Assessing flash flood hazard and damages in the southeast United States

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Abstract
Flash floods are common natural hazards in the southeast United States (SEUS) as a consequence of frequent torrential rainfall caused by tropical storms, thunderstorms, and hurricanes. Understanding flash flood characteristics is essential for mitigating the associated risks and implementing proactive risk management strategies. In this study, flash flood characteristics including frequency, duration, and intensity are assessed in addition to their associated property damages. The National Oceanic and Atmospheric Administration (NOAA) Storm Events database as well as hourly precipitation data of the North American Land Data Assimilation System project phase-2 (NLDAS-2) are utilised, and more than 14,000 flash flood events during 1996–2017 are analysed. Flash flood hazard is investigated at county, state, and regional levels across the SEUS. Results indicate increasing pattern for the frequency and intensity of flash flooding over the SEUS. The frequency of flash flooding is found to be higher in spring and summer, whereas the duration and intensity of events are higher during winter and fall, respectively. The western parts of the SEUS are prone to more frequent and intense flash flooding compared to the eastern parts. Overall, our analyses suggest that flash flood hazard in Louisiana is higher than other states in the SEUS.

KEYWORDS
duration, flash flood, frequency, hazard, intensity

1 | INTRODUCTION

Flash floods are among the most devastating natural hazards, which threaten human lives and properties in various regions of the world (Ahmadalipour & Moradkhani, 2019; Bezak, Šraj, & Mikoš, 2016; Miao, Yang, Yang, & Li, 2016). According to the National Weather Services (NWS), flash floods generally initiate within a few minutes up to less than 6 hr of an intense rainfall (Jalayer, Aronica, Recupero, Carozza, & Manfredi, 2018). The rapid onset of flash floods limits effective and timely decision making, and causes the highest number of casualties (on average) compared to the other types of flooding (e.g., coastal floods [storm surge] and river floods) (Jonkman, 2005). Flash floods caused the highest number of casualties among various flood events in the United States (Ashley & Ashley, 2008; Terti, Ruin, Anquetin, & Gourley, 2017). The frequency of heavy precipitation has been shown to increase under climate change (Halmstad, Reza, & Moradkhani, 2013; Ma et al.,...
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2018; Villarini et al., 2011; Zarekarizi, Rana, & Moradkhani, 2018). Therefore, it is expected that more people will be affected by flash flooding in the future (Kvočka, Falconer, & Bray, 2016).

More than 28,000 flash flood events have been reported across the United States during years 2007–2015 (Gourley et al., 2017). The most common driver of flash flooding is extensive rainfalls from tropical storms and thunderstorms (Smith & Smith, 2015). An indicator of the occurrence of thunderstorms is the cloud to ground (CG) lightning (Ntelekos, Smith, & Krajewski, 2007; Smith, Baecck, Ntelekos, Villarini, & Steiner, 2011). Investigation of the CG lightning over the Contiguous United States (CONUS) has indicated that the mean annual lightning density is the highest in the southeast United States (SEUS) (Orville & Huffines, 2001). The higher frequency of thunderstorms in SEUS compared to other regions shows that flash flooding is of paramount concern as well. In addition, hurricanes are often associated with widespread and torrential rainfalls, and SEUS is the hotspot of hurricane landfalls in the United States (Czajkowski, Simmons, & Sutter, 2011). Hence, due to the frequent occurrence of hurricane and thunderstorms in SEUS, flash floods are recurrent in the region, causing substantial financial damages every year.

Over the last two decades, a multitude of studies have been carried out to enhance flash flood forecasting (Abbaszadeh, Moradkhani, & Yan, 2018; Doswell, Brooks, & Maddox, 1996; Hardy et al., 2016; Norbiato, Borga, Degli, Gaume, & Valle, 2008; Reed, Schake, & Zhang, 2007; Tongal & Booij, 2018; Vergara et al., 2016; Villarini, Krajewski, Ntelekos, Georgakakos, & Smith, 2010; Vincendon, Ducrocq, Nuissier, & Vié, 2011; Yan & Moradkhani, 2016). Despite such progress, the dynamics of flash flooding and its potential impacts have not been thoroughly understood, particularly due to the uncertainties associated with rainfall forecasts (Hapuarachchi, Wang, & Pagano, 2011). Therefore, it is crucial to better understand flash flood characteristics and identify flash flood susceptibility, in order to promote proactive flash flood risk management and disaster mitigation strategies (Hapuarachchi et al., 2011).

Several studies have been conducted to investigate the characteristics of flash floods over the globe. Spitalar et al. (2014) analysed the onset, duration, and extent of flash flood events in the United States and reported the associated impacts, such as human injuries and fatalities. Trobec (2017) conducted a frequency analysis over 138 flash floods that occurred between 1951 and 2015 in Slovenia. He investigated the seasonal distribution of these flash floods and found most of them happening during summer or fall. Saharia et al. (2016) introduced a new index called flashiness, to measure flood severity over the CONUS. They proposed a model for prediction of flashiness for the entire CONUS using geomorphological and climatological variables. Recently, Khajehei, Ahmadalipour, Shao, and Moradkhani (2020) developed a socioeconomic vulnerability index at county scale across the CONUS while investigating multiple flash flood characteristics including duration, frequency, magnitude, and severity. Faccini et al. (2018) evaluated rainfall intensities that caused flash floods over Bosagno catchment in Italy and observed an increasing trend in short and intense rainfalls. Multiple studies have evaluated the connection between flash floods and rainfall spatial variability (Nikolopoulos, Anagnostou, Borga, Vivoni, & Papadopoulos, 2011; Zoccatelli, Borga, Zanon, Antonescu, & Stancalie, 2010). Additionally, a few studies have proposed flash flood indices to characterise hazard level. For instance, Smith (2010) developed the Flash Flood Potential Index by concatenating the watershed physiographic properties including soil type, forest cover, land use, and terrain slope to assess flash flood prone areas for a certain rainfall. Schroeder et al. (2016) presented a five-level post-event flash flood severity index to examine the physical damage associated with each flash flood. In addition, Alipour, Ahmadalipour, Abbaszadeh, and Moradkhani (2020) used a variety of influential factors including geographic, socioeconomic, and climatic features and machine-learning techniques to develop a risk-based model for prediction of flash flood damage.

