Analysis of flood peak scaling in mesoscale non-nested basin

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ABSTRACT

The study of flood scaling is an important means to solve the problem of flood prediction in ungauged and poorly gauged basins. With the impact of climate change and human activities, the mechanism and process of floods are constantly changing. However, in many areas, there are only simple scaling results that can be used to guide daily work. Taking the Daqinghe River basin as an example, a fixed flood scaling exponent determined in 1974 (before the change point of 1979) is still used all over the basin, which is apparently no longer appropriate. Therefore, in this paper, we aim to explore: (1) the scale relationship between the peak flows and the basin area under changing environments; (2) the validation of the scale invariance theory; (3) the physical relationship between the event-based scaling theory and the annual flood quantile-based scaling theory in the mesoscale non-nested and partly nested basins; and (4) the modification of the existing uniform flood scaling exponent in the study area. To achieve these objectives, eight simultaneous observed flood events in seven non-nested and partly nested mesoscale sub-basins of the Daqinghe River basin were selected to analyze the flood scaling theory. The results showed that there was a scaling relationship between the flood peaks and watershed area for the flood events, and the scale invariance theory was also supported herein. To analyze the effect of the environmental conditions on flood scaling in the Daqinghe River basin, the flood events were reconstructed after the change point (the year 1979). It was found that the flood scaling exponents of the reconstructed flood events are larger than those of the observed events after the change point. The flood scaling exponent changed with flood events, varying from 0.65 to 1.26 when considering the basin area as the independent variable, and decreasing with a minimum of 0.36 when taking the rainfall characteristics into consideration. It was also found that the mean of the event-based scaling exponents is larger than the annual flood quantile-based scaling exponents.

Key words | event-based flood scaling, multi-scaling, non-nested mesoscale basin, scale invariance

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INTRODUCTION

Floods are the most common natural disaster in the world. Flood prediction is a key non-project measure for flood control and disaster reduction (Li *et al.* 2014a; Deng *et al.* 2016; Lei 2016), but due to many factors, flood prediction is always a problem that is difficult to completely solve. In addition, climate change and land surface change due to human activities make flood prediction more complicated (Mantilla 2007; Lima & Lall 2010; Modarres 2010). Flood prediction requires a long period of historical flood data to statistically analyze the laws of flood occurrence. However, many parts of the world lack long-term stream flow records, and the length of the data series does not meet flood prediction requirements. Many regions do not even have any flood monitoring data. Therefore, flood prediction in ungauged and poorly gauged basins has always been a difficult problem to solve in the field of hydrology.

doi: 10.2166/ws.2019.172

At present, the most common methods for solving the flood prediction problem are regional flood frequency analysis methods (Gupta *et al.* 1994; Robinson & Sivapalan 1997). Among them, the index method and the regional regression method, which only require a little information about the flood generation mechanism, have become the most commonly used in the literature (Ries III *et al.* 2002; Ishak *et al.* 2011).

However, regional flood frequency analysis is based on multiple regression, and there is no fundamental physical connection between the statistical parameters of flood risk and the rainfall–runoff process. Therefore, exploring the physical relationship between the statistical parameters and the rainfall–runoff process can further explain the mechanism of flood occurrence in ungauged basins. Since various factors such as future climate and basin characteristics are unknown, future environmental conditions are not generally represented by historical data sets. In this sense, all basins become unknown and ungauged relative to future research periods, and the application of regional flood frequency analysis methods to predict the flood is impractical. As such, flood scaling analysis has played a crucial role (Jain & Lall 2001; Mantilla *et al.* 2006; Ayalew *et al.* 2014; Chavan *et al.* 2014). Flood scaling refers to the existence of a power law between the flood and basin characteristics for similar basins. Based on the flood scaling, the flood data in the basins can be extended or interpolated. Therefore, to solve the flood frequency analysis problem in ungauged basins, flood scaling is of great significance for flood prediction and management, future construction of water conservancy facilities, and human life and property safety (Gupta 2004; Medhi & Tripathi 2015).

Initial scale-effect research in ungauged basins was mostly to calculate the design flood, and has achieved certain results. Al-Rawas & Valeo (2010) investigated the flood scaling of the mean flow and design flood with different return periods and basin characteristics in arid northern Oman. It was found that basin characteristics such as basin area and slope had significant correlation with flood peaks, and scaling expressions of the mean flow and design flood with different return periods were obtained. Lee & Huang (2016) studied the scale effect of peak flow and rainfall characteristics. However, with the deepening of the research on the scale effect of the design flood, it was found that the physical mechanism for the design flood was not very clear from statistical laws (Gupta *et al.* 2007; Dawdy *et al.* 2012). Gupta *et al.* (2010) pointed out that to understand how the scale effect of the design flood is generated and how the scale parameters are predicted, in-depth research is required on the physical foundation of the scale effect of single flood events (Gupta *et al.* 2010). Also, integrating the scale effect of design floods and flood events has become the research focus in this field (Gupta *et al.* 2015). Furey *et al.* (2016) combined scale effects of flood events with design floods, and found a mixture in the scale effects of design floods, which was that design floods at the same frequency in the basin may come from different rainfall events, and pointed out that in flood scaling studies, single flood events were more reasonable than the design floods. Using the observed flow data from Goodwin Creek Experimental Watershed (GCEW), Ogden & Dawdy (2003) found that the mean of the event-based scaling exponent was closely related to the annual flood quantile-based scaling exponents.

Although the flood scaling theory linking flood scaling parameters with rainfall and basin physical characteristics has made some progress, the theory still needs to be further tested using observed data from different basins all over the world. Ogden & Dawdy (2003) for the first time used the empirical data of 13 sub-catchments of the GCEW in the north of Mississippi (area ranging from 0.06 km^2 to 17.66 km^2) to analyze the peak scaling of a total of 226 rainfall–runoff events, and found that the expected values of peak flows during single runoff events were described by a power law function of the catchment area. Also, it was proposed that the scaling parameters changed from event to event. After that, Furey & Gupta (2005) analyzed 148 rainfall–runoff events in the GCEW and showed that there was a scale relationship between the flood peak and the basin area, and that the scaling parameters were also affected by rainfall characteristics. Furey & Gupta (2007) used the same empirical data to verify those results, confirming that the flood scaling parameters were closely related to the excess rainfall depth, rainfall duration, and rainfall spatial distribution.

