Multiscale attribution analysis for assessing effects of changing environment on runoff: case study of the Upstream Yangtze River in China
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ABSTRACT

Evaluating the changes in runoff and analyzing its attribution under the changing environment is of great significance to water resources management. In this study, eight hydrological stations at the outlets of tributaries of the Upstream Yangtze River are selected. Based on the observed runoff data from 1951 to 2013, the spatial-temporal characteristics in runoff change are identified from time series analysis. Our results show that runoff in the Upstream Yangtze River decreases significantly with a rate of −7.6 km³ per ten years in general. The most significant declines in runoff are observed in the mainstream, Minjiang River, Tuojiang River, and Jialing River, while slight increase in runoff is found in the source area of the Yangtze River. Furthermore, the effects on runoff change from climate change and human activities are evaluated using the Soil and Water Assessment Tool (SWAT) and modified Fixing-Changing (MFC) method at multiple scales. Our results suggest that the main contributions to runoff change are from climate change variabilities (70%), land use/cover change (LUCC, 10%), and other human influence (20%). When examined at different spatial and temporal scales, climate change always appears to be the main cause of runoff change, although its contribution decreases over time.

Key words | attribution analysis, changing environment, climate change, human influence, LUCC, runoff change

HIGHLIGHTS

- Runoff in the Upstream Yangtze River decreased significantly.
- Runoff decline is attributed to climate change, LUCC and other human influence.
- Climate change appears to be the main cause of runoff change at different spatial and temporal scales.
- Contribution of climate change decreases over time.
- Precipitation and temperature are the main meteorological causes of runoff change.
Affected by the changing climate and intensive human activities, uncertainty of water resources is deepened. The impact of changing environment on the safety of water resources has become a major issue of global concern. Assessing the changes in water resources under the changing environment and identifying the causes is critical to water resources planning and management, which have become a hotspot in water science (Hall et al. 2014).

Among different components in the hydrological cycle, runoff is considered as the most important one for water resources management. Its variability significantly affects the water use pattern in different sectors (Dey & Mishra 2017). Runoff is a highly nonlinear process and closely related to many factors, such as atmospheric circulation, climate change, underlying surface, and human influence. As the result of multiple factors in the changing environment, changes in runoff are complex, uncertain, and hard to predict. Generally, researchers use long-term data to quantify its variability and analyze the attribution of runoff change, as a function of climate change and human activities. Methods such as hydrological time series analysis are usually applied in such studies, to examine the discrepancies of the hydrological cycle in different regions and to understand the underlying physics (Burn & Elnur 2002).

Climate change and human activities are the two important components of changing environment. Research on the impacts of climate change on the hydrological process has been conducted since the 1970s. Many research programs have been successively launched, such as the World Climate Impact Research Program (WCIP), Global Energy Water Exchanges (GEWEX), International Geosphere-Biosphere Programme (IGBP), International Hydrological Programme (IHP), from the World Meteorological Organization (WMO), United Nations Educational, Scientific and Cultural Organization (UNESCO), United Nations Environment Programme (UNEP), United Nations Development Programme (UNDP), and International Association of Hydrological Sciences (IAHS). Since the 1990s, the impact of climate change on the hydrological process has attracted more and more attention, with an increasing number of researchers joining such studies. After entering the 21st century, research scopes of such studies have been further expanded to interdisciplinary research in hydrology, with biology, environment, physics, humanities and other disciplines increasing significantly, and with more attention paid to the interactions and feedback effects of climate, land, and human influence (Wang 2014). Generally, the impacts of climate change on runoff are mainly illustrated by: (1) impacts of precipitation including its form, amount, intensity, process, and spatial distribution; (2) glacier and snow melting caused by rising temperature; (3) evapotranspiration changes caused by changes in climatic factors (e.g., temperature, wind, and humidity) (Wang et al. 2012; Yang et al. 2018).

In recent years, studies on the impacts of human activities on the hydrological process have also been conducted. Impacts of human activities on runoff are mainly illustrated by: (1) impact on condition of runoff generation and confluence (e.g., land use/cover change (LUCC), water and soil conservation, river regulation); (2) direct influence by humans (e.g., irrigation, water diversion projects, groundwater exploitation); (3) impact on the process of runoff
confluence (e.g., reservoir impoundment) (Zhang et al. 2013). Most studies focus on the hydrological effects caused by LUCC. With the rapid development of the global economy, urbanization and accelerated agricultural development result in atrophy of wetlands, and decreasing area of forest and grass. LUCC has affected many hydrological processes including vegetation interception, evaporation, and infiltration. It has influenced the conditions of runoff generation and confluence, and has significantly affected the runoff process, resulting in a series of eco-environmental problems (Yang et al. 2017; Zhang et al. 2017). Techniques for studying LUCC effect include the experimental catchment method, the characteristic variable time series method, and the hydrologic model method.

Hydrological models aim to characterize the hydrological processes based on the understanding of physical mechanisms in the hydrologic cycle. A collection of bottom-up or physically based models have been applied in hydrological studies, which have detailed and high resolution descriptions of small-scale processes that are numerically integrated to larger scales (e.g., catchments) (Hrachowitz & Clark 2017). With the information obtained from geographic information systems (GIS) and remote sensing (RS), bottom-up models can characterize rainfall, evapotranspiration, topography, soil, vegetation, and other underlying surface conditions spatially. They not only describe the general pattern but also provide detailed information on hydrological processes within a catchment and, therefore, have been used for evaluating the hydrological effects of climate change and LUCC. These models are often used to simulate and predict runoff processes, including extreme events such as floods and droughts. Researchers drive the models by observed daily maximum and minimum air temperature and precipitation to generate daily soil moisture values, then calculate the Soil Moisture Anomaly Percentage Index (SMAPI), which can be used as a measure of the severity of agricultural drought on a global basis (Wu et al. 2013). These models are essential for understanding the attribution of runoff change to the changing environment and, in particular, are important in light of the increasing effects of changing environment on the terrestrial water cycle.

