1 # The relative importance of antecedent soil moisture and precipitation

2 ## in flood generation in the middle and lower Yangtze River basin

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19 **Abstract**

20 Floods have caused severe environmental and social economic losses worldwide in

21 human history, and are projected to exacerbate due to climate change. Many floods are

22 caused by heavy rainfall with highly saturated soil, however, the relative importance of

23 rainfall and antecedent soil moisture and how it changes from place to place has not

24 been fully understood. Here we examined annual floods from more than 200

25 hydrological stations in the middle and lower Yangtze River basin. Our results indicate

26 that the dominant factor of flood generation shifts from rainfall to antecedent soil

27 moisture with the increase of watershed area. The ratio of the relative importance of

28 antecedent soil moisture and daily rainfall (SPR) is positively correlated with

29 topographic wetness index and has a negative correlation with the magnitude of annual

30 floods. This linkage between watershed characteristics that are easy to measure and the

31 dominant flood generation mechanism provides a framework to quantitatively estimate

32 potential flood risk in ungauged watersheds in the middle and lower Yangtze River

33 basin.

34 **Key words**: flood generation, scaling effect, topographic wetness index

1. Introduction

Flooding is one of the most destructive and costly natural hazards in the world, resulting in considerable fatalities and property losses (Suresh et al., 2013). River floods have affected nearly 2.5 billion people between 1994 and 2013 worldwide (CRED, 2015), and caused 104 billion dollars losses every year (Desai et al 2015). The damages may be further exacerbated by increasing frequency and intensity of extreme rainfall events according to climate change projection (IPCC 2012; Ohmura and Wild 2002). Flood control infrastructures and more accurate predictions are needed to reduce flood damages, which requires better understanding of the underlying mechanism of flood generation as well as the drivers of change (Villarini & Wasko 2021).

Numerous studies have been conducted to investigate the cause of floods across the world (Bloschl et al 2013; Munoz et al 2018; Zhang et al 2018). Many studies focused on examining the environmental and social characteristics that lead to specific catastrophic flood events (Bloschl et al 2013; Liu et al 2020; Zhang et al., 2018). Others concentrated on single locations, usually catchment outlets, to explore the influential factors of floods and the future trends (Brunner et al., 2016; Munoz et al 2018). Yet given the amount of data and time required, it is not practical to apply these detailed studies to hundreds of catchments to generate an overview of the flood generation mechanism at large scale.

Recently, researchers started to investigate the dominant flood generation mechanisms at regional scales (Berghuijs et al 2019b; Do et al 2020; Garg & Mishra 2019; Smith et al 2018; Tramblay et al 2021; Ye et al 2017). Most of these studies are conducted in North America and Europe with well-documented long-term records (Berghuijs et al 2016; Bloschl et al 2019; Do et al 2020; Musselman et al 2018; Rottler

61 et al 2020). Such researches were just conducted in China recently, though still limited

62 (Yang et al 2019; Yang et al 2020).

63   As the largest river in China, Yangtze River basin has long suffered from floods. In

64 summer 2020, 378 tributaries of the Yangtze River had floods exceeding the alarm level,

65 causing billions of dollars damage (Xia et al., 2021). With the increasing public

66 awareness, more accurate prediction is needed, which relies on better understanding.

67 However, due to the limitation of observations, there are only a few regional studies of

68 the flood generation mechanism in China, even little in the Yangtze River basin (Zhang

69 et al 2018; Yang et al 2019; Yang et al 2020). The large number of dams and reservoirs

70 built along the river further complicated the situation (Feng et al., 2017; Qian et al 2011;

71 Yang et al 2019).

72   Because of the relatively warm temperature, snowmelt has little impact on flood

73 generation in the Yangtze River basin (Yang et al 2020). Floods in the Yangtze River

74 basin usually occur during summer with relatively wet soil and high rainfall (Wang et

75 al 2021). Heavy rainfall with high antecedent soil moisture has also been identified as

76 dominant driver of floods across world (Beighuijs et al 2019b; Garg et al 2019;

77 Tramblay et al 2021; Wasko et al 2020). Recently, studies started to examines the

78 relative importance of rainfall and antecedent soil moisture in flood generation

79 (Brunner et al., 2021; Wasko et al., 2021; Bennett et al., 2018; Bertola et al., 2021).

80 Quantitative evaluation of the relative contribution of rainfall and antecedent soil

81 moisture and its change across watersheds is still limited and currently unavailable in

82 China (Liu et al., 2021; Wu et al., 2015).

83   Based on the watersheds in the middle and lower Yangtze River basin, this study

84 attempts to explore the following questions: 1) is there a way to quantitatively describe

85 the relative importance of antecedent soil moisture and rainfall on flood generation; and

86 2) how would this combination of flood-generation rainfall and soil moisture vary

87 across watersheds, and what are the influential factors. Based on the observations and

88 model estimation (Section 2), the spatial distribution patterns of antecedent soil

89 moisture and rainfall were obtained and analyzed to investigate their individual

90 contribution to flood generation and the influential factors (Section3). This allows for

91 further examination of the relative importance of antecedent soil moisture and rainfall

92 on flood generation and its linkage to watershed characteristics as well as its

93 implications to flood prediction (Section 4), all the results are summarized in Section 5.

94 **2 Methods**

95 **2.1 Study area**

96 The Yangtze River is the largest river in China, with a total length of 6,300 kilometers

97 and annual discharge of 920km^3 at the outlet (Yang et al., 2018). It drains through an

98 area of 1.8*10^6 km^2, lying between 90°33'and 122°25'E and 24°30'and 35°45'N, and

99 is home to over 400 million people, most of which live in the middle and lower Yangtze

100 River basin (YZRB) (Cai et al., 2020). The elevation of the YZRB declines from west

101 to east: from over 3000m in Qinghai-Tibet Plateau, to around 1000m in the central

102 mountain region, and the 100m in Eastern China Plain (Wang et al., 2013). The

103 vegetation types in the YZRB are forests, shrubs, grassland and agricultural land,

104 accounting for 11.85%, 12.65%, 32.26% and 42.88% respectively. Grassland and

105 shrubs are the dominant vegetation in the middle and upper YZRB, while the

106 downstream YZRB is dominated by forests and agricultural land (Miao et al., 2010).

107 There are more than 51,000 reservoirs of different sizes in the whole basin, including

108 280 large ones (Peng et al., 2020).