However, most previous studies were conducted in small-scale and nested catchments, following simple scaling theory. Whether the scale-effect theory is equally valid in mesoscale and large-scale basins, and whether it is still applicable in partially nested or non-nested basins, is the focus of future study

(Medhi & Tripathi 2015). Gupta *et al.* (2007) made the first attempt to confirm the existence of a flood scale effect in a large basin with an area of 32,400 km^2 in the Iowa River basin. By analyzing the historical flood event that occurred in June 2008, the scale-effect theory was demonstrated in the Iowa River basin (Furey & Gupta 2007). It also proved that the scale effect of rainfall–runoff events showed scale invariance in large basins. Ayalew *et al.* (2015) analyzed the runoff data from the Iowa River basin and verified the scale invariance of the flood peak flow that was not only established in specific large flood events, but also in smaller and medium flood events.

Currently, in the Daqinghe River basin a fixed flood scaling exponent determined in 1974 (before the change point of 1979) is still used all over the basin under the hypothesis of simple scaling. However, with the impact of climate change and human activities, such as the construction of water conservancy projects, measures of soil and water conservation and the change of land use, etc., the mechanism and process of floods are constantly changing, and this has been proved by Li *et al.* (2014a). Therefore, the existing simple scaling method should be questioned. The aims of this paper are to answer the following questions: (1) under changing environments, whether there is a scale relationship between the peak flows and the basin area; (2) whether scale invariance theory is still valid; (3) whether there is a physical relationship between event-based scaling theory and annual flood quantile-based scaling theory in the mesoscale non-nested and partly nested basins; and (4) whether the existing uniform flood scaling exponent in the study area should be modified and whether the scaling theory can be used to guide our daily work.

STUDY AREA AND DATA SOURCE

Study area

The mountainous area of the Daqinghe River basin was selected as the study area. Daqinghe River basin is located at 113°39′–117°34′E longitude and 38°10′–40°102′N latitude (Figure 1) with a basin area of 43,060 km^2, and 43% is mountainous area and 57% is plains. It belongs to the temperate continental semi-arid and semi-humid monsoon climate. The average annual precipitation in the basin is 626 mm, which yields an average annual runoff of 7.53×10^8 m^3. The average annual temperature is 12.5 °C. The potential and actual evapotranspiration are 1,265 mm and 400 mm, respectively. The distribution of precipitation during the year is uneven. About 80% of the annual precipitation is concentrated in the flood season from June to September. In July and August, the precipitation accounts for about 61% of the annual precipitation, which often occurs in the form of rainstorms with high intensity. Heavy-rain centers often appear in the Zijingguan and Fuping rain gauges. Because of the steep slope, thin soil layer, and poor vegetation in the mountain area, many tributary rivers have short response times. The floods in the basin steeply rise and drop, with high peak discharge and short duration, which can easily cause flood disasters.

In the Daqinghe River basin, seven sub-basins were selected to analyze the scale effect of the flood, including four reservoir-controlled sub-basins and three hydrological-station-controlled sub-basins without reservoirs. Among them, Zijingguan hydrological station is located upstream of Zhangfang hydrological station, and Fuping hydrological station is located upstream of the Wangkuai reservoir. Other sub-watersheds are non-nested. The characteristics of each sub-basin are shown in Table 1.

Data source

The rainstorm and flood data were provided by the Hydrological and Water Resources Survey Bureau of Hebei Province. The rainfall data used in the study comes from 51 rain gauges in the study area. The distribution of rain gauges is shown in Figure 1. The rainstorm and flood data cover the period of 1965–2000, and are hourly based. The mean rainfall is calculated by the Theissen polygon method. Rainfall–runoff events that simultaneously occurred in all the sub-basins were selected. This helps to avoid the deviation of the results due to rainfall events that only occur in some of the sub-basins. Under this principle, eight flood events were screened out including the 7-25-1965, 8-14-1973, 8-6-1978, 8-15-1979, 8-6-1981, 8-3-1982, 7-25-1993 and 7-6-2000 flood events. Studies showed that the flood peak sequence in the Daqinghe River basin during 1965–2000 was nonstationary, and the year of the change point was 1979 (Li & Tan 2015; Deng *et al.* 2016). If the measured data were directly used to

