RESEARCH ARTICLE

# High-resolution flood precipitation and streamflow relationships in two US river basins

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**Abstract**

Relationships between rainfall and river discharge are important for governing flood characteristics and predicting flood impacts. Previous studies have examined these relationships, but they lacked the high-resolution precipitation data necessary to analyse rainfall–streamflow correlations for individual flood episodes. The present study addresses this limitation by examining rainfall–streamflow relationships in two topographically and climatically different river basins: the Wabash River basin in Indiana and the Willamette River basin in Oregon, using high-resolution, sub-basin precipitation and discharge data. Results show that flood rainfall–streamflow relationships are highly spatially variable on a sub-basin scale. In the Wabash basin, strong positive correlations exist between rainfall and streamflow near urban areas and slight terrain gradients during flash floods, while weaker correlations between rainfall and streamflow are observed in other areas of the basin and for slow-rise floods. In the Willamette basin, strong positive slow-rise flood rainfall–streamflow relationships occur in referenced gauges in the eastern, mountainous part of the basin, while strong negative correlations occur in non-referenced gauges near reservoirs along the main rivers. Results suggest that in addition to high-resolution rainfall variability, the influence of urbanization, topography and water management on flood rainfall–streamflow relationships needs to be considered in order to forecast local flood impacts better.

**KEYWORDS**

floods, high-resolution data, hydrometeorology

## 1 | INTRODUCTION

Floods are one of the deadliest weather-related natural disasters in the continental United States (CONUS) (Ashley and Ashely, 2008b), with nearly 41 million people currently exposed to a 1-in-100 year flood

(Wing *et al.*, 2018). From 1980 to 2018, floods caused enormous economic devastation, resulting in over US$123.5 billion in adjusted losses (Smith, 2019). In 2019 alone, flooding along the Mississippi River—which was record-breaking at some locations (NWS, 2019)—caused over US$20 billion in damage across 19 states (NOAA National

Centers for Environmental Information, 2020). The record Mississippi flooding was caused by a unique combination of ingredients during the spring of 2019: rapid snowmelt, saturated soils and heavy rainfall (NWS, 2019). This concatenation of atmospheric, topographic and hydrologic factors is often necessary for floods to occur, though the relationship between these three systems is complex (Davis, 2001) and is difficult to predict (Herman and Schumacher, 2018a, 2018b).

To better understand the connection between the various mechanistic drivers of flooding, studies have examined the rainfall–streamflow relationships of floods. Such relationships are often used in operational settings to forecast floods in the CONUS (Davis, 2001; Gourley et al., 2013; Schroeder et al., 2016). Stephens et al. (2015) analysed the link between flood frequency, spatial extent and duration with river discharge and monthly precipitation in major global rivers. They found that mean monthly precipitation derived from a reanalysis dataset (ERA-Interim) was not well correlated with global flood activity, which they attributed to the nonlinearity of flood activity and rainfall, as well as regional and seasonal differences. Berghuijs et al. (2016) further investigated the role of different flood-generating mechanisms over the CONUS and the ability of those mechanisms to explain the variability in maximum annual streamflow. Regional and seasonal patterns in streamflow are poorly explained by rainfall alone, and Berghuijs et al. show that precipitation excess (i.e. rainfall excess compared with soil moisture-storage capacity) is a more important contributor to maximum annual streamflow. However, Villarini and Slater (2018) demonstrated that rainfall is closely related to streamflow when examining temporal changes in stream gauge height associated with changes in storm total precipitation over the CONUS. Storm total precipitation shows regional differences in relation to streamflow, displaying a greater importance on the West Coast and east of the 100th meridian. Additionally, Slater and Villarini (2016) showed that agreement between precipitation and stream gauge height increases in large and low-lying areas, highlighting the more nuanced variability in precipitation and streamflow trends.

These previous studies generally do not find a strong agreement between streamflow and rainfall, which is important for understanding the nonlinearity of rainfall and streamflow processes operating in floods and makes forecasting such events particularly challenging (Herman and Schumacher, 2018a, 2018b). However, relatively weak associations between these variables are not surprising, because many of these prior studies used coarse precipitation data averaged over large spatial or temporal scales (Stephens et al., 2015), and the studies did not consider storm-scale precipitation (aside from Villarini and

Slater, 2018, but even they used basin-averaged daily values). Examining maximum annual discharge in relation to statistics of monthly or annual precipitation masks the ability of individual storms to cause floods on the scale of hours to days, such as the Big Thompson Canyon and Rapid City flash floods (Maddox et al., 1978), Colorado floods of 2013 (Gochis et al., 2015) or Hurricane Harvey-related flooding in 2017 (NHC, 2018).

The purpose of the present study is to fill this gap by examining flood rainfall–streamflow relationships in two different river basins (the Wabash and Willamette basins) in the CONUS using high-resolution precipitation data from a climatology of flood-producing storms and streamflow during these flood episodes. The inter-basin variability in flood rainfall and discharge is examined to gain a more detailed understanding of flood behavior in two topographically and climatically different river basins. Such an approach paints a more nuanced picture of the variability in the topographic, climatic, atmospheric and hydrologic processes operating in floods on local scales, which is important for predicting local flood-related risks.

