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Hydrology and Earth System Sciences
Discussions

The relative importance of antecedent soil moisture and precipitation in flood generation in the middle and lower Yangtze River basin

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Hydrology and Earth System Sciences
Open Access
Discussions

Abstract

Floods have caused severe environmental and social economic losses worldwide in human history, and are projected to exacerbate due to climate change. Many floods are caused by heavy rainfall with highly saturated soil, however, the relative importance of rainfall and antecedent soil moisture and how it changes from place to place has not been fully understood. Here we examined annual floods from more than 200 hydrological stations in the middle and lower Yangtze River basin. Our results indicate that the dominant factor of flood generation shifts from rainfall to antecedent soil moisture with the increase of watershed area. The ratio of the relative importance of antecedent soil moisture and daily rainfall (SPR) is positively correlated with topographic wetness index and has a negative correlation with the magnitude of annual floods. This linkage between watershed characteristics that are easy to measure and the dominant flood generation mechanism provides a quantitative method for flood control and early warnings in ungauged watersheds in the middle and lower Yangtze River basin.

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

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

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 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.

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 et al 2020). Little work has been conducted on the flood generation mechanisms in

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

Hydrology and Earth System Sciences
Open Access
Discussions

China (except Yang et al 2019).

As the largest river in China, Yangtze River basin has long suffered from floods. In summer 2020, 378 tributaries of the Yangtze River had floods exceeding the alarm level, causing billions of dollars damage (Xia et al., 2021). With the increasing public awareness, more accurate prediction is needed, which relies on better understanding. However, due to the limitation of observations, there are only a few regional studies of the flood generation mechanism in China, even little in the Yangtze River basin (Zhang et al 2018; Yang et al 2019; Yang et al 2020). The large number of dams and reservoirs built along the river further complicated the situation (Feng et al., 2017; Qian et al 2011; Yang et al 2019).

Because of the relatively warm temperature, snowmelt has little impact on flood generation in the Yangtze River basin (Yang et al 2020). Floods in the Yangtze River basin usually occur during summer with relatively wet soil and high rainfall (Wang et al 2021). Heavy rainfall with high antecedent soil moisture has also been identified as dominant driver of floods across world (Beighuijs et al 2019b; Garg et al 2019; Tramblay et al 2021; Wasko et al 2020). However, little study examines the relative importance of rainfall and antecedent soil moisture in flood generation. A quantitative overview of how the combination of rainfall and antecedent soil moisture change across watersheds is currently unavailable in China (Liu et al., 2021; Wu et al., 2015).

Based on the watersheds in the middle and lower Yangtze River basin, this study attempts to explore the following questions: 1) is there a way to quantitatively describe the relative importance of antecedent soil moisture and rainfall on flood generation; and 2) how would this combination of flood-generation rainfall and soil moisture vary across watersheds, and what are the influential factors. Based on the observations and

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

Hydrology and Earth System Sciences
Discussions

model estimation (Section 2), the spatial distribution patterns of antecedent soil moisture and rainfall were obtained and analyzed to investigate their individual contribution to flood generation and the influential factors (Section3). This allows for further examination of the relative importance of antecedent soil moisture and rainfall on flood generation and its linkage to watershed characteristics as well as its implications to flood prediction (Section 4), all the results are summarized in Section 5.

2 Methods

2.1 Study area

Yangtze River is the largest river in China, with a total length of 6,300 kilometers and annual discharge of 920km^3 at the outlet (Yang et al., 2018). It drains through an area of 1.8*10^6 km^2, lying between 90°33’and 122°25’E and 24°30’and 35°45’N, and is home to over 400 million people, most of which live in the middle and lower Yangtze River basin (YZRB) (Cai et al., 2020). The elevation of the YZRB declines from west to east: from over 3000m in Qinghai-Tibet Plateau, to around 1000m in the central mountain region, and the 100m in Eastern China Plain (Wang et al., 2013). The vegetation types in the YZRB are forests, shrubs, grassland and agricultural land, accounting for 11.85%, 12.65%, 32.26% and 42.88% respectively. Grassland and shrubs are the dominant vegetation in the middle and upper YZRB, while the downstream YZRB is dominated by forests and agricultural land (Miao et al., 2010). There are more than 51,000 reservoirs of different sizes in the whole basin, including 280 large ones (Peng et al., 2020).