Considering the substantial impacts of flash floods and the fact that there is still inadequate social awareness of regional causes and impacts (Lazrus, Morss, Demuth, Lazo, & Bostrom, 2016), a comprehensive analysis of the spatiotemporal characteristics of flash floods over the SEUS will be beneficial. In light of this concern, this study provides an assessment of the flash flood hazard by analysing the frequency, duration, and intensity of the flash flood induced storms happened during the 1996–2017 period across the region. The seasonal patterns and the spatial attributes are extracted, and the property damages caused by flash floods are also investigated and discussed. This study is among the first initiatives to utilise hourly gridded observed data as well as official records of flash flood events in order to characterise flash flood characteristics across the SEUS. The overarching goal of this study is to address the following objectives:

1. Assessing frequency, duration, and intensity of flash floods across the SEUS
2. Characterising the spatial heterogeneities and the seasonal patterns attributed to flash floods at regional scales
3. Investigating the property damages associated with flash floods and evaluating the role of flash flood intensity and duration on those damages
The remainder of this paper is structured as follows: Section 2 explains the data, study area and methods, and the results of the flash flood analyses including frequency, duration, and intensity along with discussions are provided in Section 3. The findings of the study are summarised in the final section.

2 | MATERIALS AND METHODS

The study area comprises nine SEUS including Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Tennessee, altogether named as southeast United States (SEUS) hereafter (see Figure 1). Table 1 provides a summary of the study area, presenting the number of counties and flash floods in each state and their property damages during the 1996–2017 period. According to the National Oceanic and Atmospheric Administration (NOAA), the climate of SEUS varies with latitude, topography, and the distance from Atlantic Ocean and Gulf of Mexico (NOAA, 2013). The region consists of both coastal plains and mountainous regions including the Ozarks and Appalッチans. In general, precipitation declines as moving away from the Atlantic-Gulf coast, except over the Appalachian Mountains. According to the 2010 Census estimation, more than 46 million people reside in SEUS (see Figure 1). The region is regularly affected by devastating flash floods.

![Figure 1](image-url)
and more than 14,000 flash flood events have been reported in the SEUS during 1996–2017 (see Table 1).

In this study, the NOAA storm events database as well as the North American Land Data Assimilation System (NLDAS-2) are utilised to characterise flash floods across the SEUS during the period of 1996–2017. Each data source is explicitly described in the following sections.

### 2.1 NOAA storm events database

The NOAA storm events database reports different types of natural disasters such as flash flood events since 1996 to present. Every flood event that occurs and meets the NWS criteria for flash flooding will be entered in the NOAA storm events database (NWS, 2016). The criteria that determines flash floods include the following:

- A river rising in a few hours and flowing out of its banks that was a threat to life or property and needed urgent response.
- A person or vehicle being swept away by the flowing water from runoff.
- A county or state road being closed due to high water.
- Six inches or more of rapid moving water flowing over a road or bridge threatening life or property.
- Three feet or more of ponded water threatening life or property.
- Any amount of runoff flowing into or causing damage to an above ground residence or building.

The NOAA storm events database provides a comprehensive description about each event, for instance, the beginning and termination date and time, location, the associated injuries and fatalities, amount of damage to properties and crops, and event narrative. The NWS of NOAA acquires these data from a variety of sources including trained spotters, county, state and federal emergency management officials, local law enforcement officials, damage surveys, newspaper clipping services, the insurance industry, and the general public. The associated damages of each event are presented in U.S. dollar values and they are retrieved from various sources including the U.S. Army Corps of Engineers, U.S. Geological Survey, utility companies, and newspaper articles. The presented time for the beginning of each flash flood is the local time that the event was observed, and it is not the time that a flash flood warning was issued. On the other hand, the reported ending of flash flood determines the time when the water diminishes and does not threaten lives and properties (NWS, 2016).

The NOAA storm events database is among the most comprehensive flash flood records that are available at a large scale for a relatively long period, and it has been used in various studies for analysing casualties and fatalities associated with extreme events (Ashley & Ashley, 2008; Shah et al., 2017; Sharif, Jackson, Hossain, & Zane, 2015).

In this study, we have utilised the NOAA storm events database to assess the frequency, duration, and property damage of flash floods. The data is event-based, and they are extracted for each county and state, in order to investigate the regional and state-level spatiotemporal patterns.

### 2.2 NLDAS-2

The intensity of flash floods is of crucial importance besides their frequency and duration. However, the NOAA storm events database does not provide information about the intensity of flash flood events. Therefore, in order to assess the intensity of flash floods, we investigate the precipitation that occurred during each event (i.e., corresponding to the affected region during the event time) as the driving force of flash flooding. To this end, hourly precipitation data is acquired from the Phase 2 of the North American Land Data Assimilation System (NLDAS-2) at 1/8° (about 12 km) spatial resolution (Xia et al., 2012). The hourly NLDAS-2 precipitation data are generated from different data sources including daily gauge observations of the National Center for Environmental Prediction Climate Prediction Center with monthly Parameter-elevation Regressions on Independent Slopes Model adjustments, hourly National Weather Service Doppler Stage II radar-based precipitation, half-

| State       | No. of counties | No. of flash flood events | Property damage (USD) |
|-------------|-----------------|--------------------------|-----------------------|
| Alabama     | 67              | 2,027                    | $1.2 B                |
| Arkansas    | 75              | 2,079                    | $348 M                |
| Florida     | 67              | 705                      | $621 M                |
| Georgia     | 159             | 976                      | $162 M                |
| Louisiana   | 64              | 1,450                    | $3.7 B                |
| Mississippi | 82              | 2,004                    | $503 M                |
| North Carolina | 100       | 2,154                    | $277 M                |
| South Carolina | 46          | 941                      | $164 M                |
| Tennessee   | 95              | 1,981                    | $543 M                |
| Total       | 755             | 14,317                   | $7.5 B                |
hourly NOAA CPC Morphing Technique data, and 3-hourly North American Regional Reanalysis (NARR) precipitation data.

