

Spatial and seasonal variations of hydrological responses to climate and land-use changes in a highly urbanized basin of Southeastern China

Guodong Bian, Guoqing Wang, Jie Chen, Jianyun Zhang and Mingming Song

ABSTRACT

Climate and land-use changes are two major factors that significantly affect the watershed hydrology cycle. It is essential for regional water resource management to quantitatively assess the respective hydrological impact of these two factors. In this study, the Soil and Water Assessment Tool (SWAT) was constructed to quantify the contributions of climate and land-use changes to runoff at the annual and seasonal time scales in the Qinhuai River basin (QRB), where significant urbanization occurred from 1986 to 2015. Moreover, based on the partial least squares regression, the specific impact of individual land-use change on major hydrological components was evaluated at the sub-basin scale. The results showed that: (1) the predominant patterns of land-use change in the QRB included the transformations from paddy fields to urban areas and dry lands, forest to dry lands and dry lands to urban areas; (2) the flood seasonal precipitation series and all air temperature series had significant increasing trends over 1986–2015, and annual and seasonal runoff series had significant increasing trends and had an abrupt change point in 2001; (3) the average annual, flood seasonal, and non-flood seasonal runoff increased 238.5, 130.2 and 108.3 mm, of which land-use change was responsible for 77.6, 55.1, and 104.8% of the increases, respectively, while climate change was responsible for 22.4, 44.9, and –4.8%, respectively and (4) the hydrological response to land-use change showed an obvious decrease in actual evapotranspiration (ET) and significant increases in surface runoff and baseflow. The decrease of ET and increase of baseflow could be attributed to the conversion patterns from paddy fields and forest to dry lands, while the conversions from paddy fields and dry lands to urban areas caused a remarkable increase in surface runoff in the QRB. The study demonstrated that these practicable approaches were beneficial for the more unbiased views of the hydrological responses to climate change and land-use changes in the highly urbanized basin, which were also critical for the sustainable development of regional water resource and future land-use planning.

Key words | climate change, hydrological response, land-use change, Qinhuai River basin, SWAT

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HIGHLIGHTS

- The contributions of climate change and land-use changes to runoff were quantitatively separated in annual and seasonal time scales for a highly urbanized basin of Southeastern China.
- The specific effects of each land-use change pattern on major hydrological components were quantified at the sub-basin scale.

INTRODUCTION

Climate and land-use changes have been regarded as major factors driving variations in the hydrological cycle (Yang *et al.* 2017; Zhang *et al.* 2017). Global observations have demonstrated that the average global surface temperature increased by 0.85 °C from 1880 to 2012 (Chen *et al.* 2016; Wu *et al.* 2017). Climate change has intensified the watershed water cycle in recent years chiefly through increasing temperature and altering the spatial and temporal patterns of precipitation regimes (Arnell & Gosling 2013; Tan & Gan 2015). Furthermore, the rapid urbanization processes have led to significant changes in the land-use condition, giving considerable expansion to an impervious area and influences on the regional hydrological process. For instance, expansion of impervious areas would decrease canopy interception, infiltration, and evapotranspiration, and thus generate higher surface runoff (Sajikumar & Remya 2015; Yin *et al.* 2017; Zhang *et al.* 2018). With the increasing vulnerability of water resources, hydrological responses to climate change and urbanization have progressively become a focus for hydrological researchers.

In order to provide quantitative evaluation of the effects of climate and land-use changes on the hydrological process of the entire basin, three approaches are commonly used to distinguish the contributions of climate and land-use changes to the changes in runoff, including analytical approaches (Fu *et al.* 2007; Liu *et al.* 2017; Li *et al.* 2018), hydrological models (Bao *et al.* 2012; Wang *et al.* 2016; Marhaento *et al.* 2017; Zhai & Tao 2017), and integrated methods combining analytical approaches with hydrological models (Wang *et al.* 2013; Zheng *et al.* 2016). For instance, Chawla & Mujumdar (2015) applied the Variable Infiltration Capacity (VIC) model to investigate the influences of land-use and climate changes on streamflow in the upper

Ganga basin. They found that the influence of climate change on streamflow was more profound than that of land-use change. Luan *et al.* (2018) evaluated the effects of land-use change on major hydrological processes by using the Soil and Water Assessment Tool (SWAT) model in the Hetao Irrigation District and found that land-use change played an important role in the hydrological process and led to changes in the actual evapotranspiration (ET) and discharge. Wu *et al.* (2017) employed 10 commonly used quantitative methods to separate out the effects of climate change and human activities on changes in runoff in the Yanhe River basin. They compared the results of different methods and found elasticity-based methods, and the hydrological model produced consistent conclusions that climate change played a dominant role in the decline of runoff.