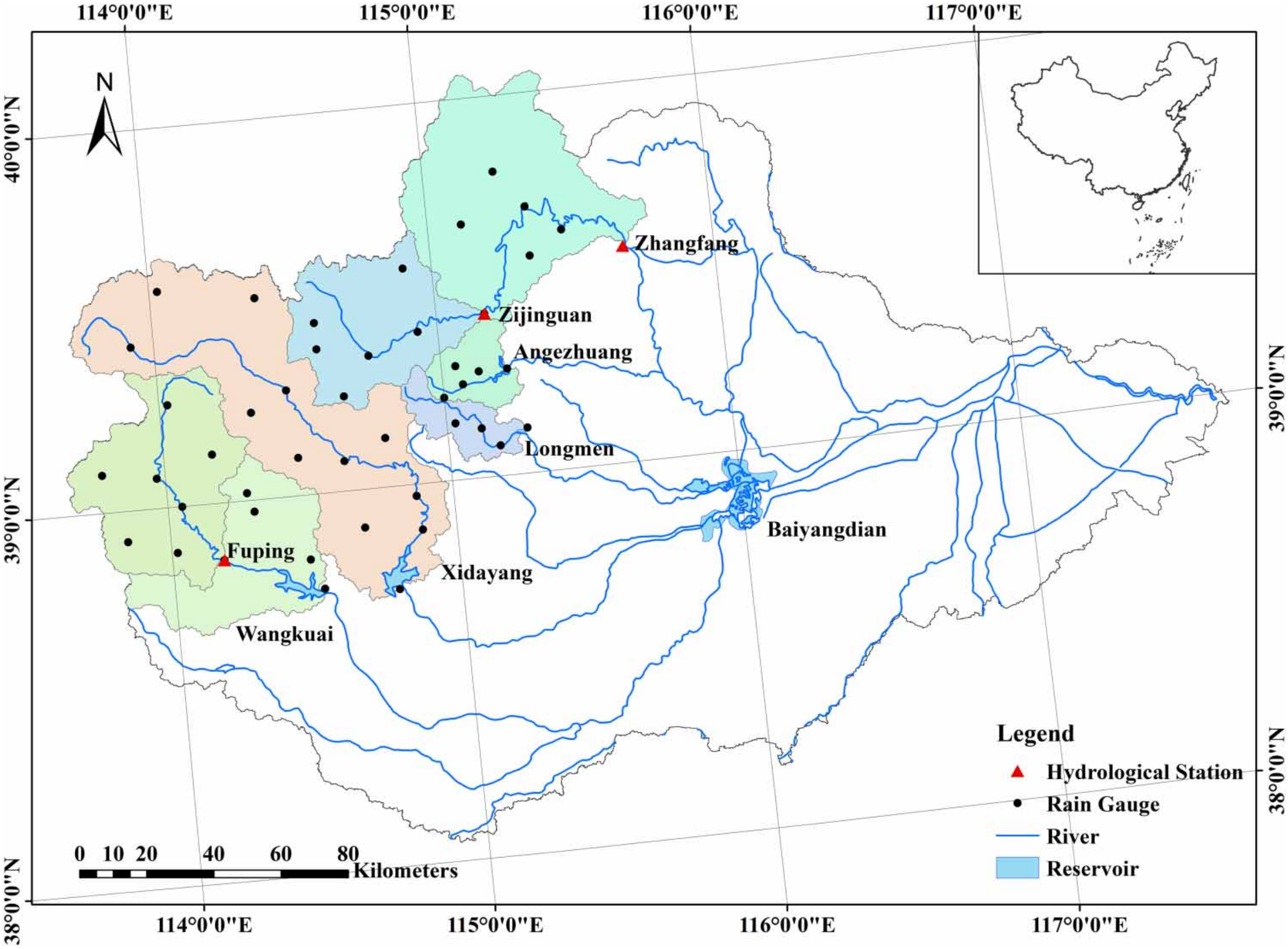

Figure 1 | Daqinghe River basin and geographic locations of the sub-basins and rain gauges.

Table 1 | Characteristics of the seven sub-watersheds

Sub-basin	Location	Drainage area (km^2)	Data length (year)
1	the upstream of Zhangfang hydrological station	4,810	1961–2001
2	the upstream of Zijingguan hydrological station	1,760	1956–2001
3	the upstream of Angezhuang reservoir	476	1961–2005
4	the upstream of Longmen reservoir	470	1961–2002
5	the upstream of Xidayang reservoir	4,420	1956–2005
6	the upstream of Fuping hydrological station	2,210	1958–2002
7	the upstream of Wangkuai reservoir	3,770	1955–2008

analyze the peak scaling, the results may deviate from the actual situation. Therefore, flood peak data after 1979 need reconstruction to obtain stationary series (Deng *et al.* 2016).

METHOD

Flood-peak reconstruction without impact of human activities

The flood sequence in the Daqinghe River basin has significant nonstationarity due to human activities, and the change point is around the year 1979. Therefore, the floods before the change point are in a natural state, and the flood peaks after the change point (1979) should be reconstructed based on rainfall–runoff relation without the impact of human activities. The specific steps are as follows:

1. Select the typical flood events in the flood records, and calculate the corresponding average rainfall depth P (mm), antecedent rainfall depth Pa (mm), and total runoff depth R (mm).
2. Establish the correlation between the calculated $P + Pa$ and R, and plot the rainfall–runoff correlation diagram before and after the change point (1979).
3. According to the rainfall–runoff correlation diagram, the total runoff depth R generated by the same rainfall amount before and after the change point can be observed. The reduction ratio β is presented in Equation (1):

   $$\beta = (R_1 - R_2)/R_1 \tag{1}$$

   where R_1 and R_2 represent the runoff produced by the same rainfall amount before and after the change point, respectively.
4. According to the reduction ratio β, the annual maximum 24 h flood depths after the year 1979 are reconstructed. And then the linear flood peak-volume relation (not shown here) is established before and after the change point to calculate the reduction ratio of flood peaks, and the flood peaks after the change point are reconstructed afterwards. Readers can be referred to Lei (2016).

Spatial heterogeneity of precipitation

The nonuniformity of rainfall spatial distribution can be expressed by indices such as the coefficient of variation (C_v), the non-uniform coefficient (μ), and the ratio between the maximum and the minimum value (η). C_v is the ratio of the mean square of the rainfall depth to the mean value (Equation (2)). The larger C_v is, the more nonuniform the rainfall is. The ratio of the average and maximum values of rainfall depth is μ (Equation (3)). The closer μ is to 1, the more uniform the rainfall. Equation (4) expresses η. When η is 1, the rainfall in the basin distributes spatially evenly. The larger η is, the more uneven the rainfall spatial distribution is.

$$C_v = \sqrt{\frac{\sum (K_i - 1)^2}{n - 1}} \tag{2}$$

$$\mu = \bar{P}/P_{\max} \tag{3}$$

$$\eta = P_{\max}/P_{\min} \tag{4}$$

where K_i is the ratio of P_i to $\bar{P}$; P_i is the rainfall depth at a certain point in the sub-basin, mm; $\bar{P}$ is the average rainfall depth of the sub-basin, mm. $P_{\max}$ and $P_{\min}$ are the maximum and minimum rainfall depths in the sub-basin, mm; and n is the number of rain gauges.

Flood scale effect

Flood scaling theory refers to the power relationship between the flood peak flow Q and the basin characteristics A, which can be used to achieve flood information transmission in basins with flood data to the ungauged and poorly gauged basins. Namely: for two different sub-basins i, j, the basin area is A_i, A_j, and the peak flood flow relationship between the two basins can be expressed by Equation (5):

$$Q(A_i) = f(A_i, A_j)Q(A_j) \tag{5}$$

where $Q(A_i)$ and $Q(A_j)$ are the flood peak discharges of the same flood event for the sub-basins i and j, respectively (m^3/s); A_i and A_j are the drainage areas of the sub-basins i and j, respectively; and $f(A_i, A_j)$ is the flood scale transformation function.

Under the assumption of simple scaling theory, the flood scale transformation function can be obtained using Equation (6) (Gupta & Waymire 1990):

$$f(A_i, A_j) = \left(\frac{A_i}{A_j}\right)^{\theta} \tag{6}$$

Take the sub-basin j, $A_j = 1$, as the reference basin, and the flood scaling can be expressed as Equation (7):

$$Q = \alpha A^{\theta} \tag{7}$$

where α is the intercept parameter, which is the flood peak produced by rainfall when the basin area is unity, i.e., $\alpha = Q$ (1); θ is called the flood scaling exponent. Flood scaling parameters α and θ change with floods event-to-event, and the regression is a log–log scale.

