Advances in Water Resources 87 (2016) 80–91

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

On the seasonality of flooding across the continental United States

Gabriele Villarini*

IIHR-Hydroscience & Engineering, The University of Iowa, 306 C. Maxwell Stanley Hydraulics Laboratory, Iowa City, IA 52242, USA

ARTICLE INFO

Article history:
Received 14 September 2015
Revised 4 November 2015
Accepted 7 November 2015
Available online 1 December 2015

Keywords:
Seasonality
Flooding
Circular statistics
Nonstationarity
Regulation
Urbanization

ABSTRACT

This study examines the seasonality of flooding across the continental United States using circular statistics. Analyses are based on 7506 USGS stream gage stations with a record of least 30 years of annual maximum instantaneous peak discharge. Overall, there is a very strong seasonality in flooding across the United States, reflecting differences in flood generating mechanisms. Most of the flood events along the western and eastern United States tend to occur during the October–March period and are associated with extratropical cyclones. The average seasonality of flood events shifts to April–May in regions where snowmelt is the dominant flood agent, and later in the spring–summer across the central United States. The strength of the seasonal cycle also varies considerably, with the weakest seasonality in the Appalachian Mountains and the strongest in the northern Great Plains. The seasonal distribution of flooding is described in terms of circular uniform, reflective symmetric and asymmetric distributions. There are marked differences in the shape of the distribution across the continental United States, with the majority of the stations exhibiting a reflective symmetric distribution.

Finally, nonstationarities in the seasonality of flooding are examined. Analyses are performed to detect changes over time, and to examine changes that are due to urbanization and regulation. Overall, there is not a strong signal of temporal changes. The strongest impact of urbanization and regulation is on the strength of the seasonal cycle, with indications that the signal weakens (i.e., the seasonal distribution becomes wider) under the effects of regulation.

1. Introduction

Understanding the seasonality of flooding is critical in a number of applications, from water resources management and assessment of flood risk, to climate change studies and regionalization (e.g., [3,6,9–13,15,22,29,43,48,57,59]). Moreover, the analysis of seasonality is useful to characterize the variety of different flood generating mechanisms (e.g., [18,27,44,56,62,67]).

The seasonality of flooding has been examined in different regions. Black and Werritty [7] analyzed 156 stream gages in northern Britain. Their analyses found that, while flood events could occur during any day of the year, 78% of the flood events at the majority of the stations were concentrated in the October–March period. Burn [9] analyzed 59 natural catchments in the Canadian Prairies and discussed similarities and differences in flood seasonality across Alberta, Saskatchewan and Manitoba, and the implications for regional flood frequency analysis. Cunderlik and Ouarda [16] worked on the temporal changes in the flood timing in Canada over the 1974–2003 period. They found that spring floods associated with snowmelt in southern Canada (in particular in the Atlantic Provinces) tended to happen earlier than in the past, but they did not detect significant changes in the timing of flooding in the fall. Parajka et al. [51] focused on annual maximum runoff and daily precipitation in the Alpine-Carpathian range over the 1961–2000 period. They showed that the annual maxima typically occurred in July–August in the Carpathian Arch and northern Alps, with a shift later in the year for southern Austria and north-east Italy. Moreover, the results for annual maximum runoff were similar to precipitation, even though more heterogeneous. Koutroulis et al. [32] examined the seasonality of heavy rainfall and flooding for the island of Crete, and showed that the largest events were concentrated in the November–December months. Macdonald [37] analyzed changes in the flood seasonality for the historical flood record for the River Ouse (northern England) since AD 1600. He found an increase in the number of February–March flood events since 1950. Köplin et al. [31] studied the projected changes in the seasonality of annual maximum discharge records at 189 catchments in Switzerland; they found that the strongest signal of change in flood seasonality was detected at sites in which snowmelt played an important role.

Various approaches have been used to describe flood seasonality (e.g., [7,17,12]), with the increasingly widespread use of circular or directional statistics in recent years (e.g., [5,9,11,12,17,19,31,38]).

Despite the importance of the topic for hydrology, flood hazard and water resources management, a comprehensive characterization

---

* Tel.: +1 319 384 0596.
E-mail address: gabriele-villarini@uiowa.edu

http://dx.doi.org/10.1016/j.advwatres.2015.11.009
0309-1708/

of the seasonality of flooding across the continental United States and of its potential changes over time is still lacking, with existing works that have only been performed at a regional or local scale. Magilligan and Graber [38] studied the seasonality of flooding for 36 stream gages in New England. They found that basin size, altitude and distance from the coast were major controls on the strength of the seasonality. Gamble [25] examined the seasonality of annual flood peaks in the southeastern United States using 84 stream gage stations. They identified five regions with similar seasonality (winter, spring, spring/high summer, fall, no dominant season). Lecce [34] focused on the seasonality of flooding in North Carolina, and divided the state into three regions (Appalachian, Piedmont and Coastal Plain); about 75% of the floods occurred in the December–April period in the Appalachian region, while this fractional contribution decreased in the Piedmont (44%) and Coastal Plain (55%) regions. Summer and fall flooding occurs more frequently in the Piedmont and Coastal Plain regions compared to the Appalachian region.

Moreover, we have little information related to changes in the seasonality of U.S. flooding over the 20th and 21st centuries despite the importance of the impacts of changes in the seasonality of extreme events on the built infrastructure (e.g., [19]). These potential changes are related to changes in the climate system as well as anthropogenic alterations of the catchments. Most of the efforts have focused on changes in runoff timing in the western and north-eastern United States associated with springtime snowmelt shifted earlier in the year (e.g., [4,14,28,42,65,66]). However, much less is known about changes in the seasonality of annual maximum discharge.