Some recent studies showed that land-use change had large impacts on the hydrological process in the highly urbanized basin (Hao *et al.* 2015; Kalantari *et al.* 2017; Wang *et al.* 2018b). These studies revealed that land-use change led to decreasing ET and increasing runoff, especially as impervious areas consistently expanded. However, few studies evaluated the specific effects of changes in individual land-use classes on the hydrological process for a highly urbanized basin. There are still valid research questions as to how mutual conversion between several land-use types influences each hydrological component. Without such accurate assessment, the impacts of each land-use change pattern on hydrological components may be underestimated, overestimated, or even misunderstood (Nie *et al.* 2011). In view of this deficiency, this study applied the hydrological model to quantitatively assess the runoff response to climate and land-use changes, and further accurately investigated the contribution of each transformation pattern of

land use to changes in major hydrological components combining the partial least squares regression (PLSR) analysis. This accurate assessment will improve the predictability of hydrological consequences of land-use changes and is thus crucial for future land-use and water resource planning and management for the highly urbanized basin.

The objectives of this study are to quantify hydrological responses to climate and land-use changes in the QRB, a highly urbanized basin, and further evaluate the specific effects of variations in individual land-use type on major hydrological components. To achieve these objectives, temporal change trends of the hydro-meteorological series from 1986 to 2015 and a land-use change matrix were assessed. Then, the hydrological process was simulated to quantitatively isolate the individual contribution of climate and land-use changes on annual and seasonal runoff based on the calibrated SWAT model. Finally, the spatial hydrological responses to each transformation pattern of land use were assessed by the PLSR.

DATA SOURCES AND METHODOLOGY

The Qinhuai River basin

The Qinhuai River is a typical tributary of the lower Yangtze River. It goes through Nanjing city and runs into the Yangtze River at the Wudingmeng sluice and the Inner Qinhuai sluice (Figure 1). The QRB is located between 118°39'E to 119°19'E, and 31°34'N to 32°10'N with a length of 36.6 km and a drainage area of 2,631 km². The QRB is located in a semi-humid area with a subtropical monsoon climate. The average annual precipitation is 1,116 mm, which is concentrated in the flood season from June to September. The mean annual air temperature is 15.4 °C. The observed long-term (1986–2015) mean annual runoff depth is about 448.4 mm. Over the years, the Qinhuai River, called ‘the mother river of Nanjing’, has played an important role in ecosystem services, including drought and flood prevention and crop irrigation.

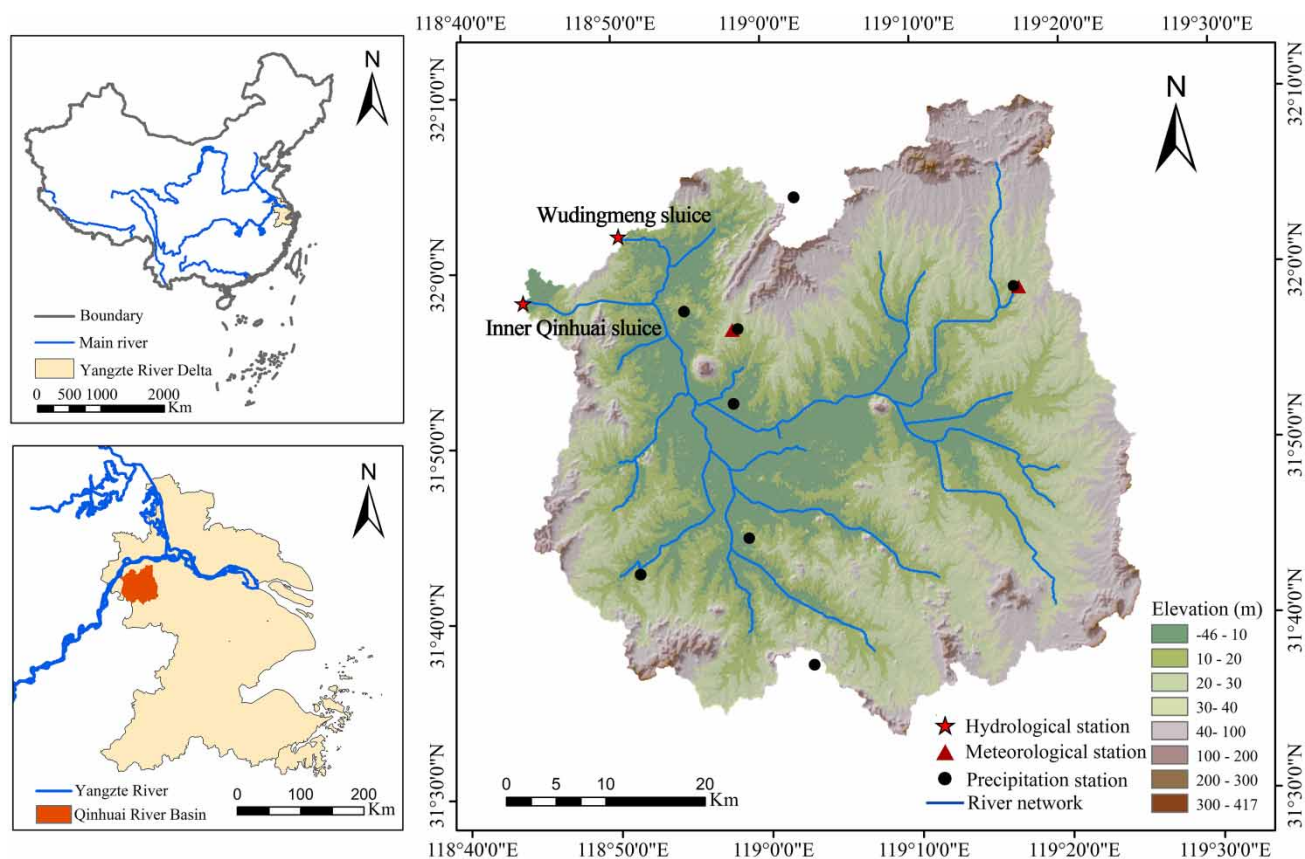


Figure 1 | The location, topography, and river network of the QRB, and the distribution of rainfall gauging stations, meteorological stations, and hydrological stations.

