



Analysis of flash flood parameters and human impacts in the US from 2006 to 2012



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SUMMARY

Several different factors external to the natural hazard of flash flooding can contribute to the type and magnitude of their resulting damages. Human exposure, vulnerability, fatality and injury rates can be minimized by identifying and then mitigating the causative factors for human impacts. A database of flash flooding was used for statistical analysis of human impacts across the U.S. 21,549 flash flood events were analyzed during a 6-year period from October 2006 to 2012. Based on the information available in the database, physical parameters were introduced and then correlated to the reported human impacts. Probability density functions of the frequency of flash flood events and the PDF of occurrences weighted by the number of injuries and fatalities were used to describe the influence of each parameter.

The factors that emerged as the most influential on human impacts are short flood durations, small catchment sizes in rural areas, vehicles, and nocturnal events with low visibility. Analyzing and correlating a diverse range of parameters to human impacts give us important insights into what contributes to fatalities and injuries and further raises questions on how to manage them.

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1. Introduction

Flash floods cause extensive disruptions to a diverse range of living, working, societal, and spatial environments, which make them one of the deadliest natural hazards worldwide. Flood damages do not only depend on precipitation amounts but are also a consequence of geomorphological factors and human influences. High velocity runoff in small basins, short lead times, fast rising water, and transport of sediments make flash floods extremely dangerous to property, infrastructure, and human lives (Creutin et al., 2013). The framework of this paper is an integrated analysis of temporal and spatial flash flood parameters and human impacts (injuries, fatalities). The aim is to cross-correlate them to identify the sensitivity of each parameter in order to shed light on the interplay between societal factors and the natural hazard.

In the field of flash flooding, Grunfest and Handmer (2001) emphasized interdisciplinary work by bringing social sciences into

physical sciences. Creutin et al. (2013) did the same with a framework for collaboration between hydrologists and social scientists. An integrated approach incorporates numerous layers that are, despite different aspects, interrelated and necessary for effective decision making and solving complex problems. Considering that the field of flash flooding is a complex blend of different sciences, we evaluated diverse parameters in an interdisciplinary way. There have been some studies that helped us understand different angles of analysis of flash flood fatalities. Jonkman and Kelman (2005) focused on 13 flood events that happened in Europe and the US in order to improve understanding of the circumstances of flood deaths and contribute to prevention strategies. Other studies have also focused on defining and understanding circumstances surrounding flood fatalities for different environments such as Australia (Coates, 1999) and Puerto Rico (Staes et al., 1994).

French et al. (1983) explored fatalities from 1969 to 1981 and pointed out a higher percentage of vehicle-related fatalities while Sharif et al. (2012) focused on vehicle fatalities specifically in Texas. Additional information about the cause of the vehicle-related deaths is needed in order to reduce their impact. Are drivers simply unaware of the dangers of water moving over the

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roadway? Do they have a false sense of security in their vehicle? Or perhaps they simply don't see the impending danger? Some of these social connotations were addressed by Ruin et al. (2008) who utilized qualitative research tools to explore information regarding flood victims on one hand and hydrometeorological circumstances on the other.

Creutin et al. (2009) has shown the influence of the watershed on society. Catchment response time is related to the size of the catchment, its geomorphological characteristics, and the natural hazard itself, thus it varies in space and time. Small catchments tend to be particularly vulnerable to human impacts because there are few structural defenses against flooding and individual exposure is enhanced (Drobot and Parker, 2007). Ruin et al. (2008) also showed through analysis of a major flooding event in the south of France in September 2002 that half of the flash flood fatalities occurred in catchments around 10 km² in area. Given the link between enhanced societal impacts and catchment response time, further consideration of additional factors is required in order to prevent fatalities, which may have been avoided due to mitigating actions and evacuations immediately following the onset of the storm (Montz and Grunfest, 2002).

The dynamics of small-sized catchments is complex as it includes geomorphological characteristics, degree of channelization, urbanization, and initial soil states and river conditions. The importance of catchment dynamics was analyzed by Costa (1987). The sample contained 12 of the largest flash floods in the conterminous United States, where in small basins (0.39–370 km²) the ratio of maximum rainfall-to-runoff was examined. He also evaluated factors such as the channel hydraulic radius, depth, velocity, energy, channel side slopes, shear stress, and unit stream power, among others. Results showed that shear stresses and unit stream powers produced by floods in small basins are higher by several hundred times than floods in large rivers. This was the case even with the small basins that had lower unit discharges. This indicates that floods are not controlled by absolute discharges alone. This is just one aspect of small watersheds and it is important to point out the differentiation from larger basins when examining human impacts. Connecting and defining human impacts with size of the watershed is important for forecast improvements and flash flood damage reduction and mitigation.

In this study, the distributions of human impacts from flash flooding (fatalities and injuries) vs. events with no human impacts are evaluated as a function of basin size, population density, seasonality, time of day, and flood duration. This paper uses an interdisciplinary, socio-hydrological approach of analyzing hazardous events, in our case flash floods, and contributes towards better understanding of human vulnerability in this context. Due to the brevity of the six-year time period used in the study, it is not intended to provide a robust, climatological analysis of flash-flooding impacts as was done in Ashley and Ashley (2008). However, this time period corresponds to precise locations and times of reported flooding in the database and includes a very large sample of 21,549 events. Thus, the results reach well beyond case-based analyses to more statistically significant findings. The paper is organized as follows. The next section discusses the details of the data analysis framework. Then, we analyze several influencing factors on the human impacts, followed by a summary of results and conclusions.