Since flash floods generally occur in small catchments of usually less than 1000 km² (Llasat, Marcos, Turco, Gilabert, & Llasat-Botija, 2016; Villarini et al., 2010), the hourly NLDAS-2 precipitation is upscaled to 0.3° grid cell (using bilinear interpolation), so that each grid cell corresponds to an area of about 1000 km². Although some studies used catchment area in their flash flood analyses, in this study we use a 0.3° grid size (almost 1,000 km²) for consistency and simplicity, since we are evaluating more than 14,000 events, many of which were pluvial events that happened in smaller parts of a basin and not necessarily at the outlet. Then, the location, start time, and duration of each flash flood event (acquired from NOAA storm events database) are utilised to extract the mean and accumulated precipitation that caused each event using the upscaled NLDAS-2 data. The calculated mean and the accumulated precipitation represent the flash flood intensity and severity, respectively. This is performed separately for each of the 14,317 flash flood events considering their specific location, onset, and duration.

3 | RESULTS AND DISCUSSION

3.1 | Frequency of flash floods

The frequency of flash flooding has been the subject of many studies (Ballesteros-Cánovas et al., 2015; Papagiannaki, Lagouvardos, Kotroni, & Bezes, 2015). The number of flash flood events reported in the NOAA storm events database is extracted for each county during the 1996–2017 period, and the results are shown in Figure 2a. The total number of flash flood events, the number of flash flood events that caused property damage, and the ratio of these two during 1996–2017 are shown in Figure 2a–c, respectively. The total number of flash floods (Figure 2a) indicates that flash flood frequency is higher in western counties of SEUS, whereas Georgia and Florida have the least number of events. The counties that indicate the largest number of flash flooding are two of the South Carolina counties, Charleston and Richland with 217 and 152 events, respectively, both of which are located in the eastern part of the state. The markedly high number of flash flooding in these counties is mainly caused by torrential precipitation of short duration, which is aggravated by relatively old drainage systems and flat topography of these counties (Morsy, Goodall, Shatnawi, & Meadows, 2016; Kanmani, Karen, Sierra & Michael, 2015).

Focusing on Figure 2b, the number of damaging flash floods is higher in the western counties compared with the eastern regions. It is also noticed that flash flood events in most of the North Carolina counties did not trigger considerable property damage. Richland County in South Carolina and Hinds County in Mississippi experienced the highest number of damaging flash flood events with 130 and 103 damaging flash floods, respectively. In general, damaging flash floods have been mostly observed in western Mississippi, Louisiana, and Arkansas.

Figure 2c shows the ratio of flash floods that caused property damage during 1996–2017. Although the frequency of flash floods in Georgia and Florida is relatively low, most of the events were destructive, implying that these states are more vulnerable to flash flooding. Vulnerability of a system is defined as the level of its susceptibility to harm from exposure to hazard (Ahmadalipour & Moradkhani, 2018). The counties with
high vulnerability to flash flooding have generally experienced higher damage (Koks, Jongman, Husby, & Botzen, 2015). In that sense, Mississippi, South Carolina, and Louisiana are identified to be susceptible to flash flooding, whereas most of the counties in North Carolina indicate low damaging ratios.

Figure 3 represents the timeseries of the total (subplots a–e) and damaging (subplots f–j) flash floods occurred in each year during 1996–2017. The results are shown for annual (a and f) and seasonal timescales. As can be seen from Figure 3a,f, the total as well as the damaging flash floods indicate an increasing pattern for the annual timescale. The Mann Kendall test shows the existence of trends for both total and damaging flash floods with significance levels of .05 (p values of .0278 and .0131, respectively). The minimum number of flash flood events across the SEUS was in 2007, which was the year associated with widespread severe drought across the region according to the U.S. Drought Monitor (Svoboda et al., 2002). In contrast, the maximum number of flash flood events in the SEUS happened in 2009. This is in agreement with the NWS report which indicated

FIGURE 3  Timeseries of the number of flash floods for each state in the SEUS. (a–e) indicate the total number of flash flood events and (f–j) show the number of damaging events per year. Subplots (a) and (f) correspond to the annual timescale, and the other subplots present the results for each season. SEUS, southeast United States
that thunderstorms brought extensive rainfall, leading to numerous flash floods during 2009 (NOAA, 2009a, 2009b). Figure 3 indicates that during fall 2015 number of flash floods in South Carolina was significant. Several hydro-meteorological factors, such as the deep tropical moisture of hurricane Joaquin, produced intense rainfall over South Carolina during fall 2015. In the first week of October 2015 only, some parts of South Carolina experienced 20 in. of rainfall (Mizzell, Malsick, & Tyler, 2016). Later in February and March 2016, Mississippi experienced severe storms with tornadoes and thunderstorms, causing record flash flooding across the state (Breaker, Watson, Ensminger, Storm, & Rose, 2016).

The seasonal pattern of flash flood frequency (during the 1996–2017 period) was evaluated across the SEUS and each state, and the results are presented in Figure 4. Figure 4a,b indicate the proportion and distribution of the number of annual flash flood events in each season, respectively. As shown in Figure 4a, the majority of flash flood events over the SEUS occurred during summer and spring. In the western parts of SEUS (e.g., Arkansas and Louisiana), the primary season of flash flooding is spring; however, moving toward the eastern regions (the Carolinas, Florida, and Georgia), most of the flash flooding occurs in summer. The number of flash floods in Louisiana, Mississippi, Tennessee, and Alabama during winter is also considerable. In general, SEUS flash floods are found to be infrequent during fall. Although Figure 4a implies that in South Carolina, flash floods are more frequent in fall than spring, according to Figures 3 and 4b, such a pattern is considerably affected by the 2015 severe storms which is an outlier (Figure 4b). Considering the seasonal distribution of flash flood events (Figure 4b), summer is still the major flash flooding season in South Carolina.

3.2 | Duration of flash floods

The duration of flood events is one of the most important flood characteristics that affects the associated damages (Karagiorgos, Thaler, Hübl, Maris, & Fuchs, 2016; Marchi, Cavalli, Amponsah, Borga, & Crema, 2016). In this study, flash flood duration is calculated considering the initiation and termination date and time of each event reported in the NOAA storm events database. The flash flood onset is observed when the flood meets the criteria explained in Section 2.1, and the termination is when these criteria no longer apply. Flash flood duration is extracted for each of the 14,317 events across the SEUS, and Figure 5 shows the spatial distribution of mean duration of events that occurred in each county during

**FIGURE 4** (a) Pie charts showing the proportion of flash flood events in each season across the SEUS and each state, and (b) boxplots presenting the distribution of the number of annual flash flood events in each season during 1996–2017. SEUS, southeast United States.
1996–2017 at annual and seasonal timescales. In general, the mean duration of flash floods is higher in Louisiana and Florida, despite the fact that Florida did not experience frequent flash flooding (Figure 2a). Overall, most parts of the SEUS experienced short duration flash floods during spring, and southern coastal parts received prolonged flash floods in summer.