Data sources

The data of this study mainly consisted of meteorological and hydrological data, and topography, soil, and land-use data. The meteorological data were acquired from two standard meteorological stations between 1986 and 2015 at the daily scale, and daily rainfall data were collected from the other five rain-gauge stations across the QRB (Figure 1). The series data of potential evapotranspiration (PET) were calculated using the FAO Penman–Monteith method (Allen *et al.* 1998) for each meteorological station. Thiessen's polygon method was used to estimate the average basin value of precipitation, PET, and air temperature based on the data from the meteorological and rain-gauge stations. The 1986–2015 daily discharge was acquired from the Wudingmen station and the Inner Qinhuai station maintained by the local hydrological department. These runoff gauging stations are located at the outlets of the QRB, which controls the outflows from the Qinhuai River and back flows from the Yangtze River.

The area's topography was based on a digital elevation model (DEM), which was derived from 1:50,000 topographic contour data. Soil spatial data were acquired from the Jiangsu Soil Handbook. In addition, Landsat TM and ETM+ images with a 30 m pixel resolution were selected as the data source, and methods of rotation forest and manual interpretation were used to extract land-use data for 1994 and 2009. According to the results in Song *et al.* (2016), the overall precision of land-use extraction reached 88.6%, which provided an acceptable precision meeting the research requirements.

Methodology

In this study, three approaches were combined to quantitatively assess the hydrological response to climate and land-use changes in the study basin. The approaches included the trend and abrupt change test, the SWAT hydrological model, and the PLSR method.

The trend and abrupt change test

The Mann–Kendall trend (M–K) test is a non-parametric method and has been recommended by the World Meteorological Organization to detect monotonic trends of hydro-

meteorological variables such as runoff, precipitation, air temperature, and PET (Chebana *et al.* 2013). The statistic S and standardized test value Z of the M–K test are calculated following Zuo *et al.* (2014). If the value of Z is greater than or equal to 2.56, the trend is significant at the significance of 0.01; if the value of Z is greater than or equal to 1.96, the trend is significant at the significance of 0.05. In addition, the trend slope β is generally jointed with the M–K test to explain the change in long-term time series. A positive value of β indicates an upward trend, whereas a negative value represents a downward trend.

The abrupt change is one of the important external manifestations of climate change and hydrological process variability, and mainly reflects the occurrence of extreme events or severe anthropogenic activities (Nayak & Villarini 2016). Hence, detecting the abrupt change point is considered as the key step to be tackled in hydrological time-series analysis (Xie *et al.* 2018). The non-parametric Pettitt test was applied to determine the change point in this study, which can quantify the statistically significant level of change points for varying meteorological and hydrological series. This method uses the Mann–Whitney statistic function $U_{t,N}$ and considers the samples x_1, \dots, x_t and x_{t+1}, \dots, x_N to be independently and identically distributed. N represents the sample size. $U_{t,N}$ is calculated as follows:

$$U_{t,N} = U_{t-1,N} + \sum_{i=1}^N \text{sgn}(x_t - x_i) \quad (t = 2, \dots, N) \quad (1)$$

If time t is satisfied by $K(t) = \max(U_{t,N})$, then t represents an abrupt change point and the formula for the significant level of P of the change point is as follows:

$$P = 2 \exp\left(\frac{-6K(t)^2}{N^3 + N^2}\right) \quad (2)$$

If $P \leq 0.05$, then detected abrupt change point is considered to be statistically significant.

The SWAT model

The SWAT is a physically based, semi-distributed and continuous daily time-step hydrological model that has been

widely used to evaluate the hydrological impact of climate change and land-use management in complex watersheds (Sun *et al.* 2017; Tamm *et al.* 2018). In this study, the ArcSWAT extension for ArcGIS 10.2 was used to carry out the SWAT model pre-processing and set-up. It divides a basin into several sub-basins based on the DEM and the river system and then further subdivides sub-basins into a number of hydrologic response units (HRUs), each of which consists of a unique combination of land use, soil type, and terrain slope. Hydrological components are simulated in each HRU, and then aggregated to each sub-basin, finally routed to the basin outlet throughout the channel network. In this study, the QRB was partitioned into 39 sub-basins with 829 HRUs. The surface runoff was estimated using a modification of the Soil Conservation Service curve number (SCS-CN) method with daily rainfall amounts. The Penman–Monteith method was chosen to calculate the PET, and the flow routing was calculated using the Muskingum schemes.