## 2 | METHODS

### 2.1 | Flood data

Floods in two US river basins—the Wabash and Willamette basins—were identified from a climatology of flood-producing storms over the CONUS (Dougherty and Rasmussen, 2019). This database identified floods from 2002 to 2013 using the National Centers for Environmental Information (NCEI) Storm Events database merged with a database of streamflow-indicated floods (Shen et al., 2017). A storm-centric view of floods with a notable hydrologic response is provided by this database in using only the NCEI flood reports (grouped into separate "episodes" by their associated meteorological system) that were close in space and time with flooded stream gauges identified from Shen et al. (2017). Note that flood episodes are comprised of numerous individual flood reports or "events." Both flash and slow-rise floods are included in this database: flash floods are defined by the National Weather Service as "a rapid and extreme flow of high water into a normally dry area, or rapid water level rise in a stream or creek above a predetermined flood level, beginning *within* six hours of the causative event (e.g. intense rainfall, dam failure, ice jam-related)"; and slow-rise floods are defined as "the inundation of a normally dry area caused by an increased water level in an established watercourse, or ponding of water, generally occurring *more* than six hours after the causative event,

and posing a threat to life or property" (NWS, 2007). Using this methodology, 3,436 (2,102) flash (slow-rise) flood-producing storms over the CONUS comprise the flood database (Dougherty and Rasmussen, 2019), and the data are clipped to the boundaries of each respective river basin to study both flash and slow-rise flood-producing storms in each basin.

Rainfall information for each flood-producing storm in the Wabash and Willamette basin is gathered from the Dougherty and Rasmussen (2019) flood database, as summarized in Table 1. Hourly, 4 km Stage IV (Lin and Mitchell, 2005) rainfall data for each flood are collected over the whole duration of each flood within $\pm 5°$ latitude and longitude of the flood centroid. To isolate the heavy, flood-contributing rainfall for each flood, only the largest contiguous area where rainfall accumulations exceeded the 75th percentile is used. Stage IV is a quality-controlled rainfall product merged over the CONUS that combines radar-estimated rainfall with rain gauge data. While Stage IV has well-documented issues over the western United States (including the Willamette basin) due to gaps in radar coverage (Nelson *et al.*, 2016), when compared with the Parameter-elevation Regression on Independent Slopes Model (PRISM) dataset that interpolates rainfall using a digital elevation model (Daly *et al.*, 2008), the results are similar (data not shown). Therefore, Stage IV is appropriate for analysing the rainfall characteristics in both flash and slow-rise floods due to its high spatial and temporal resolution that captures the variability in meteorological forcing and hydrologic impacts at varying flood durations.

Instantaneous streamflow is obtained for all gauges in the GAGES-II database (Falcone, 2011) that fall within the basin for each flood. The GAGES-II database is used because it provides an indication of which gages are "referenced" (i.e. those with the least amount of hydrologic disturbance), *versus* "non-referenced," as well as other important watershed features such as elevation, slope and the percent of urban development. Discharge over the rainfall flood duration is used for analysis in flash floods, while temporal lags of 1, 3 and 5 days after the flood rainfall starts are analysed in slow-rise floods.
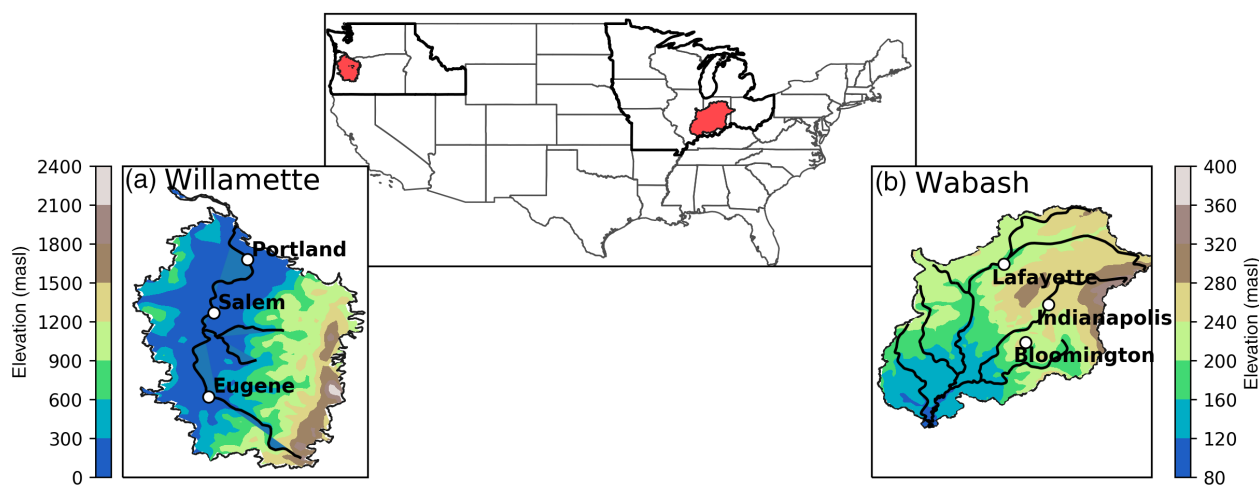
After performing a sensitivity test of these discharge lags to flood rainfall, the 3 day lags displayed the highest correlations for slow-rise floods in both basins and is used for analysis.

In all subsequent analyses, the flood discharge is normalized by contributing area to reduce the effect of catchment area on river discharge (e.g. larger catchment areas tend to produce greater flows). The relationships between average gridded flood rainfall and average discharge for stream gauges in the Wabash and Willamette basins are explored, and Spearman rank correlations for the rainfall pixel closest to the stream gauge discharge provide a quantitative metric to better understand this relationship for floods in different basins. Furthermore, correlations are split up by referenced *versus* non-referenced gauges to understand the differences between more natural flows *versus* those with an anthropogenic influence.