In considering potential nonstationarities, we have to remember that many of the watersheds across the continental United States have been subject to human modifications, including damming and construction of upstream reservoirs and urbanization. While a lot of effort has been paid to the detection of changes in the flood peak records (e.g., [26,36,39,52,60,68,70]), we have little information related to the impacts of anthropogenic modifications on flood seasonality. When comparing urban to rural catchments, Robson and Reed [55] showed that urban watersheds tend to be characterized by summer flooding (see also Bayliss and Jones [5]), while the control rural watersheds exhibit mainly a winter seasonality. These differences are likely related to the larger effect of summertime convective storms on urbanized watersheds. Moreover, the flood seasonality was wider (i.e., flood events could occur all year round) for urban than rural catchments.

Based on this brief overview, it is clear that a comprehensive characterization of the seasonality of flooding across the continental United States, as well as of its changes, requires further investigations. Therefore, the research questions I will address in this study are:

- What is the seasonality of flooding across the continental United States? Analyses will examine basic descriptors (e.g., average seasonality and its strength) and will characterize the seasonal distribution.
- Can we detect a change in the seasonal cycle of flooding over the second half of the 20th century and into the 21st century?
- What are the effects of urbanization and regulation on the seasonality of flooding?

The paper is organized as follows. Section 2 summarizes the data and provides an overview of the statistical methods (circular statistics) used to address the aforementioned research questions. Section 3 presents the results, while the main findings are summarized and the study concludes in Section 4.

2. Data and methodology

The results of this work are based on instantaneous annual peak discharge data from 7506 U.S. Geological Survey (USGS) stream gage stations over the continental United States (Fig. 1a). These stations have at least 30 years of data (in agreement with the recommendation by Cunderlik et al. [17]), with more than 5000 stations spanning the second half of the 20th century and the first decade of the 21st century (Fig. 1, panels b and c). To examine the impact of regulation, the focus is on stations that have at least 10 years of peaks with an associated code 6 (“Discharge affected by Regulation or Diversion”) and at least 10 years without it. To examine the impact of urbanization, the same criteria are applied but for peaks with the code C (“All or part of the record affected by Urbanization, Mining, Agricultural changes, Channelization, or other”). As shown in Supplementary Fig. 1, there are 755 (241) stations that fit these criteria to examine the impact of regulation (urbanization) on the flood peak seasonality.

Analyses of the seasonality of flooding across the continental United States in this study are based on circular statistics. Here I provide a brief overview of circular statistics based on Pewsey et al. [50]. For a thorough discussion on this topic, the interested reader is pointed to Mardia [40], Fisher [23], and Pewsey et al. [50], among others. I use annual maximum peak discharge data from three stream gages to support the description and applicability of circular statistics. Fig. 2 shows three possible seasonal distributions that one can encounter across the continental United States. The results in the left panels of Fig. 2 are relative to the Roanoke River at Roanoke Rapids, North Carolina (USGS ID 02080500), where annual maxima can occur any time during the year without a preferential season. The two circles in the middle column of Fig. 2 are for the East Brach Penobscot River at Grindstone, Maine (USGS ID 01029500). Here the peak discharge maxima exhibit a strong seasonality, with peaks concentrated during the April–May months. Finally, the results in the right column of Fig. 2 are relative to the Souhegan River at Merrimack, New Hampshire (USGS ID 01094000). This station exhibits an asymmetric distribution with most of the annual maxima in the March–May period, but with peaks in the December–January months as well.

Circular statistics are appropriate for data that can be represented on a circumference with unit radius. Similar to Pewsey et al. [50], let us represent the angles in radians, and consider a circle of unit radius, with $\mathbf{x} = (\cos\theta, \sin\theta)$ relating the unit vector $\mathbf{x}$ and the angle θ. We can simplify the formulation by considering $\mathbf{x}$ on the complex rather than on the real plane, with the horizontal (vertical) axis representing the real (imaginary) component. In the complex representation, we can represent an observation with vector $\mathbf{x}$ as:

$$z = e^{i\theta} = \cos\theta + i \cdot \sin\theta \tag{1}$$

where i refers to $\sqrt{-1}$. Supplementary Fig. 2 provides a graphical representation of the circular observation in the complex plane.

For circular data, the sample mean direction $\bar{\theta}$ is the most widely used measure of location. Fig. 2 (bottom panels) shows the direction of each observation, together with the mean resultant vector (black arrow) for each of the three stream gages. For the Roanoke River at Roanoke Rapids (Fig. 2, left panels), the mean direction is 336°, corresponding to December 2. On the other hand, the mean resultants for the East Brach Penobscot River at Grindstone (Fig. 2, middle panels) and for the Souhegan River at Merrimack (Fig. 2, right panels) are 116° (corresponding to April 28) and 75° (corresponding to March 17), respectively.

Fig. 2 highlights that the mean direction provides some useful information, but that it could also lead to misleading statements if not complemented by a measure of the strength of the seasonality. This is particularly true for the uniform case, in which we can have flood events throughout the course of the year. The spread in the data and the strength of the seasonality can be quantified using the sample mean resultant length $\bar{R}$. The sample mean resultant length can assume values from 0 to 1, with values of 1 when all the points are concentrated at one location, and values of 0 when the observations are uniformly distributed along the unit circle. This quantity is represented by the length of the black solid arrows in Fig. 2 (bottom