooding can occur in numerous contexts, from slot canyons to urban city centers, and that it can derive from multiple sources, from rainfall to dam breaks to clogged city storm drains, a standardized FFSI scale raises issues of generalization. For example, forecasters noted that it could be difficult to use the same scale on urban flooding as on a torrent in a mountainous catchment. A scale based on impacts (e.g. damage to buildings or floating cars) becomes difficult to apply in a setting where flooding is mainly a threat to life but not to tangible property, for example, as it would be in canyon area with hikers. As one forecaster in the West noted of this salient issue, "Most of our places that get flash flooding… our reports come from national parks who will have roads impacted or hikers stranded. So [flash flooding is] really, a lot of the times, for the canyons, based on impact to people…" In these instances, then, the FFSI scale based on damage would not be as useful in flash flooding in remote areas that affect only lives but not structures.

Another challenge in terms of developing a scale that is generalizable is a lack of information in some flash flooding instances. In designing the scale, other current weather scales, such as the Saffir-Simpson Scale and EF-Scale, were referenced as potential models that might be useful and familiar to the public. These five-point tools categorize elements of weather and/or impacts across a range of increasing severity, from one to five, with the latter being the most severe. Still, one problematic aspect of a scale based on damage alone, such as the EF-Scale, is that a flood that fails to strike buildings or cars might not be registered but may still have significant impact on a community (Doswell et al., 2009), as could be the case for affected farmland or tourism in canyons. It can likewise depend on whether or not a forecaster is able to detect and verify an event. One forecaster framed this issue as a dearth of information: "The biggest challenge is lack of data for us. We'd love to have all those gauges and things. Information is always power when it comes to forecasting the weather and issuing these short fuse warnings especially, and having more ground truth would be fantastic because sometimes we'll have these situations where you see a storm, it looks really good, it's over a flood prone area, but you know basically that this had to have happened, right? But nobody was there to see it and because it's so sparsely populated, you can't find it. You're like, 'This flood had to have occurred'."

One way to approach the design of the scale is to build in enough flexibility into the definitions of each category (e.g. moderate flash flooding) to allow for WFO-specific criteria. For example, an office that deals primarily with urban flooding could tailor the categorical definition to reflect their common issues. The challenge for this scale is to balance the value of a universal scale that allows forecasters to talk about flash flooding across the country with the unique and varying types of flash flooding faced by individual WFOs. Additional challenges arise in generalizing the scales to other countries that have different characteristics and land use practices.

3.4. Documenting Flash Flooding

Finally, forecasters were concerned about the timescales involved when documenting flash floods. This concern reflected two main issues: (1) the fleeting nature of flash floods, and (2) the amount of time forecasters have to leave their office and document each event. Forecasters noted, when asked, that on average they only make it out to survey 10-15% of flash flooding in their respective areas. Another noted that even if they do get out, flash floods are difficult to categorize in the short window available to do so: "Surveying wind damage, tornado kind of damage--people tend to get out to do that a lot more. With floods I think part of the problem in my area especially and this probably is true in a lot of different areas, is that it happens so quickly. Even with river floods, it’s not like a flood on the Mississippi where it’s days to weeks to months. Ours are a matter of hours. Our rivers can go up from five feet [1.5 m] to 29 feet [8.8 m] and then back down to five feet in two hours. So I think we would want to get out more but because it’s so quick and usually we’re tied up in the office with warnings and stuff like that, that we just don’t get a chance to get out and do as many [assessments] as we’d like to.”

Another challenge of the scale, then, would be how often forecasters are able to use it in order to build up a database of typical flash flooding for their area. While NWS forecasters are mandated to conduct damage assessments for tornadoes using the EF-Scale, the FFSI would be used on a voluntary basis. Further, each WFO has an official point of contact for conducting tornado assessments, the Warning Coordination Meteorologist (WCM). Other forecasters often help conduct these assessments but the WCM is the official lead of the damage survey and he/she records the official ranking of the tornado in the National Centers for Environmental Information’s Storm Events Database (e.g. http://www.ncdc.noaa.gov/stormevents/eventdetails.jsp?id=469067). This archive allows researchers to create maps for tornado risk (Gagan et al., 2010) and helps meteorologists identify trends and shifts in seasonal and severity occurrence (e.g. Ashley et al., 2008). To successfully integrate the FFSI scale into operations would require agency adoption of the scale, something outside the control of this interdisciplinary group.