109   Most of the YZRB is semi-humid and humid, with a typical subtropical monsoon

110   climate. The mean annual temperature is approximately 13.0 °C, varying from −4 °C

111   to 18°C downstream. The mean annual precipitation of the whole basin is about 1200

112   mm, increasing from 300mm in the western headwaters to 2400 mm downstream. (Li

113   et al., 2021). Most of the precipitation comes between June and September, the premise

114   of persistent heavy rain in the Yangtze River basin is the frequent activity of weak cold

115   air in the north (Tao et al., 1980) and the intersection of mid-latitude air mass and

116   monsoon air mass (Kato et al., 1985). Studies have found that both annual precipitation

117   and the frequency of extreme precipitation events have increased in the middle and

118   lower reaches of the Yangtze River (Qian et al., 2020; Fu et al., 2013). As a result, floods

119   have occurred frequently in the middle and lower reaches of the Yangtze River, where

120   most of the population in the YZRB live (Liu et al., 2018).

121   **2.2 Data**

122   In this work, we focus on the middle and lower reaches of the Yangtze River for the

123   high population density and increasing flood risk. The 30-meter digital elevation model

124   (DEM) was downloaded from Geospatial Data Cloud (http://www.gscloud.cn/), from

125   which the drainage area corresponding to the hydrological station was extracted by

126   ArcGIS. Daily precipitation data and temperature data between 1970 and 2016 from

127   247 meteorological stations within and near the YZRB were downloaded from China

128   Meteorological Data Network (https://data.cma.cn/) (Figure 1). The temperature data

129   was used to estimate potential evaporation. The observed precipitation and estimated

130   potential evaporation were interpolated into the whole YZRB using Thiessen polygon

131   method (Meena et al., 2013). The interpolated precipitation and potential evaporation

132   were then averaged for the drainage area corresponding to each hydrological station.

133   The daily streamflow data was collected from 267 hydrological stations from

134   Annual Hydrological Report of the People's Republic of China. Among which, 224

135   stations with at least 20 years records from both the period from 1970 to 1990 and the

136   period from 2007 to 2016 were selected (see Figure S1 for data availability).

137   Information of 361 reservoirs in the middle and lower YZRB, including capacity and

138   controlling area was downloaded and extracted from the Global Reservoir and Dam

139   database (GRanD) (Lehner et al 2011). Previous study showed that this database

140   provides reliable information of middle and large reservoirs in China (Yang et al 2021).

141   Watersheds with more than 80% of the drainage area under control reservoirs according

142   to GRanD database and/or located right downstream of reservoirs and water gates were

143   considered as watersheds under strong regulation (regulated watersheds).

144   **2.3 Calculation of hydrological and topographic characteristics**

145   *Potential evaporation estimation*

146   The temperature data was used to estimate potential evaporation following the

147   Hargreaves method (Allen et al., 1998; Vicente et al., 2014; Berti et al., 2014).

148
$$ET_0 = 0.0023 \times (Tmax - Tmin)^{0.5} \times (Tmean + 17.8) \times Ra \qquad (1)$$

149   where ET_0 is potential evaporation (mm/d), *Tmax* is the highest temperature (°C), *Tmin*

150   is the lowest temperature (°C), *Tmean* is the mean temperature (°C), and *Ra* is the outer

151   space radiation [MJ/(m^2·d)], which can be calculated as follows:

152
$$Ra = 37.6 \times d_r \times (\omega_s \sin \varphi \sin \delta + \cos \varphi \cos \delta \sin \omega_s), \qquad (2)$$

153   where d_r is the reciprocal of the relative distance between the sun and the earth, ω_s is

154   the angle of sunshine hours, δ is the inclination of the sun (rad), φ is geographic

latitude (rad). d_r, δ and ω_s can be calculated by the following formula:

$$d_r = 1 + 0.033 \times \cos\left(\frac{2\pi J}{365}\right), \tag{3}$$

$$\delta = 0.409 \times \sin\left(\frac{2\pi J}{365} - 1.39\right), \tag{4}$$

$$\omega_s = \arccos(-\tan\varphi\tan\delta)\ , \tag{5}$$

where J is the daily ordinal number (January 1st is 1).

Soil water storage estimation

The soil water storage was estimated based on the daily water balance (Berhuijs et al., 2016, 2019):

$$\frac{dS}{dt} = P - ET - \max(Q, 0), \tag{6}$$

Where S is the soil water storage (mm), which is initially set to 0. Due to the long term of simulation, the change of initial value wouldn't significantly affect the results. P is precipitation (mm/d), Q is discharge normalized by area (mm/d), ET is evaporation (mm/d), which can be calculated from potential evapotranspiration (ET_0), where the soil water storage (S) is used as the upper limit of daily ET:

$$ET = \min(0.75 \times ET_0, S), \tag{7}$$

The estimation of soil water storage and ET are highly simplified and is not used for prediction but to capture the first order of the seasonal variation and to help develop a framework that differentiates the relative contribution of precipitation and soil moisture in flood generation.

Topographic wetness index estimation

Topographic wetness index was calculated to represent the combined impacts of drainage area and topographic gradient (Alfonso et al., 2011; Grabs et al., 2009):

$$TWI = \ln(A_d / \tan\alpha), \tag{8}$$

where A_d is drainage area and α is topographic gradient estimated from DEM. TWI represents the propensity of subsurface flow accumulation and frequency of saturated conditions, thus can be used to predict relative surface wetness and hydrological responses (Meles et al 2020). It is widely used to quantify topographic impact on hydrological processes (i.e., spatial scale effects, hydrological flow path, etc.), as well as in land surface models for hydrological, biogeochemical and ecological processes (Sorensen et al 2006).

2.4 Quantification of the relative importance of soil moisture and precipitation during floods

The maximum daily discharge of each year was selected as annual flood, which was then averaged across years as the mean annual maximum flood (AMF). The observed rainfall on that day and the estimated soil water storage at the day before were also averaged across years as daily rainfall (P) and antecedent soil moisture (S_0). Since almost all the AMFs in our study region come during rainy season when rainfall comes in most of the days. To avoid the bias that may be caused in event separation, the soil moisture at the day before AMF was used as antecedent soil moisture, instead of the day before the event of AMF. To examine the impacts from long-lasting rainfall event, especially for the large watersheds with longer concentration time, we also calculated the mean accumulated rainfall from two days (rainfall on the flood day and the day

197 before, P_2) to seven days (weekly rainfall, P_7).

198 The percentile of antecedent soil moisture (S_0) was calculated to represent the

199 relative saturation of soil moisture in the time series; while the percentile of daily

200 rainfall (P) was estimated to show the relative intensity (P'), representing the relative

201 magnitude of rainfall in flood generation. The percentile of accumulated rainfall was

202 also calculated for the two-day to seven-day rainfall.

203 To quantify the relative importance of antecedent soil moisture and rainfall in flood

204 generation, the ratio between these two factors at the AMFs was derived: SPR = S'/P'.

205 When SPR is large, the antecedent soil moisture is much closer to the maximum, while

206 the daily rainfall is less extreme, floods are more affected by the antecedent soil

207 moisture. On the other hand, a smaller SPR indicates relatively larger magnitude of

208 rainfall comparing with antecedent soil moisture, that is, rainfall is more extreme and

209 influential in flood generation.