The ordinary least squares method is usually used for regression analysis of flood peaks and basin characteristics. For a given series of data $\{(A_i, Q_i)\}$ $(i = 1, 2 \cdots 7)$, the power function that minimizes the sum of the squared errors is calculated by Equation (7), to obtain the scaling parameters α and θ.

RESULTS

Scale effect analysis of flood events

Scale relationship between flood peak and basin area

Based on the rainfall–runoff relation, flood peaks after the change point (1979) without the impact of human activities were obtained. The observed and reconstructed flood peaks of the selected flood events are listed in Table 2.

As can be seen from Table 2, the flood peaks after the change point in all the sub-basins decreased significantly. Compared with the reconstructed flood peaks of the events in each sub-basin, the observed flood peaks were reduced by 7.7–71.2%. The decrease in flood peaks is mainly due to the construction of water conservancy projects within the Daqinghe River basin after 1979, which led to the reduction of flood peak and depth. In addition, the increase in forest also contributes to the downward trend of the annual maximum flood series in the Daqinghe River basin (Li *et al.* 2014a, 2014b; Habete & Ferreira 2016).

Since the basin area can better represent the overall characteristics of the basin and has a significant impact on the flood process, it is generally used as the only variable to analyze the scale effect of floods (Jothityangkoon & Sivapalan 2001; Furey & Gupta 2007). The power law was used to perform the ordinary least squares regression analysis on the flood peak Q and drainage area A, and then the flood scaling in the single flood events was obtained. The fitted relations between the observed flood peaks and drainage areas are shown in Figure 2 on log–log coordinates for the eight flood events. Similarly, the regression analysis of the reconstructed flood peaks and drainage areas of the four flood events after the change point is shown in Figure 3.

The flood peak scaling exponent varies with rainfall–runoff events. The maximum scaling exponent is 1.38, and the minimum is 0.77, with an average of 1.04. The scaling exponent of the flood events is mostly close to 1, or greater than 1, which is consistent with the results of Ayalew *et al.* (2015), and different from some studies which consider the flood scaling exponent always to be less than 1 (Menabde & Sivapalan 2001; Farmer *et al.* 2015).

The scaling parameters of the observed events and reconstructed events are listed in Table 3. For reconstructed flood peaks after the change point, the coefficients of determination R^2 considering the basin area are all larger than those of the observed events. This implies that the scaling effect is weakened with human interruptions in the Daqinghe River basin. The scaling exponents of the

Table 2 | Observed and reconstructed flood peaks of the eight events in the seven sub-basins before and after the change point (m^3/s)

	Before change point				**After change point**[a]			
Sub-basin	**7-25-1965**	**8-14-1973**	**8-6-1978**	**8-15-1979**	**8-6-1981**	**8-3-1982**	**7-25-1993**	**7-6-2000**
1	45	308	140	672	69(143)	451(799)	42(146)	684(1,145)
2	174	108	66	245	57(82)	128(169)	20(37)	25(32)
3	17	42	56	229	44(52)	172(185)	19(29)	121(135)
4	11	103	11	83	12(17)	53(90)	12(14)	21(33)
5	301	396	114	533	183(394)	278(667)	84(202)	815(1,710)
6	172	596	136	767	99(170)	285(484)	72(84)	302(444)
7	144	1,988	1,000	1,207	358(475)	553(755)	178(451)	972(1381)

[a] Observed flood peaks outside the brackets and reconstructed flood peaks in the brackets.

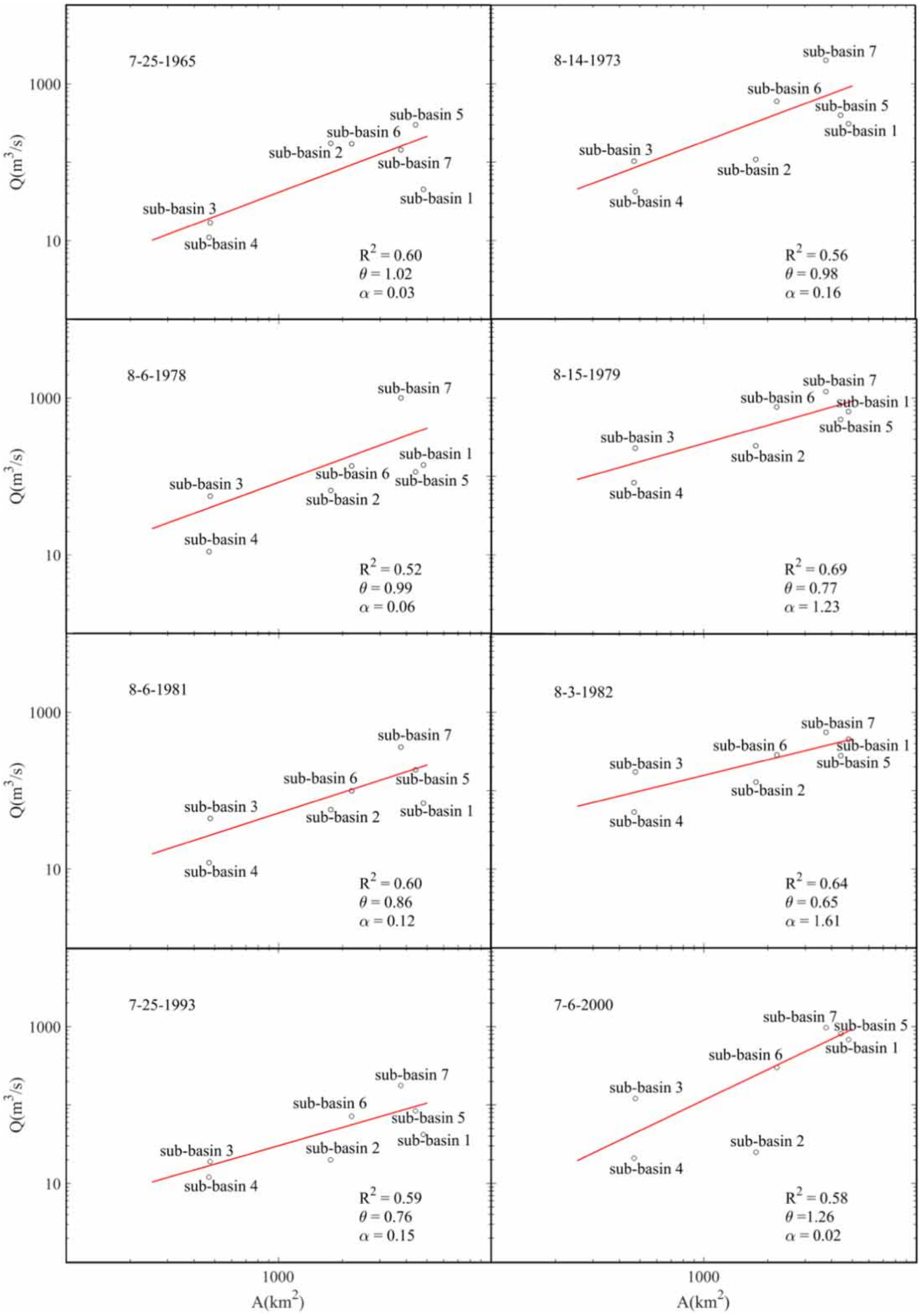

Figure 2 | Flood peak scaling of the eight flood events.