## 2.2 | Description of river basins

The Wabash and Willamette River basins are selected because they contain contrasting topography, hydrologic characteristics and atmospheric regimes. Only two basins were selected to provide examples of differing rainfall–streamflow relationships, with the goal of eventually documenting these relationships in more basins to fully understand the variability in flood rainfall and streamflow. The Wabash River basin has a drainage area of 85 237 $km^2$ and is located primarily in Indiana (Figure 1). The topography in the Wabash River basin is fairly flat, ranging in elevation from approximately 80 to 360 masl, with the highest topography located in the central to northeast portion of the basin and lower terrain to the south. Both flash and slow-rise floods are encountered throughout the year (Figure 2a), with most flash floods occurring during the warm season from May to July (likely due to convective storms), and slow-rise floods occurring during the cool season from December to March.

The Willamette River basin is situated in northwest Oregon, with the Coast Range to the west and the Cascade Mountains to the east (Figure 1). It is thus defined by more complex terrain than the Wabash basin, ranging in elevation from 3 to 2,400 masl. The Willamette River has a drainage area of 29,730 $km^2$ and is Oregon's largest river basin (Shearman, 1976; Robins, 2019). Due to its location in the Pacific Northwest, the Willamette River basin experiences slow-rise floods from November to March (Figure 2b) due to atmospheric rivers, which are highly concentrated water vapor plumes associated with extratropical cyclones coming off the Pacific Ocean

**TABLE 1** Spatial and temporal resolution of the Stage IV rainfall data and United States Geographical Survey (USGS) streamflow data used to examine flood rainfall–streamflow relationships in the Wabash and Willamette basins

| Data source | period | Spatial resolution | Temporal resolution |
|---|---|---|---|
| Stage IV rainfall | 2002–2013 | 4 km | Hourly |
| USGS streamflow | 2002–2013 | Variable | Instantaneous |

**FIGURE 1** The two basins used for analysis. The Willamette basin (a) is located in Oregon, next to the Coastal (Cascade) Mountains to the west (east) and is characteristic of the Pacific Northwest (black outline). The Wabash basin (b) is located in Indiana and parts of Illinois and Ohio and is characteristic of a relatively flat river basin in the Midwest (black outline), as shown by the filled contours
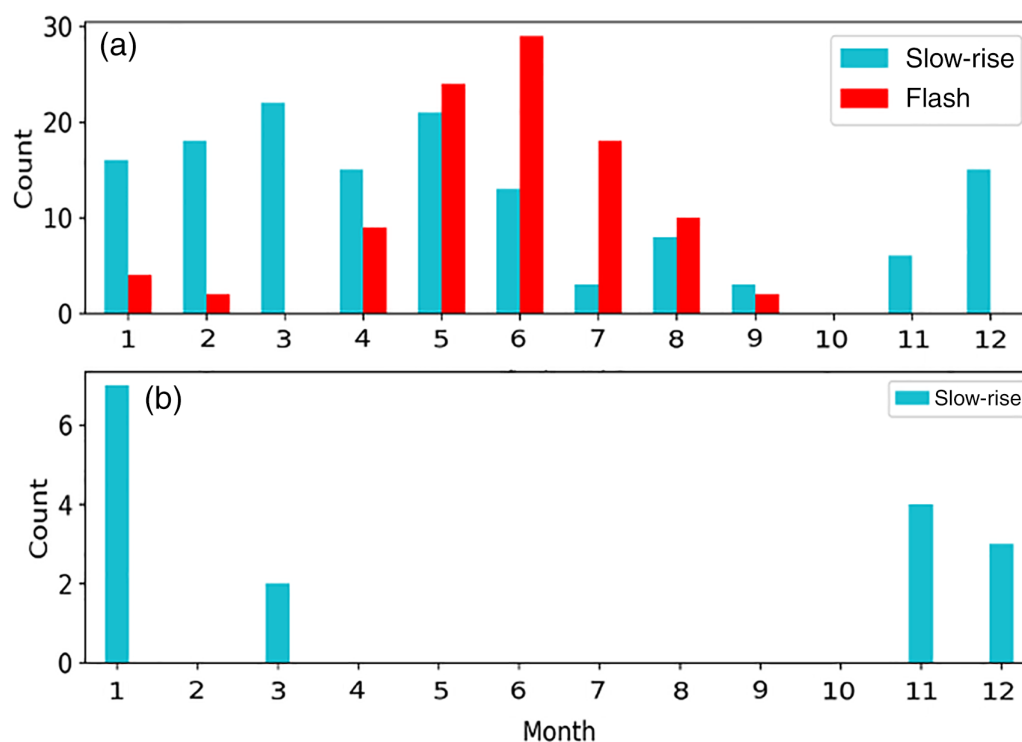
**FIGURE 2** (a) Seasonality of flash and slow-rise floods in the Wabash basin by month; and (b) as for (a), but for the Willamette basin. Floods are identified using a flood database from Dougherty and Rasmussen (2019)

(Neiman *et al.*, 2008) and other extratropical cyclone-related precipitation. Only two flash-flood episodes occurred in the Willamette basin during 2002–2013 and therefore are excluded from further analysis. The Willamette basin, which contains a complex terrain and experiences cool-season slow-rise floods, provides an ideal contrast to the flatter, inland Wabash basin, which experiences both flash and slow-rise floods year round.