210 **3 Results**

211 **3.1 Spatial patterns of antecedent soil moisture and precipitation during floods**

212 Figure 2 shows the spatial distribution of the percentile of antecedent soil moisture and

213 daily rainfall during the annual maximum floods (AMFs) in the middle and lower

214 reaches of the Yangtze River. As we can see from Figure 2a, in the middle and lower

215 reaches of YZRB, when AMFs occurred, the percentile of antecedent soil saturation

216 was generally high, most of them are larger than 0.6: the farther away from the main

217 stream, the more saturated the soil was. On the other hand, along and near the main

218 stream and the delta, the antecedent soil saturation rate could be much smaller, even

219 less than 0.4.

Figure 2b shows the daily rainfall during the AMFs. As we can see, the percentile of daily rainfall is relatively high (>0.8) at more than half of the study sites, while it is small (<0.5) for the sites along the main stream and in the delta (Figure 2b). Comparison between Figure 2a and b suggests that, except the sites on the main stream and in the delta, sites with relatively high antecedent soil saturation rate (i.e., >0.8, the blue dots) during AMFs are also the ones with relatively small daily rainfall contribution (i.e., <0.8, the light blue and cyan dots). That is, for these sites, the AMFs are usually occurring at a near saturated soil condition while extreme rainfall at flood day is not necessary, suggesting the relative importance of soil saturation rate. For the sites with both the percentile of soil moisture and rainfall between 0.6 and 1, both the antecedent soil moisture and rainfall play important roles in flood generation. As for the sites on the main stream and in the delta, both antecedent soil moisture and rainfall are low during AMFs, this is likely due to the regulations from large reservoirs and water gates.

3.2 The scaling effect in the contribution of antecedent soil moisture and rainfall

To further investigate the relative importance of antecedent soil moisture and rainfall in flood generation and the potential influential factors, we examined their correlation with catchment area (Figure 3). Given the complicated environmental and social impacts, the regulated watersheds and sites on the main stream are presented separately (the green dots and cyan dots in Figure 3 respectively). Our study will focus on the sites that are not dominated by regulation (the blue dots in Figure 3), for simplicity, we will refer them as natural watersheds.

As we can see from Figure 3, during the occurrence of AMFs, the percentile of antecedent soil saturation increases with watershed area (p-value<0.001), while the percentile of daily rainfall decreases with watershed area (p-value<0.001). That is, with

244 the increase of watershed size, antecedent soil moisture becomes more and more

245 saturated while the precipitation is less and less extreme during AMFs; suggesting the

246 rising contribution of antecedent soil moisture and declining importance of daily

247 precipitation in flood generation. As for the regulated watersheds (green dots in Figure

248 3), there is no clear correlation between drainage area and the percentile of antecedent

249 soil moisture or rainfall, which is understandable. Meanwhile, both the percentile of

250 antecedent soil moisture and rainfall decreases with watershed area for main stream

251 sites.

252 **3.3 The scaling impacts on accumulated rainfall**

253 The saturation of soil before floods could be due to previous rainfall events, and could

254 also be caused by accumulated rainfall in long-lasting rainfall events that eventually

255 generate floods (Xie et al., 2018). Figure 4 presents the correlation between the

256 percentile of accumulated rainfall and drainage area. When single day rainfall is

257 considered, it is negatively correlated with drainage area (Figure 3a); when

258 accumulated rainfall is considered, the correlation gradually shifts from negative to

259 positive correlation (Figure 4). For example, when two-day rainfall was examined, the

260 correlation between accumulated rainfall and drainage area shifts from negative to

261 positive at 10,000 km^2; the negative correlation in Figure 3a is only valid for watersheds

262 larger than 10,000 km^2 (Figure 4a). This transition area increases from 10,000 km^2 for

263 two-day rainfall to 100,000 km^2 for four-day rainfall (Figure 4c). The number of

264 watersheds with negative correlation also decreases. Eventually, the weekly rainfall has

265 similar positive correlation with drainage area like antecedent soil moisture (Figure 4f).

266 The increase of transition area may be explained by the increasing response time and

267 confluence time in large watersheds: it takes days to generate flow events by heavy

268 rainfall and for them to reach outlets where it can be observed in large watersheds. This

269 is also consistent with the conclusion in the Yellow River Basin (Ran et al., 2020) and

270 our previous findings of the dominant flood generation mechanism in the middle and

271 lower YZRB: weekly rainfall is the dominant flood driver for sites on the main streams

272 and the major tributaries (Wang et al 2021). The regulated watersheds don't show

273 significant correlation which is understandable for the strong human intervention. For

274 the negative correlation between accumulated rainfall and drainage area at main stream

275 sites, it is difficult to decide whether it is due to scaling effect or human intervention.

276 **3.4 The interlink of watershed characteristics, flood, antecedent soil moisture and**

277 **rainfall**

278 Figure 5 presents the percentile of antecedent soil moisture and rainfall during the

279 AMFs at the study watersheds, the circles are scaled by watershed size and colored with

280 topographic gradient. Except the watersheds with strong human intervention (regulated

281 ones and the ones on main stream), there is a negative correlation between the

282 contribution of rainfall and antecedent soil moisture. The lower right of the scatter are

283 mostly big blue dots, which are large watersheds with gentle topographic gradient. That

284 is, AMFs usually occur when soil moisture is close to saturation while extreme rainfall

285 is not necessary for AMFs in these watersheds. On top of the scatter are relatively small

286 yellow and green dots, those are medium to small watersheds with steep topographic

287 gradient. That is, AMFs are usually generated with extreme rainfall, while the saturation

288 of soil moisture is not necessary. This negative correlation indicates the shift of

289 dominance in AMFs generation from extreme rainfall to antecedent soil saturation from

290 small steep watersheds to large flat ones.

291 Figure 6 shows the relative importance of antecedent soil moisture and rainfall. For

the natural watersheds (the circles), SPR increases with drainage area and declines with topographic gradient. That is, the larger the drainage area is, the more essential the contribution of antecedent soil moisture to floods is, and the less influential rainfall is in flood generation. For watersheds with similar drainage area (i.e., the green or light blue dots in Figure 6b), topographic gradient also cast impacts on SPR: SPR decreases with slope. That is, the relative importance of rainfall increases at steeper watersheds. This may be attributed to the shortened hydrological response time due to the steep topography which facilitates rainfall induced floods generation. As a combination of both drainage area and topographic gradient, TWI is positively correlated with SPR at natural watersheds, with less scatter than the correlation between SPR and drainage area or topographic gradient alone. That is, watersheds with larger area and gentler topographic gradient that are easier to get wet tend to have larger SPR: soil saturation is more important in flood generation. There is no significant correlation between SPR and TWI for the regulated watersheds along tributaries (black triangles). However, the sites on main stream show opposite pattern: the SPR at these sites decreases with TWI and drainage area. It is difficult to determine whether this is because of reservoir regulation or not. More data about watersheds larger than 10,000km^2 but with limited human intervention are needed to examine this hypothesis.