Overall, the forecaster interviews revealed a more complex understanding of challenges forecasters face in determining flash flood criteria, disseminating warnings, and verifying events--that is, issues of problem definition (Morss, 2005). More needs to be understood about the way forecasters encounter the problem of flash flooding and the type of severity scale they might find most useful. This would entail further qualitative research, including interviews and participant observations, to discover more systematically what tools forecasters already use, what problems they encounter in detection and warning, and whether a flash flood scale as currently defined would address a particular need. Additionally, forecasters should be included in subsequent revisions of the scale, as user collaboration throughout the design process is widely recognized as a preferred method for creating tools to be used in an operational context (National Center for Environmental Decision-Making Research (NCEDR), 1998; Wood et al., 2002; Yan et al., 2012).

4. Flash Flood Severity Index

The preliminary framework for the FFSI has been developed based on pre-existing severe weather indices, such as the EF-Scale, the analysis of numerous case studies of previous flash flood events, and discussions centered around the responses gathered from the interviews, such as the importance of impact-based criteria. Examples of three case studies used to clarify the low, middle, and high categories on the preliminary scale are discussed below.

4.1. Preliminary Scale

Initial groundwork for the FFSI has been developed to provide a sense of the potential structure and general focus of the index (Table 1). The preliminary design of the number of categories (5) and the wording of the severity associated with each category (minor, moderate, serious, severe, and catastrophic) are modeled around the design of pre-existing severe weather indices, including those discussed previously. A scale with levels ranging from one to five was chosen to represent the severity categories as this allowed for an acceptable breaking point between each damage category without including too little or too much detail. The wording of severity associated with each category was chosen to coincide with other pre-existing indices as these terms seem to be generally well understood by the practitioners and public. However, the number of categories and the various details differentiating those levels are still open for discussion and are yet to be finalized.

The preliminary descriptions defining the damage corresponding to each category of the FFSI were designed to be similar to the systematic categorization and range of severity found in the divisions of the flood impacts associated with the Meteorological Phenomena Identification Near the Ground (mPING) project (Elmore et al., 2014). The crowdsourcing project, mPING, involves the submission of date- and time-stamped weather reports submitted by the public via smartphone applications, and is a collaborative effort between the National Severe Storms Laboratory, University of Oklahoma, and Cooperative Institute for Mesoscale Meteorological Studies.

4.2. Example Case Studies

The case studies below are given to demonstrate and clarify the difference between a minor (FFSI=1), serious (FFSI=3), and catastrophic (FFSI=5)s flash flood event as defined by the preliminary FFSI above. Each of the three events occurred between 2009 and 2013 in the state of Georgia, and each represents differing levels of physical damage as a result of their respective flash flood events.

4.2.1. Category 1: Minor Flash Flood

On 6 July 2013 a minor flash flood resulting from 95 mm of gauge-measured rainfall occurred near Dalton, GA. The most severe damage reported with the event was the overflow of a small stream as seen in Fig. 3. The photograph indicates that the stream has reached a stage that is posing a threat to infrastructure like the bridge. However, the bridge remained intact and there were no vehicles or infrastructure that were inundated or impacted by the floodwaters. As a result of the negligible damage associated with the event, using the FFSI, this event would be classified as a Category 1: Minor Flood.

<<Fig. 3>>

4.2.2. Category 3 Serious Flood

On 1 August 2013, as much as 175 mm of rain fell overnight in Gilmer County, Georgia. The ensuing flash flood caused $1.5 million USD in property damage, however no serious injuries or fatalities were reported (NOAA Storm Event Database). In the region affected, 25 structures were flooded including a few that were lifted from their foundation. One bridge and seven roads were washed away, and swift water rescues were required for eight people who were caught outdoors during the event (Fig. 4). An evaluation of the considerable damage associated with this event concluded that structures were inundated with floodwaters; however no cars or structures were swept away in the currents. As a result of these findings, using the FFSI, this event would be classified as a Category 3 Serious Flood.

<<Fig. 4>>

4.2.3. Category 5 Catastrophic Flood

In mid-September 2009, a flash flood affected the Atlanta metropolitan area. Eight days of rainfall dumped nearly 500 mm of precipitation across parts of North Georgia leading to a fatal flash flood event. Many swift water rescues were conducted, and nearly a dozen people lost their lives (http://www.srh.noaa.gov/ffc/?n=0909epicflood). Several major school systems were forced to close, while entire neighborhoods (Fig. 5), interstate thoroughfares (Fig. 6), and the local Six Flags theme park (Fig. 7) were severely inundated with floodwaters (Shepherd et al., 2011). According to a USGS report, 18 stream gauges across metro Atlanta had magnitudes exceeding the estimated 0.2 % annual exceedance probability, which resulted in a classification of a 500-year flood for these stream gages (Gotvald and McCallum, 2010). Given the unprecedented damage associated with this event, including numerous large buildings filled with floodwaters, and in some cases up to their rooflines, using the FFSI, this event would be classified as a Category 5 Catastrophic Flood.