reconstructed flood events are larger than those of the observed events. However, the points scatter in Figures 2 and 3, and the coefficients of determination are small, therefore, there may be other factors that also influence the scaling effect.

Influence of rainfall depth on the flood scaling

Although it can be found that the flood scaling power law in the seven sub-basins does exist through the previous subsection, the minimum value of the coefficients of

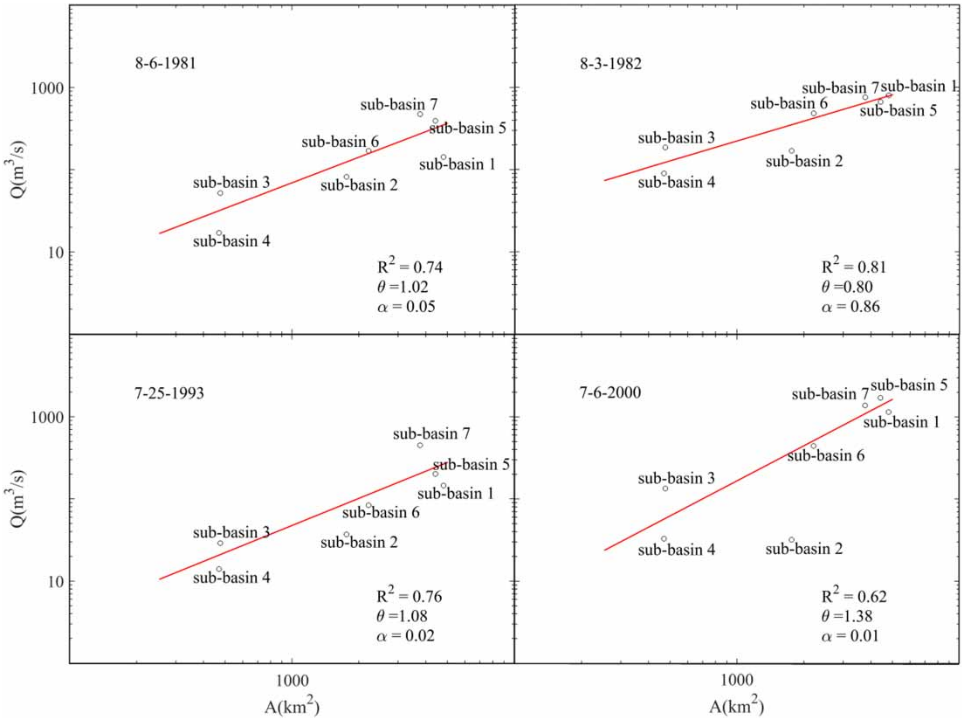

Figure 3 | Flood peak scaling of events after the change point based on the reconstructed peaks.

Table 3 | Scaling parameters of the eight flood events

		Before 1979				**After 1979**[a]			
		7-25-1965	**8-14-1973**	**8-6-1978**	**8-15-1979**	**8-6-1981**	**8-3-1982**	**7-25-1993**	**7-6-2000**
Q & A	α	0.03	0.16	0.06	1.23	0.12 (0.05)	1.61 (0.86)	0.14 (0.02)	0.02 (0.01)
	θ	1.02	0.98	0.99	0.77	0.86 (1.02)	0.65 (0.80)	0.76 (1.08)	1.26 (1.38)
	R^2	0.60	0.56	0.52	0.69	0.60 (0.74)	0.64 (0.81)	0.59 (0.76)	0.58 (0.62)
Q & AP	α	0.01	0.00	0.00	0.03	0.00 (0.01)	0.36 (0.00)	0.09 (0.01)	0.00 (0.00)
	θ	0.86	1.05	1.02	0.80	0.86 (0.76)	0.55 (0.98)	0.61 (0.87)	1.25 (1.35)
	R^2	0.29	0.78	0.67	0.82	0.63 (0.83)	0.65 (0.87)	0.61 (0.78)	0.66 (0.68)
Q & ηAP	α	0.03	0.00	0.00	0.35	0.02 0.00	0.49 (0.04)	0.55 (0.27)	0.00 (0.00)
	θ	0.64	0.83	0.87	0.56	0.67 (0.79)	0.48 (0.67)	0.36 (0.46)	1.13 (1.26)
	R^2	0.57	0.89	0.64	0.80	0.56 (0.68)	0.65 (0.72)	0.78 (0.85)	0.61 (0.67)

[a] Scaling parameters based on the observed flood peaks outside the brackets and based on the reconstructed flood peaks in the brackets.

determination R^2 in the ordinary least squares regression is only 0.52, which illustrates poor fitting. The reason may be due to the different rainfall depths in the sub-basins during the same rainfall event, as the rainfall distributes unevenly. In the study of Venkata (2009), it was also shown that the flood peak is not only related to the basin characteristics, but also affected by rainfall characteristics. In order to explore the impact of rainfall depth and basin characteristics on the flood peaks, and verify whether the speculation is reasonable, the product of the basin area A and the average rainfall depth P, that is AP, is used as a variable instead of A to perform flood scaling analysis. The results are also shown in Table 3.