Most of the YZRB is semi-humid and humid, with s a typical subtropical monsoon climate. The mean annual temperature is approximately 13.0 °C, varying from −4 °C to 18°C downstream. The mean annual precipitation of the whole basin is about 1200 mm, increasing from 300mm in the western headwaters to 2400 mm downstream. (Li et al., 2021). Most of the precipitation comes between June and September, the premise of persistent heavy rain in the Yangtze River basin is the frequent activity of weak cold air in the north (Tao et al., 1980) and the intersection of mid-latitude air mass and monsoon air mass (Kato et al., 1985). Studies have found that both annual precipitation and the frequency of extreme precipitation events have increased in the middle and lower reaches of the Yangtze River (Qian et al., 2020; Fu et al., 2013). As a result, floods have occurred frequently in the middle and lower reaches of the Yangtze River, where most of the population in the YZRB live (Liu et al., 2018).

2.2 Data

In this work, we focus on the middle and lower reaches of the Yangtze River for the high population density and increasing flood risk. The 30-meter digital elevation model (DEM) was downloaded from Geospatial Data Cloud (http://www.gscloud.cn/), from which the drainage area corresponding to the hydrological station was extracted by ArcGIS. Daily precipitation data and temperature data between 1970 and 2016 from 247 meteorological stations within and near the YZRB were downloaded from China Meteorological Data Network (https://data.cma.cn/). The temperature data was used to estimate potential evaporation. The observed precipitation and estimated potential evaporation were interpolated into the whole YZRB using Thiessen polygon method (Meena et al., 2013). The interpolated precipitation and potential evaporation were then averaged for the drainage area corresponding to each hydrological station.

The daily streamflow data was collected from 267 stations from Annual Hydrological Report of the People's Republic of China. Among which, 224 stations

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

with at least 20 years records from 1970 to 1990 and from 2007 to 2016 were selected. Information of 361 reservoirs in the middle and lower YZRB, including capacity and controlling area was downloaded and extracted from the Global Reservoir and Dam database (GRanD) (Lehner et al 2011). Previous study showed that this database provides reliable information of middle and large reservoirs in China (Yang et al 2021). Watersheds with more than 80% of the drainage area under control reservoirs according to GRanD database and/or located right downstream of reservoirs and water gates were considered as watersheds under strong regulation (regulated watersheds).

2.3 Calculation of hydrological and topographic characteristics

Potential evaporation estimation

The temperature data was used to estimate potential evaporation following the Hargreaves method (Allen et al., 1998; Vicente et al., 2014; Berti et al., 2014).

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

where ET_0 is potential evaporation (mm/d), *Tmax* is the highest temperature (°C), *Tmin* is the lowest temperature (°C), *Tmean* is the mean temperature (°C), and *Ra* is the outer space radiation [MJ/(m^2 d)], which can be calculated as follows:

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

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

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

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

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

$$\omega_S = \arccos(-\tan\varphi \tan\delta)\,, \quad (5)$$

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., 2019; Deb et al., 2019):

$$\frac{\mathrm{d}S}{\mathrm{d}t} = P - ET - \max(Q, 0)\,, \quad (6)$$

Where S is the soil water storage (mm); 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):

$$ET = \min(0.75 \times ET_0, S)\,, \quad (7)$$

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):

$$TWI = \ln(A_d/\tan\alpha)\,, \quad (8)$$

where A_d is drainage area and α is topographic gradient estimated from DEM.

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

The maximum discharge of each year was selected as annual flood, which was then

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

Hydrology and Earth System Sciences
Discussions
Open Access

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). To examine the impacts from long-lasting rainfall event, we also calculated the mean accumulated rainfall from two days (rainfall on the flood day and the day before, P_2) to seven days (weekly rainfall, P_7).

The antecedent soil moisture (S_0) was normalized by the maximum soil moisture (*Smax*) to approximate the saturation rate (*S'*) as a surrogate of the contribution of soil moisture in flood generation. The daily rainfall (*P*) was normalized by the maximum daily rainfall (*Pmax*) to show the relative intensity (*P'*), representing the contribution of rainfall in flood generation. The accumulated rainfall was also normalized by the maximum two-day to seven-day rainfall.

To quantify the relative importance of antecedent soil moisture and rainfall in flood generation, the ratio between these two factors at the AMFs was derived: SPR = *S'*/*P'*. When SPR is larger than 1, floods at those sites are more dominated by antecedent soil moisture; when SPR is less than 1, rainfall is the primary driver of floods.