This contrast between the Wabash and Willamette basins yields a useful framework from which to analyse detailed flood rainfall–streamflow relationships. While only two basins are selected for analysis, they are representative of larger climatic regimes and geographic areas. The Wabash basin exemplifies a typical flat Midwest basin that experiences flooding year round due to extratropical cyclones and convective storms, with larger

organized mesoscale convective systems (Houze, 2004) dominant during the summer (Schumacher and Johnson, 2006; Ashley and Ashely, 2008a; Kunkel et al., 2012; Dougherty and Rasmussen, 2019). Meanwhile, the Willamette basin is characteristic of the Pacific Northwest region of the United States, with complex terrain and flooding primarily confined to the cool season due to atmospheric rivers and extratropical cyclones (Kunkel et al., 2012; Saharia et al., 2017b; Dougherty and Rasmussen, 2019). Given the difference in storm mechanisms driving floods in each basin, analysing the flood rainfall–streamflow relationships in these two basins can provide an inference to flood behavior typical of the Midwest and Pacific Northwest, though further work is necessary to extrapolate the results beyond the Wabash and Willamette basins.

# 3 | RESULTS

## 3.1 | Flood rainfall and streamflow in the Wabash basin

Results show that flash and slow-rise floods occur throughout the Wabash basin, and both types of floods occur most frequently in the furthest downstream regions of the basin (indicated by the color gradient in Figure 3a, c). For flash floods, 20–60 floods occurred between 2002 and 2013 in the northern half of the basin, whereas 80–120 floods occurred in the southern half of the basin during the same period (Figure 3a). Slow-rise floods also exhibit a north-to-south gradient with a maximum of over 150 slow-rise floods occurring in the southeast Wabash basin (Figure 3c). The similar spatial variability
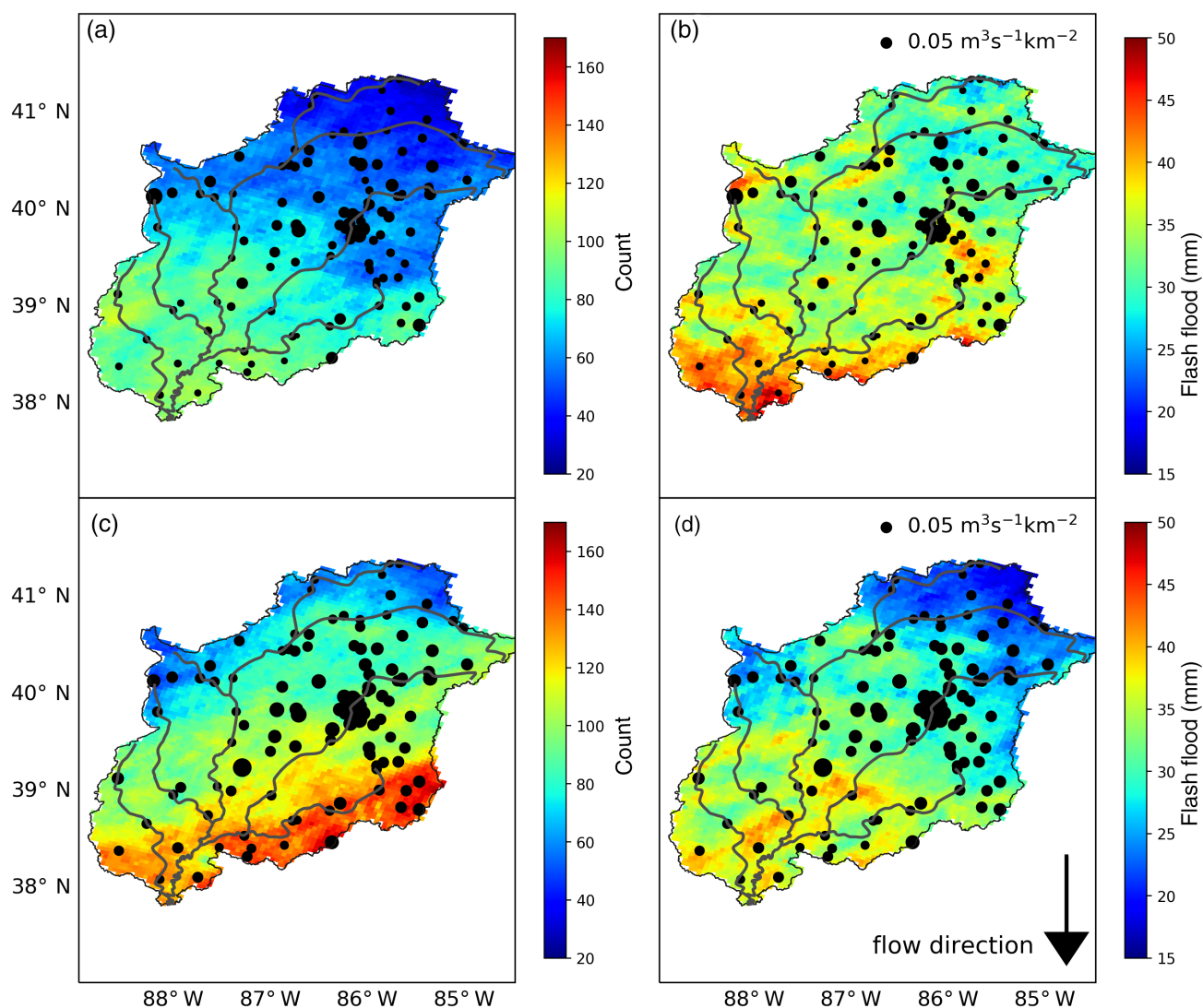


**FIGURE 3** (a) Number of flash flood episodes in the Wabash basin; (b) average flash flood rainfall in the Wabash basin; and (c, d), as for (a) and (b), respectively, except for slow-rise floods. Dots show average flood discharge (normalized by catchment area), where larger dots mean a higher discharge. The arrow indicates the general north-to-south direction of river flow

among flash and slow-rise floods suggests that the interplay between the topography, hydrology and meteorology creates a preferential hotspot for floods in the Wabash basin.