China is one of the most prominent countries regarding the contradiction between water supply and demand (Piao et al. 2010). Due to the influence of the changing environment, the spatial and temporal characteristics of water resources have changed significantly. In the past five decades, runoff has decreased significantly in six major rivers in China (i.e., the Yangtze River, the Yellow River, the Pearl River, the Songhua River, the Haihe River, the Huaihe River). The Yangtze River provides the most abundant water resources and hydropower resources in China, with an average annual runoff of 996 billion m³, on average, making up 36% of the total runoff in China, and its theoretical reserves of hydropower resources account for about 40% of the national total. The Upstream Yangtze River is the runoff formation area and hydropower storage area, accounting for 45% of basin water resources and 89.4% of basin hydropower resources, which is invaluable in China’s strategic reserve of resources. Recently, significant declines in runoff have been observed in most regions of the Upstream Yangtze River, which greatly influence the ecology and affect economic and social development, bring new risks for integrated development and utilization of water resources and joint operation of water conservancy and hydropower systems (Zhang et al. 2018). Therefore, the Upstream Yangtze River is selected as the study case to examine the runoff change and attribution to changing environment. First, time series of runoff are analyzed to identify the characteristics and spatial composition of runoff change. Then, a large-scale SWAT model is established to explore the causes of runoff change. Finally, attribution at temporal, spatial, and factorial scales is examined.

STUDY AREA AND DATA

Study area

The Yangtze River is the largest river in China, with a total length of 6,380 km and a total elevation drop of 5,400 m. As shown in Figure 1, the Upstream Yangtze River is located between 90° E–112° E and 23° N–35° N, with a total area of 1 million km² covering nine provinces. The terrain of the Upstream Yangtze River is complex, with the highest elevation in the west and the lowest elevation in the east. The western part is located over the Qinghai-Tibet Plateau.
and Hengduan Mountains, with elevations higher than 3,000 m, while the southeastern part is located in valleys and basins with elevations under 500 m. The special topography and landform gave birth to many rivers. The Tongtian River is the source river of the Yangtze River, originating from the eastern foot of Geladaindong Peak to Zhimenda (station), with a total length of 1,292 km. The Jinsha River is located between Zhimenda and Yibin city (Pingshan station), with a total length of 6,464 km and a total drop of 5,100 m, accounting for 95% of the total drop of the Yangtze River. The Yalong River is the largest tributary of the Jinsha River. The mainstream of the Upstream Yangtze River is located between Yibin city and Yichang city with a length of 1,040 km. Three major rivers (the Minjiang River, the Tuojiang River, and the Jialing River) flow into the mainstream in the north, while the Wujiang River flows into the mainstream in the south. Based on the watershed and the tributaries, the Upstream Yangtze River basin is further divided into the Jinsha River basin (JSR), the Mintuo River basin (MTR), the Jialing River basin (JLR), the Wujiang River basin (WJR), and the mainstream basin (MS). The JSR includes the Yanglong River basin (YLR) and the source area basin (SA). The MTR includes the Minjiang River basin (MJR) and the Tuojiang River basin (TJR). Detailed information on these basins is listed in Table 1.

![Map of the Upstream Yangtze River](image)

**Table 1** Information on basins in the Upstream Yangtze River

| Basin | Area (km²) | R (mm) | P (mm) | T (°C) |
|-------|------------|--------|--------|-------|
| JSR   | 500,000    | 297.5  | 723.4  | 8.6   |
| MTR   | 163,640    | 625.6  | 1,003.6| 11.3  |
| JLR   | 159,812    | 423.2  | 964.7  | 16.3  |
| WJR   | 86,815     | 584.6  | 1,102.3| 15.0  |
| MS    | 113,000    | 642.1  | 1,133.9| 16.8  |

P, T, R represent average annual precipitation, average annual mean temperature and average annual runoff depth.
Data

Hydrological data

To identify the characteristics and spatial composition of runoff change, eight hydrological stations with monthly observations of runoff series are selected at the outlets of the mainstream and important tributaries (Figure 1). Runoff observations are obtained from 1951 to 2013 in most stations, except Zhimenda station (from 1957 to 2010) and Xiaodeshi station (from 1958 to 2010), with details of these stations listed in Table 2. Zhimenda station is selected for examining changes in runoff over the source area of the Yangtze River. Zhimenda station and Pingshan station are selected for conjoint analysis of runoff change in the Jinsha River (which is directly connected to the source area). Xiaodeshi station, Zhimenda station, and Pingshan station are selected for examining changes in runoff in both the mainstream and tributary of the Jinsha River. Other stations are selected because they are the control station of every important tributary. All runoff series data are provided by the Bureau of Hydrology, Changjiang Water Resources Commission.

Meteorological data

Daily time series of meteorological data from 80 National Meteorological Observatory (NMO) stations within the Upstream Yangtze River were collected from the National Meteorological Information Centre of China (NMIC) (http://data.cma.cn), including daily precipitation, mean air temperature, maximum air temperature, minimum air temperature, mean air pressure, mean wind speed, mean relative humidity, and sunshine duration (Figure 1).

Topographic data

The topography is represented by the digital elevation model (DEM) with a spatial resolution of 90 m, obtained from the Consultative Group on International Agricultural Research (CGIAR) Consortium for Spatial Information (CGIAR-CSI) (http://srtm.csi.cgiar.org). The DEM map for the Upstream Yangtze River is extracted as shown in Figure 2. The DEM map is the basis of the SWAT model for sub-basin division, river system generation, and hydrological process simulation.

Land use/cover data

Land use/cover maps with a scale of 1:100,000 for the late 1980s (1990), 1995, 2000, 2005, 2010, were obtained from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn) (Figure 3).

Soil type data

A soil type map with a scale of 1:1,000,000 was obtained from the RESDC (http://www.resdc.cn) (Figure 4).