The reported ending time of a flash flood in the NOAA storm event database is when the flood waters receded to a level where there was no longer an immediate threat to life (NWS, 2016). Several flash flood events that lasted for a long duration occurred during the past two decades across the SEUS. The counties that are shown in yellow in Figure 5 correspond to some of these prolonged events (more than 2 days) and we describe some of the attributes of such events for further clarification. During March 1998, torrential rainfall caused flooding across Pasco County in Florida. This event devastated more than 100 homes and infrastructures, and caused 1.5 million dollars damage. Recently, Louisiana was extremely affected by two intense flash floods in 2016 (Watson, Storm, Breaker, & Rose, 2017). During March 2016, several severe thunderstorms caused widespread rainfall across northern Louisiana and southern Arkansas (Breaker et al., 2016). According to the NOAA storm events database, extensive flash flooding occurred across the northern half of the state due to the heavy rainfall. Consequently, several roads and bridges were washed out. Citizens of north Louisiana had to evacuate their houses and be accommodated in shelters provided by the Red Cross and local churches. The emergency management community announced it as an unprecedented devastating flood. Later in the same year, during August 2016, extensive thunderstorms and showers occurred in southern Louisiana and Mississippi, which resulted in heavy rainfall across the region, and caused 20–30 in. of precipitation happening in only 48 hr in St. Helena County (Van Der Wiel et al., 2017). The heavy rainfall led to catastrophic flash flooding and record river flooding. Ten billion dollars of damage was reported over southern Louisiana and southern Mississippi, in addition to the deaths of 12 people.

The timeseries of the total and mean duration of flash floods during 1996–2017 are displayed in Figure 6 for each state and the SEUS. This figure also shows the seasonal mean duration of flash floods across the region over this period. From Figure 6a, during 1999, the total duration of flash floods in North Carolina was markedly high due to heavy rainfalls associated with hurricanes Floyd, Dennis, and Irene (Atallah & Bosart, 2003; Bales, Oblinger, & Sallenger, 2000). In 2009, numerous flash floods occurred across the state of Arkansas (NOAA, 2009a), and the high number of flash flood events during this year led to prolonged total durations of flash flooding in Arkansas, as seen in Figure 6a. In Figure 6b, the severe 2016 Louisiana flash flooding shows its impact on the state mean duration in this year. In the states of Florida and South Carolina, a decreasing trend in mean duration of events can be observed (Mann Kendall trend test with .0016 and .0321 p values, respectively) (Figure 6b).

Figure 6c indicates that the total (shown in blue) and mean (shown in red) duration of flash floods over the
SEUS reached their lowest value in 2007, due to the widespread droughts that affected majority of the SEUS in that year (Li, Luo, & Wood, 2008). Similarly, the total and mean duration of flash floods in 2000 indicate the least values as a consequence of protracted drought in that year (Barber & Stamey, 2000). The 2016 Louisiana flooding substantially increased the total and mean duration of flash floods in the region.

Figure 6d indicates that the mean duration of flash flood events is higher in fall and winter over the SEUS. Generally, the SEUS flash flood events have the lowest duration in spring compared to other seasons. In the western states (i.e., Arkansas, Louisiana, Mississippi, and Tennessee), the mean duration of flash floods is higher in winter, whereas in the eastern states, mean duration of flash flooding is higher during fall. Overall, the mean duration of flash flooding in Mississippi and South Carolina is lower than that of other states.

3.3 | Intensity of flash floods

Since a flash flood occurs within 6 hr after the causative rainfall starts, we defined the intensity of flash flood as the average precipitation that a region receives from 6 hr before the flash flood’s onset until the event’s termination. Similarly, severity of the event is defined as the total precipitation in the same timeframe. The role of rainfall intensity on flash flood events has been investigated in several studies (Saulnier & Le Lay, 2009; Varikoden, Preethi, Samah, & Babu, 2011). The intensity of flash floods is therefore extracted from the NLDAS-2 data separately for each of the 14,317 events. In addition, the severity of flash floods is also assessed by analysing the total precipitation that occurred corresponding to each event. Figure 7 shows the long-term average intensity (a) and severity (b) of flash floods that occurred in each county at annual and seasonal time scales. Overall, the intensity and severity of events are higher in western regions. Louisiana and most of the counties near the Gulf of Mexico generally experience higher severity of flash floods, whereas Tennessee and Georgia are mostly identified by lower intensities and severities.

Several counties in North Carolina and Louisiana indicate exceptionally high values of flash flood intensity and severity, thus some of these events are described here for further clarification. On October 2016, Hurricane Matthew poured 8–15 in. of torrential rainfall over the
central and eastern parts of North Carolina and caused several catastrophic flash floods, resulting in numerous washed out roads and the deaths of 14 people (Musser, Watson, & Gotvald, 2017). The approximate property and crop damage of these flood events was more than $800 million. In addition to Hurricane Matthew, on August 2011, the heavy rainfall associated with Hurricane Irene promoted flash flooding across 11 counties in North Carolina including Hyde and Tyrrell counties (Williams, 2015). The state of Louisiana has also experienced frequent and severe flash floods. Apart from the previously mentioned 2016 flash flood events in Louisiana (Section 3.2), Hurricane Harvey (on August 2017) produced heavy rainfalls across the state of Louisiana, with extreme rainfall records up to 30 in. in the southwest parishes such as Calcasieu (Van-Olderborgh et al., 2017). This resulted in devastating flash flooding and consequently 1,572 damaged properties in that parish.