3 Results

3.1 Spatial patterns of antecedent soil moisture and precipitation during floods

Because of the latitude and the relative warm climate, floods in the middle and lower Yangtze River basin usually occur in summer, with little influence of snowmelt (Wang et al., 2015; Yang et al 2019). Therefore, in this study we mainly focus on the impacts of antecedent soil moisture and rainfall on flood generation. Figure 2 shows the spatial distribution of normalized antecedent soil moisture and daily rainfall during the annual

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

maximum floods (AMF) in the middle and lower reaches of the Yangtze River.

As we can see from Figure 2a, in the middle and lower reaches of YZRB, when AMFs occurred, the antecedent soil saturation rate was generally higher at sites along the major tributaries (i.e., >0.6): the farther away from the main stream, the more saturated the soil was. On the other hand, along and near the main stream and the delta, the antecedent soil saturation rate could be less than 0.4. This may be attributed to the more complicated flood generation mechanism at large scale as well as the strong reservoir control on main stream and water gates regulation in the delta (Gao et al., 2018; Long et al., 2020; Zhang et al., 2017).

Figure 2b shows the normalized daily rainfall during the AMFs. As we can see, the daily rainfall is relatively high (>0.4) at more than half of the study sites, while it is small (<0.2) for the sites along the main stream, main tributaries, 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 green dots) during AMFs are also the ones with relatively small daily rainfall contribution (i.e., <0.2, the red dots). That is, for these sites, the AMFs are usually occurring at a near saturated soil condition while heavy rainfall at flood day is not necessary, suggesting the relative importance of soil saturation rate. For the sites with both saturation rate and normalized rainfall between 0.4 and 0.6, both the antecedent soil saturation 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

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

To further investigate the contribution 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 red 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 antecedent soil saturation rate increase with watershed area (p-value<0.001), while the normalized daily rainfall decreases with watershed area (p-value<0.001). That is, with the increase of watershed size, antecedent soil moisture becomes more and more important in flood generation while the contribution of daily rainfall declines. On the other hand, heavy rainfall in a single day could only be the dominant driver of floods when watershed area is smaller than 1000km^2.

As for the regulated watersheds (green dots in Figure 3), there is no clear correlation between drainage area and antecedent soil saturation rate or normalized rainfall, which is understandable. Meanwhile, both antecedent soil saturation rate and normalized rainfall decreases with watershed area for main stream sites. One explanation is flood regulation: as 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). The other explanation is that when watershed size is larger than 100,000km^2, the impact of antecedent soil moisture declines. 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.

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

Hydrology and Earth System Sciences
Discussions

3.3 The scaling impacts on accumulated rainfall

The saturation of soil before floods could be due to previous rainfall events, and could also be caused by accumulated rainfall in long-lasting rainfall events that eventually generate floods (Xie et al., 2018). Figure 4 presents the correlation between normalized accumulated rainfall and drainage area. When single day rainfall is considered, it is negatively correlated with drainage area (Figure 3a); when accumulated rainfall is considered, the correlation gradually shifts from negative to positive correlation (Figure 4). For example, when two-day rainfall was examined, the correlation between accumulated rainfall and drainage area shifts from negative to positive at 1000 km^2; the negative correlation in Figure 3a is only valid for watersheds larger than 1000 km^2 (Figure 4a). This transition area increases from 1000 km^2 for two-day rainfall to 10,000 km^2 for three-day rainfall (Figure 4b), and 100,000 km^2 for five-day rainfall (Figure 4e). Eventually, the weekly rainfall has similar positive correlation with drainage area like antecedent soil moisture (Figure 4f). The increase of transition area may be explained by the increasing response time and confluence time in large watersheds: it takes days for the flow events generated by heavy rainfall to reach outlets where it can be observed in large watersheds. This is also consistent with the conclusion in the Yellow River Basin (Ran et al., 2020) and our previous findings of the dominant flood generation mechanism in the middle and lower YZRB: weekly rainfall is the dominant flood driver for sites on the main streams and the major tributaries (Wang et al 2021). The regulated watersheds don't show significant correlation which is understandable for the strong human intervention. For the negative correlation between accumulated rainfall and drainage area at main stream sites, it is difficult to decide whether it is due to scaling effect or human intervention.

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

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

Figure 5 presents the contribution of antecedent soil moisture and rainfall to the AMFs at the study watersheds, the circles are scaled by watershed size and colored with topographic gradient. Except the watersheds with strong human intervention (regulated ones and the ones on main stream), there is a negative correlation between the contribution of rainfall and antecedent soil moisture, indicating the shift of dominance from rainfall to antecedent soil moisture across watersheds.