In addition, the procedures of parameter calibration, verification, and sensitivity analysis in the SWAT model can be conducted by SWAT Calibration and Uncertainty Programs (SWAT-CUP). The sensitivity analysis of the parameters is determined by the *t*-statistics and the *p*-value. A larger absolute value of the *t*-statistic represents greater sensitivity of the parameters, and the *p*-value, closer to zero, is more sensitive. Furthermore, the performances of the SWAT model are evaluated by the coefficient of determination (R^2), the Nash–Sutcliffe coefficient, and percent bias (PBIAS).

SWAT model application

The impacts of climate and land-use changes on hydrology were quantitatively separated by scenario analysis based on the SWAT output of four scenarios (Table 1). The study period was divided into two time slices: 1986–2001 was considered as the ‘baseline period’ and 2002–2015 was considered to be the ‘change period’.

When the meteorological data and the land-use map were within the same period, the simulation results represented the ‘real value’ affected by the combination of land-use and climate changes. Alternatively, when one driving factor varied and another remained constant, the simulation results showed the effects of the variable factors

Table 1 | Simulated hydrological process by the SWAT under different scenarios considering both climate and land use

Scenarios	Climate	Land use	Simulation
S1 Land-use and meteorological data from the baseline period	1986–2001	1994	Q_{S1}
S2 Climate change while land-use constant	2002–2015	1994	Q_{S2}
S3 Land-use change while climate constant	1986–2001	2009	Q_{S3}
S4 Both climate change and land-use change	2002–2015	2009	Q_{S4}

on hydrological components. For example, to assess the runoff response to climate change, the first simulation (Q_{S1}) was simulated under the 1986–2001 climate and 1994 land-use condition. The second simulation (Q_{S2}) was based on the 2002–2015 climate and 1994 land-use condition. Thus, the difference between Q_{S1} and Q_{S2} was the effect of the climate change on runoff. Similarly, the difference between the third simulation (Q_{S3}) and fourth simulation (Q_{S4}) could also be considered as the effect of the climate change on runoff. Therefore, the impacts of climate change on runoff were calculated by the following formula:

$$\Delta Q_C = \frac{(Q_{S2} - Q_{S1}) + (Q_{S4} - Q_{S3})}{2} \quad (3)$$

Furthermore, the effects of land-use change on runoff can be determined by applying the difference between the first and third simulations, or between the second and fourth simulations, as in the following formula:

$$\Delta Q_L = \frac{(Q_{S3} - Q_{S1}) + (Q_{S4} - Q_{S2})}{2} \quad (4)$$

The combined effects of climate and land-use changes on runoff were equal to the sum of the individual impacts. The total changes were recorded:

$$\Delta Q = \Delta Q_C + \Delta Q_L \quad (5)$$

Hence, the percentage contributions of climate and land-use changes in the variations in runoff were calculated

as follows:

$$P_C = \frac{\Delta Q_C}{|\Delta Q|} \times 100\% \quad \text{and} \quad P_L = \frac{\Delta Q_L}{|\Delta Q|} \times 100\% \quad (6)$$

Partial least squares regression

PLSR is a robust multivariate regression method that can be used when the predictors exhibit numerous independent variables and multicollinearity (Yan *et al.* 2013; Woldesenbet *et al.* 2016). The PLSR combines the features of principal component analysis and multiple linear regression, and it is used to determine the relationship between a response variable and a set of predictor variables. The basic PLSR algorithm is not described in this paper, but detailed information on PLSR can be obtained from Ma *et al.* (2015). In this study, the PLSR is used to evaluate the contribution of each land-use change pattern to hydrological components at the sub-basin scale. The predictor variables are four kinds of land-use change pattern, i.e. paddy field to urban area, paddy field to dry land, forest to dry land, and dry land to urban area. On the other hand, the dependent variables are the changes in the major hydrological components, i.e. evapotranspiration, surface flow, and baseflow. Two main indices, goodness of fit (R^2) and goodness of prediction (R_{cross}^2), are calculated to assess the validity and strength of the PLSR model. If the R^2 value is greater than 0.8 and the R_{cross}^2 value is greater than 0.5, the PLSR model has a good predictive ability.

In the PLSR model, the variable importance of the projection (VIP) and regression coefficients (RCs) were used to explain the relative importance of each independent variable. It is thus possible to determine which land-use change pattern most strongly interacts with the hydrological components. The predictors having large VIP values are the most relevant for explaining the dependent variable. In general, an independent variable with a VIP value greater than 0.8 is very relevant and significant in explaining the dependent variable, whereas a value less than 0.5 indicates that the variable does not significantly explain the dependent variable. The RCs of the PLSR models indicate the direction and strength of the relationship between the changes in each land-use change pattern and hydrological components. If the land-use change pattern has

a small value of RCs but a large VIP, this land-use change pattern is important and contributes significantly to the prediction.

RESULTS

Land-use change from 1994 to 2009

During 1986–2015, land use changed dramatically in the QRB. The land-use compositions of 1994 and 2009 are shown in Figure 2. Owing to rapid urban expansion, the proportion of urban areas consistently increased from 4.3% (111.3 km²) to 13.6% (349.9 km²), and the proportion of dry lands increased from 26.6% (682.8 km²) to 35.7% (916 km²). In contrast, there was an obvious decrease in paddy fields from 47.5% (1,219.1 km²) to 33.7% (863.8 km²) and a decrease in forest from 16.8% (431.7 km²) to 9.8% (250.6 km²). The proportions of bare lands and water bodies were small and exhibited only slight changes.