2. Data analysis framework

In this study we used a recently assembled database of flash flooding described in Gourley et al. (2013), available at <http://blog.nssl.noaa.gov/flash/database/>, to carry out our analysis of crucial factors involved in human impact and non-human impact

flash-flood events. One component of the database includes *Storm Data* reports collected by the National Weather Service. These reports include extensive information about the event type, year, month, state, county, region, time zone, beginning date and time, end date and time, property damages, fatalities (direct, indirect), injuries (direct, indirect), flood cause, location (latitude and longitude), and event narratives. All of the indirect and direct fatality reports were grouped together, as well as for the injury reports. The time scale of collected data in the compiled database goes from October 2006 until 2012 and involves 21,549 flash flood events. There were 224 total reports of injuries and 326 fatalities in the database. *Storm Data* reports cover a much longer timeframe than that, but the recent six years have the reports stored as georeferenced polygons, whereas they were previously reported by political boundaries (i.e., by county). Population density, event duration, time of day, location, and basin size were all co-analyzed with human impacts for each event. Considering that 20,999 or 97.4% of flash flood events had no human impacts, it was important to include this group into the analysis for comparative purposes.

3. Results

3.1. Annual and interannual variability of flash flood events

Using descriptive statistics to characterize the dependency of impacts on the considered physical parameters provides an interdisciplinary approach to analyzing the societal factors of flash floods. It exposes various aspects of the problem and provides a more holistic understanding of flash flood impacts, a necessary first step before implementing mitigating practices and procedures. Fig. 1 shows the impacts across years for the high-resolution *Storm Data* reports from October 2006 through the end of 2012. Only three months of reports are included in 2006, which explains the low numbers for that year. The numbers of impacts are computed in terms of number of events per year with injuries, fatalities, and then those that yielded no human impacts, referred to hereafter as NHI events. Annual variations from October 2006 to 2012 reveal that injury and fatality events are correlated and there are two peaks in 2007 and 2010. NHI events have less interannual variability, but there was a noted lull in events in 2012, which coincided with a significant warm season drought that affected the southern Great Plains of the U.S.

Fig. 2 shows the monthly anomalies computed from the annual median values of injury, fatality and NHI events. Positive anomalies

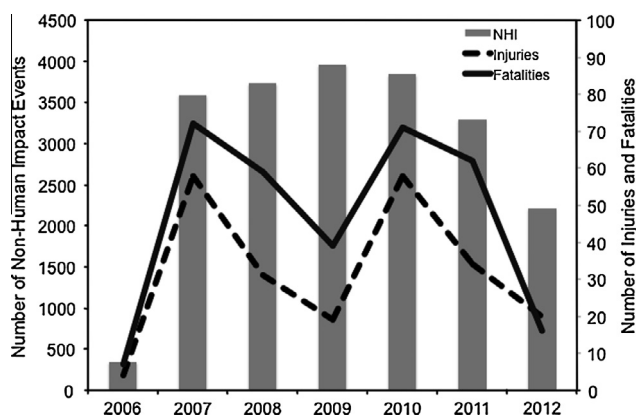


Fig. 1. Annual flash flooding events that resulted in no human impacts (NHI), injuries, and fatalities for the 6-year *Storm Data* database used in the study. Note that 2006 only contains events from October through December. The NHI events (gray columns) are plotted against the primary ordinate while the injuries and fatalities are on the secondary ordinate.

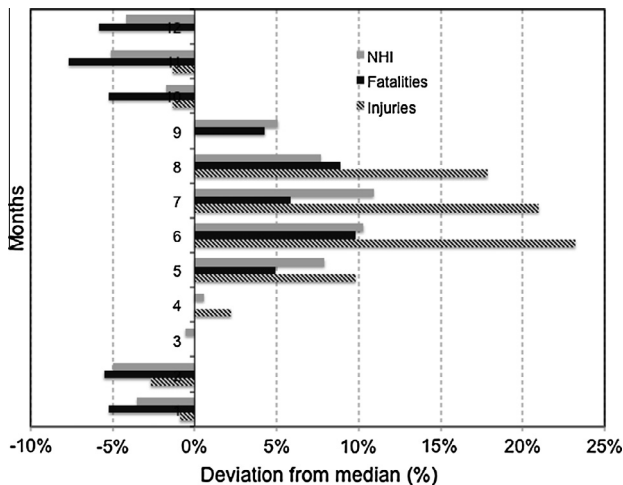


Fig. 2. Monthly deviations from the median of flash flooding events that resulted in no human impacts (NHI) (gray), injuries (hatched), and fatalities (black).

for all flash flood event types occur during the warm season from May through September. The maximum in fatality events occurs in June where the deviation from the median reaches 10%. Our results correlate with the fatality analysis done by Ashley and Ashley (2008) who showed the peak months being June, July, and August. Injury events are also a warm season phenomenon with positive anomalies reaching 23% in June, 21% in July, and 18% in August. NHI events have the same seasonal trend as those that had human impacts, but there is a peak in the anomalies in July (11%) instead of June.