Figure 6 shows the influential factors of 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 blue and 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. There is also positive correlation between SPR and TWI for the regulated watersheds along tributaries (black triangles), though much scatter. 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

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

Hydrology and Earth System Sciences
Discussions

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 watersheds. Floods in large watershed are usually generated when soil is almost saturated despite of the relatively small rainfall amount, while heavy rainfall is the dominant driver in small to medium watersheds (Figure 3). This shift of dominance may be attributed to the longer confluence time in the large watersheds and the fact that small watershed is easy to reach saturation (Sharma et al., 2018). 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).

As a result, 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

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

Hydrology and Earth System Sciences
Open Access
Discussions

flat, flood occurrence is mainly determined by soil saturation; when a watershed is small and steep, heavy rainfall takes over the dominance; when a watershed is small and the topographic gradient is also gentle, the occurrence of AMF requires both highly saturated soil and relatively heavy rainfall.

4.2 Linkage between topographic characteristics, SPR and floods

The correlation between TWI and SPR (Figure 6c) suggests that the relative importance of soil moisture and rainfall could be inferred from topographic characteristics. Despite of the strong human intervention, this correlation sustains even in those regulated watersheds (black squares in Figure 6c). That is, we could derive the relative dominance of soil moisture and rainfall in flood generation in specific watershed from its TWI. This helps quantify the importance of soil moisture and rainfall in flood generation in the existing work. 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 al 2021; Ye et al 2017). Our findings further identified the influential factors of their importance and provide a way to quantitatively estimate it from topographic characteristics that are easy to measure.

Meanwhile, the SPR also present a negative correlation with the magnitude of AMFs (Figure 7). Similar correlation was also found in the observations from our experimental watershed, a headwater of Yangtze River (Liu et al 2021). The ratio of observed antecedent soil moisture and event precipitation also presents similar decline trend with discharge at event scale. That suggests that the negative correlation between flow and SPR is not only valid across watersheds, and may also be applied at event scale within watershed.

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

Hydrology and Earth System Sciences Discussions

That is, based on the topographic characteristics, we could derive the relative importance of soil moisture and rainfall in flood generation (SPR); and from this relative importance ratio, we could further infer the average flood magnitude at these watersheds. As a result, we could link the topographic characteristics and annual floods through the characteristic SPR during the AMFs.

4.3 Implications

These findings could be helpful for potential flood risk evaluation and early warning in ungauged basins, e.g., headwaters in the mountainous region. With the construction of large reservoirs, the capability of flood risk control has improved substantially along main stream (Zou et al., 2011; Zhang et al., 2015). However, it is still difficult for early warnings in upstream mountainous watersheds, which are vulnerable to floods but difficult for hydrological modeling and prediction due to little hydrologic records.

Our findings suggest that we could derive the flood-generation SPR of each watershed from drainage area and topographic gradient that are easy to measure. Using the soil moisture from remote sensing data and precipitation forecast, we could have real-time prediction of SPR values. Once the predicted SPR value gets closer to the flood-generation SPR in Figure 6c, early warnings of floods can be generated. Mountainous watersheds are usually small and steep, where heavy rainfall is the dominant driver of AMFs (Figure 5). Thus, the requirement of the accuracy of antecedent soil moisture would be lower, soil moisture from recent remote sensing images may be used for approximation. Combining with real-time precipitation forecast, early warnings of AMFs could be generated once the estimated SPR is close to the flood-generation SPR. Besides, the correlation between SPR and flood peak provides information of the likely flood magnitude in ungauged watersheds. Flood control

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

infrastructures could then be designed based on the potential flood peak derived from the flood-generation SPR that is estimated from topographic characteristics.

4.4 Limitations

Previous works usually identify the dominant flood generation mechanism based on the comparison of the timing of events (Berghuijs et al 2016; 2019b; Bloschl et al 2017; Ye et al 2017). Similar work has been implemented in our study watersheds, suggesting the importance of soil moisture and rainfall (Wang et al 2021). Based on that, we further looked into the records to quantitatively evaluate the relative importance of soil moisture and rainfall in flood generation. However, there are limitations in our methods.