The coefficients of determination R^2 (>0.67 except for the 7-25-1965 flood event) after considering the average rainfall depth P are presented in Table 3. They are higher than those only considering the basin area. The flood scaling

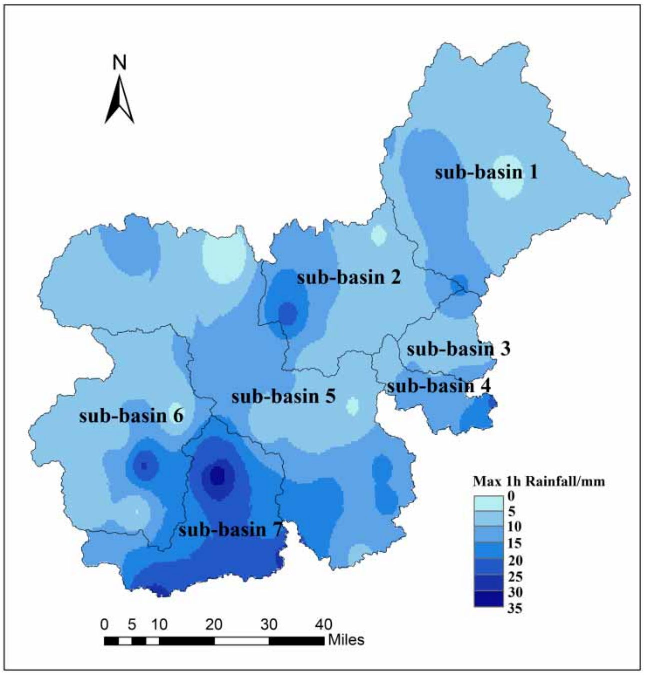

Figure 4 | Spatial distribution of rainfall of the maximum 1 h rainfall in the 7-25-1965 event.

exponents of the 8-14-1973, 8-6-1978, 8-15-1979, and 8-6-1981 flood events are slightly larger, while those of the 7-25-1965, 8-3-1982, 7-25-1993 and 7-6-2000 flood events are smaller, with a maximum difference of 0.16. It shows that the scale effect of the flood peak is indeed influenced by rainfall depth. When analyzing the scale effect of floods, only considering the basin characteristics may lead to errors, so it is necessary to consider the rainfall characteristics. Especially in mesoscale and large-scale basins, the rainfall nonuniformity is even more pronounced. In addition, after considering average rainfall depth P, the flood scaling exponents of the 8-3-1982, 7-25-1993, and 7-6-2000 events, which are reconstructed after the change point, are larger than the flood scaling exponents of the observed floods, with differences of 0.43, 0.26 and 0.10, and the flood scaling exponent of the 8-6-1981 reconstructed event is smaller than that of the observed flood, with a difference of 0.10.

Influence of the rainfall spatial distribution (RSD) on the flood scaling

After considering the average rainfall depth P, the coefficient of determination R^2 for the 7-25-1965 flood event is only 0.29, and the scaling effect is not significant. This may be due to the uneven rainfall spatial distribution in the sub-basins. Taking the 7-25-1965 flood event as an example, the spatial distribution of rainfall is shown in Figure 4. It can be seen that the heavy rains are mainly concentrated in sub-basins 2, 6 and 7. In these sub-basins, the spatial distribution of rainfall is very uneven. Among them, the maximum 1 h rainfall in sub-basin 6 is 40 times the maximum 1 h rainfall in sub-basin 1. At the same time, the heavy rain centers in sub-basins 6 and 7 are located downstream of each sub-basin. In the same rainfall event, high-intensity rainfall in sub-basins 6 and 7 results in significantly higher flood peaks than those of the other sub-basins. From Figure 5, we can see that in the 7-25-1965 flood event, the flood peak of sub-basin 6 is above the fitting curve, and is three times more than sub-basin 1, while its drainage area is less than half of sub-basin 1. The peak discharge in sub-basin 1 is relatively small, far below the fitting curve. In this case, the coefficient of determination R^2 is only 0.29. The same situation can be found in other flood events, which leads to the speculation that not only average rainfall depth, but also spatial distribution of rainfall has a significant impact on the scale effect of flood peaks.

The values of C_v, μ, η for the eight rainfall–runoff events in the seven sub-basins are shown in Table 4. Most of the C_v values are above 0.25, with a maximum of 0.71. The μ values are less than 1 and the minimum value is 0.25. The η values are all greater than 1, with a maximum of 79.89. The above results indicate that the spatial distribution of rainfall in the

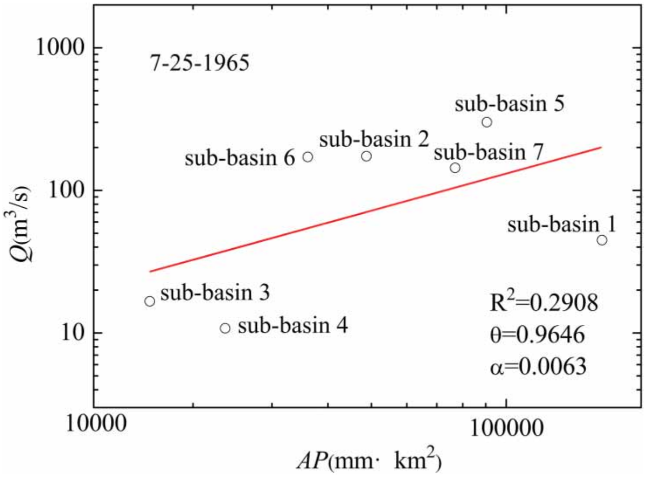

Figure 5 | Flood scaling of the 7-25-1965 event considering rainfall depth.

Table 4 | Coefficient of variation C_v, non-uniform coefficient μ and ratio coefficient η of the rainfall spatial distribution in the sub-basins