The warm season preference of all flash flooding events is primarily related to the spatio-temporal pattern of rainfall over the continental United States rather than societal factors. Extreme rainfall events are uncommon (2.6% of total rain occurrence) but contribute significantly to the total rain volume (Lin and Hou, 2012). Strong diurnal thunderstorms frequent the Great Plains as early as March. As the warm season commences, diurnally forced thunderstorms become more of a phenomenon in mountainous regions, but they propagate across the Plains and yield a well-known nocturnal rainfall maximum (Wallace, 1975). Tropical cyclones that make landfall are also large contributors to heavy rainfall events (Schumacher and Johnson, 2006). Precipitation amounts are usually greater over the southeast part of the U.S. during summer, with a decreasing gradient from the coastal areas toward inland. The western U.S. receives less precipitation compared to the central and eastern parts, and the rainfall patterns are controlled more by the underlying terrain and position of the subtropical high. During the winter season, heavy rainfall is much less common and flash flooding events have strong negative anomalies from October through February. The seasonality of flash flooding events in the U.S. is more similar to that for the inland European countries (Slovakia, Austria, Romania) as shown in the compilation of flash flood events in Gaume et al. (2009). This contrasts significantly with the autumn maximum of flash floods that occurs in Spain, France, and Italy, all of which encompass the Mediterranean Sea.

3.2. Analysis of flash-flood parameters

The main goal of the study is to advance the understanding of flash-flood impacts beyond the primary influencing factor of heavy rainfall. Identifying and quantifying the influence of high-level impact parameters is crucial for a number of applications, such as improving the specificity of flash-flood warnings, increasing

emergency preparedness, and ultimately decreasing societal vulnerability. The considered flash flood parameters have been grouped into the three general categories: spatial, temporal and hydrological. The spatial category comprises population density and thus urban vs. rural events; the temporal category includes duration of the event and the time of day at which it occurred and the role of visibility and vehicles; finally, the hydrological category includes watershed size. Catchment size was computed in GIS by collocation of the events from the high-resolution *Storm Data* database to a DEM-derived flow accumulation map.

The next goal is to present an overall picture of the distribution of flash-flood events as they relate to each of the flash flood parameters. Probability density functions (PDFs) are used to describe and illustrate the relationship between each of the parameters and their corresponding impacts. Two types of PDFs are used to describe the influence of each parameter: (i) the traditional PDF by occurrence of flash-flood events (PDF_c) and (ii) the PDF of occurrences weighted by the number of injuries and fatalities (PDF_w). The PDF_c provides statistical information on the flash-flood distribution and highlights the sensitivity of flash-flood occurrence as a function of the factor considered; it is computed as a ratio between the number of the flash floods inside each (factor) bin to the total number of events. The PDF_w represents the relative contribution of each bin to the total number of injuries and fatalities; it is computed as a ratio between the sum of the injuries and fatalities inside each bin to the total sum of injuries and fatalities. In hydro-meteorological studies the PDF_w was computed with rainfall magnitude as the weighting factor (Wolff and Fisher, 2009; Amitai et al., 2009; Kirstetter et al., 2012). It is therefore an important characteristic of the flash flood from the perspective of evaluating their human impacts.

3.2.1. Spatial parameters

First, we analyzed the sensitivity of injury and fatality events on population density (Fig. 3). The aim is to discover which areas (urban, rural) are more commonly associated to injury, fatality, and NHI events. This parameter has significance on operational warning and verification procedures, because warnings tend to be issued more frequently in urban areas where people are present and can thus verify the issued warnings. Delineation between rural and urban categories is based on population density thresholds as shown in Table 1 following the classification criteria used by Cromartie and Bucholtz (2008). Three area groups are defined: urbanized area corresponding to places with densities over 386 persons per km^2 ; urban clusters with densities between 193 and 386 persons per km^2 , and rural areas with densities less than 193 persons per km^2 . Population densities were extracted from United States Census Bureau by each county for the year 2011.

The distributions of human-impacting and NHI flash-flood events as a function of population density are shown in Fig. 3a. The shapes of the PDF_c for injury and fatality events are similar indicating they tend to occur in similar areas with population densities lower than 386 people per km^2 , i.e., in rural areas and urban clusters. The fatality event PDF_c presents a slight shift towards higher densities compared to the injury event PDF_c . While the injuries PDF_c is rather monomodal with a maximum (>50%) around density = 1 person per km^2 , the fatalities PDF_c presents two modes around 1 and 10 people per km^2 .

Calianno et al. (2013) showed flash-flood impacts depend on population density. The plots of PDF_w of injuries and fatalities as functions of population density show rural areas are still more exposed than urban areas when it comes to flash flood vulnerability (Fig. 3b). Yet the contribution of flash floods over urban areas (above the threshold marked by the vertical line, which delineates urban areas from urban clusters) to the total injuries and fatalities is notable. The modes of PDF_w for both injury and fatality events