The precipitation data we used were averaged for the study watersheds from 247 meteorological stations. Given the large area and considerable spatial heterogeneity, the precipitation data we used may not always be representative of the actual precipitation events. The daily data could also average the rainfall intensity at hourly scale, which could be influential in small mountainous watersheds. The estimation of soil moisture is for sure highly simplified, which cannot be considered as precise estimation. Yet, after normalizing by the maximum, this can still provide the generation variation trend of soil moisture in the water cycle, and used for the relative comparison with rainfall. For further implementation of this method, more sophisticated models or remote sensing data are needed to improve our estimation of soil moisture, and refine the estimation of the flood-generation SPR.

Moreover, this work is focused on the importance soil moisture and rainfall, without consideration of snowmelt due to the warm and humid climate in the study watersheds. To apply our findings to cold watersheds with significant impact of snow,

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

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.

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 antecedent soil saturation rate and normalized rainfall as coordinates, the flood generation mechanism(s) of study watersheds could be grouped into three classes: antecedent soil moisture dominated large 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

https://doi.org/10.5194/hess-2021-531
Preprint. Discussion started: 23 November 2021

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 presents negative correlation with area normalized flood peak.

With the potential increase of extreme rainfall events (Gao et al., 2016; Chen et al., 2016), upstream mountainous watersheds in the middle and lower Yangtze River basin are facing higher risk of extreme floods. The lack of hydrological records further increases the vulnerability of people in these watersheds. Our findings provide a quantitative way to estimate the possible flood risk for these ungauged watersheds. Based on measurable watershed characteristics (i.e., drainage area and topographic gradient), the flood-generation SPR of each watershed can be derived. The real-time SPR can be approximated by recent soil moisture data from remote sensing images and real-time rainfall forecast, especially in the small and steep watersheds where heavy rainfall is the most dominant factor. Early warnings could then be generated once the real-time SPR approaches the flood-generation SPR. Flood control infrastructures could also be designed based on the flood magnitude estimated from the flood-generation SPR.

Future analysis at event scale could help generate the flood-generation curve between SPR and discharge at event scale to further improve flood risk predictions in these small ungauged watersheds. With more data from other regions and improved estimation or observation of soil moisture, we could expand our analysis to watersheds with more diverse climate and topographic characteristics to examine and refine our findings and to enhance our understandings of flood generation.

Data availability

DEM data was downloaded from Geospatial Data Cloud at http://www.gscloud.cn/. Climatological data used in this study was obtained from China Meteorological Data Network, which can be accessed at http://data.cma.cn/. Discharge data comes from Annual Hydrological Report of the People's Republic of China issued by Yangtze River Water Resources Commission.

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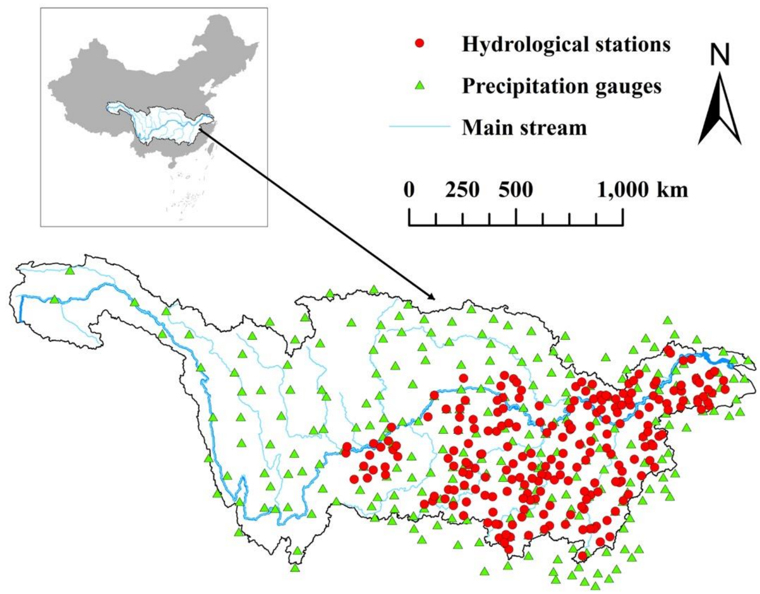