Table 2 | Information on the hydrological stations investigated in this study

| Station | River   | Latitude (°N) | Longitude (°E) | Control basin | Control area (km²) |
|---------|---------|---------------|----------------|---------------|--------------------|
| Zhimenda| Tongtian| 33.03         | 97.25          | TTR           | 137,704            |
| Pingshan| Jinsha  | 28.63         | 104.17         | JSR           | 485,099            |
| Xiaodeshi| Yalong | 26.78         | 101.83         | YLR           | 117,000            |
| Gaochang| Minjiang| 28.80        | 104.41         | MJR           | 135,378            |
| Fushun  | Tuojiang| 29.13         | 104.97         | TJR           | 19,613             |
| Beibei  | Jialing  | 29.85        | 106.42         | JLR           | 156,142            |
| Wulong  | Wujiang  | 29.32        | 107.75         | WJR           | 83,035             |
| Yichang | Mainstream| 30.70     | 111.28         | MS            | 1,005,501          |
METHODS

General approach

In this study, time series analysis methods are used to identify the characteristics and spatial composition of runoff change. We first detected the abrupt points of the time series, and used it to divide the whole study period into a base period and a change period, where the former is less affected by climate change or human activities, and the latter is more affected by the changing environment. Then we applied a large-scale SWAT model to simulate runoff in the Upstream Yangtze River under different environments and examined the major causes of runoff change using the modified Fixing-Changing (MFC) method. Finally, we compared the attribution at different temporal, spatial, and factorial scales. Detailed methods are explained in the sections below.

Time series analysis methods for identifying runoff change

Before analyzing the causes of runoff change under the changing environment, the temporal trends and abrupt change points are identified for the runoff observations obtained in the eight stations. We applied four statistical methods in this study (as different statistical methods could yield different results). (1) The non-parametric Mann–Kendall test (Li et al. 2008), which is highly recommended by the WMO and widely used to detect monotonic trends in long-term hydrological variations. (2) The Spearman’s Rho test (Li et al. 2008), which is a quick and simple test to determine whether correlation exists between two classifications of the same series of observations. (3) The non-parametric Pettitt’s test (Pettitt 1979), which is a rank-based and distribution-free test, and is often used to detect the abrupt change point in long-
term hydrological variations. (4) A sequential clustering method (Sharma 1985), which is also used to identify the occurrence of an abrupt change point in time series. In this study, the Mann–Kendall test and the Spearman’s Rho test are used to detect monotonic trends in historical hydrological series and meteorological series, and evaluate the significance of the trends. The non-parametric Pettitt’s test is used to detect the abrupt change point in runoff series, and the sequential clustering method is used to identify the abrupt change point as a reconfirmation for Pettitt’s test.

**SWAT model for runoff simulation**

SWAT is a widely used bottom-up model for simulating surface runoff, groundwater discharge, evapotranspiration, and
soil water content, and has been certified as an effective tool for evaluating water resources at a wide range of scales. In this study, the SWAT model is applied for the Upstream Yangtze River. Based on the DEM data, the river system is generated and 99 subbasins are divided as shown in Figure 5. After inputting the soil type data and land use/cover data in 1990, the land use, soils and slope are overlaid, and 702 hydrological response units (HRUs) are defined for the SWAT model.

The Latin hypercube one-at-a-time (LH-OAT) approach proposed by Griensven et al. (2006) is used for screening out the sensitive parameters and avoiding complex calibration processes. These selected parameters are calibrated for the SA, YLR, JSR, MJR, TJR, JLR, WJR, and MS, respectively. The coefficient of determination ($R^2$) and the Nash–Sutcliffe model efficiency coefficient (NSE) are selected to evaluate the performance of the calibrated model. $R^2$ is used to evaluate linear correlation between simulated results and observed runoff. NSE is used to evaluate the fitting and predictive power (Nash & Sutcliffe 1970). The equations are given as follows:

$$R^2 = \frac{\sum_i^n (\text{obs}_i - \overline{\text{obs}})(\text{sim}_i - \overline{\text{sim}})}{\sqrt{\sum_i^n (\text{obs}_i - \overline{\text{obs}})^2 \cdot \sum_i^n (\text{sim}_i - \overline{\text{sim}})^2}}$$

$$\text{NSE} = 1 - \frac{\sum_i^n (\text{obs}_i - \text{sim}_i)^2}{\sum_i^n (\text{obs}_i - \overline{\text{obs}})^2}$$

where $\text{obs}_i$ is the observed value on time $i$, $\overline{\text{obs}}$ is the mean observed value, $\text{sim}_i$ is the simulated value on time $i$, $\overline{\text{sim}}$ is the mean simulated value, and $n$ is the length of the time series.

**MFC method for attribution calculation**

The Fixing-Changing (FC) method is commonly used for attribution calculation. The general idea of this method is to: (1) fix the land use/cover inputs and change the meteorological inputs, to analyze the runoff change caused by climate change; (2) fix the meteorological inputs and change
the land use/cover inputs, so as to analyze the runoff change caused by LUCC. Different routes can be used to calculate the attribution, as shown in the two-factor (i.e., climate change and LUCC) example (Figure 6). The attribution can be calculated along either route 1 or route 2; this can lead to different results, because the responses of runoff to forcing changes vary under land use/cover, and the responses of runoff to LUCC also vary under different forcing inputs. To solve the problem, Liu et al. (2014) proposed the MFC method, which calculates the mean value of attribution in all different routes, and they proved the method to be more objective and reliable in their research.

In this study, different environments covering all routes are created and inputted into the SWAT model. Changes in runoff are attributed to climate change, LUCC, and other human influence using the MFC method, and the steps are given as follows:

(1) Divide the whole study period into \( N + 1 \) (\( N \geq 1 \)) segments based on the previous time series analysis.

(2) Fix the land use/cover data and meteorological data in segment \( t_{i-1} \) (\( i = 1, 2, \ldots, N \)), and simulate runoff series twice by the SWAT model, with meteorological data in segment \( t_{i-1} \) and segment \( t_{i} \), respectively. These runoff series are denoted with \( W(L_{i-1}, C_{i-1}) \) and \( W(L_{i-1}, C_{i}) \), where \( (L_{i-1}, \cdot) \) means land use/cover data in segment \( t_{i-1} \), \( (\cdot, C_{i-1}) \) and \( (\cdot, C_{i}) \) means meteorological data in segment \( t_{i-1} \) and \( t_{i} \).
(3) Fix the land use/cover data and meteorological data in segment \(i\), and simulate runoff series twice by the SWAT model, with meteorological data in segment \(i-1\) and segment \(i\), respectively. These runoff series are denoted with \(W(L_i, C_{i-1})\) and \(W(L_i, C_i)\), where \((L_i, C_i)\) means land use/cover data in segment \(i\).