The seasonal and temporal variations of flash floods intensity and severity are investigated across the SEUS (Figure 8). Figure 8a shows the annual average intensity and severity of SEUS flash floods for each year, and Figures 8b displays their seasonal distribution. Overall, an increasing pattern is observed for the intensity of flash floods during the 1996–2017 period (Figure 8a). The minimum severity and intensity of flash floods happened in 2007, which corresponds to the year that widespread drought affected the region. According to Figure 8b, the
severity and the intensity of flash floods in the SEUS are higher in fall. Winter flash floods are also associated with relatively high intensity and severity. A possible explanation is that during fall and winter, the SEUS is highly affected by frontal systems, which can cause flash flooding (Ingram et al., 2013).

### 3.4 Property damage of flash floods

An approximation of property damage associated with each flash flood event is reported in the NOAA storm events database, and the reported data have been utilised here to assess the property damages caused by flash flooding. Figure 9 shows the mean (a) and total (b) property damages caused by flash floods in each county of the SEUS during 1996–2017 for annual and seasonal time-scales. Considering the mean damages at an annual timescale (Figure 9a), the average flash flood damage is found to be higher in southern Florida and Louisiana. Moreover, the total reported annual damage (Figure 9f) indicates that the majority of SEUS counties were substantially damaged by flash flood events, especially in the western parts.

The total property damage of flash flooding during 1996–2017 (Figure 9f) reaches above half a billion dollars in several counties. In 1999, Hurricane Irene prompted flash floods that caused millions of dollars of damage in several counties of Florida (Agusti-Panareda et al., 2004). Later, in May 2003, about 5–8 in. of rain occurred in just 1 hr in Jefferson County, Alabama—the most populated county in Alabama—which caused significant flooding across this county. Several bridges and roads along with other infrastructure were damaged, resulting in more than a billion dollars damage. Similarly in South Carolina, flash floods during the fall 2015 resulted in more than $100 million of property damage (Feaster et al., 2015). In addition, Louisiana parishes experienced many catastrophic flash flood events especially in 2016. For instance, the 2016 flash flooding in Livingston Parish caused $576 million in property damage alone (Wang et al., 2016).

Figure 10 shows the total (a) and mean (b) seasonal property damage over each state as well as the entire SEUS. Focusing on the SEUS (the last columns), the property damage is found substantially higher in spring and summer (in both plots a and b). The total and mean damage during summer and spring are higher than other seasons, which can be a result of high number of flash flood events in these seasons. The August 2016 Louisiana flash flooding resulted in considerably high damage in summer. In addition, severe property damages caused by the 2003 spring flash flooding in Jefferson County, Alabama, has had remarkable impact on the spring property damage shown in Figure 10. According to the result for the mean damage (b), flash floods in Florida are associated with significant damages. Meanwhile, frequency analyses (Figures 2a and 4b) indicated that flash floods are not common in Florida. Thus, although infrequent, flash flooding in Florida can be devastating.

Having quantified flash flood frequency, duration, intensity, and damage, the flash flood hazard is investigated considering the aforementioned characteristics, and the results are reported in Figure 11. The size, position, and colour of markers in Figure 11 illustrate the frequency, mean duration, mean intensity, and mean damage among the counties of each state in the SEUS during 1996–2017, respectively. The error bars indicate the variance (1 SD) of duration and intensity, plotted along the corresponding axes among the counties of each state. Figure 11 shows that the flash flood hazard in Louisiana (having high values for all characteristics) is higher than other states in the SEUS. In contrast, the states that had lower flash flood duration and intensity received less property damage. For instance, the duration and intensity of flash floods in Florida were relatively high, and...
flash floods in Florida are usually associated with higher damage (on average). In addition, Alabama and Arkansas experienced the highest number of flash flooding (i.e., they have the largest marker size), whereas flash floods in Georgia were infrequent (i.e., smallest marker size). In addition, flash floods in most of the South Carolina counties were associated with least duration and intensity values.

The monetary damage caused by flash flooding in the SEUS has increased (Figure S1). This may be due to a rise in the intensity, severity, or the frequency of flash floods. Liu, Hertel, Delgado, Ashfag, and Noah (2015) found a positive correlation between the frequency and intensity of flash flooding with the amount of damage they cause. The increase of the frequency and intensity of flooding can be due to increasing extreme precipitation, which is partly a consequence of climate change (Berg & Hall, 2015; Trenberth, 2011; Xi et al., 2018). In addition to climate change, land use alteration may highly affect the frequency of flash flooding (Wagner, 2007). Urbanisation, cultivation, and deforestation can aggravate flood impacts and may result in more intense flooding (Akter, Quevauviller, Eisenreich, & Vaes, 2018; Kong, Miao, Borthwick, Lei, & Li, 2018; Rogger et al., 2017).

4 | SUMMARY AND CONCLUSION

This study employed an exploratory data analysis to enhance our knowledge of the patterns, seasonality, regional characteristics, and trends of primary flash flood characteristics, namely intensity, severity, duration, and
property damages. We assessed over 14,000 reported flash flood induced storms in the region and extracted the details of their associated rainfall, which helped us determine the attributes of each flash flood event in the 1996–2017 period, and thus provided accurate and reliable characterizations of the regional spatiotemporal patterns. Notably, the hazardous regions and their seasonality are identified. Additionally, the property

FIGURE 10  (a) The total and (b) mean property damage of flash floods at a seasonal scale across each state and the SEUS during 1996–2017. SEUS, southeast United States

FIGURE 11  Composite plot of flash flood characteristics, namely, intensity, duration, frequency, and property damage across the SEUS states. The marker size, x and y axes, and marker colour represent the mean frequency, mean duration, mean intensity, and the mean property damage of flash floods per event, respectively. The error bars indicate the variation (1 SD) of duration and intensity (plotted along the corresponding axes) among the counties of each state. SEUS, southeast United States
damage of each region is extracted, and the role of each flood characteristic is investigated. It should be noted that these property damage estimates are subject to uncertainties. Follow-up studies can develop geospatial models to estimate the property damage of upcoming events for any part of the study area considering the rainfall forecast and regional domain attributes. In addition, the damage ratio (number of damaging events/total number of events) depends on various components of vulnerability, hazard, exposure, and geographical attributes of the region. Quantifying these underlying components and determining their impacts require thorough investigation of all possible affecting factors (such as the land use, drainage system, disaster response, adaptive capacity, exposure, critical infrastructure, and more), which is subject to further investigation.