		Rainfall events							
RSD	**Sub-basins**	**7-25-1965**	**8-14-1973**	**8-6-1978**	**8-15-1979**	**8-6-1981**	**8-3-1982**	**7-25-1993**	**7-6-2000**
C_v	1	0.71	0.51	0.23	0.26	0.32	0.26	0.44	0.27
	2	0.37	0.47	0.17	0.40	0.18	0.44	0.70	0.22
	3	0.26	0.57	0.65	0.13	0.07	0.30	0.55	0.15
	4	0.26	0.41	0.22	0.16	0.16	0.13	0.52	0.42
	5	0.48	0.57	0.38	0.33	0.16	0.48	0.68	0.36
	6	0.50	0.59	0.25	0.58	0.34	0.54	0.52	0.29
	7	0.57	0.50	0.27	0.40	0.27	0.29	0.19	0.26
μ	1	0.55	0.55	0.74	0.83	0.82	0.72	0.58	0.78
	2	0.61	0.62	0.80	0.58	0.80	0.55	0.47	0.71
	3	0.71	0.52	0.86	0.88	0.91	0.67	0.58	0.90
	4	0.72	0.65	0.75	0.80	0.83	0.83	0.52	0.70
	5	0.54	0.49	0.53	0.64	0.82	0.59	0.39	0.61
	6	0.50	0.57	0.67	0.43	0.60	0.44	0.60	0.68
	7	0.53	0.57	0.65	0.49	0.73	0.64	0.25	0.67
η	1	3.27	3.79	1.85	2.22	2.70	1.88	2.99	1.93
	2	3.05	3.72	1.50	2.93	1.78	3.46	4.65	1.71
	3	1.78	4.18	1.72	1.37	1.20	2.06	3.41	1.50
	4	1.90	2.93	1.68	1.41	1.46	1.44	2.72	3.62
	5	27.05	6.22	3.45	3.49	1.65	4.56	52.36	3.35
	6	4.59	9.28	1.92	4.88	2.23	3.83	5.47	2.42
	7	6.24	10.89	2.13	3.82	2.08	2.38	79.89	2.42

sub-basins is uneven, which may have an impact on flood scaling.

Based on the study of sub-section 'Influence of rainfall depth on the flood scaling' above, the three indices are included in the flood scaling analysis, and the rainfall non-uniform ratio coefficient η performs better than other two indices. Therefore, ηAP is used as a variable. The results are also shown in Table 3. It can be seen that after considering the spatial distribution of rainfall, the coefficient of determination R^2 is significantly improved, and all of them are greater than 0.57. The flood scaling exponents are smaller than from using A and AP as the independent variable. The flood scaling exponents are generally less than 1 except for the 7-6-2000 flood event. In addition, the flood scaling exponents of the reconstructed flood events are larger than those of the observed flood events, with a difference ranging from 0.11 to 0.18.

Relationship between flood scaling of flood events and design floods

Lei (2016) conducted flood scaling in the same sub-basins by quantile-based floods, and the scaling exponents are listed in Table 5. The quantile-based flood peak represents a significant scale effect due to high values of R^2. Under the environment before 1979, the flood scaling exponent ranges from 0.40 to 0.56, while under the environment after 1979, the flood scaling exponent ranges from 0.43 to 0.57. For design floods with the same return period, the flood scaling exponent of the reconstructed series under the environment condition after 1979 is larger than that before 1979, which is contrary to the previous results in this study obtained from event-based flood scaling. The scaling exponent θ_T under both environment conditions gradually increased with the increase of the return period, and the floods in the sub-basins present multiscaling features.

Table 5 | Scaling exponents of flood quantiles at different return periods, cited from Lei (2016)

Return period (year)		**10**	**20**	**50**	**100**	**200**	**500**
Environment condition before 1979	θ_T	0.40	0.47	0.52	0.53	0.55	0.56
	R^2	0.46	0.75	0.84	0.85	0.84	0.83
Environment condition after 1979	θ_T	0.43	0.49	0.53	0.55	0.56	0.57
	R^2	0.43	0.69	0.81	0.83	0.84	0.83

In the scale effect analysis based on rainfall–runoff events, the average flood scaling exponent of the flood events without human impact is 1.01 when only considering the basin area, and 0.96 when considering the rainfall depth, and 0.76 when including the spatial rainfall distribution. For the observed flood events after 1979, the average flood scaling exponent only considering the basin area is 0.88, and 0.82 after considering the rainfall depth, and 0.66 when including the spatial rainfall distribution. The event-based average flood scaling exponents are much larger than those of the design floods, which does not support Ogden & Dawdy's (2003) results that the mean of the event-based scaling exponents is closely related to the annual flood quantile-based scaling exponents. The reason may be that the study area is a partly nested basin where the basin floods present multiscaling features (Furey *et al.* 2016).

CONCLUSIONS

Taking the mountainous area of the Daqinghe River basin in northern China as the research area, eight typical storm-flood events are selected to analyze the flood scaling, to verify whether there is a scale relationship between the peak flows and the basin area, and whether the scale invariance theory is still established, in the mesoscale non-nested basins. The following conclusions are obtained:

(1) There is a scale relationship between the flood peaks and the basin area in mesoscale non-nested basins. The flood scaling exponents obtained by the reconstructed flood events after 1979 are larger than the flood scaling exponents of observed events.

(2) Rainfall has a significant impact on the flood peak. After considering the characteristics of rainfall, the coefficient of determination R^2 significantly increases and the scale effect becomes more obvious. The flood scaling exponents considering the rainfall characteristics are smaller than those only considering the basin area, with a maximum difference of 0.40.

(3) There is no explicit physical connection between the flood scaling exponent of the flood events and the design floods. The mean flood scaling exponents of the flood events is much larger than that of the design floods, which proves that the theory of the connection between flood events and design floods proposed by Ogden & Dawdy (2003) is not valid in such mesoscale non-nested basins.

ACKNOWLEDGEMENTS

This work is supported by the National Key R&D Program of China (No. 2018YFC0407902) and National Natural Science Foundation of China (No. 51779165 and 51609165). We would like to thank the Hydrology and Water Resource Survey Bureau of Hebei Province for providing the hydrometeorological data.

REFERENCES

Al-Rawas, G. A. & Valeo, C. 2010 Relationship between wadi drainage characteristics and peak-flood flows in arid northern Oman. *Hydrological Sciences Journal* **55** (3), 377–393.

Ayalew, T. B., Krajewski, W. F. & Mantilla, R. 2014 Connecting the power-law scaling structure of peak-discharges to spatially variable rainfall and catchment physical properties. *Advances in Water Resources* **71**, 32–43.

Ayalew, T. B., Krajewski, W. F. & Mantilla, R. 2015 Analyzing the effects of excess rainfall properties on the scaling structure of peak discharges: insights from a mesoscale river basin. *Water Resources Research* **51** (6), 3900–3921.

Chavan, S. R., Basu, B. & Srinivas, V. V. 2014 Design flood estimation using scaling approach. In: *World Environmental and Water Resources Congress* 2013 (C. L. Patterson, S. D. Struck & D. J. Murray, Jr, eds), ASCE, Reston, VA, USA, pp. 3163–3172.

Dawdy, D. R., Griffis, V. W. & Gupta, V. K. 2012 Regional flood-frequency analysis: how we got here and where we are going. *Journal of Hydrologic Engineering* **17** (9), 953–959.