(4) The attribution can be calculated as follows:

\[
\Delta W_{C,i} = \frac{W(L_{i-1}, C_i) + W(L_i, C_i)}{2} - \frac{W(L_{i-1}, C_{i-1}) + W(L_i, C_{i-1})}{2}
\]

\[
\Delta W_{L,i} = \frac{W(L_i, C_{i-1}) + W(L_i, C_i)}{2} - \frac{W(L_{i-1}, C_{i-1}) + W(L_{i-1}, C_i)}{2}
\]

where \(\Delta W_{C,i}\) and \(\Delta W_{L,i}\) indicate the runoff change in segment \(i\), caused by climate change and LUCC, respectively.

(5) The remaining runoff change is attributed to other human influence and calculated as:

\[
\Delta W_{O,i} = \Delta W_{T,i} - \Delta W_{C,i} - \Delta W_{L,i}
\]

where \(\Delta W_{O,i}\) indicates the runoff change caused by other human influence in segment \(i\), \(\Delta W_{T,i}\) indicates the total runoff change in segment \(i\).

**RESULTS**

**Runoff change**

Historical time series of annual runoff at eight selected hydrological stations are examined in Figure 7, and the changes are assessed using the Mann–Kendall test and the Spearman’s Rho test in Table 3. As the control station for the whole Upstream Yangtze River, the observed runoff in the Yichang station reflects the overall characteristics of the runoff change in the Upstream Yangtze River. During the study period, runoff in the Upstream Yangtze River declined at a rate of \(-7.6\) km\(^3\)/10 a, observed in the Yichang station from the mainstream basin and other tributaries. The Tongtian River, the source river of the Yangtze River, is mainly supplied by ice and snow melt water, followed by precipitation and groundwater recharge. Under changing environment, its runoff increased by a rate of \(0.5\) km\(^3\)/10 a during the study period. Runoff in the Yalong River, Jinsha River, Minjiang River, Tuojiang River, Jialing River, and Wujiang River all decreased, with rates of \(-0.1\) km\(^3\)/10 a, \(-0.8\) km\(^3\)/10 a, \(-2.2\) km\(^3\)/10 a, \(-0.6\) km\(^3\)/10 a, \(-2.1\) km\(^3\)/10 a, and \(-1.1\) km\(^3\)/10 a, respectively. Results are consistent in the hydrological stations except that the confidence level is slightly inconsistent in Beibei station. Runoff observed in Yichang station, Gaochang station, Fushun station, and Beibei station all decreased significantly, with higher decline rates.

Both the non-parametric Pettitt’s test and the sequential clustering method are used to detect the occurrence of the abrupt change point in runoff series. As shown in Figure 8(a), the test statistic value from the Pettitt’s test is highest in the year 1993, indicating the year 1993 as the abrupt change point. The same result is obtained in the sequential clustering method. As shown in Figure 8(b), when the whole study period is divided by the year 1993, values of the sum of squared deviation in subperiods are lowest, which indicates runoff after 1993 changed statistically. Therefore, the year 1993 is identified as the abrupt change point of the runoff change in the Upstream Yangtze River, and is used to divide the study period into a base period (i.e., 1950–1993) and a change period (i.e., 1994–2013). The average values, standard deviations, and coefficient of variation of the annual runoff series in the two periods are calculated separately and listed in Table 4. The average annual runoff in the change period decreased by 28.7 km\(^3\) (8.4%) compared to that in the base period. Statistically significant differences in the annual runoff between the two periods can be found with a confidence level of 95% using the \(t\)-test, while differences in the standard deviations are not statistically significant when evaluated from the \(F\)-test. In addition, the coefficient of variation is 0.1 in the base period, which increased to 0.13 in the change period, indicating that the runoff varies more after 1993.

**SWAT model calibration and validation**

Based on the sensitivity analysis, highly sensitive parameters are screened out for calibration, with their descriptions and initial ranges listed in Table 5. Since runoff in the SA is
Figure 7 | Historical annual runoff series observed in the selected hydrological stations: (a) Yichang, (b) Zhimenda, (c) Xiaodeshi, (d) Pingshan, (e) Gaochang, (f) Fushun, (g) Beibei, (h) Wulong.
closely related to snowmelt, parameters of snow properties (i.e., SMTMP, SFTMP, SMFMX, SMFMN) are added for calibration. Runoff series of the hydrological stations from 1951 to 1980 (runoff series of Zhimenda station from 1957 to 1980, runoff series of Xiaodeshi station from 1958 to 1980) are used for model calibration and the runoff series from 1981 to 1993 are used for validation. Calibrated values of the selected parameters are also listed in Table 5. Simulated and observed runoff during the calibration and validation periods are plotted for the control hydrological stations in Figure 9. The \( R^2 \) and the NSE values are calculated for the hydrological stations in both calibration and validation periods and are listed in Table 6. In Yichang station, the \( R^2 \) and the NSE values are 0.75 and 0.74 in the calibration period, and the values are 0.78 and 0.67 in the validation period. For the hydrological stations of the tributaries, the \( R^2 \) values range from 0.75 to 0.85 and the NSE values range from 0.70 to 0.85 in the calibration period, whereas the \( R^2 \) values range from 0.52 to 0.84 and the NSE values range from 0.64 to 0.80 in the validation period. Mosbah et al. (2015) suggest that NSE values greater than 0.75 are considered excellent, values greater than 0.65 are considered good, and values greater than 0.5 are considered satisfactory for hydrological model evaluation. They further conclude that \( R^2 \) values greater than 0.5 are regarded as acceptable for model simulation. In validated data, 37.5% of NSE values are above 0.75, 50.0% of NSE values are between 0.65 and 0.74, and 12.5% of NSE values are between 0.5 and 0.64. All the \( R^2 \) values are greater than 0.5. Therefore, performance of the SWAT model established for the Upstream Yangtze River is considered as good in this study.

