The Flashiest Watersheds in the Contiguous United States

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ABSTRACT

The authors identify the flashiest watersheds in the contiguous United States based on frequency of discharge peaks exceeding 1 m$^3$ s$^{-1}$ km$^{-2}$. The entire digitized record of USGS instantaneous discharge data is used for all stream gauging stations with over 10 years of data. Using the 1 m$^3$ s$^{-1}$ km$^{-2}$ threshold, the flashiest basins in the contiguous United States are located in urban areas along a swath of states from the south-central United States to the mid-Atlantic and in mountainous areas of the West Coast, especially the Pacific Northwest. The authors focus on small watersheds to identify the flashiest cities and states across the country and find Tulsa, Oklahoma; Baltimore, Maryland; and St. Louis, Missouri, to be the flashiest cities in the contiguous United States. Thunderstorms are major agents for peak-over-threshold flood events east of the Rocky Mountains, and tropical cyclones play a secondary role, especially in the Southeast. West Coast flood events are associated with winter storms. Flooding west of and within the Rockies is linked to steeply sloped terrain and compact watersheds. The authors find that watersheds northeast (downwind) of city centers are flashier than other urban watersheds, consistent with the downwind maximum in rainfall found in many urban regions. They examine anomalous flood response in the Illinois–Missouri region; St. Louis is among the flashiest cities in the United States, while Chicago is among the least flashy. Their flashiness map is compared with other measures of flooding, including flood damage and National Weather Service flash flood reports.

1. Introduction

Flooding and flash flooding are a significant problem in the United States that is likely to worsen with an increasingly urbanizing country (Leopold 1968; Hollis 1975) and a changing climate (Milly et al. 2002; Yang et al. 2013). Flooding causes substantial casualties and damages (Ashley and Ashley 2008; Pielke et al. 2002) and is the second-most fatal weather hazard in the United States, according to National Weather Service (NWS) assessments (http://www.nws.noaa.gov/os/hazstats.shtml). The majority of flood fatalities are caused by flash floods (Ashley and Ashley 2008). Frequent flash flooding can alter channel and floodplain structure, in particular causing channel incision and widening (Booth 1990; Paul and Meyer 2001) and cutting streams off from the riparian zone. These changes in channel morphology can in turn affect the frequency of overbank flooding and associated flood hazards.

Despite the significant threats posed by flash flooding, there is a lack of research into the spatial distribution of flash flooding across the United States. O’Connor and Costa (2004) investigated the largest rainfall-induced floods across the United States using the U.S. Geological Survey (USGS) streamflow record. Michaud et al. (2001) investigated flooding in small watersheds for the median and 25-yr flood and exceptional flood events. Maddox et al. (1979) looked at 5 years of flash flood events based on the NOAA Storm Data publication. A U.S. flash flood database has been compiled to help address the need for national flash flood information (Gourley et al. 2013). However, there has been no comprehensive study on the locations and characteristics of watersheds with the most frequent flash flooding in the United States. We address this gap in knowledge through our analyses of the “flashiest” watersheds in the contiguous United States.

We utilize the USGS instantaneous value streamflow gauge network to examine properties of the watersheds with the most frequent discharge peaks over 1 m$^3$ s$^{-1}$ km$^{-2}$. The discharge threshold is not directly related to bankfull
flow measures, but it does capture flood events with fast response times (as represented by volume-to-peak ratios) throughout much of the United States. Our approach necessarily limits us to gauged watersheds, which are not uniformly placed throughout the country. Despite this limitation, our approach does allow us to develop a map of the flashiest watersheds and cities within the contiguous United States. We utilize this data to investigate the flood response characteristics of flashy watersheds across the country. In this study we focus on the following questions:

1) What are the flashiest gauged watersheds in the contiguous United States?
2) What are the flashiest cities in the contiguous United States?
3) What processes lead to the frequent occurrence of flood peaks with large unit discharges?
4) Are flashy watersheds more likely to be located downwind of urban areas (consistent with rainfall maxima in many urban areas of the United States)?
5) How do these measures of flashiness compare to other measures of flood severity and damage across the United States?

Results from this study will help establish potential locations of frequent flash flooding in small watersheds for forecasting purposes. The peak discharge threshold definition will be particularly useful for guidance in flood mitigation and conveyance design structures that depend on streamflow volume. The emphasis of flashiness location in relation to city center will be useful in guidance both for watershed management planning and for flood emergency response.

2. Data and methodology

Streamflow data were obtained from the USGS Instantaneous Values Service (post-October 2007; http://waterservices.usgs.gov/rest/IV-Test-Tool.html) and the USGS Instantaneous Data Archive (pre-October 2007; http://ida.water.usgs.gov/ida/). Instantaneous Values Service data were downloaded from the website while the Instantaneous Data Archive was obtained as an SQL database from the USGS. The data were combined to form complete streamflow records with time resolutions between 1 and 60 min for 11 840 USGS gauges. Data were used from the start of the USGS record until the end of the 2013 water year, with data for some stations extending back as far as 1951, but usually no farther than the mid-1980s. The datasets used for each watershed gauge vary in length, which may cause issues of stationarity to come into play. For example, if flashiness increases with urbanization, adding years of data before a watershed urbanized may decrease the total flashiness. However, removing these impacts would be extremely difficult as changes in time have not occurred uniformly over the country, and it would decrease the size of dataset.

The aim of the study is to utilize the streamflow record to its greatest extent with as few limitations as possible.