Besides TWI, SPR is also correlated with the magnitude of AMF (Figure 7). As Figure 7 shows, the area normalized flood peak declines with flood-generation SPR. Watersheds with large flood peak are mostly the ones with steep topographic gradient and small SPR (i.e., SPR<1) and *vice versa*. Similar correlation was also found at event scale in our experimental mountainous watershed, which locates at a headwater of Yangtze River (Liu et al 2021).

4 Discussion

4.1 The relative importance of antecedent soil moisture and rainfall in flood generation

While soil moisture and rainfall are the two main drivers of floods in the middle and lower Yangtze River basin, the dominance of each factor varies across the relatively natural watersheds. Floods in large watersheds are usually generated when soil is almost saturated despite of the relatively small rainfall amount, while extreme rainfall is usually observed during floods in small to medium watersheds (blue dots in Figure 3). The rising contribution of antecedent soil moisture in large watersheds was consistent with the findings in Australian watersheds (Wasko & Nathan, 2019); and the declining influence of rainfall at larger watersheds was also found in Indian watersheds (Garg et al 2019). This contrast correlation with watershed size indicates a shift of dominance in AMFs generation, which may be attributed to the longer confluence time in the large watersheds and less heterogeneity in small watersheds.

This shift of dominance can be observed more straightforward from the negative correlation between the percentile of rainfall and antecedent soil moisture in Figure 5. The natural watersheds in Figure 5 could be grouped into three classes based on their drainage area and topographic gradient. When a watershed is large and flat, flood occurrence is mainly determined by soil saturation (i.e., the big blue dots at the lower right of the scatter); on the other hand, when a watershed is small and steep, heavy rainfall takes over the dominance (i.e., the small yellow and green dots at the upper left of the scatter). Between these two groups are relatively small watersheds with gentle topographic gradient, where the occurrence of AMF requires both highly saturated soil and relatively heavy rainfall. That is, the dominant influential factor(s) in AMFs

generation across watersheds is correlated with the topographic characteristics (i.e., watershed size and topographic gradient). This helps quantify the relative importance of soil moisture and rainfall in flood generation in the existing work.

This shift of dominance is not observed in the main stream sites (i.e., cyan dots in Figure 3), where the percentile of both antecedent soil moisture and precipitation declines with drainage area. This may be attributed to the more complicated flood generation mechanism at large scale as well as the strong human intervention on main stream (e.g., reservoirs, water gates regulation, etc.) (Gao et al., 2018; Long et al., 2020; Zhang et al., 2017). The major responsibilities of reservoirs on the main stream are to reduce peak flow and postpone the time to flood peak (Volpi et al., 2018). As a result, the original flood peak would be delayed by regulation and the actual flood peak would occur when rainfall declines/stops and soil water drains. Another possibility is that when watershed size is larger than $100,000km^2$, the impact of antecedent soil moisture declines as well. To examine this hypothesis, more data from watersheds larger than $100,000km^2$ and with limited human intervention is needed. However, this is above the scope of this work and requires future studies.

4.2 Linkage between topographic characteristics, SPR and floods

The correlation between TWI and SPR (Figure 6c) demonstrates that the relative importance of soil moisture and rainfall could be inferred from topographic characteristics quantitatively. We could derive the relative dominance of soil moisture and rainfall in flood generation in specific watershed from its TWI for the natural watersheds without significant human intervention. Rainfall and soil moisture level have been identified as dominant drivers of floods, individually or together, in watersheds worldwide (Berghuijs et al 2016, 2019b; Garg & Mishra 2019; Tramblay et

364 al 2021; Ye et al 2017). Our findings provide a framework to quantify the relative

365 importance of rainfall and soil moisture and to further identify the influential factors of

366 their importance based on topographic characteristics that are easy to measure.

367   Meanwhile, the SPR also present a negative correlation with the magnitude of

368 AMFs (Figure 7). That is, we could infer the mean annual AMF based on SPR for each

369 watershed. Since the characteristic SPR could be estimated from TWI, we could derive

370 quantitative estimation of the mean AMFs from topographic characteristics that are

371 easy to measure, even in watersheds with little hydrologic records. This would be

372 helpful for flood control management in ungauged watersheds, especially in the

373 mountainous watersheds with risks of flash floods. Similar correlation was also found

374 in the observations from our experimental watershed, a headwater of Yangtze River

375 (Liu et al 2021). The ratio of observed antecedent soil moisture and event precipitation

376 also presents similar decline trend with discharge at event scale. However, the

377 correlation between SPR and discharge at event scale is preliminary, more data with

378 higher resolution and detailed analysis are needed for validation at event scale. For this

379 study, our goal is to present the framework to derive flood generation SPR that could

380 be estimated from topographic characteristics and to provide information of mean

381 AMFs.

382   In conclusion, based on the topographic characteristics, we could derive the relative

383 importance of soil moisture and rainfall in flood generation (SPR); and from this

384 relative importance ratio, we could further infer the average flood magnitude at these

385 watersheds. As a result, we could link the topographic characteristics and annual floods

386 through the characteristic SPR during the AMFs.

387 **4.3 Implications**

388 Our findings could be helpful for potential flood risk evaluation in ungauged basins,

389 e.g., headwaters in the mountainous region. With the construction of large reservoirs,

390 the capability of flood risk control has improved substantially along main stream (Zou

391 et al., 2011; Zhang et al., 2015). However, it is still difficult for quantitative evaluation

392 of flood risk in upstream mountainous watersheds, which are vulnerable to floods but

393 difficult for hydrological modeling and prediction due to little hydrologic records.

394 Our findings suggest that we could derive the flood-generation SPR of each

395 watershed from drainage area and topographic gradient that are easy to measure. The

396 correlation between SPR and flood peak provides information of the mean annual

397 floods in ungauged watersheds. Therefore, in regions without observation data, to build

398 flood control infrastructure such as dams and gates, the mean annual flood peak

399 obtained by SPR based on the topographic characteristics can be used to provide

400 quantitative information for flood control and disaster management. Flood control

401 infrastructures could be designed based on the estimated mean annual flood peak as

402 well as the demographic information. With further validation of this framework at event

403 scale, by using the observed soil moisture from remote sensing data and precipitation

404 forecast to generate real-time prediction of SPR values, we could further provide early

405 warning of floods in these ungauged watersheds. But this needs more data and

406 examination in future studies.

407 **4.4 Limitations**

408 Previous works usually identify the dominant flood generation mechanism based on the

409 comparison of the timing of events (Berghuijs et al 2016; 2019b; Bloschl et al 2017; Ye

410 et al 2017). Similar work has been implemented in our study watersheds, suggesting

411 the importance of soil moisture and rainfall (Wang et al 2021). Based on that, we further

412   looked into the records to quantitatively evaluate the relative importance of soil

413   moisture and rainfall in flood generation. However, there are limitations in our methods.