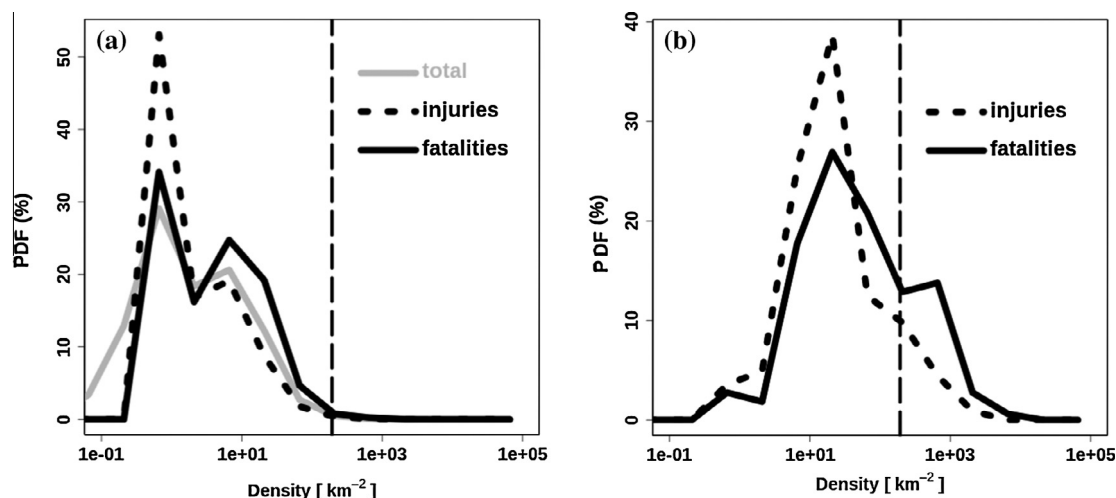


Fig. 3. Probability distribution by (a) occurrence (PDF_c) and (b) by occurrences weighted by the number of injuries and fatalities (PDF_w) of all flash flooding events (gray), injurious events (dashed black), and fatality events (solid black) as functions of population density. Threshold marked by the vertical line delineates urban zones from urban clusters as defined in Table 1.

Table 1

Classification based on the population density thresholds by Cromartie and Bucholtz (2008).

| Area type | Urban | Urban clusters | Rural |
|-------------------------------|------------|----------------|------------|
| Population density (km^2) | ≥ 386 | 196–386 | ≤ 196 |

are shifted toward higher densities (~ 20 people per km^2) compared to the PDF_c . This means that while injury and fatality events occur more frequently in rural areas, when they do occur in urban regions, they tend to injure and especially kill a lot more people for each event.

In general, the urban environment is considered to be more vulnerable to flash flooding due to channelization and lack of infiltration in the built environment. These factors tend to increase the volume and speed of runoff. The apparent vulnerability of rural areas to fatality and injury events found in this study may be explained by a number of factors. First, it is easier to implement mitigating strategies in an urban environment during a flash-flood emergency. First responders are in close proximity to the location of the floods in urban zones and are thus able to block flooded roadways and to rescue stranded motorists in a timely manner. Flash floods are defined by their short time scale, which may not leave sufficient time for mitigating strategies or help from lay people in rural areas. Another explanation involves less financial means to implement structural and non-structural measures for sustainable protection strategies (Jonkman, 2005), especially with dangerous low-water crossings (as opposed to built bridges), which can manifest in higher flash-flood fatality rates. Third, rural areas may be more associated to headwater catchments compared to urban zones, and thus have fast-reacting streams. This latter factor is examined later in Section 3.2.3.

3.2.2. Temporal parameters

The second category of flash-flood parameters involves the temporal characteristics of flash-flood duration and the time of day of occurrence. Flash-flood duration has been computed as a difference between beginning and end time of the event. Fig. 4 shows the PDF_c of events having caused injuries and/or fatalities (Fig. 4a) and the PDF_w of injuries and fatalities (Fig. 4b). The distributions of the flash-flood events for all categories are decreasing functions of the event duration. Most of the causative events occur

within 5 h. Flash floods exhibit similar PDF_c for injuries and fatalities (Fig. 4a) but in proportion more injurious events occur within 5 h than for fatality events. These differences are rather slight and most likely a result of the small sample size. Moreover, comparison of the PDF_c in Fig. 4a to the PDF_w in Fig. 4b yields small differences that are not significant. In summary, the analysis indicates that it is the very fast-reacting events that cause the most injuries and fatalities. Events with short duration give much less time for warnings to reach people and for emergency procedures to take place (i.e., road closures, rescues, evacuations), especially in remote, rural areas where human vulnerability has been shown to be higher in the previous section.

The time of day at which the events occurred is analyzed in Fig. 5. All times are taken as the event start time from the *Storm Data* database, and are reported as local time. The PDF_c of all events reveal a lull in activity during the overnight and early morning hours from 0300 to 1000 local time (Fig. 5a). The frequency of events increases steadily through the day for all categories reaching maximum values at 1700 local time for injurious events and for all events combined. The maximum frequency of fatality events occurs at 2100 local time, which is significantly later than for the other categories. The PDF_w analysis in Fig. 5b indicates maxima for both injurious and fatality events occur at 2100 local time. The shift of the maximum in the PDF_c for injurious events to the later time in the PDF_w indicates that injurious events are more common earlier, but when they do occur at night they result in much more injuries per event.