We used the USGS Geospatial Attributes of Gages for Evaluating Streamflow, version II, database (GAGES II; see Falcone 2011; Falcone et al. 2010) for watershed boundaries and watershed characteristics. The GAGES II database includes GIS boundaries and over 200 watershed characteristics for 9322 USGS gauged watersheds.

Our study focused on the 5436 USGS gauges that have more than 10 yr of instantaneous data, are included in the GAGES II dataset, and are located within the contiguous United States. For the chosen gauges, we extracted the streamflow peaks that exceed 1 m$^3$s$^{-1}$km$^{-2}$ and are separated by at least 6 h. We labeled these peaks as peaks over threshold (POT) and calculated the peaks per year (PPY) as the number of POT per each year of data, excluding data gaps of more than 2 months. We considered the flashiest watersheds to be those with the highest PPY. Drainage basin areas for the gauges were obtained from the USGS Instantaneous Values Service.

Setting a uniform discharge peak limit across all watersheds favors flashy watersheds with smaller drainage areas. Our intent is to focus on the small, often urban, watersheds that have frequent flash flooding events. It is worth noting that the flashiest watersheds in the United States are located outside of the contiguous United States. Many small watersheds in Hawaii, Puerto Rico, and Alaska have extremely high PPY (e.g., Smith et al. 2005c).

For portions of this study we utilized cloud-to-ground (CG) lightning data from the National Lightning Data Network (NLDN; see Orville 2008; Cummins and Murphy 2009). The NLDN measures the time, location, polarity, peak current, and multiplicity of CG lightning flashes. We used 23 years of NLDN lightning data, 1991–2013, and tallied CG lightning strikes with intensities greater than or equal to 10 kA [as recommended in Cummins et al. (1998)]. Hurricane track data were obtained from the Atlantic Hurricane Database (HURDAT; Landsea et al. 2004) and annual rainfall data were taken from the GAGES II dataset.

Watershed land-use and land-cover data, including impervious percentage and developed area, came from the GAGES II dataset. The 2010 U.S. Census shapefile was used to identify urban and rural watersheds as well as the city to which urban watersheds belonged based on the location of the watershed gauge (https://www.census.gov/geo/reference/ua/urban-rural-2010.html). Urban areas in the U.S. Census designation contain more than 50 000
people and rural areas contain less than 2500 people. The census data delineate metropolitan regions rather than political boundaries, so cities often include suburban areas far from the city core. For example, the Chicago urban area extends into Indiana, and the New York City urban area is identified as “New York–Newark, NY–NJ–CT.” State outlines were obtained from the National Map North American Atlas–Political Boundaries (http://nationalmap.gov/small_scale/). City centers were determined as the center of mass of the 2006 National Land Cover Database (NLCD) impervious land-cover database (Fry et al. 2011) clipped to the census polygon for the city’s metropolitan area.

3. Results and discussion

a. Threshold

Analysis of the 1 m$^3$s$^{-1}$km$^{-2}$ threshold was carried out to ensure that the identified watersheds were truly “flashy.” The PPY for each watershed was calculated using three thresholds: 0.5, 1.0, and 2.0 m$^3$s$^{-1}$km$^{-2}$. Then, the top 100 flashiest watersheds were found for each threshold. Halving the threshold to 0.5 m$^3$s$^{-1}$km$^{-2}$ substantially changes the selection of flashiest watersheds; only 30% of the top 10 and 63% of the top 100 remain the same. Doubling the threshold to 2.0 m$^3$s$^{-1}$km$^{-2}$ has less impact on the watershed selection; the top 10 remain 90% the same (with the top six in exactly the same order) and the top 100 remain 82% the same. This suggests that lowering the threshold would have substantial impact on the results and raising the threshold would have little impact on the results.

To check if thresholds were measuring flashy flood events, with sharp rises and falls in streamflow, the median volume-to-peak ratio for all POT flood events in the 100 flashiest watersheds was calculated for each threshold. The volume-to-peak ratio (hours) was calculated as the volume under the hydrograph (defined as any discharge between the peak and the 12-h minimum discharges) divided by the peak discharge of the hydrograph [see also Bradley and Potter (1992)]. The volume-to-peak ratio provides a measure of response time using only streamflow data. Volume-to-peak ratios on the order of 1–10 h are representative of small flashy urban watersheds (e.g., Smith et al. 2002; Wright et al. 2012; Smith et al. 2013). For all thresholds, volume-to-peak ratios fall roughly in two categories, those below 15 h and those that are much higher, up to nearly 100 h (Fig. 1). The high values of volume-to-peak ratios tend to represent watersheds located in the Rocky Mountains and westward. The mean volume-to-peak ratios for watersheds west of and within the Rockies, as defined by a 103°W longitude boundary, are 40.3, 33.4, and 28.1 h for the 0.5, 1.0, and 2.0 m$^3$s$^{-1}$km$^{-2}$ thresholds, respectively. The numbers of western peaks included in the top 100 for each threshold are 41, 15, and 9. Again, the 0.5 m$^3$s$^{-1}$km$^{-2}$ threshold stands out. This threshold includes too many watersheds with large volume-to-peak ratios from within the Rocky Mountains and westward.