714
715 **Figure 1**: Map of the Yangtze River basin, and the climate stations and hydrological
716 stations. The blue line is the main stream of Yangtze River.
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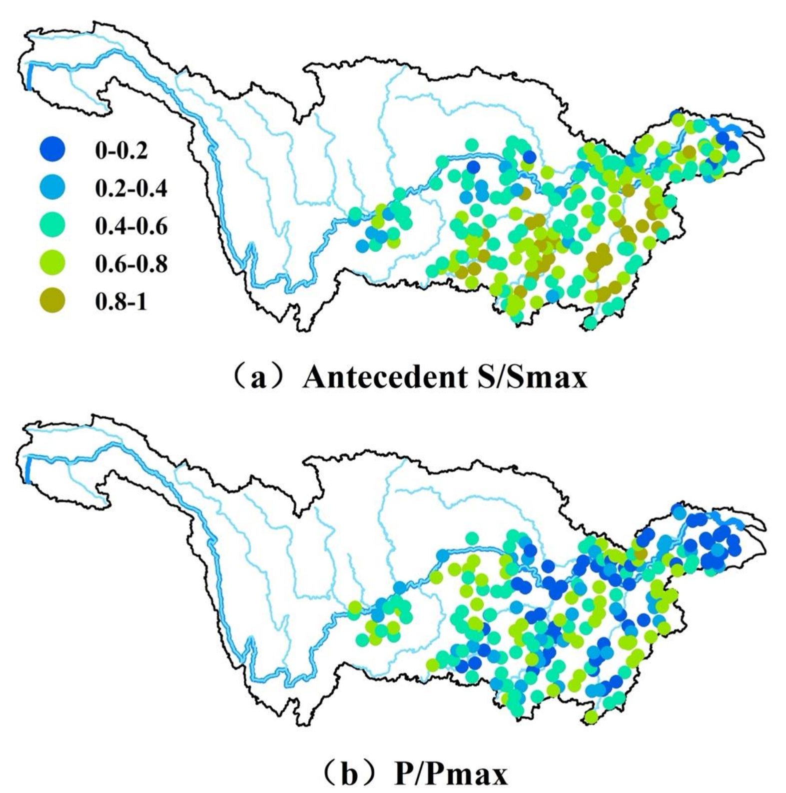

Figure 2: the spatial distribution of (a) antecedent soil moisture during annual maximum flood, normalized by maximum storage; (b) daily precipitation during annual maximum flood, normalized by maximum daily precipitation.

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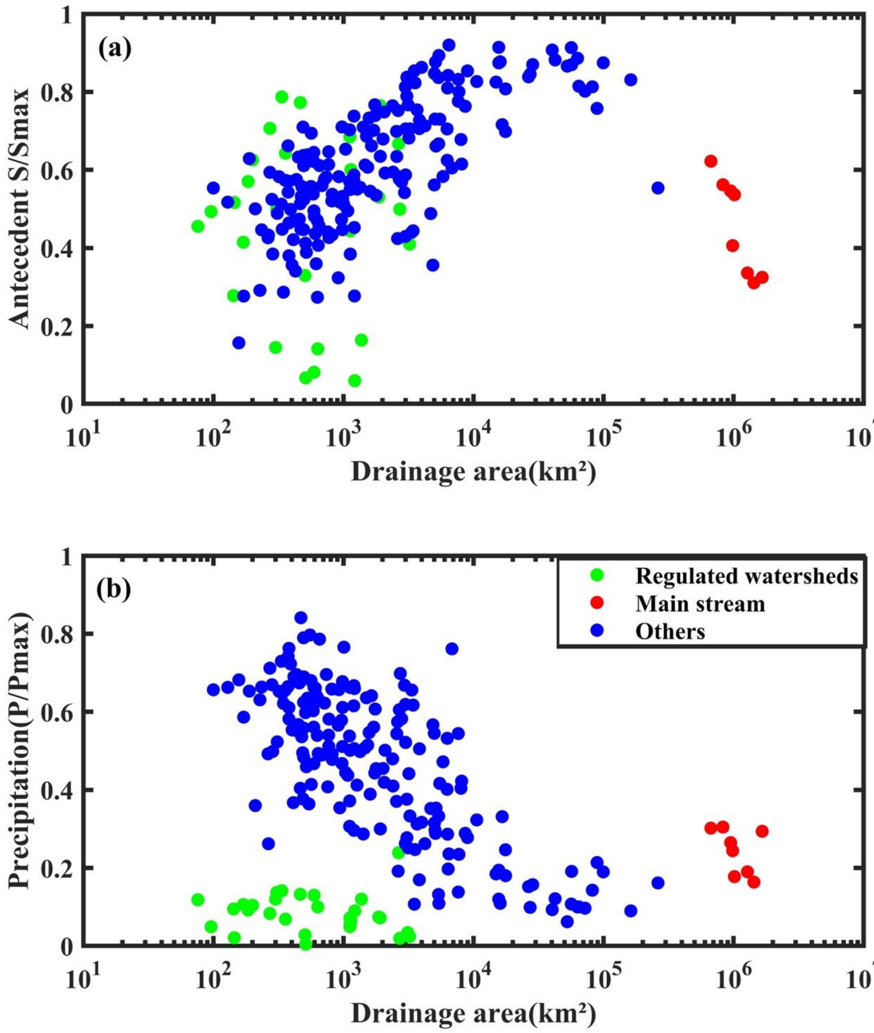