<<Fig. 5>>

<<Fig. 6>>

<<Fig. 7>>

5. Summary and Conclusions

Flash floods are a leading cause of weather-related deaths in the world and continue to be one of the most difficult weather phenomena to forecast and warn on because of the complex, multifaceted nature of the problem. As a result, flash floods require clear communication of the severity and potential hazards among forecasters, researchers, emergency managers, and the general public. Before communication can be successful, however, there must be a clear understanding of stakeholder's local flash flood issues, including the difficulty in detecting and classifying flash flood events and conveying this risk clearly to the public.

Current methods of classifying flooding events, such as the return period and the NWS 4-tier river flood severity scale, are insufficient for flash flood classification and risk communication, as definitions are often misunderstood. Furthermore, calculations rely on stream gauges, which are generally found only on larger streams and rivers and are often lacking in small headwater basins where flash floods are more common. Plus, the practice of measuring discharge and computing a return period applies to streams and rivers, and not to flash flooding situations often characterized by widespread inundation of infrastructure like roads or land surfaces. Taking into account these drawbacks, the FFSI scale needs to be (1) relevant to current NWS forecaster practices for evaluating flash flood risks and easy to communicate to the public, (2) universally applicable to all geographic locations prone to flash flooding, and (3) a stand-alone product without the necessity of an associated stream gauge site. To accomplish this, semi-structured phone interviews were conducted with NWS forecasters while simultaneously parsing through past case studies and developing the preliminary scale. This approach was taken in order to better understand current expert flash flood definitions, warning challenges, and tools most useful to them; this knowledge helped the group derive a more well-rounded tool. Interviews revealed a complex set of challenges forecasters face in determining flash flood criteria, disseminating warnings, and verifying events. However, mixed support for the FFSI was found, with the majority of interviewees noting that it may be of use to forecasters depending on the design of the scale. The interview feedback incited discussions, which helped to shape the details and development of the scale, as well as next steps for further development.

Taking into account other weather-related scales and the results from the interviews and case studies examined in this research, the FFSI's preliminary structure was developed with five severity categories ranging from one to five, with associated text descriptions of minor, moderate, serious, severe, and catastrophic. These categories were defined based on physical damage resulting from floodwaters and loosely based off of the current flash flood categorical breakdown used in the NSSL's mPING project. Furthermore, the FFSI was created to be a geographically universal damage-based scale to assist weather professionals and their colleagues in categorizing the magnitude and risk associated with past and future flash flooding events, and the scale would initially serve only as a post-event assessment tool to aid in comparisons of flood events. The collection and analysis of photographs of flash flooding were found to be quite useful in the identification of specific impacts and their magnitudes. Future forecaster training activities will incorporate photographs into the description of the FFSI categories.

Additional work is needed to refine the FFSI and further develop clearly defined categories consistent with a larger case study pool. Also, more work is necessary to account for some of the concerns that were raised during the interview process. NWS forecasters highlighted three main challenges in regard to the development of the FFSI including (1) choosing criteria for the scale, (2) the generalizability of the scale across different topographies and flash flood types, and (3) the difficulty for the forecasters to evaluate every flash flood. Some of these challenges may be able to be circumvented via the use of emerging technologies, including crowdsourcing and social media to verify and classify events, as well as the use of Unmanned Aerial Vehicles (UAVs) to cover large areas quickly and efficiently (Davis, 2013). However, further research and discussion are necessary to determine the feasibility of a universally applicable scale. Additionally, a testbed will need to be identified and implemented in order to evaluate the design, functionality, and applicability of the FFSI. Once these challenges have been addressed and a satisfactory FFSI is finalized, additional interviews of forecasters and other potential end-users will need to be conducted to gather input on further improvements that can be incorporated into the scale.

After a solid FFSI design is in place and an a priori database of categorized events is sufficiently populated for each area, forecasters may begin to recognize patterns and characteristics of previous events and compare current flash floods to those of the past. Therefore, over time, the index has the potential to be applied as a warning tool used to communicate risk, one of the common expressed desires among the first round of interviewees. This is possible because once commonalities are established for an area, forecasters could potentially issue warnings that include potential FFSI categories into the impact statements, as they sometimes do with the EF-Scale for tornadoes. This could lead to more concrete communication of the magnitude of the threat to emergency management officials, city planners, the media, and the general public during an event, which has the potential to save additional lives. However, until the database is populated, the scale will merely provide a framework for scientists to discuss and compare the magnitude and severity of past flash flood events, which is still an area that has been identified as needing improvement.