Looking at only watersheds east of the Rockies, the POT method does identify watersheds with faster, flashier response times. For the 1.0 m$^3$s$^{-1}$km$^{-2}$ threshold, the Spearman correlation between PPY and median volume-to-peak ratios for the top 100 watersheds is −0.69, suggesting that more frequent unit peak discharges do correspond to flashier watersheds. The correlation for a threshold of 2.0 m$^3$s$^{-1}$km$^{-2}$ is −0.75. The results obtained with the 1.0 and 2.0 m$^3$s$^{-1}$km$^{-2}$ thresholds are broadly similar, but the average number of POT events per top 100 watershed for the 1.0 m$^3$s$^{-1}$km$^{-2}$ threshold is 112 and for the 2.0 m$^3$s$^{-1}$km$^{-2}$ threshold it is 39. In the interest of including more POT events, the 1.0 m$^3$s$^{-1}$km$^{-2}$ threshold is used.

b. All watersheds

A map of the peaks per year, or flashiness, for each of the gauges considered in this study (Fig. 2) highlights flashiness along the mid-Atlantic Interstate 95 (I-95) corridor and in the Missouri–Oklahoma–Arkansas region near the Ozark Mountains. The region near the Ozark Mountains is similar to the region of small watersheds that experienced large median flood peaks in Michaud et al. (2001). Urban areas throughout the eastern half of the United States south of New York City are affected by a high frequency of flood peaks exceeding 1 m$^3$s$^{-1}$km$^{-2}$. Mountainous regions of the Pacific Northwest are similarly affected. Our reliance
on USGS gauges does place limitations on our ability to see spatial patterns of flash flooding. Very few POT events are detected in the Great Plains and Intermountain West. The gauge network in these areas is less dense, particularly when considering gauges with a small drainage area (see Fig. 3). Frequent POT flooding events may occur on ungauged streams in mountain watersheds or in urban areas with storm drains and buried streams.

The impacts of impervious area and drainage area on flashiness are shown through the correlation of watershed characteristics with the watershed’s PPY for different areas (Fig. 4). The drainage area is the most highly correlated characteristic for all larger watershed gauges, reaching correlations of −0.48. At larger scales, runoff cannot concentrate quickly enough to reach peak magnitudes of 1 m$^3$ s$^{-1}$ km$^{-2}$ without substantial rainfall volumes. For gauges with smaller drainage areas, percentage of impervious area is the most highly correlated to PPY, reaching correlations up to 0.79. At these small scales, increasing the runoff volume through impervious coverage results in higher peak discharges per unit of watershed area for the same rainfall event. Thus, increasing impervious cover could increase the number of peak discharges exceeding the 1 m$^3$ s$^{-1}$ km$^{-2}$ threshold. The correlations between drainage area with PPY and impervious surface with PPY cross at an area of 220 km$^2$ (85 mi$^2$). The dominance of impervious cover in determining PPY at smaller scales explains the negative correlation between slope and PPY at small scales. Urban areas tend to be flatter, and the correlation between slope and impervious fraction for watersheds smaller than 2.6 km$^2$ (10 mi$^2$) is −0.66. The annual runoff ratio is minimally correlated with PPY because of the difference in time scales between fast discharge peaks and annual runoff and rainfall.

The top 10 flashiest watersheds in the contiguous United States are ranked based on the frequency of peak discharge values greater than 1 m$^3$ s$^{-1}$ km$^{-2}$ (Table 1). The top 10 flashiest watersheds are small watersheds with drainage areas ranging from 3.11 km$^2$ (1.2 mi$^2$) to 34.55 km$^2$ (13.34 mi$^2$). These watersheds are in urban areas running in a strip from the south-central United States to the East Coast, and more specifically in two regions—the southern Missouri–northern Oklahoma and Arkansas region near the Ozark Mountains, and the mid-Atlantic I-95 corridor.

Within the 10 flashiest watersheds in the contiguous United States, there are four watersheds from the St. Louis, MO, area and two watersheds from the Baltimore, MD, area. Many of these streams are known to have flooding and runoff problems. Rocky Branch was considered severely degraded and ranked as North Carolina’s most polluted stream in 1978 (Doll et al.)
Flash flooding in Moores Run, due to fast concentration of runoff in large storm drains, has been well documented. Moores Run has been called an urban end member watershed (Smith et al. 2013) as well as the flashiest watershed in the conterminous United States (Smith et al. 2005b). West Branch Herring Run, also near Baltimore, has similar properties to Moores Run in hydrologic flood response analyses (Smith et al. 2013). The River des Peres, near St. Louis, is noted for having frequent sanitary sewer overflows and had extreme

![Map showing mean PPY for small subset watersheds within states and cities.](image)

FIG. 3. Mean PPY for small subset watersheds within (a) states and (b) cities. Data for cities and states are displayed for those that contain at least three gauges with drainage areas under 38.8 km² [shown as black points in (a)]. The color scale for states runs from 0.00–0.02 (yellow) to 3.62–7.08 (dark blue) in varying intervals and for cities from 0.00–0.02 (yellow) to 7.83–8.56 (dark blue) in varying intervals.
flooding during Hurricane Ike due to floodplain development (Denney 2013; Criss and Kusky 2008). Cowmire Creek, also near St. Louis, has a documented history of efforts to control its stormwater problems (Miller and Loucks 1999; Buechter and Weiland 2006).