The matrix of land-use transformation was calculated to reflect the direction of change in the various land-use types, as shown in Table 2. The predominating patterns of land-use change in the QRB were that the paddy fields transformed into urban areas and dry lands, forest transformed into dry lands, and dry lands transformed into urban areas. Specifically, the net changed areas of conversions from paddy fields to urban areas and dry lands were 139.2 and 204.2 km², respectively, and those from forest to dry lands and from dry lands to urban areas were 99.5 and 56.4 km², respectively. On the whole, the land-use changes in the QRB were characterized by decreases in paddy fields and forest and expansions of urban areas and dry lands.

Variation trends and abrupt changes for annual and seasonal hydro-meteorological series

The change trends of time series for precipitation, air temperature, PET, and runoff for annual, flood seasonal (June to September) and non-flood seasonal (January to May and October to December) time periods are shown in Figure 3. According to the results of the M–K test (Figure 3), the annual precipitation series had an insignificant increasing trend and the non-flood seasonal precipitation series had an insignificant decreasing trend, while the flood seasonal

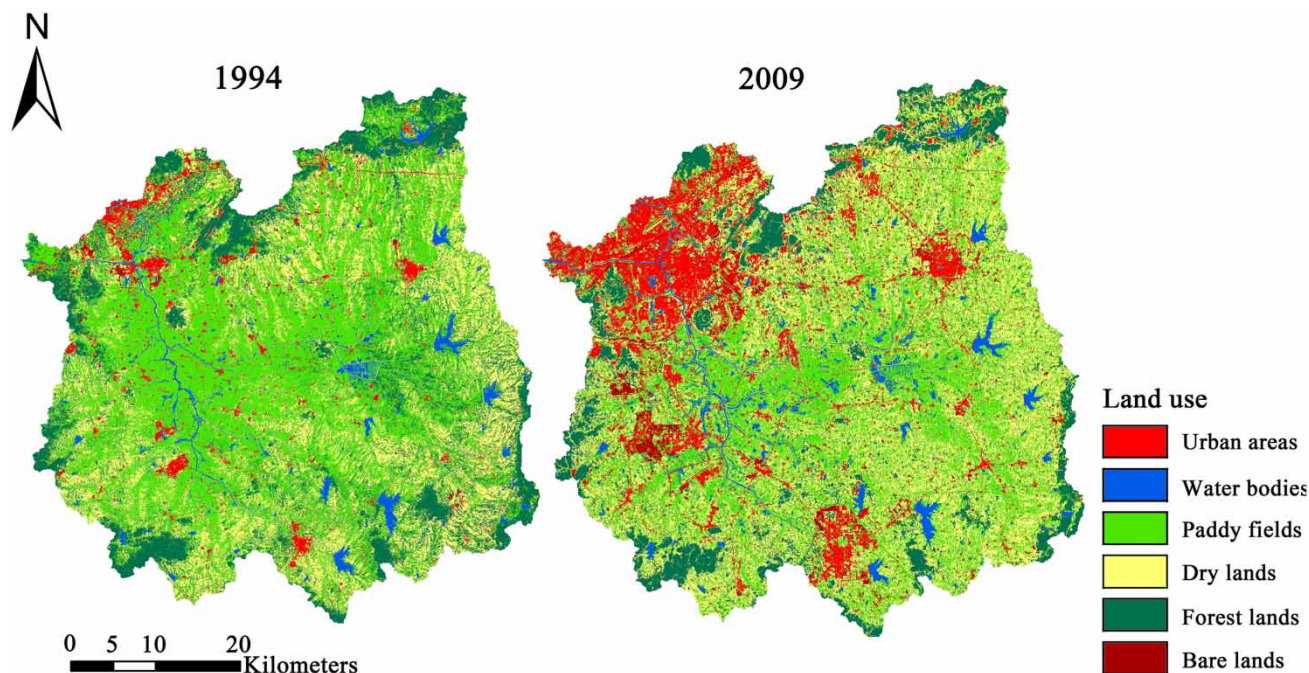


Figure 2 | Land-use classified maps for 1994 and 2009 in the QRB.

Table 2 | Matrix of land-use transformation in the QRB for 1994–2009 (km²)

Transformation matrix 1994	2009						
	Urban areas	Dry lands	Paddy fields	Forest	Bare lands	Water	Total
Urban areas	57.7	20.9	25.7	2.2	2.9	1.9	111.3
Dry lands	77.3	322.5	218.2	28.4	21.4	15.0	682.8
Paddy fields	164.9	422.4	491.0	53.9	33.2	53.7	1219.1
Forest	33.1	127.9	93.2	161.9	7.8	7.8	431.7
Bare lands	9.4	5.2	4.0	0.4	1.2	0.4	20.6
Water	7.5	17.1	31.7	3.8	1.2	38.1	99.4
Total	349.9	916	863.8	250.6	67.7	116.9	2564.9
Area change from 1994 to 2009 (%)	+9.3	+9.1	−13.9	−7	+1.8	+0.7	−

precipitation series had a significant increasing trend at the 5% significance level. The annual, flood seasonal and non-flood seasonal air temperature series had significant increasing trends at the 5% significance level, while all PET series showed insignificant change trends. In addition, the annual, flood seasonal and non-flood seasonal runoff series had significant increasing trends at the 5% significance level. These results indicated that climate conditions and hydrological processes in the QRB had changed markedly over the last three decades, as characterized by the

remarkable increases in precipitation series (flood season), air temperature series, and runoff series.