The spatial distributions of average rainfall (indicated by the color gradient in Figure 3b, d) and discharge (indicated by the dots in Figure 3b, d) associated with flash and slow-rise floods exhibit more variability than distributions of flood occurrence. The maximum rainfall associated with flash floods occurs in the southern part of the Wabash basin, reaching 50 mm on average. More localized maxima in average flash flood rainfall occurs throughout the basin, particularly in the east-central Wabash basin, which indicates the transient and localized nature of flash flood-producing storms. Average flash flood discharge does not directly match the spatial variability of flash flood average rainfall, with maxima (i.e. the larger dots in Figure 3b) located in the central region of the basin. The maxima of flash flood discharge coincide with the location of Indianapolis and higher terrain, suggesting that urbanization and topography (however slight) influence flood discharge trends, which has been previously documented (Davis, 2001; Ashley and Ashely, 2008b; Smith and Smith, 2015; Saharia *et al.*, 2017a). The maximum slow-rise flood discharge (Figure 3d) is similarly located in the central portion of the Wabash, again showing the importance of the basin's topography and land use. Slow-rise flood average rainfall displays a broader maximum in the southern half of the basin, with lower maximum rainfalls of 40 mm. Such a result is consistent with the larger area and less intense nature of slow-rise flood-producing storms (Dougherty and Rasmussen, 2019), which tend to be caused by synoptic systems.

To provide a more quantitative understanding of flood rainfall–discharge relationships, correlations between flash and slow-rise flood rainfall and discharge were analysed. When aggregated across the entire Wabash basin, the correlation between flash flood rainfall accumulation (rain frequency) and river discharge is $-0.12$ $(-0.049)$ (Figure 4a). Rainfall accumulation and discharge independently exhibit stronger correlations with the percentage of urban area ($\rho = -0.11$ and $0.14$, respectively), elevation ($\rho = -0.51$ and $0.18$, respectively), and slope ($\rho = 0.44$ and $-0.38$, respectively) where they are also significant ($p < .05$). The contrasting signs of correlations between rainfall and discharge with basin attributes likely explain why the basin-wide correlation is weak between the two variables. This can be seen in Figure 3b, where flash flood rainfall maximizes in the flatter, less urbanized southern portion of the basin, whereas flash flood discharge maximizes in the slightly higher topography and more urbanized east central portion of the basin.

The correlation between slow-rise flood rainfall accumulation (rain frequency) and river discharge is $0.27$ $(0.26)$—weak, but stronger, significant ($p < .05$), and of opposite sign than for flash floods (Figure 4b). Correlations between slow-rise flood rainfall and percentage of urban area, elevation and slope are similar to flash flood-rainfall and all significant ($p < .05$). Slow-rise flood discharge exhibits weaker correlations than flash floods to these variables, with $\rho = 0.086$ for discharge and percentage of urban area, $\rho = 0.14$ for discharge and elevation, and $\rho = 0.044$ for discharge and slope. Such relationships indicate that there is a stronger correlation between slow-rise flood rainfall and discharge, but not slow-rise flood discharge and watershed characteristics likely due to the more widespread, less intense nature of these floods.
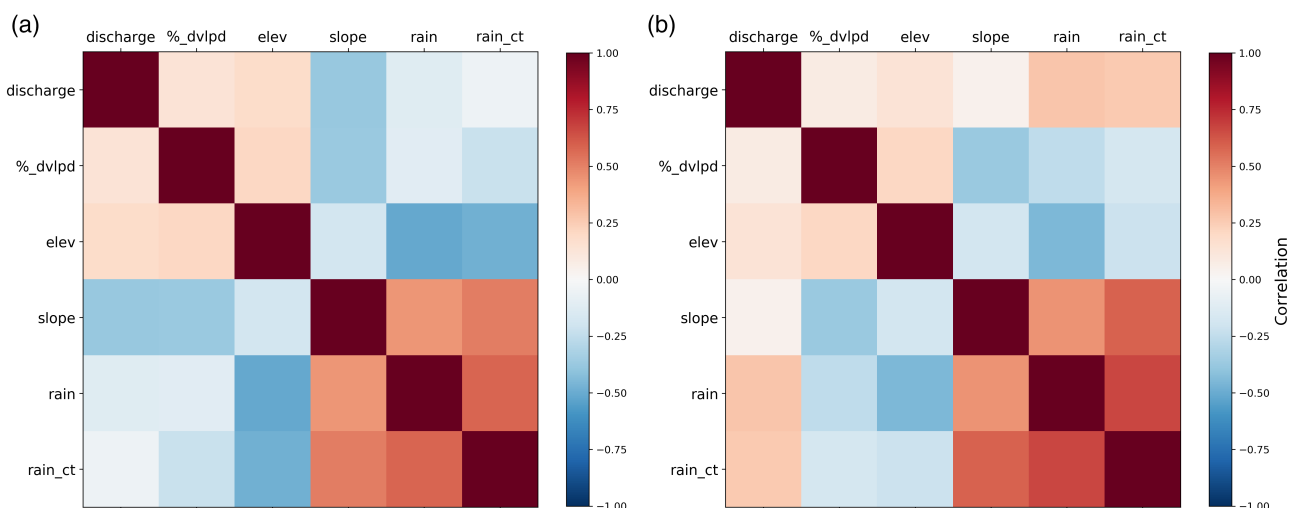


**FIGURE 4** Correlation matrix of average discharge (*discharge*), percentage of urban area (*%_dvlpd*), elevation (*elev*), slope, average flood rainfall (*rain*) and flood frequency (*rain_ct*), averaged across the entire Wabash basin for (a) flash floods and (b) slow-rise floods