The 10 flashiest watersheds in the contiguous United States are all in urban areas, but none has impervious area greater than 44%. Flooding in urban areas has often been linked to impervious coverage (Leopold 1968), but other elements of urban infrastructure and stormwater management can play a role in determining flash flooding properties. The 10 flashiest watersheds have impervious fractions ranging from 24% for West Branch Herring Run in Baltimore to 44% for River des Peres in St. Louis. The flashiest watershed in the United States, Rocky Branch in Raleigh, NC, has an impervious fraction of 38%. The most densely urbanized areas of major cities do not typically have extensive stream gauging, so the absence of flashy watersheds with impervious fraction greater than

<table>
<thead>
<tr>
<th>Rank</th>
<th>Drainage basin name</th>
<th>USGS ID</th>
<th>PPY</th>
<th>Drainage area (mi²)</th>
<th>Impervious area (%)</th>
<th>Gauging ratio</th>
<th>GPD shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Rocky Branch below Pullen Drive, Raleigh, NC</td>
<td>0208735012</td>
<td>24.1</td>
<td>1.20</td>
<td>37.5</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>Town Branch Tributary at Highway 16, Fayetteville, AR</td>
<td>07048490</td>
<td>19.2</td>
<td>1.31</td>
<td>36.5</td>
<td>0.14</td>
<td>−0.01</td>
</tr>
<tr>
<td>3</td>
<td>Sebago Creek near Rock Hill, MO</td>
<td>07010070</td>
<td>18.5</td>
<td>1.89</td>
<td>40.0</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>Joe Creek at 61st Street, Tulsa, OK</td>
<td>07164600</td>
<td>17.8</td>
<td>11.62</td>
<td>37.4</td>
<td>0.20</td>
<td>0.18</td>
</tr>
<tr>
<td>5</td>
<td>Moores Run at Radecke Avenue, Baltimore, MD</td>
<td>01585230</td>
<td>16.4</td>
<td>3.51</td>
<td>32.4</td>
<td>0.30</td>
<td>0.34</td>
</tr>
<tr>
<td>6</td>
<td>River des Peres near University City, MO</td>
<td>07010022</td>
<td>13.4</td>
<td>8.22</td>
<td>44.0</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>7</td>
<td>Fourmile Run at Alexandria, VA</td>
<td>01652500</td>
<td>12.4</td>
<td>13.36</td>
<td>34.3</td>
<td>0.45</td>
<td>−0.05</td>
</tr>
<tr>
<td>8</td>
<td>Cowmire Creek at Bridgetton, MO</td>
<td>06935980</td>
<td>11.9</td>
<td>3.75</td>
<td>43.3</td>
<td>0.09</td>
<td>0.34</td>
</tr>
<tr>
<td>9</td>
<td>West Branch Herring Run at Idlewylde, MD</td>
<td>01585200</td>
<td>11.6</td>
<td>2.32</td>
<td>24.2</td>
<td>0.06</td>
<td>0.49</td>
</tr>
<tr>
<td>10</td>
<td>Mattese Creek near Mattese, MO</td>
<td>07019317</td>
<td>11.0</td>
<td>7.95</td>
<td>39.0</td>
<td>0.12</td>
<td>0.47</td>
</tr>
</tbody>
</table>
44% reflects, to some extent, stream gauging distribution properties. Additionally, surface channels have often been buried in areas with extensive impervious surfaces. There are, however, 24 stream gauging stations with impervious fraction greater than 44% in our record and nine stations with impervious fraction greater than 50%.

Streamflow records in small urban watersheds can be compromised by measurement errors that arise in constructing stage–discharge rating curves (see Lindner and Miller 2012; Smith et al. 2005b). Errors in rating curves are especially problematic when the largest direct stage–discharge measurements for a gauging station are much smaller than the stages they are applied to. It is difficult to obtain direct discharge measurements of large flood peaks in small urban drainage basins where

\[
F_{\xi,\mu,\sigma}(z) = \begin{cases} 
1 - \left(1 + \xi \frac{z - \mu}{\sigma}\right)^{-1/\xi} & \text{for } \xi \neq 0, \quad z \geq \mu \\
1 - \exp\left(-\frac{z - \mu}{\sigma}\right) & \text{for } \xi = 0, \quad \mu \leq z \leq \mu + \frac{\sigma}{\xi}
\end{cases}
\]

The cumulative density function represents the probability that a random variable will take a value less than or equal to \(z\). The shape parameter of the GPD \(\xi\) provides an index of the thickness of the upper tail of the distribution with higher values representing thicker tails and thus higher probability of higher peak discharge values [see, e.g., Villarini and Smith (2010) for results for the eastern United States]. Variable \(\mu\) is a location parameter and \(\sigma\) is a scale parameter. Positive values of the shape parameter imply unbounded, thick-tailed distributions, negative values imply distributions that are bounded above, and shape parameters of zero imply exponential tails. Estimated shape parameters for the flashiest watersheds (Table 1) are more positive than shape parameters for the eastern United States (Villarini and Smith 2010). For Town Branch in Fayetteville, AR, and Fourmile Run in Alexandria, VA, the GPD shape parameter is slightly negative, implying that the POT distribution is bounded. Bounded discharge values in urban watersheds can be tied to capacity constraints in the distribution system.

c. Small watershed subset

A subset of small watersheds is utilized to investigate the flashiness of cities across the country. This small watershed subset is composed of stream gauges with drainage areas less than 38.8 km² (15 mi²). This area is large enough to include the very flashy watersheds, but small enough to decrease the dependence of flashiness on drainage area. There are 473 gauged watersheds with drainage area less than 38.8 km² (15 mi²). The conditions can be dangerous and flood peaks are quick. Gauging ratio is one measure of the potential quality of streamflow data for high discharge peaks. It is the ratio of the largest direct measurement of streamflow to the largest observed discharge peak (Potter and Walker 1985). Gauging ratios for the top 10 flashiest watersheds are small, with many values under 10%, suggesting that the streamflow records for these watersheds may be flawed. Flashy watersheds in St. Louis have particularly small gauging ratios, with gauging ratio values less than 0.12 for the four St. Louis watersheds in the top 10 flashiest watersheds.