Additionally, the Pettitt test was applied to identify the abrupt change point in annual and seasonal runoff series. As shown in Figure 4, the significant abrupt change points for annual and flood seasonal runoff series were both detected in 2001. The non-flood seasonal runoff series had a significant change point in 1997. According to previous studies (Du *et al.* 2012; Bian *et al.* 2017), the annual runoff coefficient of the QRB abruptly changed around the 2000s, which was mainly

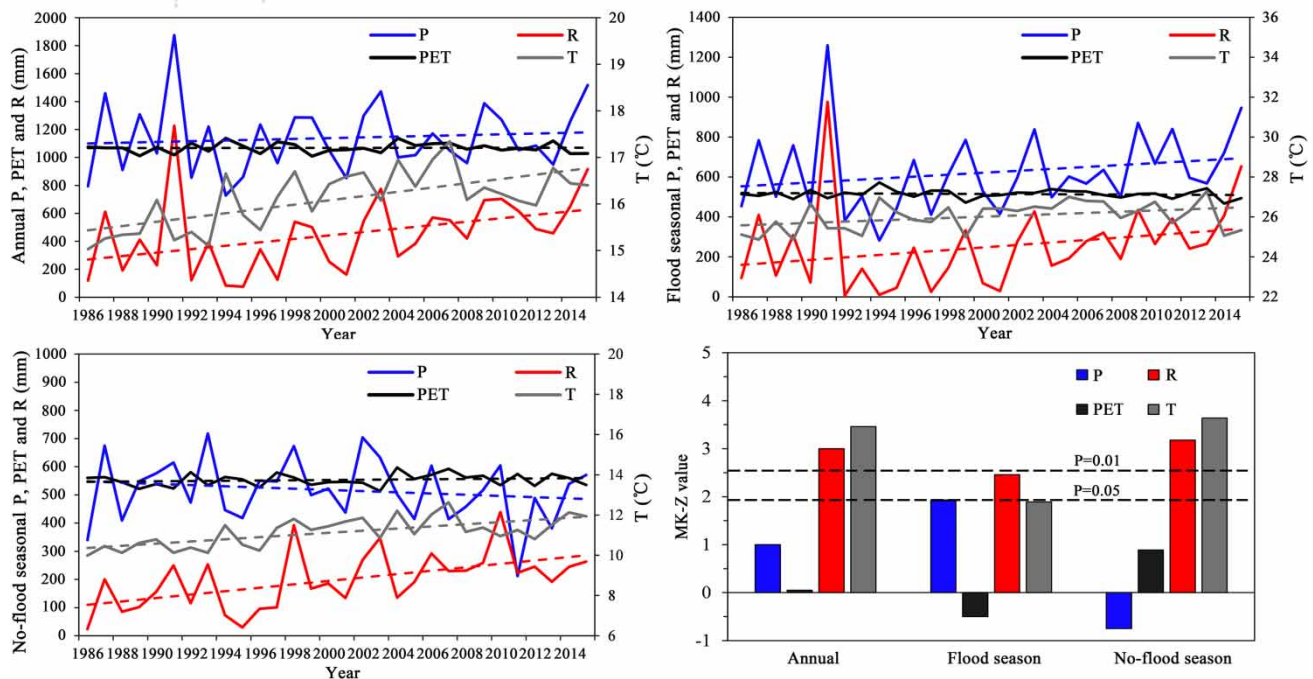


Figure 3 | Change trends in annual, flood seasonal (June to September) and non-flood seasonal (January to May and October to December) series of precipitation (P), temperature (T), runoff (R), and potential evapotranspiration (PET) during 1986–2015, and the results of the M-K test.

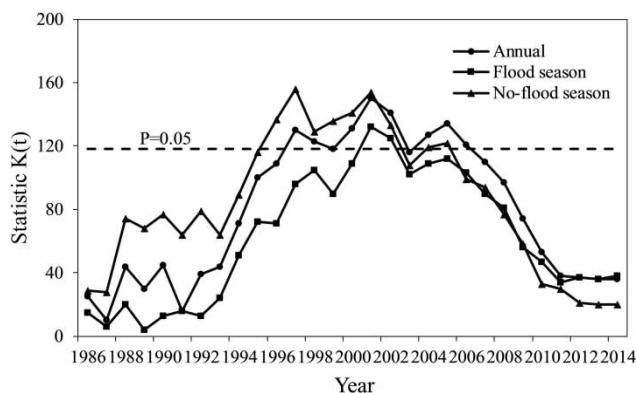


Figure 4 | Results of the Pettitt test for annual, flood seasonal (June to September) and non-flood seasonal (January to May and October to December) runoff series.

attributed to land-use change predominated by urbanization. Therefore, 2001 was selected as the abrupt change point, and the study period could be divided into two periods (baseline period: 1986–2001 and change period: 2002–2015).