Runoff change attribution

Climate change

The Mann–Kendall test and the Spearman’s Rho test are also used to analyze changes in the annual meteorological series including annual precipitation, mean air temperature,

Table 3 | Results of the trend analysis for runoff series observed in the hydrological stations

| Station   | Mann–Kendall | Spearman’s Rho |
|-----------|--------------|----------------|
|           | Trend        | Confidence level | Trend        | Confidence level |
| Yichang   | ↓            | 95%             | ↓            | 95%             |
| Zhimenda  | ↑            | –               | ↑            | –               |
| Xiaodeshi | ↓            | –               | ↓            | –               |
| Pingshan  | ↓            | –               | ↓            | –               |
| Gaochang  | ↓            | 99%             | ↓            | 99%             |
| Fushan    | ↓            | 99%             | ↓            | 99%             |
| Beibei    | ↓            | 90%             | ↓            | 80%             |
| Wulong    | ↓            | –               | ↓            | –               |

↑ and ↓ represent increasing and decreasing trend. – represents a confidence level lower than 80%.

Figure 8 | Abrupt change point detected in runoff series of the Upstream Yangtze River: (a) Pettitt’s test; (b) the sequential clustering method.
maximum air temperature, minimum air temperature, mean air pressure, mean wind speed, mean relative humidity, and sunshine duration. Results are listed and compared in Table 7. During the study period, all the meteorological variables changed significantly, indicating obvious climate change in the Upstream Yangtze River. Statistically significant decreases are detected in annual precipitation, mean air pressure, mean wind speed, mean relative humidity, and sunshine duration series, while significant increases are detected in annual mean temperature, maximum temperature, and minimum temperature series. Results of the two methods are consistent for the meteorological series except that the confidence level is slightly inconsistent for the annual mean relative humidity and sunshine duration series.

The average values, standard deviations, and coefficient of variation of the annual runoff variables in the two periods are separately calculated and listed in Table 8. Differences at 99% confidence level are detected in the average values of mean air temperature, maximum temperature, minimum temperature, mean air pressure, mean wind speed, and mean relative humidity between the base period and change period using the t-test. Differences at 95% confidence level are detected in the average values of precipitation between the two periods, and difference is found in sunshine duration at a confidence level of 80%. Using the F-test, a significant difference at a confidence level of 99% is detected in standard deviations of maximum temperature between the two periods, as well as in the

### Table 4 | Characteristics of the annual runoff series observed in the hydrological stations before and after abrupt change point

| Period       | Average (km$^2$) | SD (km$^2$) | CV  |
|--------------|-----------------|-------------|-----|
| Base period  | 438.6           | 42.8        | 0.10|
| Change period| 409.8           | 53.1        | 0.13|
| Change       | −28.7           | 10.3        | 0.03|

CV represents coefficient of variation; SD represents standard deviation.

### Table 5 | Parameters' descriptions, initial ranges, and calibrated value in the basins

| Parameters name | Description                                      | Initial ranges | Calibrated value |
|-----------------|--------------------------------------------------|----------------|------------------|
|                |                                                  | SA  | YLR | JSR | MJR | TJR | JLR | WJR | MS  |
| CN2             | SCS runoff curve number                          | 35–98| 50  | 69.68 | 86  | 82.25 | 73.37 | 69.91 | 90.80 | 95.6 |
| SOL_AWC         | Available water capacity of the soil layer       | 0–1 | 0.075 | 0.01 | 0.06 | 0.01 | 0.005 | 0.104 | 0.175 | 0.3  |
| CANMX           | Maximum canopy storage (mm)                      | 0–100| 10.53 | 2.74 | 7.25 | 5.41 | 4.43  | 1.21  | 4.75  | 3.75 |
| REVAPMNX        | Threshold depth of water in the shallow aquifer for 'revap' to occur (mm) | 0–500| 470  | 465 | 435 | 274 | 467 | 483 | 330  | 435  |
| ALPHA_BF        | Base flow alpha factor (days)                    | 0–1 | 0.775 | 0.783 | 0.895 | 0.25 | 0.699 | 0.658 | 0.875 | 0.835 |
| SURLAG          | Surface runoff lag time                          | 0.05–24| 9.205 | 6.083 | 6.415 | 6.392 | 6.396 | 5.211 | 6.005 | 6.579 |
| GW_REVAP        | Groundwater re-evaporation coefficient           | 0.02–0.2| 0.096 | 0.026 | 0.024 | 0.085 | 0.027 | 0.024 | 0.024 | 0.025 |
| GW_DELAY        | Groundwater delay (days)                         | 0–500| 5    | 47.8 | 12.8 | 33.9 | 25.6 | 10 | 57.5 | 12.8 |
| ESCO            | Soil evaporation compensation factor             | 0–1 | 0.976 | 0.983 | 0.992 | 0.346 | 0.97 | 0.988 | 0.05 | 0.992 |
| RCHRG_DP        | Deep aquifer percolation fraction                | 0–1 | 0.475 | 0.041 | 0.003 | 0.313 | 0.054 | 0.232 | 0.425 | 0.043 |
| GWQMN           | Threshold depth of water in shallow aquifer required for return flow to occur (mm) | 0–5000| 352  | 12   | 13  | 15  | 15  | 8   | 55  | 38  |
| SMTMP           | Snow melt base temperature (°C)                  | −20–20| −3.56 | −     | −    | −    | −    | −    | −    |
| SFTMP           | Snowfall temperature (°C)                        | −20–20| −7.56 | −    | −    | −    | −    | −    | −    |
| SMFMX           | Maximum melt rate for snow during year (occurs on summer solstice) (mm/day °C) | 0–20 | 6.56 | −    | −    | −    | −    | −    | −    |
| SMFMN           | Minimum melt rate for snow during the year (occurs on winter solstice) (mm/day °C) | 0–20 | 7.57 | −    | −    | −    | −    | −    | −    |
Figure 9 | Calibration and validation in the control hydrological stations: (a) Yichang, (b) Zhimenda, (c) Xiaodeshi, (d) Pingshan, (e) Gaochang, (f) Fushun, (g) Beibei, (h) Wulong.
mean relative humidity. Coefficients of variation from all meteorological variables in the base period are close to that in the change period.