The signal of events being more impactful according to injuries and fatalities at 2100 local time (four hours later than the typical occurrence of rainfall and streamflow response) can be explained by societal factors. The extensive use of cars as a transportation mean in the U.S. plays a large role here as a very high proportion of flash-flood fatalities is related to vehicles (Kellar and Schmidlin, 2012). French et al. (1983) found 42% of the victims occurred in a vehicle and Ashley and Ashley (2008) computed numbers as high as 63%. Ruin et al. (2009) showed an increasing trend in vehicle-related deaths and also identified the significance of their occurrence during the late evening hours. Our analysis indicates that the total number of flash-flood events and the frequency of injurious events occurs at the intersection of the climatology of heavy rainfall during the warm season and rush hour (i.e., when people are commuting to/from work). While the events during the afternoon rush hour are frequently reported and often

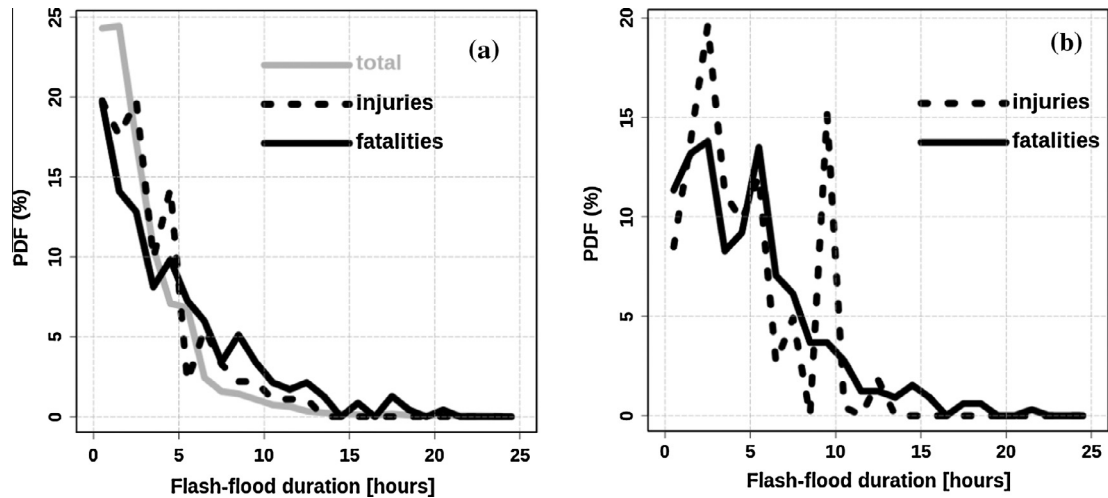


Fig. 4. Probability distribution by (a) occurrence (PDF_c) and (b) by occurrences weighted by the number of injuries and fatalities (PDF_w) of all flash flooding events (gray), injurious events (dashed black), and fatality events (solid black) as functions of event duration (in hours).

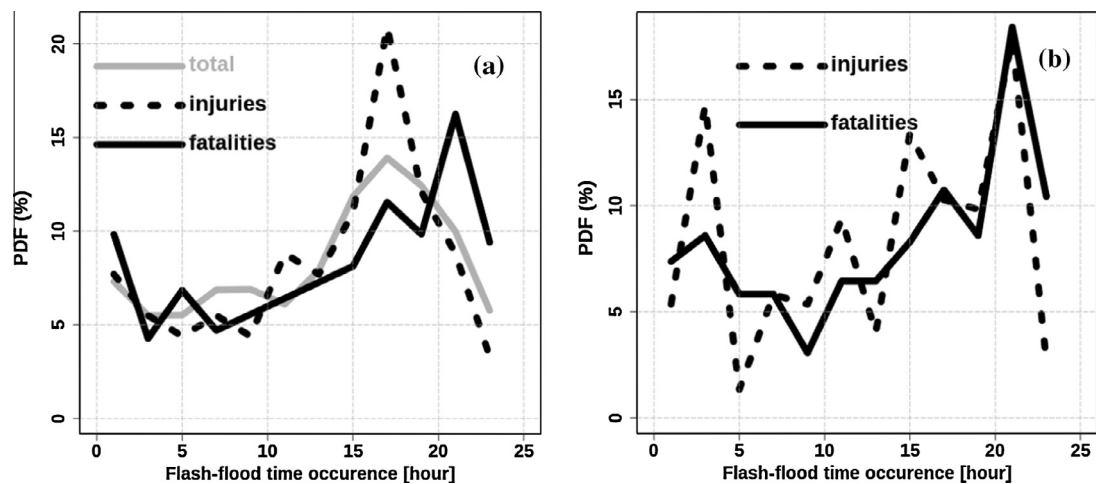


Fig. 5. Probability distribution by (a) occurrence (PDF_c) and (b) by occurrences weighted by the number of injuries and fatalities (PDF_w) of all flash flooding events (gray), injurious events (dashed black), and fatality events (solid black) as functions of the time of day (in local time) at which the events occurred.

trigger injuries and fatalities, the PDF_w curves show that the critical time when more human impacts happen is later in the evening in dark conditions.

It is hypothesized that fatality events become more numerous later because motorists are unable to see flooded roadways and enter them by accident. Fig. 6 shows the statewide distribution of local sunset time at the longest day of the year in June. We can see that a majority of the states have a local sunset time before 2100, which is the peak time for fatalities. The states that have sunset after 2100 are northern tier states that do not have flash-flooding events as predominantly as those in the southern tier states as shown by Ashley and Ashley (2008). So, we can conclude that visibility plays a role in the anomalously high fatality events that occur at 2100.