Acknowledgements

This research was partially supported by National Science Foundation grant AGS-1157425. The Princeton Environmental Institute at Princeton University through the Mary and Randall Hack ‘69 Research Fund provided funding for the ninth co-author (B. Smith). The third co-author (J. Hardy) was supported by the National Science Foundation Graduate Research Fellowship Program under Grant no. DGE-1102691. Partial funding for the tenth author was provided by NOAA-University of Oklahoma Cooperative Agreement #NA11OAR4320072, U.S. Department of Commerce The authors would like to acknowledge all who participated in the SPREAD workshops for their contributions to the discussions that formed the FFSI project. Additionally, the authors would like to thank all the interview participants for contributing their time, and the NSSL Deputy Director, Lans Rothfusz, for input early in the development process. Comments from an anonymous reviewer and Dr. Massimiliano Zappa improved the quality of the manuscript. Their time and attention to the review process is greatly appreciated.

References

Alfieri, L., Velasco, D., and Thielen, J., 2011. Flash flood detection through a multi-stage probabilistic warning system for heavy precipitation events, *Adv. Geosci.,* **29,** 69-75.

Alfieri, L., Pappenberger, F., and Wetterhall, F., 2014. The extreme runoff index for flood early warning in Europe, *Nat. Hazards Earth Syst. Sci.,* **14,** 1505-1515.

Alfieri, L. and Thielen, J., 2015, A European precipitation index for extreme rain-storm and flash flood early warning. *Met. Apps,* **22**, 3-13.

Ashley, S.T., Ashley, W.S., 2008. Flood fatalities in the United States. *Journal of Applied Meteorology and Climatology*. **47,** 805-818.

Ashley, W.S., Krmenec, A.J., Schwantes, R., 2008. Vulnerability due to nocturnal tornadoes. *Weather and forecasting*. **23,** 795-807.

Barredo, J. I., 2007. Major flood disasters in Europe: 1950-2005. *Natural Hazards.* **42,** 125-148.

Bell, H.M., Tobin, G.A., 2007. Efficient and effective? The 100-year flood in the communication and perception of flood risk. *Environmental Hazards.* **7,** 302-311.

Blaikie, P., Cannon, T., Davis, I. and Wisner, B., 2014. *At risk: natural hazards, people's vulnerability and disasters*. Routledge.

Boeije, H., 2009. *Analysis in qualitative research*. Sage publications.

Castillo, V., Gomez-Plaza, A., Martınez-Mena, M., 2003. The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. *Journal of Hydrology*. **284,** 114-130.

Clark, R. A., J. J. Gourley, Z. L. Flamig, Y. Hong, Clark, E., 2014. CONUS-wide evaluation of National Weather Service flash flood guidance products, *Weather and Forecasting*, **29,** 377-392. doi:10.1175/WAF-D-12-00124.1.

Cutter, S.L., Emrich, C.T., Webb, J.J. and Morath, D., 2009. Social vulnerability to climate variability hazards: A review of the literature. *Final Report to Oxfam America*, *5*.

Davis, R.L., 2013. The practicality of utilizing unmanned aerial vehicles for damage assessments. Austin Fire Department, http://www.usfa.fema.gov/pdf/efop/efo48084.pdf.

Davis, R. S., 2001. Flash flood forecast and detection methods. *Severe Convective Storms*, C. A. Doswell, III, Ed., Amer. Meteor. Soc., 481-525.

Denzin, N.K. and Lincoln, Y.S., 2008. *Collecting and interpreting qualitative materials* (Vol. 3). Sage.

Doswell, C. A., III, H. E. Brooks, R. A. Maddox, 1996. Flash flood forecasting: an ingredients-based methodology. *Weather and Forecasting*, **11,** 560-581.

Doswell, C.A., Brooks, H.E., Dotzek, N., 2009. On the implementation of the enhanced Fujita scale in the USA. *Atmos.Res.* **93,** 554-563.

Elmore, K.L., Flamig, Z., Lakshmanan, V., Kaney, B., Farmer, V., Reeves, H.D., et al., 2014. mPING: Crowd-sourcing weather reports for research. *Bull. Amer. Meteor.. Soc.*, **95,** 1335-1342.