POT discharge data are modeled using the generalized Pareto distribution (GPD; Wang 1991), for which the cumulative distribution function is given by

The same swath of the south-central United States to the mid-Atlantic region that dominates flashy watersheds in Fig. 2 is also prominent in the results for flashy cities and states in Fig. 3. For the Pacific Northwest, flashy states are not linked to flashy cities. East of the Rocky Mountains, the flashiness of cities is more representative of the flashiness of the state, as in the cases of Tulsa and Oklahoma or Baltimore and Maryland that are all quite flashy while Chicago and Illinois are not. Of course, this effect may be impacted by the nonuniform placement of watershed gauges on a state-by-state basis.

The mean PPY is used to compile a list of flashiness for cities in the continental United States (Table 2). This list includes all cities that contain at least three gauges from the small watershed subset. The Pacific Northwest cities are low on the list, with a PPY for Seattle of 0.02 and for Portland of 0.38. Baltimore and St. Louis, which each have multiple watersheds in the top 10 flashiest watersheds, are among the flashiest cities in the contiguous United States. Both also have a relatively dense network of small gauged watersheds. Tulsa, OK, ranks first, but has fewer watershed gauges than Baltimore and St. Louis (4 vs 11 and 21). Many of the well-gauged flashiest cities have been studied for their flash flooding problems. Baltimore is the site of the first urban National Science Foundation Long Term Ecological Research
site, which has resulted in many studies of the city’s flooding problems (e.g., Smith et al. 2005a,b; Ntelekos et al. 2007; Meierdiercks et al. 2010a,b; A. J. Miller et al. 2011, unpublished manuscript; Ogden et al. 2011; Smith et al. 2013, 2015). Other cities with extensive flood research records include Atlanta (Ferguson and Suckling 1990; Wright et al. 2012) and Charlotte (Martens 1968; Smith et al. 2002; Villarini et al. 2009, 2010; Wright et al. 2014).

d. Small flashy watershed subset

Within the small watershed subset, 156 watersheds have at least one peak discharge greater than 1 m$^3$ s$^{-1}$ km$^{-2}$ per year, on average. We divide this sample of watersheds by the 103°W longitude into the portion east of the Rocky Mountains and the portion within the Rocky Mountains and westward. While 103°W longitude does not represent the eastern edge of the Rocky Mountains, no flashy watersheds are located between 103°W and the eastern edge of the Rockies. The differences in volume-to-peak ratios in these watersheds suggest that POT flood events east to the Rockies are driven by different mechanisms than those in the Rockies and westward. Among these flashy watersheds, there are 100 urban watersheds east of the Rocky Mountains, 33 rural watersheds east of the Rockies, six urban watersheds west of and within the Rockies, and 16 rural watersheds west of and within the Rockies. Flashy watersheds east of the Rocky Mountains are likely to be urban. Within the entire small watershed subset east of the Rockies, 159 of 248 watersheds are urban (64%) and within the small flashy watershed subset 100 of 133 watersheds are urban (75%). Using a simple binomial distribution calculation, the probability of 100 of 133 randomly selected small subset watersheds being urban is 0.19%. This agrees with results in Fig. 3, showing that impervious area is highly correlated with flashiness at this small scale.

Watersheds within the Rocky Mountains and westward tend to have high slopes (Fig. 5). Watersheds in the Pacific Northwest have particularly high slopes—the median slope for the 12 rural and one urban small flashy watersheds in Washington and Oregon is 29.6%. All rural watersheds west of and within the Rockies have a median slope of 29.3%. Rural watersheds nationally typically have higher slopes than urban watersheds. Much of the flashiness west of and within the Rocky Mountains occurs in steeply sloped rural watersheds. In both the east and west, flashy rural watersheds are more compact, with a higher compactness value (area divided by the squared perimeter), than are flashy urban watersheds. West of and within the Rocky Mountains this difference is more pronounced, with rural western watersheds having a median compactness of 2.68 compared to urban western watersheds with 2.11 (not shown here).

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**TABLE 2. Flashiness of cities in the contiguous United States.**