Reservoirs

Details of 21 large reservoirs built in the Upstream Yangtze River are listed in Table 9. It can be seen that 19 reservoirs began to be operated in the change period of this study, with a total capacity of 106.7 km$^3$, which directly reduces runoff. Moreover, reservoir impoundment can also lead to an increase in human water consumption, and the loss is considerably large, although most of them will be returned to runoff. The survey shows that the annual water loss in the Three Gorges Reservoir caused by the leakage of the dam foundation was $1.8 \times 10^6$ m$^3$ which, in general, cannot be completely converted into runoff. Moreover, most of the other reservoirs in the Upstream Yangtze River do not have such good closure conditions and geodetic structures. According to planning, a complex water conservancy and hydropower system that contains more than 100 large reservoirs will be built in the Upstream Yangtze River.

LUCC

The land use/cover conditions are shown in Figure 3, with the areas of land use/cover types in the five different periods listed in Table 10. In the Upstream Yangtze River, the major land use/cover types are grass land, forest land and crop land, accounting for more than 90% of the total area. Changes in the areas of different types range from /$4,000$ to $4,000$ km$^2$. Evaporation over water surfaces is generally greater than that over land surfaces due to the increased water area. Since the impoundment of the Three Gorges Reservoir in 2003, the submerged land area and water surface area increased with the gradual increase of the reservoir level, and the water loss caused by evaporation increased from $0.10$ km$^3$ in 2003 to $0.34$ km$^3$ in 2011. Another 18 large reservoirs and more middle-to-small reservoirs were also built in the change period. As shown in Table 10, water surfaces increased by $4,000$ km$^2$ from 1990 to 2010. Mean annual actual evapotranspiration in the Yangtze River basin is $520$ mm and mean annual pan evaporation is $1,400$ mm (Xu et al. 2006). What is more, actual evaporation from an airy and open water surface is greater than the pan evaporation. Therefore, increase in actual evaporation caused by the increased water surfaces can be estimated at $1$ m per year. Based on these calculations, the increased water surfaces can result in $4$ km$^3$ more water loss in runoff.

Attribution calculation

The runoff change caused by climate change, LUCC, and other human influence is calculated and listed in Table 6 | $R^2$ and NSE values of simulated and observed runoff series in the hydrological stations

| Station  | Calibration | Validation |
|----------|-------------|------------|
|          | $R^2$ | NSE | $R^2$ | NSE |
| Yichang  | 0.75 | 0.74 | 0.78 | 0.67 |
| Zhimenda | 0.77 | 0.76 | 0.74 | 0.64 |
| Xiaodeshi | 0.80 | 0.80 | 0.52 | 0.66 |
| Pingshan | 0.75 | 0.74 | 0.72 | 0.71 |
| Gaochang | 0.76 | 0.70 | 0.66 | 0.64 |
| Fushun | 0.76 | 0.75 | 0.71 | 0.68 |
| Beibei | 0.85 | 0.85 | 0.84 | 0.79 |
| Wulong | 0.85 | 0.85 | 0.81 | 0.80 |

Table 7 | Results of the trend analysis for meteorological series in the Upstream Yangtze River

| Factor               | Mann-Kendall | Spearman’s Rho |
|----------------------|--------------|----------------|
|                      | Trend | Confidence level | Trend | Confidence level |
| Precipitation        | ↓     | 95%              | ↓     | 95%              |
| Mean temperature     | ↑     | 99%              | ↑     | 95%              |
| Maximum temperature  | ↑     | 99%              | ↑     | 99%              |
| Minimum temperature  | ↑     | 99%              | ↑     | 99%              |
| Mean air pressure    | ↓     | 99%              | ↓     | 99%              |
| Mean wind speed      | ↓     | 99%              | ↓     | 99%              |
| Mean relative humidity | ↓     | 95%              | ↓     | 99%              |
| Sunshine duration    | ↓     | 99%              | ↓     | 95%              |

↑ and ↓ represent increasing and decreasing trend.
According to the analysis of runoff change, the period before the year 1993 is close to a natural condition, and the period after the year 1993 is more affected by the changing environment. Land use/cover maps of 1990 and 2010 are selected as the land use input of the calibrated SWAT model for the two periods, respectively. According to the steps of the MFC method, the meteorological input and land use input are fixed and changed to create different environments and the runoff series are simulated. Among all the factors, climate change has the greatest effects on the significant runoff change in the Upstream Yangtze River. Contributions of climate change, LUCC, and other human influence are around 7:1:2.

Table 8. Characteristics of the meteorological series in the Upstream Yangtze River before and after abrupt change point

| Factor                      | Base period (Mean) | SD | CV | Change period (Mean) | SD | CV | Change (km³) |
|-----------------------------|-------------------|----|----|----------------------|----|----|--------------|
| Precipitation (mm)          | 999.9             | 72.1| 0.07| 954.8               | 63.1| 0.07| −45.1 |
| Mean temperature (°C)       | 13.4              | 0.2 | 0.02| 13.9                | 0.4 | 0.03| 0.5  |
| Maximum temperature (°C)    | 17.9              | 0.4 | 0.02| 18.6                | 0.4 | 0.02| 0.7  |
| Minimum temperature (°C)    | 7.5               | 0.3 | 0.04| 8.1                 | 0.3 | 0.03| 0.6  |
| Mean air pressure (hPa)     | 833.9             | 4.3 | 0.01| 829.5               | 4.3 | 0.01| −4.4 |
| Mean wind speed (m/s)       | 1.8               | 0.1 | 0.06| 1.6                 | 0.1 | 0.06| −0.2 |
| Mean relative humidity (%)  | 70.3              | 1.1 | 0.02| 68.4                | 2.1 | 0.03| −1.9 |
| Sunshine duration (h)       | 1,754.1           | 85.1| 0.05| 1,718.1             | 67.8| 0.04| −36.0 |

CV represents coefficient of variation; SD represents standard deviation.