The main findings of this study are summarised as follows:

- The frequency of flash floods has increased across the SEUS during the 1996–2017 period. In general, the frequency of flash floods is higher in the summer and spring. The primary season of flash flooding for western regions is spring, whereas in the eastern states (the Carolinas, Florida, and Georgia), summer is the dominant flash flooding season.
- Flash flood events across the SEUS are associated with higher duration in winter and fall. Most parts of the SEUS experience short duration flash floods during spring. Overall, the mean duration of flash floods is higher in Louisiana and Florida.
- The intensity of flash floods in the SEUS has increased during the 1996–2017 period. The flash floods that happened in fall were usually more severe and more intense compared with the other seasons. In general, the intensity and severity of events are higher in western parts of the SEUS. Louisiana and most of the counties that are located close to the Gulf of Mexico are generally associated with more severe flash floods.
- Flash floods have caused substantial damage in the majority of counties over the SEUS. In general, the average flash flood damage is higher in southern Florida and Louisiana. In particular, flash flood events in Florida are infrequent but devastating. Spring and summer are associated with the highest property damage caused by flash flooding across the SEUS.
- The property damages are proportional to flash flood intensity and duration. Flash flood hazard in Louisiana is found to be higher than other states in the SEUS. In contrast, the majority of South Carolina counties experienced low flash flood duration and intensity indicating less hazard compared to the other states in the SEUS.

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Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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REFERENCES
Abbaszadeh, P., Moradkhani, H., & Yan, H. (2018). Enhancing hydrologic data assimilation by evolutionary particle filter and Markov chain Monte Carlo. *Advances in Water Resources*, *111*, 192–204. https://doi.org/10.1016/j.advwatres.2017.11.011
Agusti-Panareda, A., Thorncroft, C. D., Craig, G. C., & Gray, S. L. (2004). The extratropical transition of hurricane Irene (1999): A potential-vorticity perspective. *Quarterly Journal of the Royal Meteorological Society*, *130*(598 PART A), 1047–1074.
Ahmadalipour, A., & Moradkhani, H. (2018). Multi-dimensional assessment of drought vulnerability in Africa: 1960–2100. *Science of the Total Environment*, *644*, 520–535. https://doi.org/10.1016/j.scitotenv.2018.07.023
Ahmadalipour, A., & Moradkhani, H. (2019). A data-driven analysis of flash flood hazard, fatalities, and damages over the CONUS during 1996–2017. *Journal of Hydrology*, *578*, 124106.
Akter, T., Quevauviller, P., Eisenreich, S. J., & Vaes, G. (2018). Impacts of climate and land use changes on flood risk management for the Schijn River, Belgium. *Environmental Science and Policy*, *89*, 163–175. https://doi.org/10.1016/j.envsci.2018.07.002
Alipour, A., Ahmadalipour, A., Abbaszadeh, P., & Moradkhani, H. (2020). Leveraging machine learning for predicting flash flood damages in the southeast US. *Environmental Research Letters*, *15*, 024011. https://doi.org/10.1088/1748-9326/ab6ed9
Ashley, S. T., & Ashley, W. S. (2008). Flood fatalities in the United States. *Journal of Applied Meteorology and Climatology*, *47*(3), 805–818.
Atallah, E. H., & Bosart, L. F. (2003). The Extratropical transition and precipitation distribution of hurricane Floyd (1999). *Monthly Weather Review*, *131*(6), 1063–1081. https://doi.org/10.1175/1520-0493(2003)131<1063:TETAPD>2.0.CO;2
Bales, J. D., Oblinger, C. J., & Sallenger, A. H. J. (2000). Two months of flooding in eastern North Carolina, September–
October 1999: Hydrologic, water quality, and geologic effects of hurricanes Dennis, Floyd, and Irene (Water Resources Investigations Report 00-4093). Retrieved from http://pubs.usgs.gov/wri/wri004093/

Ballesteros-Cánovas, J. A., Czajka, B., Janecka, K., Lempa, M., Kaczka, R. J., & Stoffel, M. (2015). Flash floods in the Tatra Mountain streams: Frequency and triggers. Science of the Total Environment, 511, 639–648. https://doi.org/10.1016/j.scitotenv.2014.12.081

Barber, N. L., & Stamey, T. C. (2000). Droughts in Georgia (No. 2000–380). https://doi.org/10.3133/ofr2000380

Berg, N., & Hall, A. (2015). Increased interannual precipitation extremes over California under climate change. Journal of Climate, 28(16), 6324–6334. https://doi.org/10.1175/JCLI-D-14-00624.1

Bezak, N., Šraj, M., & Mikloš, M. (2016). Copula-based IDF curves and empirical rainfall thresholds for flash floods and rainfall-induced landslides. Journal of Hydrology, 541, 272–284. https://doi.org/10.1016/j.jhydrol.2016.02.058

Breaker, B. K., Watson, K. M., Ensminger, P. A., Storm, J. B., & Rose, C. E. (2016). Characterization of peak streamflows and flood inundation of selected areas in Louisiana, Texas, Arkansas, and Mississippi from Flood of March 2016 (No. 2016–5162). U.S. Geological Survey

Czajkowski, J., Simmons, K., & Sutter, D. (2011). An analysis of coastal and inland fatalities in landfalling US hurricanes. Natural Hazards, 59(3), 1513–1531. https://doi.org/10.1007/s11069-011-9849-x

Doswell, C. A., Brooks, H. E., & Maddox, R. A. (1996). Flash flood forecasting: An ingredients-based methodology. Weather and Forecasting, 11(4), 560–581. https://doi.org/10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2

Faccini, F., Luino, G., Paliaga, G., Sacchini, A., Turconi, L., & de Jong, C. (2018). Role of rainfall intensity and urban sprawl in the 2014 flash flood in Genoa City, Bisagno catchment (Liguria, Italy). Applied Geography, 98(July), 224–241. https://doi.org/10.1016/j.apgeog.2018.07.022

Feaster, T. D., Shelton, J. M., & Robbins, J. C. (2015). Preliminary peak stage and streamflow data at selected USGS streamgaging stations for the South Carolina flood of October 2015 (Open-file report 2015–1201), 19. https://doi.org/10.3133/ofr20151201