Whereas rainfall–discharge correlations across the entire basin fail to capture the spatial variability in the Wabash basin, correlations of flood rainfall at individual stream gauges yield higher correlations (Figure 5). Flash floods display strong positive correlations above $\rho = 0.5$ in the centre of the basin, suggesting a non-negligible role of a slight terrain gradient and urbanization on concentrating rainfall and discharge, similar to the effect of the Balcones Escarpment in central Texas (Caracena and Fritsch, 1983; Smith *et al.*, 2000; Nielsen *et al.*, 2016). Strong positive correlations also exist near the basin's outlet. These correlations tend to be stronger in referenced stream gauges (circles), with an average $\rho = 0.58$ compared with non-referenced gauges (squares) where $\rho = 0.39$. Slow-rise flood correlations show weaker correlations at most gauges overall where $\rho \sim 0.25$. Again, referenced gauges exhibit stronger correlations ($\rho = 0.31$) than non-referenced gauges ($\rho = 0.26$). Strong positive correlations in slow-rise floods occur more broadly than flash floods in the northern half and edges of the basin. Despite the different correlation patterns in flash and slow-rise floods, both highlight the heterogeneous spatial patterns when flood rainfall–discharge correlations are examined locally.

## 3.2 | Flood rainfall and streamflow in the Willamette basin

In the Willamette basin, slow-rise floods occur most often in the eastern and northwestern regions of the basin, areas that both border mountain ranges (see Section 2.2), with a maximum of 30 slow-rise floods from 2002 to 2013

(indicated by the color gradient in Figure 6a). The fewest number of slow-rise floods occur in the central part of the basin, bordering the Willamette River (north–south river/the black line in the basin). Similarly, the maximum average slow-rise flood rainfall occurs in the eastern and northwestern regions of the basin, reaching averages of 150–225 mm (Figure 6b). The spatial trends in slow-rise flood discharge are more complex than flood occurrence or average rainfall, but a maximum is observed in the east central Willamette basin, coinciding with the maximum in slow-rise flood occurrence and rainfall. Thus, while topography showed some importance in the Wabash basin, the higher topography in the Willamette basin displays a more prominent influence on the spatial variability of slow-rise flood rainfall and occurrence. Such a result is unsurprising, as the high terrain in the Pacific Northwest acts to focus and enhance rainfall in the stable, moist airmass characteristic of extratropical cyclones and associated atmospheric rivers coming off the Pacific Ocean (Neiman *et al.*, 2008). This appears to exhibit some influence on slow-rise flood discharge as well, at least in the east central Willamette basin, though elsewhere, discharge is spatially variable.

The variability in slow-rise flood discharge from Figure 6 creates a less clear spatial pattern in slow-rise flood discharge and rainfall correlations. Basin-wide, this correlation is 0.38 (0.38) between flood rainfall (frequency) and discharge (Figure 7), where only correlations between flood rainfall and discharge are significant ($p < .05$). Slow-rise flood rainfall exhibits a weak correlation with the percentage of urban area ($\rho = .0044$), a negative correlation with elevation of ($\rho = -.26$), and a weak
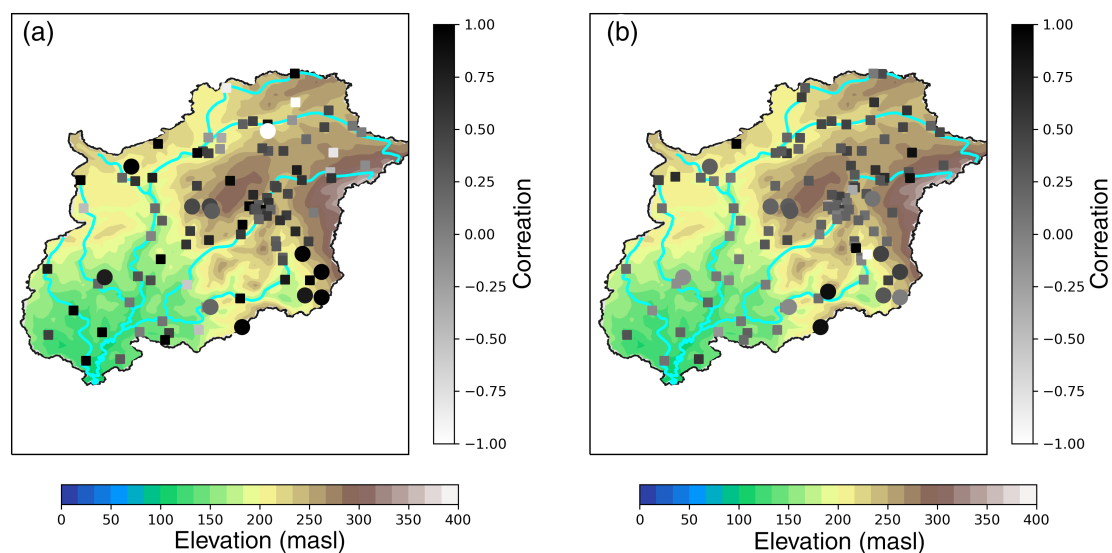