414   The precipitation data we used were averaged for the study watersheds from 247

415   meteorological stations. Given the large area and considerable spatial heterogeneity, the

416   precipitation data we used may not always be representative of the actual precipitation

417   events. The daily data could also average the rainfall intensity at hourly scale, which

418   could be influential in small mountainous watersheds. ET was scaled as $0.75*ET_0$ to

419   make sure it is smaller than the potential evaporation. This is a simplified estimation of

420   ET; more sophisticated method is needed in further analysis on specific catchments at

421   event scale.

422   The estimation of soil moisture is also highly simplified, which cannot be

423   considered as precise estimation at event scale. To reduce the influence from this

424   simplification, we used the percentile of soil moisture to represent the relative saturation

425   of soil moisture as well as the seasonal trend of soil moisture, which was then compared

426   with the percentile of rainfall. While more sophisticated models can be used for soil

427   moisture estimation, there could still be substantial uncertainties (Zaherpour et al., 2018;

428   Ran et al 2020). Yet the seasonal trend and the relative magnitude, after averaging

429   through long-term records would be less impacted by the simplification in estimation

430   (Berghuijs et al 2019; Zhang et al 2019).

431   It is possible that soil moisture at the day before the AMFs may not be the soil

432   moisture before event in large catchments due to the long concentration time. We

433   estimated the concentration time for 10 sites with largest drainage area (larger than

434   100,000 km²): the ones on the main stream and at the outlets of major tributaries

435   following the USBR method (USBR 1973; Gericke & Smithers 2014). The

concentration time is mostly within two days for main stream sites and is less than 24hr for sites at the outlets of major tributaries (Table S1). Since the rest of the sites are all smaller than these ones, so would be the concentration time. That is, for the natural watersheds we focused on, the concentration time is likely to be within one day. Thus, the soil moisture at the day before AMFs would contribute to the generation of AMFs, and should be applicable for this study.

Besides, the exchange with groundwater was not considered in the soil moisture estimation. The exchange with groundwater is more complicated and heterogenous (i.e., rivers could receive groundwater recharge in hilly area and recharge groundwater in lower land (Che et al 2021)). According to Huang et al. (2021), the variation of groundwater level in the Yangtze River basin is relatively small. Since the goal of this study is to capture the first order seasonal variation of soil moisture and develop a framework that differentiates the relative importance of precipitation and soil moisture in flood generation, in this study, we estimated the soil moisture following Berhuijs (et al 2016, 2019) with a simple water balance equation.

Moreover, this work is focused on the relative importance soil moisture and rainfall, the impact of snowmelt is not considered due to the warm and humid climate in the study watersheds. To apply our findings to cold watersheds with significant impact of snow, the snowmelt component needs to be incorporated. In addition, our method is based on the average values from many years. While previous work indicated that the occurrence of floods in our study watersheds are highly concentrated (Wang et al 2021), there could be strong inter-annual variability in other watersheds. In future studies, annual scale and event scale analysis are needed to examine and improve our findings before it can be applied to watersheds with more diverse climate and landscape

conditions. more comprehensive models with sophisticated groundwater component, remote sensing data, and reanalysis product with higher spatial-temporal resolution are needed to provide more accurate estimation of soil moisture, ET, and refine the estimation of the flood-generation SPR.

5 Conclusions

Heavy rainfall on highly saturated soil was identified as the dominant flood generation mechanism across world (Berghuijs et al 2019; Wang et al 2021; Wasko et al 2020). This study aims to further evaluate the relative importance of antecedent soil moisture and rainfall on floods generation and the controlling factors. Climate and hydrological data from 224 hydrological stations and 247 meteorological stations in the middle and lower reaches of the Yangtze River basin was analyzed, along with the modeled soil moisture. Except the regulated watersheds, the relative importance of antecedent soil moisture and daily rainfall present significant correlation with drainage area: the larger the watershed is, the more essential antecedent soil saturation rate is in flood generation, the less important daily rainfall is.

Using the percentile of antecedent soil moisture and rainfall as coordinates, the flood generation mechanism(s) of study watersheds could be grouped into three classes: antecedent soil moisture dominated large flat watersheds, heavy rainfall dominated steep and small to middle size watersheds, and small to middle size watersheds with gentle topographic gradient where floods occurrence requires both highly saturated soil and heavy rainfall. Our analysis further shows that the ratio of relative importance between antecedent soil moisture and rainfall (SPR) can be predicted by topographic wetness index. When the topographic wetness index is large, the dominance of antecedent soil moisture for extreme floods is stronger, and *vice versa*. The SPR also

484 presents negative correlation with area normalized flood peak.

485   With the potential increase of extreme rainfall events (Gao et al., 2016; Chen et

486 al., 2016), upstream mountainous watersheds in the middle and lower Yangtze River

487 basin are facing higher risk of extreme floods. The lack of hydrological records further

488 increases the vulnerability of people in these watersheds. The flood risks could be

489 reduced by construction of flood control facilities, but it is difficult to set flood control

490 standards in these ungauged watersheds. Our findings provide a framework to

491 quantitatively estimate the possible flood risk for these ungauged watersheds. Based on

492 measurable watershed characteristics (i.e., drainage area and topographic gradient), the

493 flood generation SPR could be derived, which could then be used to estimate the mean

494 annual flood. This information can provide scientific support for flood control

495 management as well as infrastructures construction.

496   Future analysis at event scale could help generate the flood-generation curve

497 between SPR and discharge at event scale to further improve flood risk predictions in

498 these small ungauged watersheds. With more data from other regions and improved

499 estimation or observation of soil moisture, we could expand our analysis to watersheds

500 with more diverse climate and topographic characteristics to examine and refine our

501 findings and to enhance our understandings of flood generation.