Calibration and validation of the SWAT model

This study used SWAT-CUP to calibrate and validate the SWAT model. The years 1986–2001 and 2002–2015 were

treated as calibration and validation periods, respectively. In addition, the land-use map of 1994 was used for the calibration of the SWAT model, and the land-use map of 2009 was used for the validation of the model. We chose 20 parameters that might be sensitive in the QRB according to the relevant literature and then the top 10 most sensitive parameters were chosen to calibrate the SWAT model, as listed in Table 3.

The performance of the SWAT model in the QRB is shown in Table 4 and Figure 5. There was good agreement between the observed and simulated runoff at the monthly level for both the calibration and validation periods. As shown in Table 4, the coefficient of determination (R^2) and the Nash-Sutcliffe coefficient (ENS) coefficient were higher than 0.85 in the calibration and validation periods, and the PBIAS values were all in the range of $\pm 10\%$. The performance of the SWAT model in the QRB could be considered very good in terms of the model evaluation criteria described by Moriasi *et al.* (2007). Therefore, the SWAT model was able to effectively simulate the hydrological process in the QRB.

Table 3 | List of parameters and ranking for 10 highest relative sensitivity values in SWAT calibration

Parameters	Rank	Description	Default	t-Statistics	p-Value	Fitted value
V_ESCO.hru	1	Soil evaporation compensation factor	0–1	−33.65	0.00	0.85
V_GW_REVAP.gw	2	Groundwater ‘revap’ coefficient	0.02–0.2	21.18	0.00	0.18
R_SOL_AWC.sol	10	Available water capacity of the soil layer	−0.2 to 0.2	4.51	0.00	0.13
V_CANMX.hru	5	Maximum canopy storage	0–95	3.50	0.00	70.85
V_GW_DELAY.gw	6	Groundwater delay	0–500	1.38	0.16	4.35
V_ALPHA_BF.gw	1	Baseflow alpha factor	0–1	−0.78	0.38	0.42
V_EPCO.bsn	8	Plant uptake compensation factor	0–1	0.56	0.42	0.57
R_CN2.mgt	7	SCS runoff curve number	−0.05 to 0.05	−0.32	0.49	0.01
V_CH_N2.rte	3	Manning’s ‘n’ value for the main channel	0.01–0.3	−0.19	0.54	0.02
V_CH_K2.rte	2	Effective hydraulic conductivity in the main channel	5–99	0.03	0.67	25.21

Table 4 | Evaluation of the SWAT model performance at monthly time step

Period	R ²	ENS	PBIAS (%)
Calibration (1986–2001)	0.92	0.92	−0.7
Validation (2002–2015)	0.89	0.88	−1.5

The attributions of climate and land-use changes on annual and seasonal runoff

To quantitatively evaluate the effects of climate and land-use changes on annual and seasonal runoff, the hydrological processes were simulated under various scenarios (Table 1) based on the calibrated SWAT model. As shown in Table 5, the joint impacts of climate and land-use changes

caused an increase in annual runoff by 238.5 mm from the baseline period 1986–2001 to the change period 2002–2015. Comparing the simulations of different scenarios, the land-use change led to an increase in annual runoff of 185.2 mm, with the relative contribution of 77.6%, and climate change increased the annual runoff by 53.3 mm, with the relative contribution of 22.4%. These results indicated that land-use change played a dominant role in the increase in annual runoff in the QRB. On a seasonal basis, the joint impacts of climate and land-use changes caused the increase of flood seasonal and non-flood seasonal runoff by 130.2 and 108.3 mm, respectively. Specifically, climate and land-use changes led to an increase in flood seasonal runoff by 58.5 and 71.7 mm, with the relative contribution of 44.9

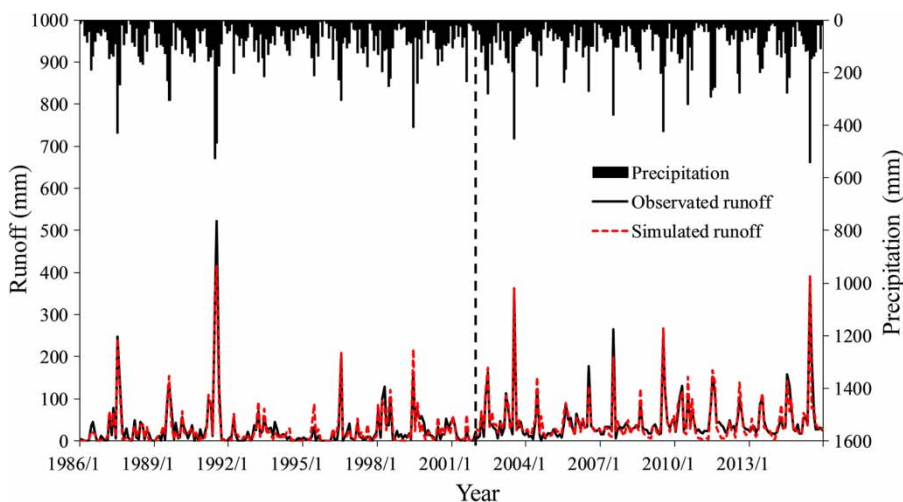
**Figure 5** | Comparison between observed and simulated monthly runoff values for the calibration period (1986–2001) and the validation period (2002–2015).