<table>
<thead>
<tr>
<th>Rank</th>
<th>City</th>
<th>State</th>
<th>Mean PPY</th>
<th>No. of gauges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Tulsa</td>
<td>Oklahoma (OK)</td>
<td>8.56</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Baltimore</td>
<td>Maryland (MD)</td>
<td>8.33</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>St. Louis</td>
<td>Missouri (MO)</td>
<td>7.83</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>Greensboro</td>
<td>North Carolina (NC)</td>
<td>4.14</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Charlotte</td>
<td>NC</td>
<td>3.42</td>
<td>18</td>
</tr>
<tr>
<td>6</td>
<td>Louisville</td>
<td>Kentucky (KY)</td>
<td>2.94</td>
<td>7</td>
</tr>
<tr>
<td>7</td>
<td>Atlanta</td>
<td>Georgia (GA)</td>
<td>2.00</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>New York</td>
<td>New York (NY)</td>
<td>1.65</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>Tampa</td>
<td>Florida (FL)</td>
<td>1.65</td>
<td>7</td>
</tr>
<tr>
<td>10</td>
<td>San Francisco</td>
<td>California (CA)</td>
<td>1.50</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>Santa Barbara</td>
<td>CA</td>
<td>1.01</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>Stamford</td>
<td>Connecticut (CT)</td>
<td>0.84</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>Los Angeles</td>
<td>CA</td>
<td>0.65</td>
<td>3</td>
</tr>
<tr>
<td>14</td>
<td>Riverside</td>
<td>CA</td>
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<td>3</td>
</tr>
<tr>
<td>15</td>
<td>Portland</td>
<td>Oregon (OR)</td>
<td>0.38</td>
<td>4</td>
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**FIG. 5. Box plot of watershed slope for the small flashy subset.** Watersheds are divided by urban–rural census designation and location east or west of the Rocky Mountains. The limits of the box represent the 25th and 75th percentiles, while the line inside represents the median (50th percentile). The whiskers indicate the 10th and 90th percentiles. Sample sizes for boxes are 100, 33, 6, and 16 for (from left to right) eastern urban, eastern rural, western urban, and western rural, respectively.
The principal storm agents for POT events in the small watershed subset vary substantially across the United States (Fig. 6). The number of POT caused by tropical cyclones was calculated as any POT event occurring within 500 km and 7 days of the HURDAT storm track [as in Smith et al. (2011)]. As in Villarini and Smith (2010), the time and spatial windows were chosen to capture the wide extent of rainfall for tropical cyclones. The number of POT events caused by thunderstorms was calculated as any POT event not caused by a tropical cyclone, occurring within 5 km and 24 h after or 12 h before a lightning strike. This time window was chosen to accommodate flash peak events in the Rockies and westward where response times may be longer than in the eastern United States. Thunderstorms dominated POT events east of the Rocky Mountains, particularly in the Midwest and south-central United States where up to 100% of POT events are caused by thunderstorms. Warm season thunderstorms are a frequent driver of flash flooding (Doswell et al. 1996; Baeck and Smith 1998; Ntelekos et al. 2007). In the Pacific Northwest, no more than 20% of POT events are due to thunderstorms. Along the East Coast from Florida to Maryland, many POT events are caused by tropical cyclones. North Carolina and Georgia have a particularly high proportion of POT events caused by tropical cyclones, with percentages up to 44% in Georgia and 28% in North Carolina. The western coast of Florida and the Baltimore–Washington, D.C., metro area are also affected by tropical storm POT events, but percentages do not exceed 25%. POT events on the West Coast are rarely due to thunderstorms and occur primarily in the winter (Fig. 7). These flash floods are caused by a mixture of rain on snow events (Leung et al. 2004) and heavy rainfall from atmospheric rivers (Ralph et al. 2006). This difference in POT generation reflects the differences in volume-to-peak ratios between watersheds east of the Rocky Mountains and watersheds within and west of the Rocky Mountains.

Fig. 6. Percentage of POT events due to thunderstorms and tropical cyclones for the subset of small flashy watersheds: the scale runs from 0%–10% (faint yellow) to 90%–100% (dark blue) in increments of 10%.
Many of the watersheds in the small flashy subset are in urban areas, and rainfall properties can vary around cities. A significant body of research has found rainfall maxima downwind of cities (Shepherd 2005; Dixon and Mote 2003), and there has been some evidence of increased flood peaks downwind of the Baltimore city center (Smith et al. 2013). We investigated the potential relationship between a watershed’s location upwind or downwind of an urban area and the flashiness of that watershed. Such a relationship would be difficult to investigate at a more regional level, where few gauged watersheds are located near an urban area and where other factors (terrain, impervious cover, etc.) can impact watershed flashiness. The direction from the center of the city to watershed gauge for the small flashy subset was calculated for any watershed within 10 km of the census-designated metropolitan area for the 50 most populous metropolitan areas in the United States plus any city listed in Tables 1 and 2. Watersheds located northeast of the city center have a higher PPY value and more frequent flash flooding than do watersheds located in any other direction from the city center (Fig. 8). This northwest direction is often found to be downwind in urban rainfall modification studies (see below). The median PPY value for the northeast direction is 2.12, while the median value for the opposite, southwest direction is 1.26. The median PPY value for the northwest direction is particularly low at 0.25 with a narrow distribution of values. This analysis included 185 watersheds in total, and the PPY samples are statistically different at a 90% confidence level based on the Kruskal–Wallis test \( (p \text{ value} = 0.069) \). These results suggest a potential link between the urban downwind maxima of rainfall documented in previous studies and impacts on flooding.