Few, Roger. "Health and climatic hazards: framing social research on vulnerability, response and adaptation." Global Environmental Change 17.2 (2007): 281-295.

Fujita, T.T., Fujita, T.T., Fujita, T.T., 1971. Proposed characterization of tornadoes and hurricanes by area and intensity, University.

Given, L.M. ed., 2008. *The Sage encyclopedia of qualitative research methods*. Sage Publications.

Gagan, J.P., Gerard, A., Gordon, J., 2010. A historical and statistical comparison of “Tornado Alley” to “Dixie Alley.”. Natl.Wea.Dig. 34, 145-155.

Gotvald, A.J., McCallum, B.E., 2010. Epic flooding in Georgia, 2009. US Geological Survey Fact Sheet. 3107.

Groisman, P.Y., Knight, R.W., Easterling, D.R., Karl, T.R., Hegerl, G.C., Razuvaev, V.N., 2005. Trends in intense precipitation in the climate record. *J. Clim.* **18,** 1326-1350.

Gruntfest, E., Carsell, K., Plush, T., 2002. An Evaluation of the Boulder Creek Local Flood Warning System. University of Colorado at Colorado Springs, Colorado Springs.

Gutowski, W., Hegerl, G., Holland, G., Knutson, T., Mearns, L., Stouffer, R., et al., 2008. Causes of observed changes in extremes and projections of future changes, in: Karl, T.R., Meehl, G.A., Miller, C.D., Hassol, S.J., Waple, A.M., Murray, W.L., (Eds), Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean and US Pacific Islands. U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

IPCC, 2013. Summary for Policymakers, in: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., et al., (Eds), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Keller, C., Siegrist, M., Gutscher, H., 2006. The role of the affect and availability heuristics in risk communication. *Risk analysis.* **26,** 631-639.

Leopold, L.B., 1968. Hydrology for urban land planning--A guidebook on the hydrologic effects of urban land use. Circular 554.

Ludy, J., Kondolf, G.M., 2012. Flood risk perception in lands “protected” by 100-year levees. *Nat.Hazards.* **61,** 829-842.

Maddox, R. A., C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and meso-alpha aspects of flash flood events. *Bull. Amer. Meteor. Soc.,* **60,** 115–123.

MartõÂnez-Mena, M., Albaladejo, J., Castillo, V., 1998. Factors influencing surface runo generation in a Mediterranean semi-arid environment: Chicamo watershed, SE Spain. *Hydrol. Process.* **12**, 741-754.

McDonald, J.R., Mehta, K.C., 2006. A recommendation for an enhanced Fujita scale (EF-scale), Wind Science and Engineering Center, Texas Tech University.

Milly, P., Julio, B., Malin, F., Robert, M., Zbigniew, W., Dennis, P., et al., 2007. Stationarity is dead. *Ground Water News & Views*. **4,** 6-8.

Min, S., Zhang, X., Zwiers, F.W., Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. *Nature*. **470**, 378-381.

Morss, R.E., 2005. Problem definition in atmospheric science public policy: The example of observing-system design for weather prediction. *Bull. Amer. Meteor. Soc.*, **86,** 181-191.

National Center for Environmental Decision-Making Research (NCEDR), 1998. Stakeholder Participation in the U.S. National Assessment of Possible Consequences of Climate Variability and Change: Suggested Guidelines for Doing It Right. . NCEDR/98- 19.

National Research Council (NRC), 2006. Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts. National Academy Press, Washington, DC. Available at: /http://books.nap.edu/catalog.php?record_id=11699S.

Norbiato, D., Borga, M., Degli Esposti, S., Gaume, E., Anquetin, S., 2008. Flash flood warning based on rainfall thresholds and soil moisture conditions: An assessment for gauged and ungauged basins. *Journal of Hydrology*. **362,** 274-290.

Noy, C., 2008. Sampling knowledge: The hermeneutics of snowball sampling in qualitative research. *International Journal of social research methodology*,***11*****(4)**, 327-344.

Palmer, W.C., 1965. Meteorological drought, US Department of Commerce, Weather Bureau Washington, DC, USA.

Patton, M.Q., 2005. *Qualitative research*. John Wiley & Sons, Ltd.

Potter, K.W., Walker, J.F., 1985. An Empirical Study of Flood Measurement Error. *Water Resour.Res.*, **21,** 403-406.

Reed, S., Schaake, J., Zhang, Z., 2007. A distributed hydrologic model and threshold frequency-based method for flash flood forecasting at ungauged locations. *Journal of Hydrology*. **337**, 402-420.