Figure 3: Scatterplot between the drainage area and (a) the antecedent soil moisture of AMF events normalized by maximum storage (the linear regression for blue dots: R^2 = 0.46, *p*-value<0.001); (b) the precipitation at the day of AMF events normalized by maximum daily precipitation (the linear regression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

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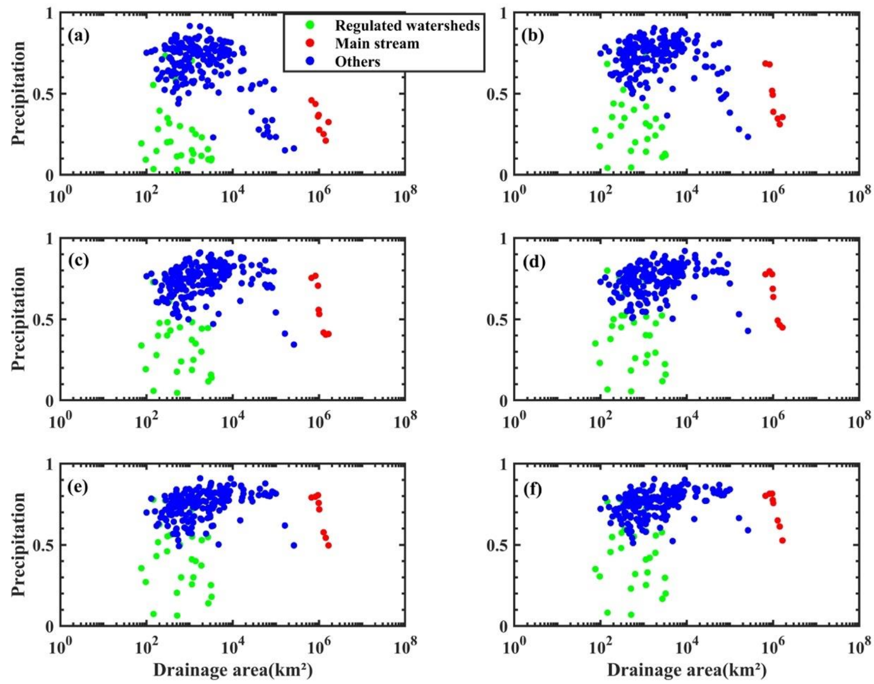

Figure 4: Scatterplot between the drainage area and the accumulated rainfall of (a) two days; (b) three days; (c) four days; (d) five days; (e) six days; and (f) seven days on AMF events, normalized by maximum of accumulated precipitation.

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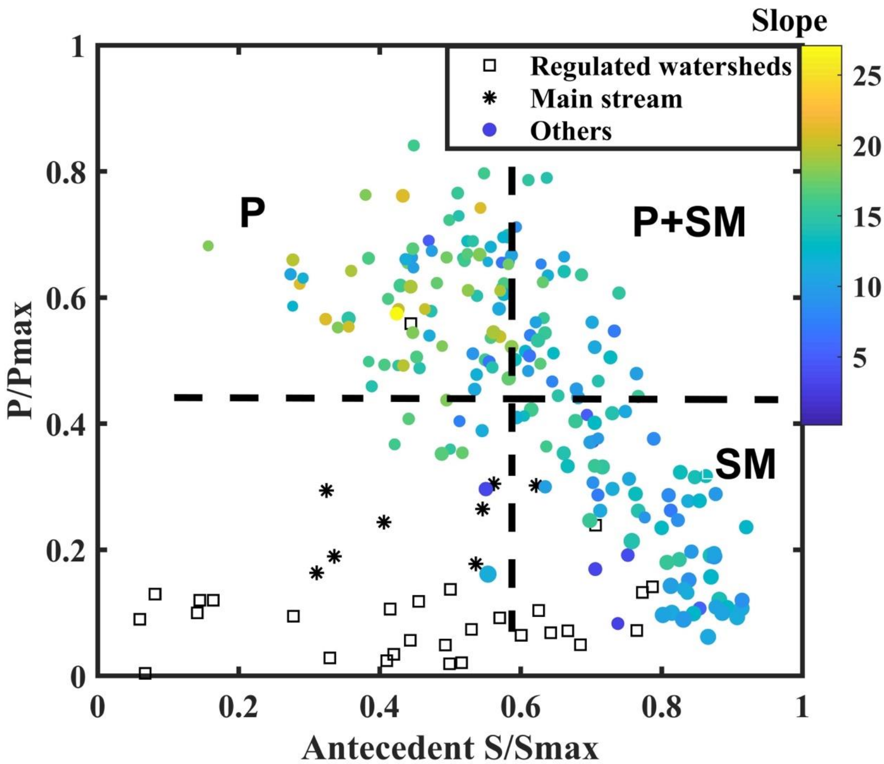