Gourley, J. J., Flamig, Z. L., Vergara, H., Kirstetter, P. E., Clark, R. A., Argyle, E., et al. (2017). The flash project improving the tools for flash flood monitoring and prediction across the United States. Bulletin of the American Meteorological Society, 98(2), 361–372. https://doi.org/10.1175/BAMS-D-15-00247.1

Halmstad, A., Reza, M., & Moradkhani, H. (2013). Analysis of precipitation extremes with the assessment of regional climate models over the Willamette River basin, USA. Hydrological Processes, 27(18), 2579–2590. https://doi.org/10.1002/hyp.9376

Hapuarachchi, H. A. P., Wang, Q. J., & Pagano, T. C. (2011). A review of advances in flash flood forecasting. Hydrological Processes, 25(18), 2771–2784. https://doi.org/10.1002/hyp.5040

Hardy, J., Gourley, J. J., Kirstetter, P. E., Hong, Y., Kong, F., & Flamig, Z. L. (2016). A method for probabilistic flash flood forecasting. Journal of Hydrology, 541, 480–494. https://doi.org/10.1016/j.jhydrol.2016.04.007

Ingram, K. T., Dow, K., Carter, L., & Anderson, J. (2013). Climate of the Southeast United States Variability, Change, Impacts and Vulnerability. Washington DC: Island Press.

Jalayer, F., Aronica, G. T., Recupero, A., Carozza, S., & Manfredi, G. (2018). Debris flow damage incurred to buildings: An in situ back analysis. Journal of Flood Risk Management, 11, S646–S662. https://doi.org/10.1111/jfr3.12238

Jonkman, S. N. (2005). Global perspectives on loss of human life caused by floods. Natural Hazards, 34(2), 151–175. https://doi.org/10.1007/s11069-004-8891-3

Kanmani, V., Karen, M., Sierra, G., & Michael, S. (2015). Risk Nexus: What can be learned from the Columbia and Charleston floods 2015? https://doi.org/10.13140/RG.2.2.25128.16641

Karagiorgos, K., Thaler, T., Hübl, J., Maris, F., & Fuchs, S. (2016). Multi-vulnerability analysis for flash flood risk management. Natural Hazards, 82, 63–87. https://doi.org/10.1007/s11069-016-2296-y

Khaiehi, S., Ahmadalipour, A., Shao, W., & Moradkhani, H. (2020). A place-based assessment of flash flood hazard and vulnerability in the contiguous United States. Scientific Reports, 10, 448. https://doi.org/10.1038/s41598-019-57349-z

Koks, E. E., Jongman, B., Husby, T. G., & Botzen, W. J. W. (2015). Combining hazard, exposure and social vulnerability to provide lessons for flash flood risk management. Environmental Science and Policy, 47, 42–52. https://doi.org/10.1016/j.envsci.2014.10.013

Kong, D., Miao, C., Borthwick, A. G., Lei, X., & Li, H. (2018). Spatiotemporal variations in vegetation cover on the loess plateau, China, between 1982 and 2013: Possible causes and potential impacts. Environmental Science and Pollution Research, 25(14), 13633–13644.

Kvočka, D., Falconer, R. A., & Bray, M. (2016). Flood hazard assessment for extreme flood events. Natural Hazards, 84(3), 1569–1599. https://doi.org/10.1007/s11069-016-2501-z

Lazrus, H., Morss, R. E., Demuth, J. L., Lazo, J. K., & Bostrom, A. (2016). ‘Know what to do if you encounter a flash flood’: Mental models analysis for improving flash flood risk communication and public decision making. Risk Analysis, 36(2), 411–427. https://doi.org/10.1111/risa.12480

Li, H., Luo, L., & Wood, E. F. (2008). Seasonal hydrologic predictions of low-flow conditions over eastern USA during the 2007 drought. Atmospheric Science Letters, 9, 61–66. https://doi.org/10.1002/asl

Liu, J., Hertel, T. W., Delgado, M., Ashfaq, M., & Noah, D. (2015). Future property damage from flooding—Sensitivities to economy and climate change. Climate Change, 132(4), 741–749. https://doi.org/10.1007/s10584-015-1478-z

Llasat, M. C., Marcos, R., Turco, M., Gilabert, J., & Llasat-Bojia, M. (2016). Trends in flash flood events versus convective precipitation in the Mediterranean region: The case of Catalonia. Journal of Hydrology, 541, 24–37. https://doi.org/10.1016/j.jhydrol.2016.05.040

Ma, M., Wang, H., Jia, P., Liu, R., Hong, Z., Laibrator, L. G., ... Miao, L. (2018). Investigation of inducements and defenses of flash floods and urban waterlogging in Fuzhou, China, from 1950 to 2010. Natural Hazards, 91(2), 1–16. https://doi.org/10.1007/s11069-017-3156-0

Marchi, L., Cavalli, M., Amponsah, W., Borga, M., & Crema, S. (2016). Upper limits of flash flood stream power in Europe. Geomorphology, 272, 68–77. https://doi.org/10.1016/j.geomorph.2015.11.005

Miao, Q., Yang, D., Yang, H., & Li, Z. (2016). Establishing a rainfall threshold for flash flood warnings in China’s mountainous
areas based on a distributed hydrological model. Journal of Hydrology, 541, 371–386. https://doi.org/10.1016/j.jhydrol.2016.04.054

Mizzell, H., Mallick, M., & Tyler, W. (2016). The historic South Carolina rainfall and major floods of October 1–5, 2015. Journal of South Carolina Water Resources, 3(3), 3–7.

Morsy, M. M., Goodall, J. L., Shatnawi, F. M., & Meadows, M. E. (2016). Distributed Stormwater controls for flood mitigation within urbanized watersheds: Case study of rocky branch watershed in Columbia, South Carolina. Journal of Hydrologic Engineering, 21(11), 05016025. https://doi.org/10.1061/(asce)he.1943-5584.0001430

Musser, J. W., Watson, K. M., & Gotvald, A. J. (2017). Characterization of peak streamflows and flood inundation at selected areas in North Carolina following Hurricane Matthew, October 2016 (No. 2017–1047). U.S. Geological Survey. https://doi.org/10.3133/ofr20171047

Nikolopoulos, E. I., Anagnostou, E. N., Borga, M., Vivoni, E. R., & Papadopoulos, A. (2011). Sensitivity of a mountain basin flash flood to initial wetness condition and rainfall variability. Journal of Hydrology, 402(3–4), 165–178. https://doi.org/10.1016/j.jhydrol.2010.12.020

NOAA. (2009a). Flood damages suffered in the United States during water year 2009. Retrieved from http://www.nws.noaa.gov/os/water/FloodLossReports/WY09FloodLossSummary.pdf

NOAA. (2009b, September 18–23). Southeast United States floods. Retrieved from https://www.weather.gov/media/publications/assessments/se_floods10.pdf

NOAA. (2013, January). NOAA Technical Report NESDIS 142-3 Regional Climate Trends and Scenarios for the U.S. National Climate Assessment.