502

503 **Data availability**

504 DEM data was downloaded from Geospatial Data Cloud at http://www.gscloud.cn/.

505 Climatological data used in this study was obtained from China Meteorological Data

506 Network, which can be accessed at http://data.cma.cn/. Discharge data comes from

507 Annual Hydrological Report of the People's Republic of China issued by Yangtze River

508 Water Resources Commission.

509

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514

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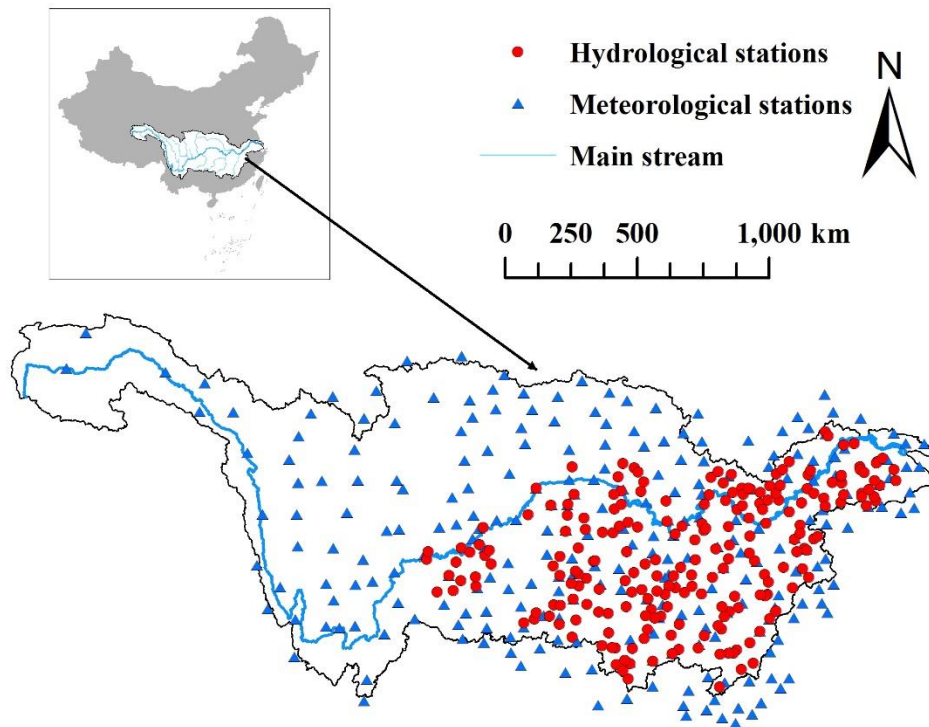
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827 **Figure 1**: Map of the Yangtze River basin, and the meteorological stations and

828 hydrological stations. The blue line is the main stream of Yangtze River.

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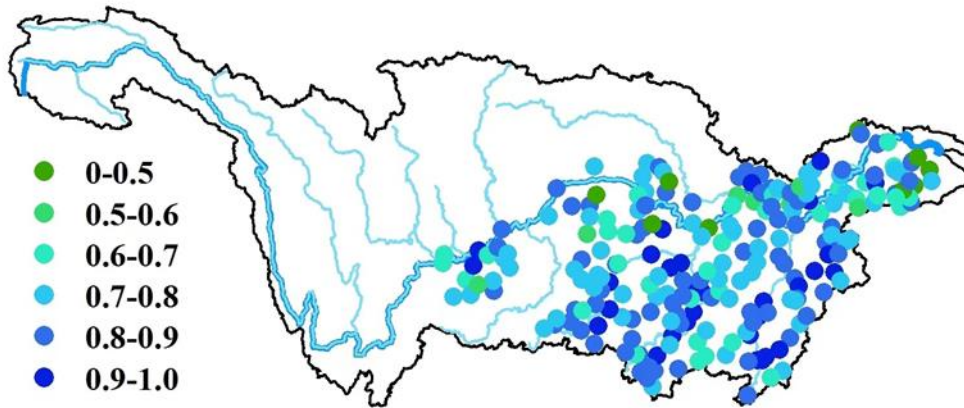
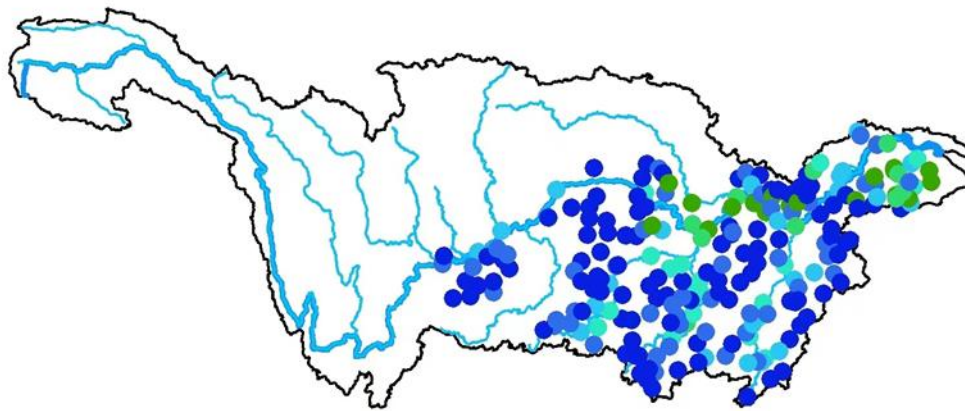

(a)Percentile of antecedent soil moisture

(b)Percentile of precipitation

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831 **Figure 2**: The spatial distribution of (a) the percentile of antecedent soil moisture during

832 annual maximum flood; (b) the percentile of daily precipitation during annual

833 maximum flood.