**FIGURE 5** Correlation between average discharge and average rainfall at each stream gauge, where circles indicate referenced gauges and squares indicate non-referenced gauges for (a) flash floods and (b) slow-rise floods. Major rivers are depicted in blue, while filled contours show the topography
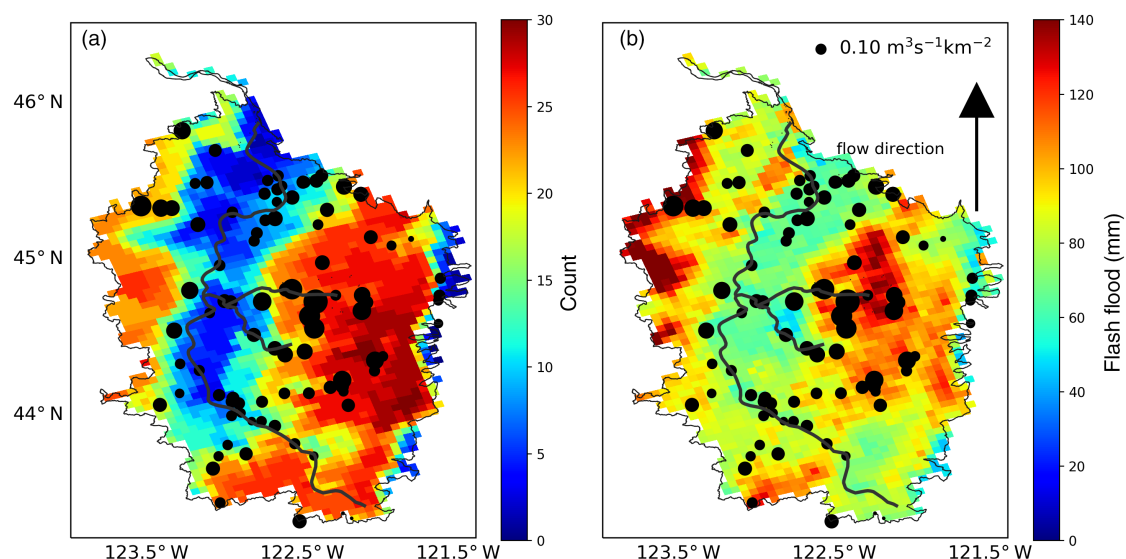
**FIGURE 6** (a) Number of slow-rise flood episodes in the Willamette basin; and (b) average slow-rise flood rainfall in the Willamette basin. Dots show average flood discharge (normalized by catchment area), where larger dots mean a higher discharge. The arrow indicates the general south-to-north direction of river flow
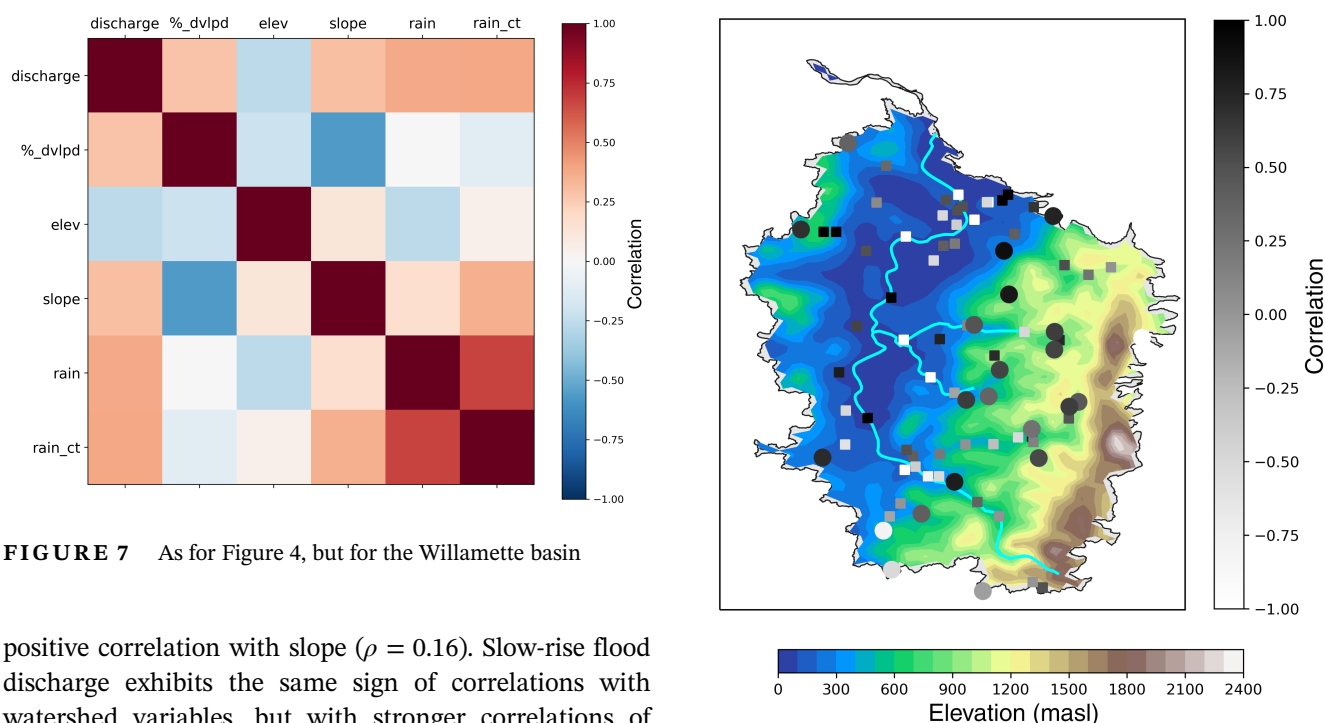


**FIGURE 7** As for Figure 4, but for the Willamette basin

positive correlation with slope ($\rho = 0.16$). Slow-rise flood discharge exhibits the same sign of correlations with watershed variables, but with stronger correlations of $\rho = 0.29$ to the percentage of urban area, $\rho = -0.25$ with elevation, and $\rho = 0.3$ with slope. Such correlations indicate that basin-wide, slow-rise flood discharge maximizes where slow-rise flood rainfall does, but it is negatively related to elevation and positively related to slope.