Norbiato, D., Borga, M., Degli, S., Gaume, E., & Valle, M. (2008). Flash flood warning based on rainfall thresholds and soil moisture conditions: An assessment for gauged and ungauged basins. Journal of Hydrology, 362(3–4), 274–290. https://doi.org/10.1016/j.jhydrol.2008.08.023

Ntelekos, A. A., Smith, J. A., & Krajewski, W. F. (2007). Climatological analyses of thunderstorms and flash floods in the Baltimore metropolitan region. Journal of Hydrometeorology, 8(1), 88–101. https://doi.org/10.1175/JHM558.1

NWS. (2016). National Weather Service Instruction 10-1605. Retrieved from http://www.nws.noaa.gov/wson/

Orville, R., & Huffines, G. (2001). Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–98. Monthly Weather Review, 129(5), 1179–1193.

Papagiannaki, K., Lagouvardos, K., Kotroni, V., & Bezes, A. (2015). Flash flood occurrence and relation to the rainfall hazard in a highly urbanized area. Natural Hazards and Earth System Sciences, 15(8), 1859–1871. https://doi.org/10.5194/nhess-15-1859-2015

Reed, S., Schaeke, J., & Zhang, Z. (2007). A distributed hydrologic model and threshold frequency-based method for flash flood forecasting at ungauged locations. Journal of Hydrology, 337 (3–4), 402–420. https://doi.org/10.1016/j.jhydrol.2007.02.015

Rogger, M., Agnoletti, M., Alaaoui, A., Bathurst, J. C., Bodner, G., Borga, M., ... Blöschl, G. (2017). Land use change impacts on floods at the catchment scale: Challenges and opportunities for future research. Water Resources Research, 53, 5209–5219. https://doi.org/10.1002/2017WR020723

Saharia, M., Kirschetter, P.-E., Vergara, H., Gourley, J. J., Hong, Y., & Giroud, M. (2016). Mapping flash flood severity in the United States. Journal of Hydrometeorology, 18(2), 397–411. https://doi.org/10.1175/jhm-d-16-0082.1

Saulnier, G. M., & Le Lay, M. (2009). Sensitivity of flash-flood simulations on the volume, the intensity, and the localization of rainfall in the Cévennes-Vivarais region (France). Water Resources Research, 45(10), 1–9. https://doi.org/10.1029/2008WR006906

Schroeder, A. J., Gourley, J. J., Hardy, J., Henderson, J. J., Parhi, P., Rahmani, V., ... Taralsden, M. J. (2016). The development of a flash flood severity index. Journal of Hydrology, 541, 523–532. https://doi.org/10.1016/j.jhydrol.2016.04.005

Shah, V., Kirsch, K. R., Cervantes, D., Zane, D. F., Haywood, T., & Horney, J. A. (2017). Flash flood swift water rescues, Texas, 2005–2014. Climate Risk Management, 17, 11–20. https://doi.org/10.1016/j.crm.2017.06.003

Sharif, H. O., Jackson, T. L., Hossain, M. M., & Zane, D. (2015). Analysis of flood fatalities in Texas. Natural Hazards Review, 16 (1), 04014016. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000145

Smith, B., & Smith, J. (2015). The flashiest watersheds in the contiguous United States. Journal of Hydrology, 16, 2365–2381. https://doi.org/10.1175/JHM-D-14-0217.1

Smith, G. (2010). Development of a flash flood potential index using physiographic data sets within a geographic information system. Salt Lake City, UT: The University of Utah.

Smith, J. A., Baeck, M. L., Ntelekos, A. A., Villarini, G., & Steiner, M. (2011). Extreme rainfall and flooding from orographic thunderstorms in the Central Appalachians. Water Resources Research, 47, 1–24. https://doi.org/10.1029/2010WR010190

Spitalar, M., Gourley, J. J., Lutolf, C., Kirschetter, P. E., Brilly, M., & Carr, N. (2014). Analysis of flash flood parameters and human impacts in the US from 2006 to 2012. Journal of Hydrology, 519 (PA), 863–870. https://doi.org/10.1016/j.jhydrol.2014.07.004

Svoboda, M., Lecomte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., et al. (2002). The drought monitor. Bulletin of the American Meteorological Society, 83(8), 1181–1190. https://doi.org/10.1175/1520-0477-83.8.1181

Terti, G., Ruin, I., Anquetin, S., & Gourley, J. J. (2017). A situational-based analysis of flash flood fatalities in the United States. Bulletin of the American Meteorological Society, 98(2), 333–346. https://doi.org/10.1175/BAMS-D-15-00276.1

Tongal, H., & Booij, M. J. (2018). Simulation and forecasting of stream flows using machine learning models coupled with base flow separation. Journal of Hydrology, 564(July), 266–282. https://doi.org/10.1016/j.jhydrol.2018.07.004

Trenberth, K. E. (2011). Changes in precipitation with climate change. Climate Research, 47, 123–138. https://doi.org/10.3354/cr00953

Trobec, T. (2017). Frequency and seasonality of flash floods in Slovenia. Geographica Pannonica, 21(4), 198–211.

Van-Olderborgh, G. J., Van-der-Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., ... Cullen, H. (2017). Attribution of extreme rainfall from hurricane Harvey, august 2017. Environmental Research Letters, 12, 124009.

Varikoden, H., Preethi, B., Samah, A. A., & Babu, C. A. (2011). Seasonal variation of rainfall characteristics in different intensity classes over peninsular Malaysia. Journal of Hydrology, 404 (1–2), 99–108. https://doi.org/10.1016/j.jhydrol.2011.04.021