Saffir, H., 1973. Hurricane wind and storm surge. *Mil.Eng.* **423,** 4-5.

Schumacher, R. S., 2016. The Studies of Precipitation, flooding, and Rainfall Extremes Across Disciplines (SPREAD) workshop: An interdisciplinary research and education initiative. *Bull. Amer. Meteor. Soc. (in press)*. doi: http://dx.doi.org/10.1175/BAMS-D-15-00084.1

Shepherd, M., Mote, T., Dowd, J., Roden, M., Knox, P., McCutcheon, S.C., et al., 2011. An overview of synoptic and mesoscale factors contributing to the disastrous Atlanta flood of 2009. *Bull. Amer. Meteor. Soc.*, **92,** 861-870.

Sivapalan, M., Samuel, J.M., 2009. Transcending limitations of stationarity and the return period: process-based approach to flood estimation and risk assessment. *Hydrol.Process.* **23**, 1671-1675.

Smith, G.E., 2010. Development of a flash flood potential index using physiographic data sets within a geographic information system.

Smith, B.K., Smith, J.A. 2015. The flashiest watersheds in the contiguous United States. *J. Hydrometeor*, **16**, 2365–2381. doi: http://dx.doi.org/10.1175/JHM-D-14-0217.1

Villarini, G., Smith, J.A., Serinaldi, F., Bales, J., Bates, P.D., Krajewski, W.F., 2009. Flood frequency analysis for nonstationary annual peak records in an urban drainage basin. *Adv.Water Resour.*, **32**, 1255-1266.

Wood, N.J., Good, J.W., Goodwin, R.F., 2002. Vulnerability assessment of a port and harbor community to earthquake and tsunami hazards: integrating technical expert and stakeholder input. *Nat.Hazards Rev.* **3,** 148-157.

Yan, Z., Han, J., Jiao, M., Chen, J., Ye, Q., Zhao, L., et al., 2012. Formation of an interactive user-oriented forecasting system: Experience from hydrological application in Linyi, Eastern China. *Acta Meteorologica Sinica.* **26,** 13-25.

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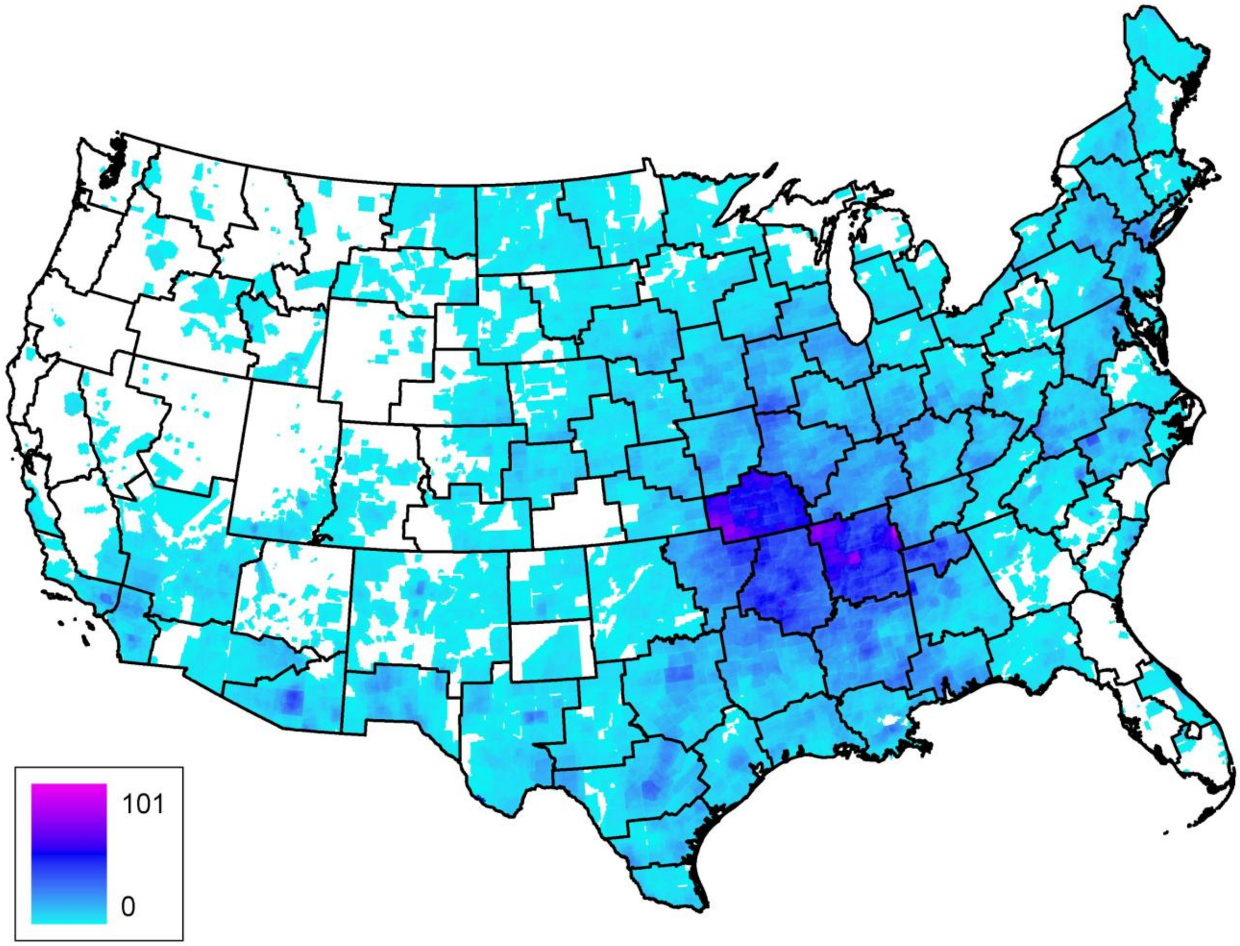