Deng, X., Ren, W. & Feng, P. 2016 Design flood recalculation under land surface change. *Natural Hazards* **80** (2), 1153–1169.

Farmer, W. H., Over, T. M. & Vogel, R. M. 2015 Multiple regression and inverse moments improve the characterization of the spatial scaling behavior of daily streamflows in the Southeast United States. *Water Resources Research* **51** (3), 1775–1796.

Furey, P. R. & Gupta, V. K. 2005 Effects of excess rainfall on the temporal variability of observed peak-discharge power laws. *Advances in Water Resources* **28** (11), 1240–1253.

Furey, P. R. & Gupta, V. K. 2007 Diagnosing peak-discharge power laws observed in rainfall–runoff events in Goodwin Creek experimental watershed. *Advances in Water Resources* **30** (11), 2387–2399.

Furey, P. R., Troutman, B. M., Gupta, V. K. & Krajewski, W. F. 2016 Connecting event-based scaling of flood peaks to regional flood frequency relationships. *Journal of Hydrologic Engineering* **21** (10), 04016037.

Gupta, V. K. 2004 Emergence of statistical scaling in floods on channel networks from complex runoff dynamics. *Chaos Solitons & Fractals* **19** (2), 357–365.

Gupta, V. K. & Waymire, E. 1990 Multiscaling properties of spatial rainfall and river flow distributions. *Journal of Geophysical Research: Atmospheres* **95** (D3), 1999–2009.

Gupta, V. K., Mesa, O. J. & Dawdy, D. R. 1994 Multiscaling theory of flood peaks: regional quantile analysis. *Water Resources Research* **30** (12), 3405–3421.

Gupta, V. K., Troutman, B. M. & Dawdy, D. R. 2007 Towards a nonlinear geophysical theory of floods in river networks: an overview of 20 years of progress. In: *Nonlinear Dynamics in Geosciences* (A. A. Tsonis & J. B. Elsner, eds), Springer, New York, USA, pp. 121–151.

Gupta, V. K., Mantilla, R., Troutman, B. M., Dawdy, D. R. & Krajewski, W. F. 2010 Generalizing a nonlinear geophysical flood theory to medium-sized river networks. *Geophysical Research Letters* **37** (11), 402.

Gupta, V. K., Ayalew, T. B., Mantilla, R. & Krajewski, W. F. 2015 Classical and generalized Horton laws for peak flows in rainfall–runoff events. *Chaos* **25** (7), 075408.

Habete, D. & Ferreira, C. M. 2016 Impact of forecasted land use change on design peak discharge at watershed and catchment scales: simple equation to predict changes. *Journal of Hydrologic Engineering* **21** (7), 04016019.

Ishak, E. H., Haddad, K., Zaman, M. & Rahman, A. 2011 Scaling property of regional floods in New South Wales Australia. *Natural Hazards* **58** (3), 1155–1167.

Jain, S. & Lall, U. 2001 Floods in a changing climate: does the past represent the future? *Water Resources Research* **37** (12), 3193–3205.

Jothityangkoon, C. & Sivapalan, M. 2001 Temporal scales of rainfall–runoff processes and spatial scaling of flood peaks: space–time connection through catchment water balance. *Advances in Water Resources* **24** (9–10), 1015–1036.

Lee, K. T. & Huang, J. K. 2016 Influence of storm magnitude and watershed size on runoff nonlinearity. *Journal of Earth System Science* **125** (4), 777–794.

Lei, Y. 2016 *Regional Flood Scaling Effect Analysis under Changing Climate*. Tianjin University, Tianjin, China.

Li, J. & Tan, S. 2015 Nonstationary flood frequency analysis for annual flood peak series, adopting climate indices and check dam index as covariates. *Water Resources Management* **29** (15), 5533–5550.

Li, J., Feng, P. & Chen, F. 2014a Effects of land use change on flood characteristics in mountainous area of Daqinghe watershed, China. *Natural Hazards* **70** (1), 593–607.

Li, J., Tan, S., Chen, F. & Feng, P. 2014b Quantitatively analyze the impact of land use/land cover change on annual runoff decrease. *Natural Hazards* **74** (2), 1191–1207.

Lima, C. H. R. & Lall, U. 2010 Spatial scaling in a changing climate: a hierarchical Bayesian model for non-stationary multi-site annual maximum and monthly streamflow. *Journal of Hydrology* **383** (3–4), 307–318.

Mantilla, R. 2007 *Physical Basis of Statistical Scaling in Peak Flows and Stream Flow Hydrographs for Topologic and Spatially Embedded Random Self-Similar Channel Networks*. PhD thesis, University of Colorado at Boulder, Boulder, CO, USA.

Mantilla, R., Gupta, V. K. & Mesa, O. J. 2006 Role of coupled flow dynamics and real network structures on Hortonian scaling of peak flows. *Journal of Hydrology* **322** (1–4), 155–167.

Medhi, H. & Tripathi, S. 2015 On identifying relationships between the flood scaling exponent and basin attributes. *Chaos* **25** (7), 075405.

Menabde, M. & Sivapalan, M. 2001 Linking space–time variability of river runoff and rainfall fields: a dynamic approach. *Advances in Water Resources* **24** (9–10), 1001–1014.

Modarres, R. 2010 Low flow scaling with respect to drainage area and precipitation in Northern Iran. *Journal of Hydrologic Engineering* **15** (3), 210–214.

Ogden, F. L. & Dawdy, D. R. 2003 Peak discharge scaling in small Hortonian watershed. *Journal of Hydrologic Engineering* **8** (2), 64–73.

Ries III., K. G., Crouse, M. Y., Atkins, J. B., Dusenbury, R., Gray, M., Jennings, M. E., Kirby, W. H., Riggs, H. C., Sauer, V. B. & Thomas Jr, W. O. 2002 *The National Flood Frequency Program, Version 3: A Computer Program for Estimating Magnitude and Frequency of Floods for Ungaged Sites*. Water-Resources Investigations Report 02–4168, USGS, Denver, CO, USA.

Robinson, J. S. & Sivapalan, M. 1997 An investigation into the physical causes of scaling and heterogeneity of regional flood frequency. *Water Resources Research* **33** (5), 1045–1059.

Venkata, P. M. 2009 *Role of Rainfall Variability in the Statistical Structure of Peak Flows*. PhD thesis, University of Iowa, Iowa City, IA, USA.

First received 10 July 2019; accepted in revised form 1 November 2019. Available online 18 November 2019