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The development of a flash flood severity index

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SUMMARY

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.

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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), MartõÂnez-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 (Maddox et al., 1979; Doswell et al., 1996; Davis, 2001; Alfieri et al., 2011, 2014; Alfieri and Thielen, 2015). 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

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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 2975 out of the total 8833 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 to 10 corresponding to the hydrologic sensitivity of the basin from least to most. These scaling factors are used to adjust a 25.4 mm h^{-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