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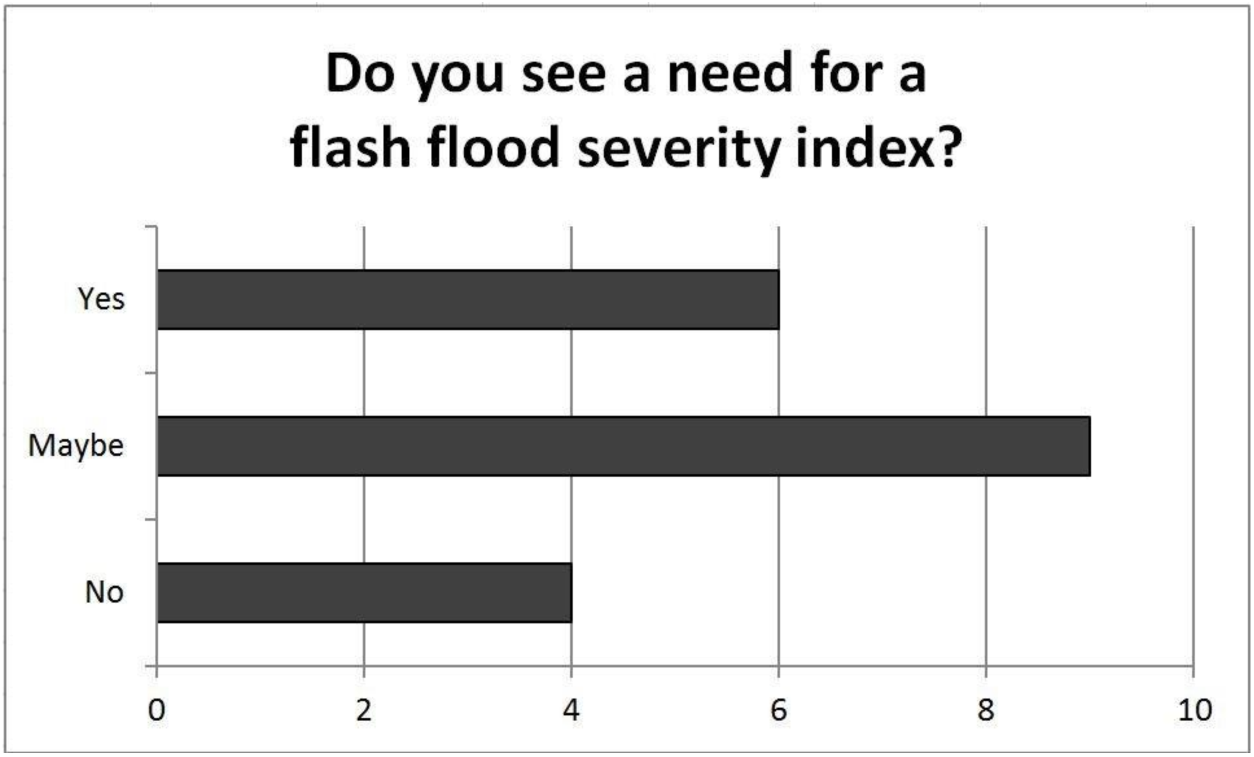