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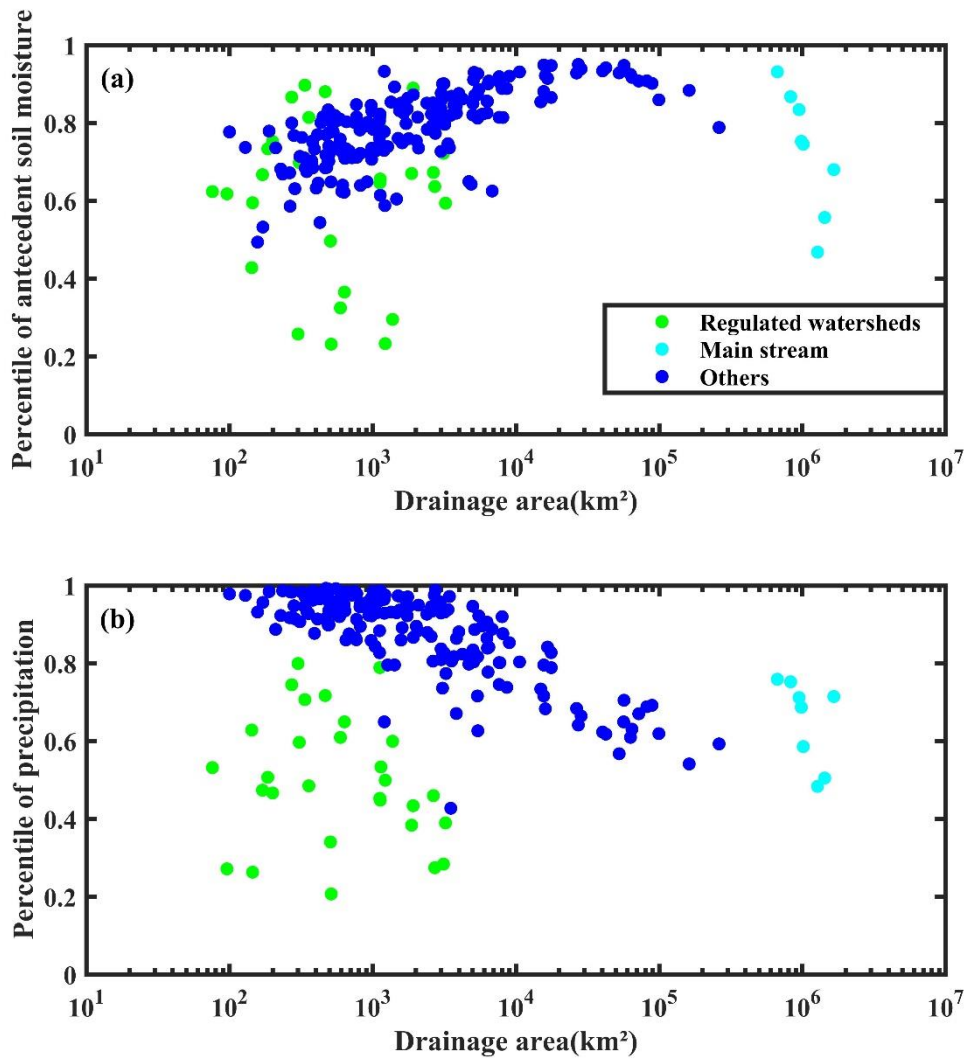
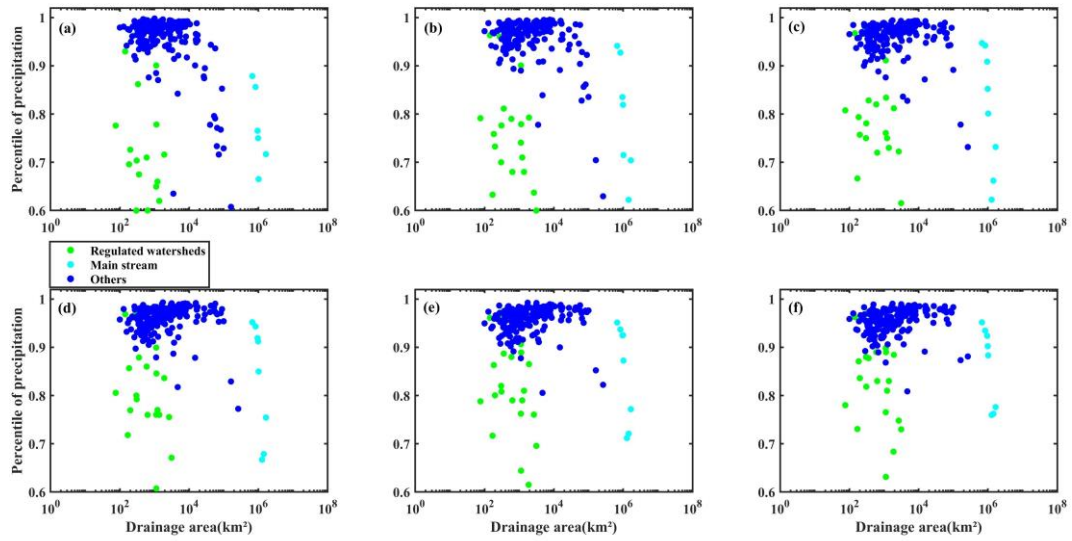


Figure 3: Scatterplot between the drainage area and (a) the percentile of antecedent soil moisture of AMF events (the linear regression for blue dots: $R^2 = 0.46$, *p*-value<0.001); (b) the percentile of precipitation at the day of AMF events (the linear regression for blue dots: $R^2 = 0.61$, *p*-value<0.001). The green dots represent the regulated watershed, the cyan dots represent the sites on the main stream, and the rest sites are shown in blue.

844

845 **Figure 4**: Scatterplot between the drainage area and the percentile of accumulated

846 rainfall of (a) two days; (b) three days; (c) four days; (d) five days; (e) six days; and (f)

847 seven days on AMF events.

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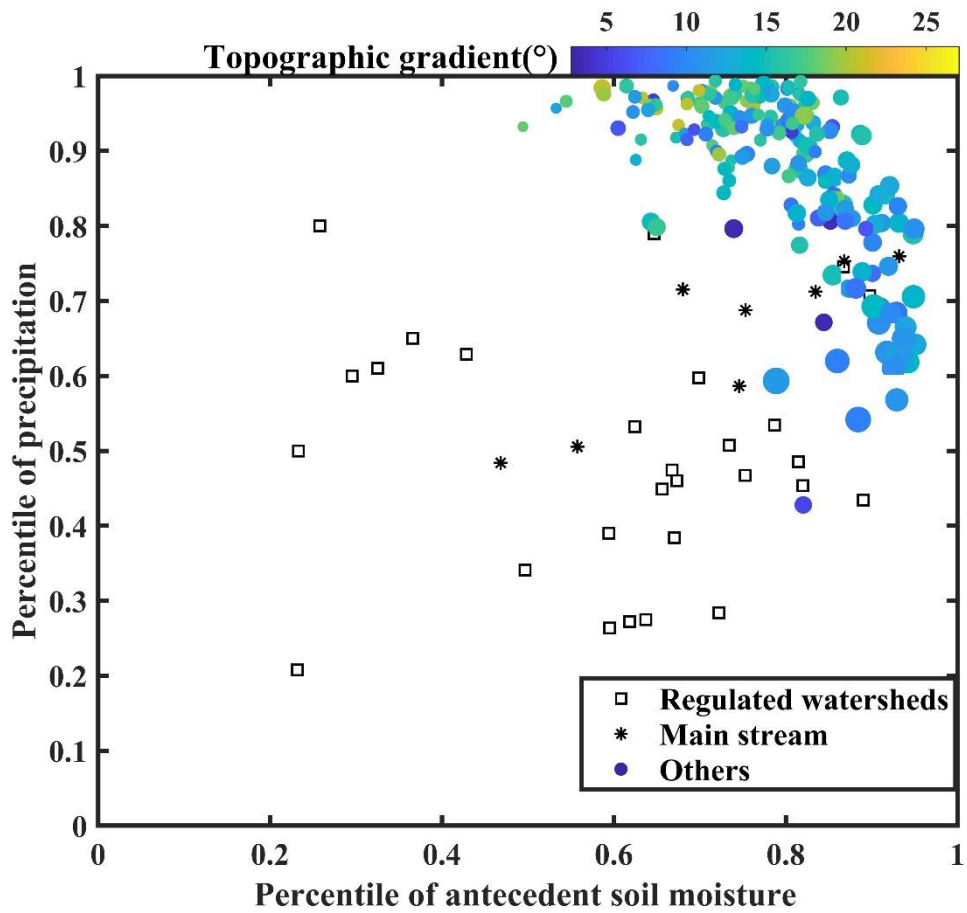
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850 **Figure 5**: Scatterplot of the percentile of precipitation and antecedent soil moisture, the

851 color represents topographic gradient and the size of circles is scaled by drainage area.