These basin-wide correlations present a misleading result because they mask the variability in correlations amongst areas with different watershed characteristics. Most notably, slow-rise flood discharge and streamflow exhibit strong positive correlations in the eastern



**FIGURE 8** Correlation between average discharge and average rainfall at each stream gauge for slow-rise floods, where circles indicate referenced gauges and squares indicate non-referenced gauges. Major rivers are depicted, while filled contours show the topography

Willamette basin near high terrain, but strong negative correlations along the Willamette River and its main tributaries (Figure 8). The gauges along the Willamette River

and tributaries are mostly non-referenced gauges due to the proximity to reservoirs and thus have considerably altered flow. This suggests that in addition to the local variability in topography, hydrology and precipitation that influence flood rainfall–streamflow relationships, management is an important factor too, which needs to be taken into account when forecasting for flood impacts.

# 4 | DISCUSSION

Examining basin-averaged flood rainfall–streamflow correlations can lead to a misleading understanding that these correlations are weak (e.g. Stephens et al., 2015). However, results from the present study show that they are highly spatially variable in both the Wabash and Willamette basins, with some locations showing strong positive correlations over $\rho = 0.5$. These results point to the need to consider sub-basin flood relationships in order to better forecast flood impacts, which clearly vary on highly localized scales and can have dramatically different impacts depending on the storm rainfall characteristics, land use, topography and water management at a particular location.

The variability of flood rainfall and its relationship to streamflow necessitates the use of high-resolution precipitation data, which was accomplished in the present study by using Stage IV precipitation data at an hourly resolution with a 4 km grid spacing. There are other similarly high-resolution precipitation data, such as PRISM or Multi-Radar/Multi-Sensor System (Daly et al., 2008; Zhang et al., 2016), that could also accomplish this task, but regardless of the precipitation data used for analyses, it is important to note that high-resolution precipitation data are necessary to capture the heterogeneity in storm rainfall amount, intensity and spatial distribution over the duration of flash and slow-rise floods. This rainfall variability can produce markedly different streamflow responses depending on the watershed characteristics, which is often missed by using coarse precipitation data (e.g. Stephens et al., 2015), or only relating streamflow to monthly or annual precipitation statistics.

An additional consideration in understanding flood rainfall–streamflow relationships is the inclusion of non-referenced or human-impacted streamflow. While many studies only consider stream gauges with the least amount of hydrologic disturbance, in the present study the comparison of referenced versus non-refenced gauges' relationship to rainfall presents important information. This is especially true in the Willamette basin, where non-referenced gauges along the Willamette River with nearby reservoirs display strong negative correlations to slow-rise flood rainfall, but referenced gauges in the mountainous eastern region exhibit strong positive correlations (Figure 8). Such information is important because floods still impact hydrologically disturbed gauges, whether due to reservoir management or urbanization, and taking these gauges into account can assist with flood forecasting. In particular, this information could assist reservoir operations and predicting hydrologic impacts in urban areas where most people live. The importance of man-made alterations was mentioned by Mallakpour and Villarini (2015) when explaining the discrepancy between the increasing (decreasing) frequency of rainfall (flood events) in Nebraska and Kansas. The inclusion of heavily managed flows as well as more natural flows in flood rainfall–streamflow relationships is necessary to gain a comprehensive understanding of flood behavior in all regions of the basin due to both physical and man-made factors.

# 5 | CONCLUSIONS

The present study examines the sub-basin correlations between rainfall and streamflow in flood-producing storm episodes in the Wabash and Willamette river basins using high-resolution precipitation data. Such a high-resolution spatial analysis between flood-producing storm rainfall data and instantaneous streamflow data within individual floods on a sub-basin scale has not been previously examined, but is necessary to predict local flood impacts. Results highlight the utility in conducting a high-resolution spatial analysis given the spatial variation in flood rainfall–streamflow relationships in both river basins.

In the Wabash basin, strong positive correlations occur in the center of the basin in flash floods near urban areas and terrain gradients, while these correlations are generally weaker elsewhere in the basin and in slow-rise floods. Stronger positive correlations in flash and slow-rise flood rainfall and discharge occur in referenced gauges, and also between flash flood discharge and watershed characteristics. In the Willamette basin, strong positive slow-rise flood rainfall–discharge correlations occur in referenced gauges in the eastern, mountainous terrain, while strong negative correlations occur in non-referenced gauges near reservoirs on the Willamette River and its tributaries. While the present study only considers two basins, they are characteristic of larger geographic and climate regimes, so flood rainfall–streamflow relationships might be similar in other basins, though further research is needed to quantify this.

The results highlight the need for high-resolution precipitation data to characterize the variation in flood discharge within basins that depend on topography,

urbanization and water management. Additional factors not considered but which are also important for regulating the streamflow response to rainfall in floods include soil moisture and snowpack (Berghuijs *et al.*, 2016). Such considerations are important for local flood forecasting as well as water management strategies that help to effectively use water resources and protect communities against flood-related hazards.

## DATA AVAILABILITY STATEMENT

The GAGES-II dataset used in the present study is available at: https://water.usgs.gov/GIS/metadata/usgswrd/XML/gagesII_Sept2011.xml. Instantaneous streamflow data used in the research are available at: https://waterdata.usgs.gov/nwis/sw. Flood episode and rainfall information is from Dougherty and Rasmussen (2019), who used Stage IV data, which are available at: https://data.eol.ucar.edu/dataset/21.093, and storm event data, available at: https://www.ncdc.noaa.gov/stormevents/ftp.jsp.

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