A further analysis was carried out using only watersheds near cities with known rainfall maxima northeast (downwind) of the city. These cities were Atlanta (Wright et al. 2012), Baltimore (Smith et al. 2012), Charlotte (Wright et al. 2014), Cleveland (Huff and Changnon 1973), Dallas (Shepherd et al. 2002), Houston (Burian and Shepard 2005), Indianapolis (Niyogi et al. 2011), St. Louis (Changnon 1979), San Antonio (Shepherd et al. 2002), and Washington, D.C. (Smith et al. 2012). The results of this test (not shown here) included only 72 watersheds total. Again, the northwest stands out with the lowest PPY values, with a median of 2.2, although it includes only eight watersheds. The upwind (southwest) and downwind (northeast) directions have similarly high PPY values with medians of 5.7 and 5.3, respectively, while the southeast has a lower median PPY of 3.2. These results highlight the important impact of the city on flooding and rainfall generation. Upwind of cities, increased convergence—due to urban surface roughness—can impact rainfall patterns, and downwind of cities the combination of increased convergence, urban heat island
lifting, and urban aerosols can impact rainfall patterns. In the northwest and southeast directions, these mechanisms should not impact rainfall and flash flood generation.

e. Chicago–St. Louis urban subset

The difference in mean flashiness between Chicago and St. Louis is striking. Two cities in close geographical proximity, with metropolitan areas in the same state, rank 3 and 18 in flashiness in a list of 20 cities in the contiguous United States (Table 2). Chicago has an average PPY of 0.09 while St. Louis has an average PPY of 7.83. We focus on a number of urban watersheds in the greater Illinois–Missouri region to further investigate the differences in flashiness between these two cities.

First, we investigate whether differences in climate may cause differences in flashiness between Chicago and St. Louis. Both Chicago and St. Louis display a seasonal peak in POT events in the summer, with maximum frequency in late May and June, respectively (Fig. 9). This reflects the prominent role of warm season thunderstorm systems as flood agents for both cities (Fig. 6). The average annual lightning flash density (strikes per square kilometer) in each basin over the June–August period is similar for both cities. Watersheds in Chicago receive between 2.7 and 4.6 strikes per square kilometer, and watersheds in St. Louis receive between 3.7 and 4.9 strikes per square kilometer on average. The cities also receive similar amounts of rain annually; Chicago watersheds receive an average of 940 mm (37 in.) while St. Louis watersheds receive an average of 1030 mm (41 in.). St. Louis receives slightly more extreme rainfall at short durations; the 1-yr, 2-h rain rate is 36 mm (1.4 in.) in Chicago and 41 mm (1.6 in.) in St. Louis on Technical Paper 40 (TP-40) maps (Hershfield 1961). The climate for Chicago and St. Louis watersheds may vary somewhat, with St. Louis watersheds having slightly more summertime lightning strikes and rainfall, but the climate is not sufficiently different to explain the large difference in flashiness between the two cities.

A measure of response time is used to assess the hydrologic response of the watersheds for POT events. The median volume-to-peak ratios for Chicago watersheds are extremely long, between 17 and 27 h (Fig. 10). Median volume-to-peak ratios in all other watersheds in this subset (including watersheds in other cities within the Illinois, Missouri, Indiana, Michigan, Wisconsin, and Kentucky area) are less than 13 h, with all but two below 10 h. To further assess hydrologic response for the St. Louis and Chicago regions, we examine normalized hydrographs for all POT events for all urban watersheds with drainage areas of approximately 28 km² (11 mi²) in the region. The similar watershed size eliminates area as a factor in this analysis. For Chicago we include three

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**Fig. 8.** Box plot of POT per year for watersheds based on the direction from city center to gauge location. The limits of the box represent the 25th and 75th percentiles, while the line inside represents the median (50th percentile). The whiskers indicate the 10th and 90th percentiles. Sample sizes for boxes are 26, 36, 65, and 58 for (from left to right) northwest, northeast, southwest, and southeast, respectively.

**Fig. 9.** Probability density function for day of year of POT discharge events for all watersheds in Chicago (solid) and St. Louis (dashed).
watersheds with areas of 28.7, 29.0, and 29.8 km², and for St. Louis we include two watersheds with areas of 29.3 and 30.3 km². For reference, we also include three watersheds from other cities in the region with areas of 28.2, 29.3, and 30.3 km². Normalized hydrographs were calculated by scaling discharge values to produce a total runoff volume of 1 mm, then centering the peak discharge at time zero. The difference between the hydrologic responses to POT events across the cities, even for basins of similar drainage areas, is striking (Fig. 11). Chicago is the clear outlier, with peak discharges below 0.75 m³ s⁻¹ mm⁻¹ and very long response times.

The volume-to-peak analyses and normalized hydrograph analyses suggest that the lack of flashiness in Chicago’s small watersheds is closely linked to land surface processes that control characteristic flow times over urban surfaces and through the urban drainage network. Slopes in Chicago range from 0.4 to 1.2 with a median value of 0.6, falling in the low range of slopes, even for urban watersheds (Fig. 5). Many of the watersheds in cities surrounding Chicago and St. Louis, however, have similar slopes to those in Chicago, but have lower volume-to-peak ratios and higher PPY values. Possible explanations for the long response times in Chicago, in addition to low slopes, include stormwater management infrastructure and soil-drainage properties. The Chicago metropolitan area, and much of the state, is built on drained wetlands. The state was divided into drainage districts in the 1870s, and hundreds of thousands of acres of land were drained (Herget 1978). This legacy of drainage may play a role in the anomalously low flashiness of urban watersheds in the region. Chicago also has a unique history of stormwater problems due to the reversal of the Chicago River for sanitation purposes. Chicago began installing the Deep Tunnel system in 1975 to store stormwater below the city’s rivers (Changnon and Westcott 2002).