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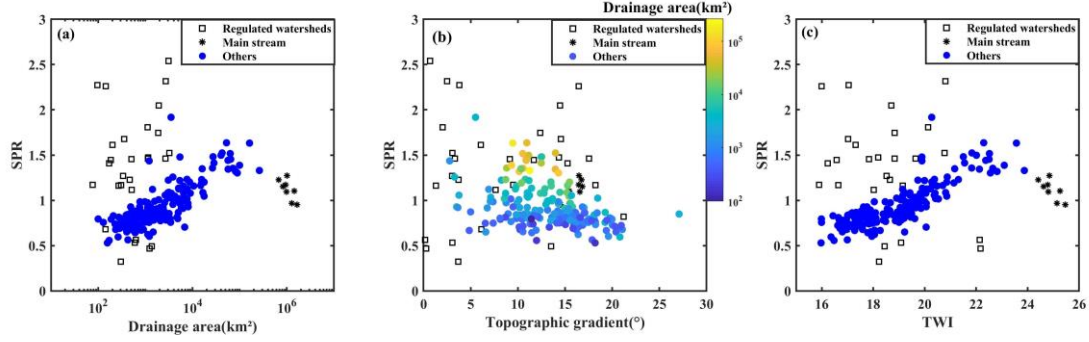
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855 **Figure 6**: Scatterplots between the ratio of antecedent soil moisture and precipitation
856 (SPR) and (a) drainage area; (b) slope; and (c) topographic wetness index (TWI).
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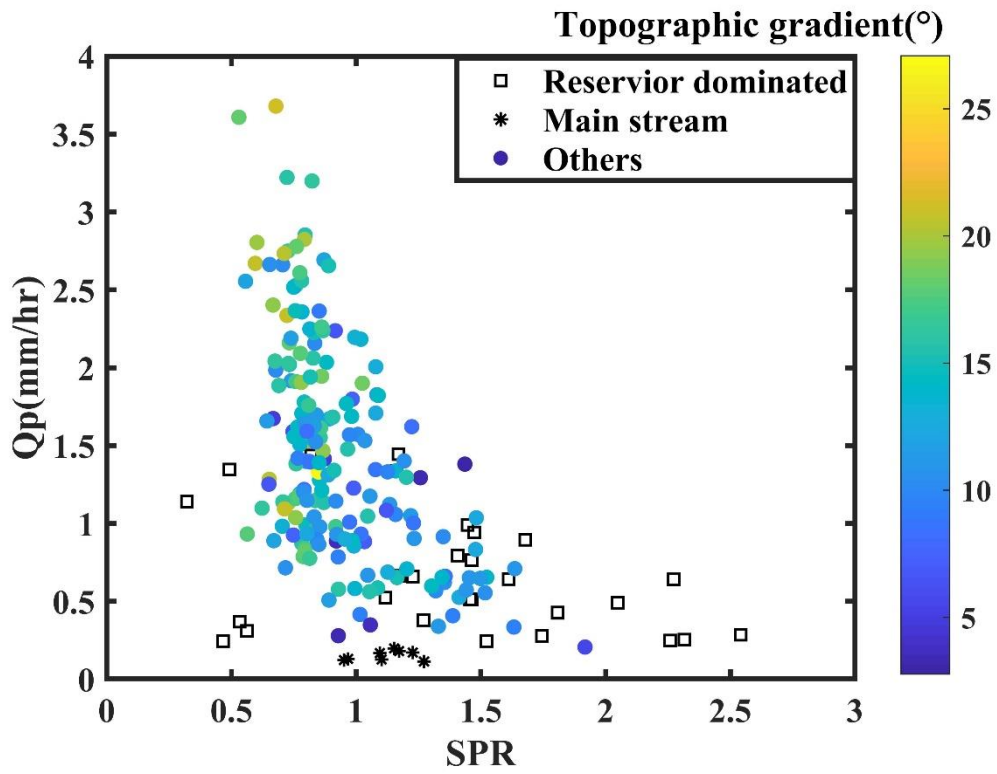
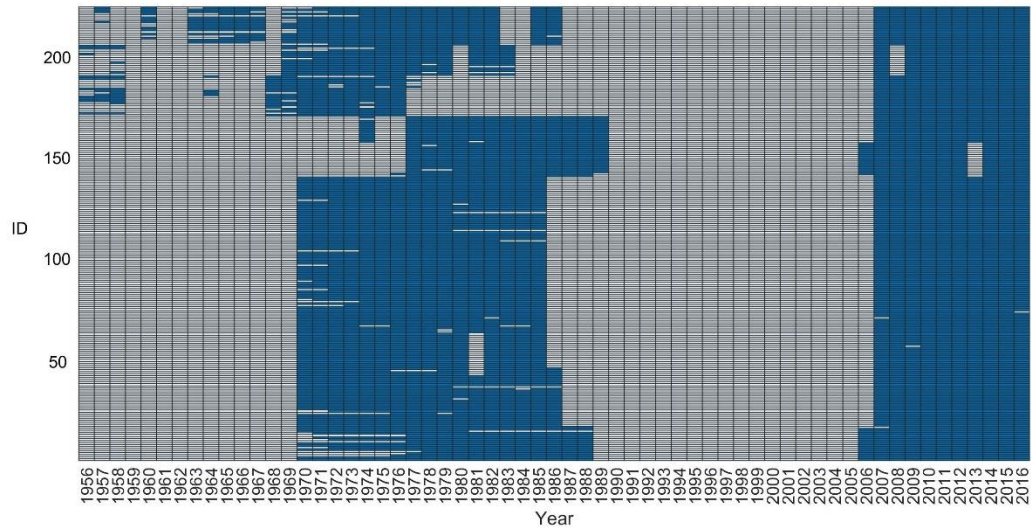


Figure 7: Scatterplot between the ratio of antecedent soil moisture and precipitation
(SPR) and area weighted annual maximum discharge (Q_P), the color represents
topographic gradient.

Supplementary

Table S1: Estimated concentration time for 10 sites with largest drainage area: the ones on main stream (MS) and the ones at the outlets of major tributaries (TR).

Site Name	Concentration Time (hr)	Drainage Area (km²)
TR-Hukou	17.9	161,979
TR-Chenglingji	18.8	261,986
MS-Zhutuo	32.7	668,661
MS-Cuntan	32.8	827,799
MS-Wanxian	37.6	948,524
MS-Yichang	41.5	982,948
MS-Jianli	45.2	1,014,690
MS-Luoshan	46.3	1,276,676
MS-Hankou	51.0	1,432,008
MS-Datong	54.3	1,657,604

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873 **Figure S1**: The data availability of each station, each column indicates each year while

874 each row is corresponding to each station, blue grid indicates there is record of this year.