In order to better understand the role of vehicles, we examined the event narratives compiled in the *Storm Data* database for an in-depth analysis of the circumstances that led to death and injuries. Our aim was primarily to determine the role of vehicles in the human-impact events and analyze their occurrence as a function of time of day. Out of 326 total flash flood fatalities in the database, 222 (68%) were vehicle-related and 138 (62%) of injuries were also vehicle-related. These results agree quite well with the findings in Ashley and Ashley (2008). The temporal distributions of

vehicle-related fatalities and injuries are presented in Fig. 7. Low visibility appears to be an important factor for fatalities because 64% of them fall between the low-visibility hours of 2200 and 0600 local time, whereas 40% of injuries happen during the same time period. Fig. 7 shows secondary peaks in fatality events at around 0600 and 1800, both of which correspond to times when people are commuting to or from work. The distribution of injuries is more irregular and doesn't show a specific correlation with time.

Jonkman and Kelman (2005) contrasted US and European floods and concluded that the most striking difference appears to be vehicle-related deaths, which are a worse problem in the US than Europe. Vehicles, rather than public transportation, are used much more ubiquitously in the US by working commuters. The US has more rural roads that intersect with low-water crossings and arroyos in desert regions, which pose bigger threats. Lastly, large sport utility vehicles (SUVs) are much more prevalent in the US than in Europe. Despite their large sizes, Grunfest and Handmer (2001) reports that 0.61 m of rushing water is enough to float most vehicles including large trucks and SUVs.

3.2.3. Hydrological parameter

The last category considers the basin catchment area. Each flash-flooding event in the NWS *Storm Data* database is recorded

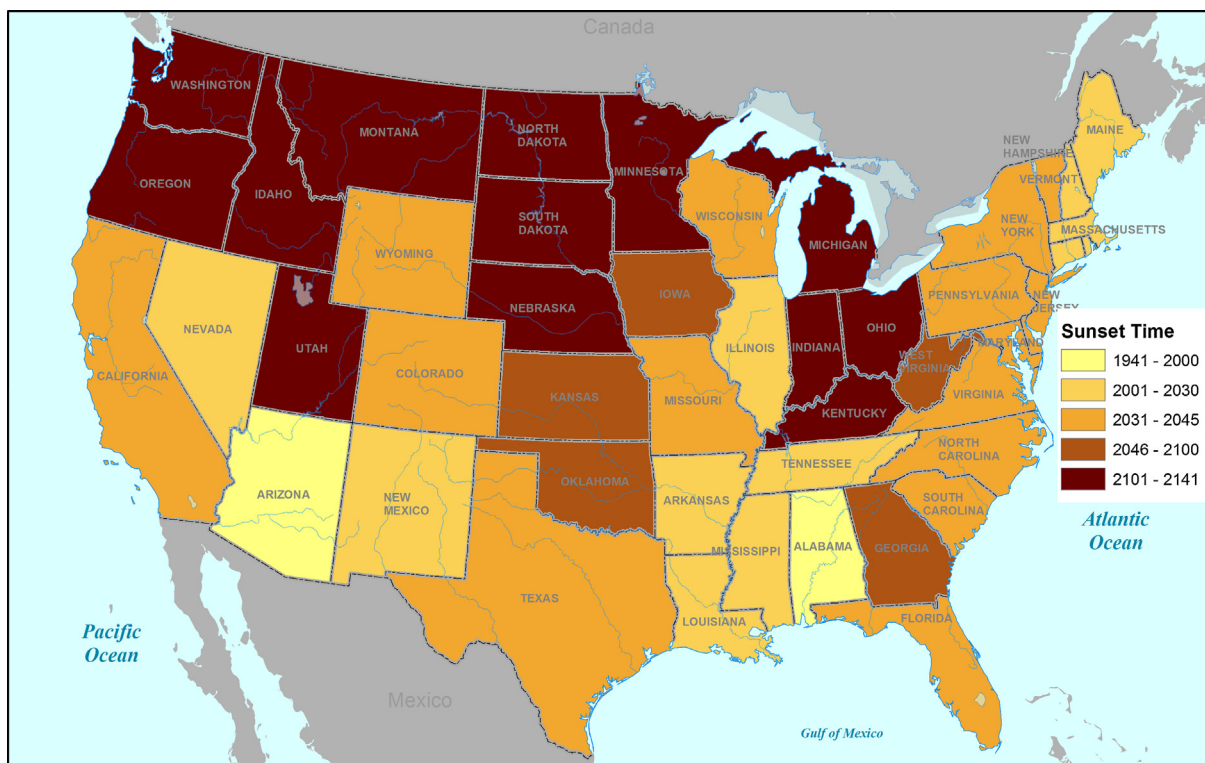


Fig. 6. Local sunset time for the northern solstice (21 June).

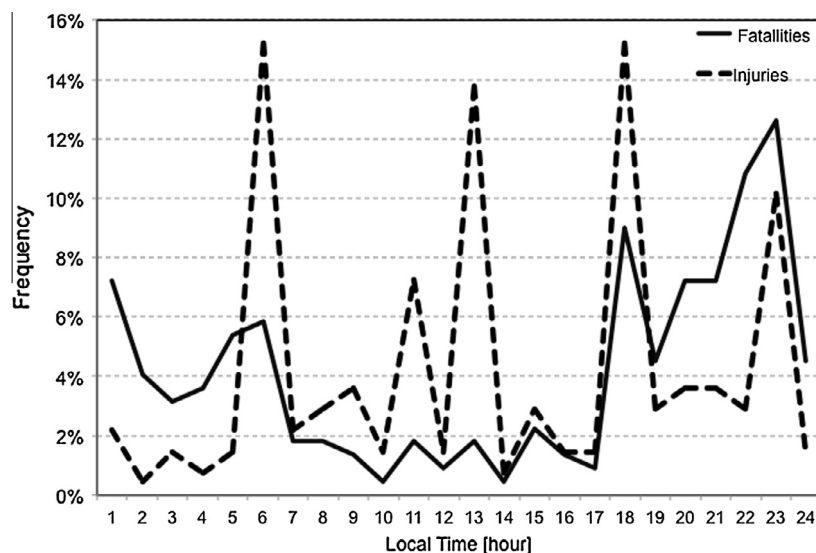


Fig. 7. Frequency of vehicle-related fatalities and injuries as a function of local time.