Table 9. Information on large reservoirs in the Upstream Yangtze River

| River | Reservoir  | Control area (10⁴ km²) | Total capacity (km³) | Operation time (since) |
|-------|------------|------------------------|----------------------|------------------------|
| Yangtze | Three Gorges | 100                     | 45.07                | 2003                   |
| Jinsha | Liyuan     | 22                     | 0.805                | 2014                   |
| Ahai   | 23.54      | 0.885                  | 2012                 |                        |
| Jinanqiao | 23.74    | 0.913                  | 2011                 |                        |
| Longkaiou | 24         | 0.558                  | 2012                 |                        |
| Ludila | 24.73      | 1.718                  | 2013                 |                        |
| Guanyinyan | 25.65     | 2.25                   | 1966                 |                        |
| Xiluodu | 45.44     | 12.67                  | 2013                 |                        |
| Xiangjiaba | 45.88   | 5.163                  | 2012                 |                        |
| Yalong | Ertan      | 11.64                  | 5.8                  | 1998                   |
| Jinping | 10.3       | 7.99                   | 2012                 |                        |
| Minjiang | Zipingpu  | 2.27                   | 1.112                | 2004                   |
| Pubugou | 6.85       | 5.332                  | 2009                 |                        |
| Wuijiang | Goupitan | 4.33                   | 6.454                | 2009                   |
| Silin   | 4.56       | 1.593                  | 2008                 |                        |
| Shatuo  | 5.45       | 0.921                  | 2012                 |                        |
| Pengshui | 6.9        | 1.465                  | 2007                 |                        |
| Jialing | Bikou      | 2.6                    | 0.217                | 1997                   |
| Baozhusi | 2.84      | 2.55                   | 1996                 |                        |
| Tingzikou | 6.1       | 4.067                  | 2013                 |                        |
| Caojic  | 15.61      | 2.218                  | 2010                 |                        |

Table 10. Areas of different land use/cover types on historical maps (unit: ×10⁴ km²)

| C | F | G | W | D | B | Total |
|---|---|---|---|---|---|-------|
| 22.3 | 33.9 | 36.1 | 1.5 | 5.7 | 0.5 | 100.0 |
| 21.9 | 34.2 | 37.2 | 1.7 | 4.6 | 0.4 | 100.0 |
| 22.1 | 33.9 | 36.2 | 1.5 | 5.8 | 0.5 | 100.0 |
| 21.6 | 34.4 | 36.1 | 1.6 | 5.7 | 0.6 | 100.0 |
| 21.9 | 34.0 | 35.8 | 1.9 | 5.9 | 0.5 | 100.0 |
| −0.4 | 0.1 | −0.3 | 0.4 | 0.2 | 0.0 |       |

C represents crop land; F represents forest land; G represents grass land; W represents water; D represents developed land; B represents barren land.

Table 11. Results of runoff change attribution in the Upstream Yangtze River

| Attribution | ΔW_C | ΔW_L | ΔW_O | ΔW_T |
|-------------|------|------|------|------|
| Contribution (km³) | −19.8 | −3.2 | −5.7 | −28.7 |

ΔW_T represents total runoff change; ΔW_C represents runoff change caused by climate change; ΔW_L represents runoff change caused by LUCC; ΔW_O represents runoff change caused by other human influence.

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DISCUSSION

Attribution at different temporal scale

As the characteristics of runoff change may vary at different temporal scales, detailed attribution can be obtained using a division of the change period, as suggested in Zhang et al. (2015) and Heo et al. (2015). As shown in Figure 7(a), the annual runoff series observed in Yichang station show a mixture of high and low values in the change period, where the runoff is observed to be lower in 1994–1997, higher in 1998–2005, and lower again in 2006–2016. Therefore, the change period is further divided into three segments (i.e., 1994–1997, 1998–2005, and 2006–2016) for a gradual attribution. The land use/cover maps in 1995, 2000, and 2010 are used as the land use inputs for the three segments, respectively. Runoff change in the Upstream Yangtze River can be attributed to the climate change, LUCC, and other human influence by the MFC method (N = 3). The gradual attribution is listed in Table 12. From the analysis, climate change is found as the main cause of runoff decline in all three segments. Runoff change at different temporal scale are presented in Figure 7(b). The characteristic of runoff change alters over time, and the contributions of LUCC and other human influence increase over time.

Attribution at different spatial scale

As shown in Table 3, besides Yichang station, runoff observed in Gaochang station, Fushun station, and Beibei station decreased significantly during the study period. To evaluate the effect of changing environment on runoff change at different spatial scales, runoff changes are analyzed in MJR, TJR, and JLR, respectively, using the attribution approach. Pettitt’s test and the sequential clustering method are used to detect the abrupt change points of runoff series in MJR, TJR, and JLR, and the results are listed in Table 13. Consistent results are obtained in both methods, where the years 1968, 1968, and 1985 are identified as the abrupt change points for MJR, TJR, and JLR, respectively, and these points are different from that in the whole Upstream Yangtze River scale (year 1993). For each basin, the study period is divided by its abrupt change point, the simulation model is established, and attribution of runoff change is calculated by the MFC method. The results of attribution calculation are listed in Table 14, which shows that the spatial attribution is related to basin characteristics. Contributions of the causes at each basin are different from those in the whole Upstream Yangtze River, where climate change still appears to be the main cause of runoff decline in MJR, TJR, and JLR.