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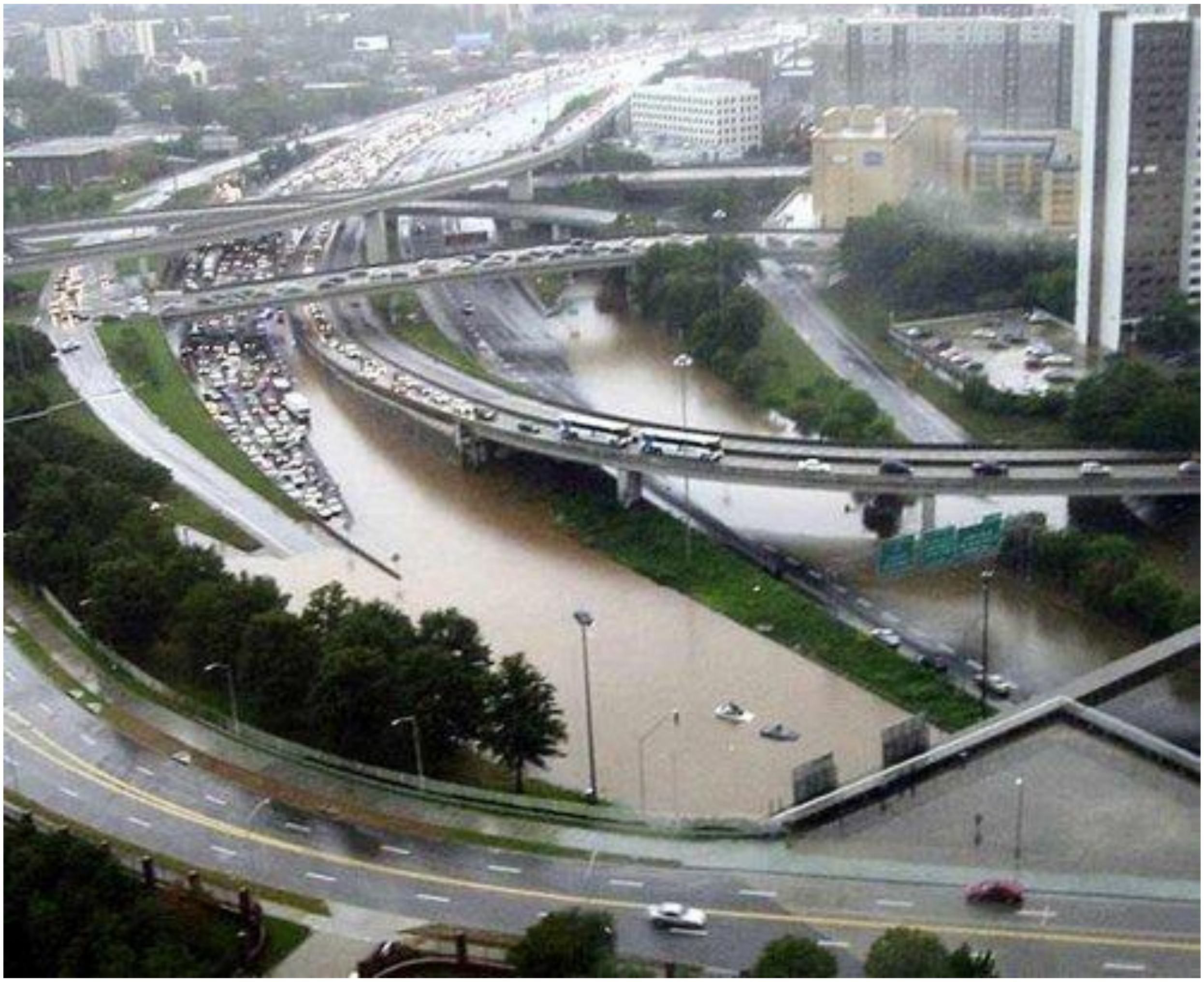

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Table 1

Proposed Flash Flood Severity Index.

Category	Impact
1 – Minor Flood	River/creek overflowing; cropland/yard/basement flooding
2 – Moderate Flood	Street/road flooding; road closures
3 – Serious Flood	Vehicles, homes and/or buildings inundated with water; road/bridge damage
4 – Severe Flood	Vehicles and/or mobile homes swept away
5 – Catastrophic Flood	Buildings/Large infrastructures submerged; permanent homes swept away