by latitude and longitude in decimal degrees. We collocated each event to a projected 250-m resolution flow accumulation grid using GIS procedures. Since the events were reported to 0.01° , the location could vary by 0.5 km in any direction. Considering this uncertainty, two delineations were run: one using the point locations as given in the database, and another using points that have been “snapped” to the nearest stream if within 0.5 km. Collocation with snapping shifted points onto the nearest stream within 0.5 km, so the contributing areas became larger but are more representative and realistic. The original data sample was 21,549 points over the CONUS. Since several events occurred over the

same watershed, the sample for this particular analysis was reduced to 19,173 unique point locations.

Fig. 8 explores the influence of the watershed size and shows that the vast majority of flash floods associated to injuries, fatalities, and NHI events all occur over the smallest catchments. The PDF_c of all categories of flash-flood events have single, well-defined modes at catchment areas of $0.125\text{--}0.3125\text{ km}^2$, corresponding to 2–5 contributing grid cells. The fact that the shapes of the PDF_c for all impact categories are nearly identical suggests that societal factors are insignificant in comparison to the dominant effect of small catchments on flash-flood impacts. The PDF_w for both

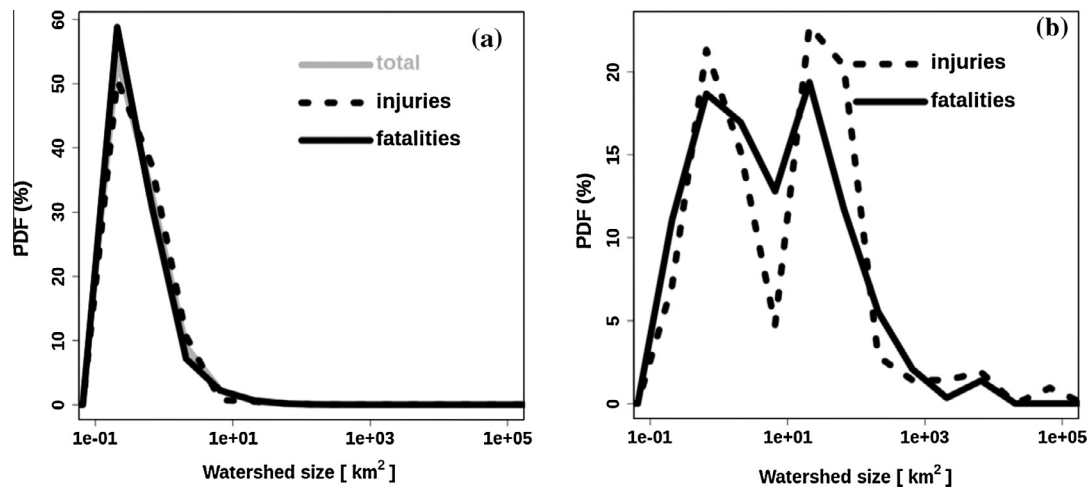


Fig. 8. Probability distribution by (a) occurrence (PDF_c) and (b) by occurrences weighted by the number of injuries and fatalities (PDF_w) of all flash flooding events (gray), injurious events (dashed black), and fatality events (solid black) as functions of basin catchment area, also referred to as watershed size (in km²).

injuries and fatalities present two modes as opposed to only one mode for the PDF_c. However, these are likely a result of sample size. The signal that is worth interpreting is the values in the PDF_w are shifted to the right of the maxima in the PDF_c yielding heavier tails in the distributions for catchments >100 km². This means that although the frequency of flash flooding is low for these larger catchments, when they do occur, they tend to result in greater numbers of injuries and fatalities per event. We noted the same behavior for the analysis of flash-flooding events conditioned on population densities. In summary, headwater catchments in rural areas are impacted most frequently and result in the most fatalities and injuries. Fatality and injury events are less frequent in urban zones or in basins with larger catchment areas, but a single event is likely to impact many more people living in these zones. Concerning the latter point, flash floods typically begin in the smallest catchments and then cascade as time progresses to larger scale basins. Our results indicate their impacts evolve during this dynamic period from occurring frequently and causing a great deal of human impacts early to less frequent occurrences but impacting many more people per event during the transition to larger scales. Clearly, a dynamic treatment of flash floods must be adopted when considering their impacts on society.