Table 12 | Results of gradual runoff change attribution in the Upstream Yangtze River (unit: km³)

| Segment | ΔW₁ | ΔW₂ | ΔW₃ | ΔW₄ | ∆ | ∆₂ | ∆₃ | ∆₄ |
|---------|-----|-----|-----|-----|---|---|---|---|
| 1994–1997 | −37.4 | −3.0 | −6.5 | −46.9 | 46.9 | (80%) | (6%) | (14%) | (100%) |
| 1998–2005 | 30.1 | 3.5 | −7.6 | 25.8 | 43.0 | (74%) | (8%) | (18%) | (100%) |
| 2006–2016 | −34.0 | −4.9 | −10.4 | −49.3 | 49.3 | (69%) | (10%) | (21%) | (100%) |

ΔW₁ represents total runoff change; ΔW₂ represents runoff change caused by climate change; ΔW₃ represents runoff change caused by LUCC; ΔW₄ represents runoff change caused by other human influence.

Table 13 | Abrupt change points of runoff series detected in MJR, TJR and JLR

| Basin | Pettitt’s test | Sequential clustering method |
|-------|---------------|-------------------------------|
| MJR   | 1968          | 1968                          |
| TJR   | 1968          | 1968                          |
| JLR   | 1985          | 1985                          |

Table 14 | Results of runoff change attribution in MJR, TJR and JLR (unit: km³)

| Basin | ΔW₁ | ΔW₂ | ΔW₃ | ΔW₄ |
|-------|-----|-----|-----|-----|
| MJR   | −7.3 | −1.0 | −1.2 | −9.5 |
| TJR   | −2.4 | −0.1 | −0.3 | −2.8 |
| JLR   | −6.4 | −1.6 | −2.4 | −10.4 |

ΔW₁ represents total runoff change; ΔW₂ represents runoff change caused by climate change; ΔW₃ represents runoff change caused by LUCC; ΔW₄ represents runoff change caused by other human influence.
Attribution at different factorial scale

In this study, climate change is found to be the main cause of runoff change at different temporal and spatial scales. To further evaluate the effect of climate change on runoff change at different factorial scales, changes in climate are decomposed into changes in different meteorological factors. Different environments are created for the meteorological factors, and runoff change is attributed to the changes in these factors. A four-factor example is shown in Table 15. Runoff change caused by the four factors can be calculated as follows:

\[
\Delta W_1 = \frac{(E_2 - E_1) + (E_4 - E_5) + (E_6 - E_3) + (E_8 - E_7)}{8}
\]

\[
\Delta W_2 = \frac{(E_3 - E_1) + (E_4 - E_2) + (E_7 - E_5) + (E_8 - E_6)}{8}
\]

\[
\Delta W_3 = \frac{(E_5 - E_1) + (E_6 - E_2) + (E_7 - E_3) + (E_8 - E_4)}{8}
\]

\[
\Delta W_4 = \frac{(E_9 - E_1) + (E_{10} - E_2) + (E_{11} - E_3) + (E_{12} - E_4)}{8}
\]

(9)

where \(\Delta W_1, \Delta W_2, \Delta W_3, \Delta W_4\) represent runoff change caused by meteorological factor 1, 2, 3, 4; for simplicity, \(E_i\) represents simulated runoff under \(E_i\). It can be extended to \(n\)-factor situation:

\[
\Delta W_j = \frac{1}{2^{n-1}} \sum_{i=1}^{2^n} a_{ij} \cdot E_i \cdot j = 1, \ldots, n
\]

where \(\Delta W_j\) represents runoff change caused by meteorological factor \(j\); \(n\) represents the number of factors; for simplicity, \(E_i\) represents simulated runoff under \(E_i\); \(a_{ij}\) represents the weight coefficient (−1 or 1). Contributions of precipitation, mean temperature, mean wind speed, mean relative humidity, and sunshine duration are calculated and listed in Table 16. Precipitation is found to be the leading factor among the meteorological factors, followed by temperature. Changes in precipitation, temperature, and wind speed have a positive effect on runoff decline, while changes in humidity and sunshine duration have a negative effect on runoff decline.

The sensitivity curve method, with the procedure of plotting relative changes of a dependent variable against relative changes of an independent variable as a curve, is employed to determine the change in runoff expected for change in one of the meteorological variables. Thirteen climate change scenarios (i.e., \(\Delta X = 0, \pm 5\%, \pm 10\%, \pm 15\%, \pm 20\%, \pm 25\%, \pm 30\%)\) are used as the input for the SWAT model. The results of the sensitivity analysis are shown in Figure 10. For the same relative change of the variable, the larger the corresponding relative changes of runoff, the stronger the sensitivity of the variable. It is clear that precipitation and temperature are the two most sensitive variables.

**CONCLUSIONS**

Significant runoff changes have occurred in the Upstream Yangtze River under the changing environment. In this
study, the spatial-temporal characteristics of runoff change are identified. Causes of runoff change are explored and the attribution is calculated. The findings are concluded as follows:

(1) During the study period, runoff decreases significantly by \(-7.6 \text{ km}^3/10 \text{ a}\) in the Upstream Yangtze River. Spatially, runoff decreases in most tributaries except in the Yangtze River source area. Among the rivers, the Minjiang River, the Tuojiang, and the Jialing River decrease significantly. In both the base period (before the year 1993) and the change period (after 1993), the mean runoff in the Upstream Yangtze River is found to be significantly different.

(2) Causes of runoff change are explored and evidence is found. Influenced by global climate change, meteorological factors in the Upstream Yangtze River change significantly. Changes in different types of land use/cover range from \(-4,000\) to \(4,000 \text{ km}^2\). For quantitative attribution, a large-scale SWAT model is established and proven to work well, and the attribution is calculated using the MFC method. Results show climate change is the main cause of runoff decline, where the contributions of climate change, LUCC, and other human influence are around 7:1:2.

(3) The effect of changing environment on runoff change at different temporal, spatial, and factorial scales are also discussed. Climate change is always the main cause of runoff change at different temporal and spatial scales, although its contribution decreases over time. Contributions of climate change and human activities in basins vary from that at the whole Upstream Yangtze River scale. Furthermore, changes in climate change are decomposed into changes in meteorological factors, where the decreased precipitation and the increased temperature are found to be the two primary causes of runoff decline.

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**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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