The normalized hydrograph results (Fig. 11) show that St. Louis is anomalously flashy for the region. Watersheds in St. Louis have higher discharge peaks, with one peak up to 3.7 m³ s⁻¹ mm⁻¹ and several over 3 m³ s⁻¹ mm⁻¹, than do watersheds in other nearby cities, with all discharge peaks below 2.5 m³ s⁻¹ mm⁻¹. Watershed slopes in St. Louis range from 2.4 to 6.7, with a median value of 3.6, and are higher than slopes for other urban watersheds in the region (slopes range from 0.4 to 3.1, with a median of 1.85). It is possible that rating curves in St. Louis overpredict large flood peaks. At 0.05, 0.09, and 0.12, the gauging ratios for the three flashiest watersheds in St. Louis are all on the lower end of gauging ratio values for the top 10 flashiest watersheds in the contiguous United States (Table 1), suggesting that the
flood peak data for these watersheds is less reliable than for other watersheds.

f. Comparisons to other flood measures

NWS flash flood reports provide an interesting point of comparison to flashiness based on the USGS streamflow gauge system. The NWS flash flood reports refer to flash floods that pose a potential threat to life or property and have moving water more than 6 in. in depth or standing water more than 3 ft in depth (Gourley et al. 2013). These reports may be biased by population, as well as local reporting practices. Comparison of the flashiness maps (Figs. 2, 3) and NWS flash flood report maps (Fig. 12) highlights the elevated frequency of flash flooding in the Missouri–Oklahoma–Arkansas region. Both flash flood measures also depict the frequent flooding in Baltimore and St. Louis. The measures differ markedly in Chicago, with 129 NWS flash flood reports for the city over the 5+ yr period. Chicago streams are not flashy, as defined by our flashiness metric, but do overtop their banks at unit discharges substantially less than 1 m$^3$ s$^{-1}$ km$^{-2}$ based on the NWS reports. The difference in these two measures of flash flood frequency highlights the need to better understand the channel–floodplain environment that is key to flash flood hazards in urban environments.

The other major difference between the flashiness map and NWS flash flood report map is in the Pacific Northwest. The flashiness measure suggests that some of the flashiest watersheds in the contiguous United States are in the Pacific Northwest. However, the Pacific Northwest has relatively low incidence of flash flood reports, with only 30 flash floods in Washington and eight in Oregon. Flashy watersheds within and west of the Rocky Mountains have long response times, based on the volume-to-peak ratio, suggesting that these watersheds may not be experiencing true flash flood events. This aspect of the flashiness measure likely magnifies the differences between the flashiness and flash flood report measures in the Pacific Northwest, though it is also possible that lower population in these areas leads to some underreporting.

Flood damage, fatalities, and injuries do not closely resemble the flash flood frequency throughout the United States (Fig. 13). These measures are
influenced by state population and large flood events such as the Big Thompson flood in Colorado and Rapid City flood in South Dakota (Pielke et al. 2002; Ashley and Ashley 2008). Additionally, flash flood casualties are impacted by social factors that vary across the country. Large economic damages are tied more closely to large floods than to frequent moderate flooding events. However, the flood fatality map does depict the swath of the south-central to mid-Atlantic states that have frequent flash flooding by both our flashiness measure and the NWS flash flood reports.

4. Summary and conclusions

The flashiest watersheds in the contiguous United States are presented based on PPY or frequency of
The flashiest watersheds in the contiguous United States are small urban watersheds concentrated in the Missouri–Oklahoma–Arkansas region near the Ozark Mountains and in the mid-Atlantic I-95 corridor in Maryland, Virginia, and North Carolina. Tulsa, St. Louis, and Baltimore stand out as the flashiest cities in the contiguous United States. Baltimore and St. Louis alone contain 6 of the 10 flashiest watersheds in the contiguous United States.

2) Many of the flashiest watersheds in the contiguous United States are located in the Pacific Northwest. However, these watersheds have higher volume-to-peak ratios than flashy watersheds east of the Rocky Mountains, suggesting that they may not meet typical definitions of frequent flash flooding. Flashy watersheds in the western United States are tied to steeper slopes and wintertime precipitation.

3) Thunderstorms are the major agent of flooding in flashy watersheds east of the Rocky Mountains, causing up to 100% of the POT events. Tropical cyclones account for up to 30%–40% of POT events in Georgia and North Carolina and up to 25% of POT events in western Florida and the Baltimore–Washington, D.C., metropolitan area.

4) Cities do have an impact on watershed flashiness. Watersheds located northeast of urban centers are flashier than watersheds located in any other direction from the city center for small, flashy watersheds located in the most populous 50 cities in the contiguous United States. The rainfall maxima downwind of cities appear to cause corresponding flashiness maxima downwind of cities. For small, flashy watersheds located in cities with known downwind rainfall maxima, watersheds upwind and downwind of the city center are significantly flashier. Watersheds to the northwest of city centers are substantially less flashy than other watersheds near cities.

5) St. Louis is one of the flashiest cities in the United States while Chicago is one of the least flashy. St. Louis has a slightly more conducive climate to flash flooding than does Chicago, but differences in rainfall climatology are not sufficient to explain the dramatic contrasts in flood response. Chicago has unusually long response times as displayed by the volume-to-peak ratio of the POT events in its watersheds and by its modified unit hydrographs. These response times may be related to the unique history of stormwater management in Chicago.

6) The flashiness metric matches NWS flash flood reports and flood fatalities in some settings, especially in the swatch from the south-central United States to the mid-Atlantic states. NWS flash flood reports differ from the flashiness measure in Chicago, and the flashy watersheds in the Pacific Northwest are not matched with an elevated frequency of NWS flash flood reports.

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