The effect of catchment scale on basin response time has been shown in numerous studies. Creutin et al. (2009) showed a response time of approximately 40 min for basin sizes of 0.65 km² up to 5 h for a basin of 165 km² in Europe. These response times depend on a number of factors including initial soil saturation, land surface conditions (e.g., degree of urbanization), steepness, rainfall intensity and duration, and may not apply to all events for a given basin or to other basins of similar sizes. Nonetheless, individuals may need to react quickly, on the order of minutes, in these small basins. This quick response has significant implications on the present mode of flash-flood monitoring and prediction used for warning the public by the NWS in the U.S. and beyond. First, flash-flood forecasting in ungauged basins poses significant challenges to hydrologic models due to the lack of observed streamflow to estimate parameters (Sivapalan et al., 2003). Alternative approaches to parameterization such as relying on physical parameters tied to observable land surface and soil properties are needed. Lead times can be increased through the use of more accurate precipitation forecasts (rather than radar-based estimates). Spatially accurate quantitative precipitation forecasts (QPFs) are rarely available at the small basin scale where flash floods occur. Novel probabilistic approaches are needed using ensemble QPFs. Even when the hydrologic forecasts are accurate, this does not

guarantee that the people in harm's way will react. It is proposed that probabilistic, impact-specific products may be a better utilization of observational and model outcomes in order to reach out to the public so that flash-flood warnings become actionable.

4. Conclusions

This study used a detailed database of 21,549 flash-flooding events from October 2006 to 2012 in the U.S. to characterize their spatio-temporal behavior and then introduced parameters that reveal societal factors for events that had (1) no human impacts (NHI), (2) injuries, and (3) fatalities. We adopted an interdisciplinary approach to aid in the interpretation of the results given that flash flooding has strong influences from meteorological, hydrological, and societal factors. The analysis relies heavily on the computation of probability distributions by occurrence (PDF_c) and the PDF of occurrences weighted by the number of injuries and fatalities (PDF_w) for different spatial, temporal, and hydrologic parameters. The hydrometeorological community has shown the utility of computing both these PDFs, as the latter one places more emphasis on those events that resulted in multiple injuries or multiple fatalities (rather than equating them to other events that may have had only a single injury or fatality). Interesting societal factors revealed themselves in the cases when the plots of PDF_c differed amongst the three flash-flood categories. Similarly, societal factors could be ascertained when the plots of PDF_c deviated from the PDF_w for a given flash-flood category. The main points from the study are summarized as follows:

- In terms of seasonality, there was a strong preference for the events to occur during the warm season months from May through September. Most fatality and injury events occur in the month of June.
- Fatality and especially injury events were much more common in rural areas than in urban regions. This characteristic was attributed to the lack of fast-responding units for rescues, evacuations, and road closures in rural areas. Further, the fact that rural areas are less populated also diminishes the chance to receive first help from lay people that could potentially reduce the impact. It is also possible that a lack of mitigating structures in rural areas, such as bridges over low water crossings cause more fatalities. Thirdly, rural areas tend to be collocated with headwater basins that respond much more quickly and provide less time for people to be warned and to react to impending flash flood disasters. The analysis of the PDF_w curves showed

that although urban regions had less frequent human-impacting events, when the events did occur, they resulted in much more significant impacts per event than in rural areas.

- The analysis that examined the duration of flash flooding events indicated that the shortest duration events (<1 h) caused the most fatalities, injuries, and NHI events. There were no discernible differences in the PDF_c and PDF_w curves for the different categories. This indicates that the event duration is a dominant factor for flash-flood impacts and overwhelms secondary factors. Evidently, it is quite important for warnings to reach people and for emergency procedures to take place (i.e., road closures, rescues, evacuations) in order to reduce human impacts. This becomes quite a challenging prospect for hydro-meteorological forecasting of short-duration, intense events, especially in rural areas.
- The frequency of flash-flood events for all three categories increased steadily during daylight hours. All events combined and injurious events were most frequent at 1700 local time. Fatality events were more common four hours later at 2100 local time. This analysis highlighted a strong societal component related to motorists and visibility. Rush hour is approximately 1700 and also coincides with the maximum in streamflow responses. NHI and injurious events reach maximum frequencies at this time due to the socio-hydrologic intersection. Fatalities, however, occur later after visibility is reduced after sunset. An in-depth analysis of circumstances of death showed that 68% of fatalities and 62% of injuries are vehicle-related. Low visibility is an important factor since 51% of fatalities happened between 2200 and 0500, while only 20% of the vehicle-related injuries occurred during these hours. Flooded roadways cannot be seen as easily and people drive into dangerous situations.
- Flash floods for all three categories were most common in very small catchments areas of 0.125–0.3125 km². The PDF_w analysis showed a shift toward larger catchment areas compared to the PDF_c curves. This suggests that while the large-basin flash flood events are less common, when small catchment flash floods propagate to larger scale basins with time, they have a much greater impact on humans per event than in the small basins. Flash floods need to be analyzed as dynamic, cascading processes with temporally evolving impacts on society.

This study advances the understanding of human impacts resulting from flash floods. It also highlights the challenges that remain to reduce the impacts. The principal factors that emerged for human impacts are rural areas, short-duration events, small catchment sizes, vehicles and events that occur during times with reduced visibility. These events are particularly challenging for implementing mitigating strategies because of relatively large distances to emergency services and first responders, lack of mitigating structures in rural areas such as bridges over small streams instead of low-water crossings, poor visibility at night, and less time for people to react to impending disasters. It is plausible that services from operational agencies like the National Weather Service could be modified to include precipitation forecasts into flash flood prediction systems and to make products probabilistic and specific to location and anticipated impact. However to reduce the vulnerability, future work should also delve deeper into the social dimension by examining human behaviors, perceptions, and specific reactions during flash-flood events.

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