Figure 5: Scatterplot of the normalized rainfall and antecedent soil moisture, the color represents topographic gradient and the size of circles is scaled by drainage area.

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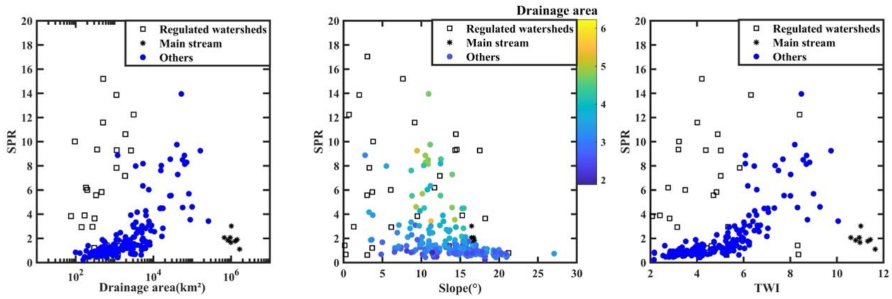

Figure 6: Scatterplots between the ratio of antecedent soil saturation rate and normalized precipitation (SPR) and (a) drainage area; (b) slope; and (c) topographic wetness index (TWI).

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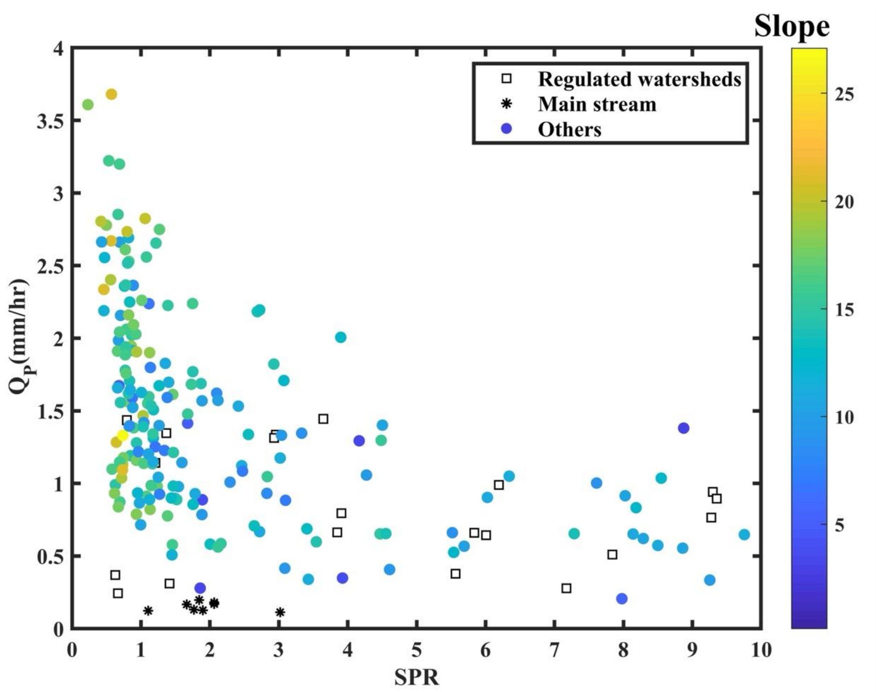

Figure 7: Scatterplot between the ratio of antecedent soil saturation rate and normalized precipitation (SPR) and area weighted annual maximum discharge (Q_P), the color represents topographic gradient.