Table 5 | Simulated average values of annual and seasonal runoff under four scenarios by the SWAT model and the relative contributions of climate and land-use changes to runoff

	Q_{s1} (mm)	Q_{s2} (mm)	Q_{s3} (mm)	Q_{s4} (mm)	ΔQ_c (mm)	ΔQ_L (mm)	P_c (%)	P_L (%)
Annual	334	378.2	510.1	572.5	53.3	185.2	22.4	77.6
Flood season	202.6	256.3	269.6	332.8	58.5	71.7	44.9	55.1
Non-flood season	131.9	121.8	240.5	240.2	-5.2	113.5	-4.8	104.8

and 55.1%, respectively. Climate change decreased the non-flood seasonal runoff by 5.2 mm with the contribution of -4.8%, and the land-use change increased it by 113.5 mm with the contribution of 104.8%. Overall, land-use change was considered as the predominant factor causing the increases in annual and seasonal runoff in the study basin, while the impacts of climate change were important, especially for the flood season.

The effects of land-use change on hydrological components at the basin scale

The land-use change was identified as the predominant factor that significantly affected the hydrological process in the QRB. In order to evaluate the specific influences of land-use change on the hydrological process, the major hydrological components were simulated by the calibrated SWAT under 1994 and 2009 land-use conditions and constant climate scenarios 1986–2015. The changes in annual and seasonal hydrological components were calculated as shown in Table 6. Compared with the land-use condition in 1994, the average annual value of ET decreased 203.6 mm under the land-use condition of 2009. The average annual surface runoff increased from 343.1 to 443.9 mm. In addition, the average annual value of baseflow increased from 31.9 to 123.9 mm. Similarly, the average value of flood and non-flood seasonal ET decreased 96.4 and

107.2 mm, respectively. At the same time, the average value of flood and non-flood seasonal surface runoff increased 41.2 and 59.6 mm, respectively, and the average value of their baseflow increased 33.8 and 58.2 mm, respectively. It was apparent that the change characteristics of annual and seasonal hydrological responses to land-use change were a dramatic decrease in ET and a remarkable increase in surface runoff and baseflow for annual, flood seasonal, and non-flood seasonal periods.

The spatial variations of hydrological responses to each pattern of land-use change

While the SWAT model results showed the changes in the hydrological components under the different land-use scenarios, the quantitative hydrological impacts of individual patterns of land-use change could be further determined at the sub-basin scale. Therefore, PLSR models were applied in this study to evaluate the contribution of individual pattern of land-use change to the changes in hydrological components and land-use change. According to the matrix of land-use transformation (Table 2), the predominant patterns of land-use change in the QRB included the transformations from paddy fields to urban areas and dry lands, forest lands to dry lands, and dry lands to urban areas. The spatial distribution of each pattern of land-use change for the years 1994 and 2009 was summarized for

Table 6 | Average annual values of hydrological components under 1994 and 2009 land-use scenarios during the period of 1986–2015 in the QRB

	Annual			Flood season			Non-flood season		
	ET (mm)	Surface runoff (mm)	Baseflow (mm)	ET (mm)	Surface runoff (mm)	Baseflow (mm)	ET (mm)	Surface runoff (mm)	Baseflow (mm)
1994 land use	742.4	343.1	31.9	357.2	233.6	7.8	385.2	109.5	24.1
2009 land use	538.8	443.9	123.9	260.8	274.8	41.6	278.0	169.1	82.3
Changes	-203.6	100.8	92.0	-96.4	41.2	33.8	-107.2	59.6	58.2

sub-basins of the QRB, as shown in Figure 6. In addition, the corresponding changes of primary hydrological components for each sub-basin under the fixed 1986–2015 climate condition were calculated based on the SWAT model, as shown in Figure 7.

A summary of the PLSR is provided in Tables 7 and 8. The PLSR models were developed for annual and seasonal different response variables: actual evapotranspiration as ET, surface runoff as SQ, and baseflow as BF. These PLSR models could be considered to have a good predictive power due to the R^2 value being greater than 0.8 and the R^2_{cross} value being greater than 0.5 (Table 7). Each PLSR model included two significant components based on the cross-validation for response variables (Table 7). In addition, the VIP values of the PLSR models indicated the comprehensive importance of each pattern of land-use change for hydrological components. The predictors with VIP values

more than 0.9 were considered to be of great importance for predictions. For the annual ET model, a higher VIP value was observed for the pattern of transformation from forest to dry lands (VIP = 1.45), followed by transformation from paddy fields to dry lands (VIP = 1.02). Specifically, the RC of forest to dry lands was -0.46 , and the RC of paddy fields to dry lands was -0.32 . The seasonal ET model had the same results as the annual ET model, which indicated that the decreases of ET could be attributed to the transformations of paddy fields and forest to dry lands during the past 30 years in the QRB. For annual, flood seasonal and non-flood seasonal SQ models, the more important predictors were paddy fields to urban areas (VIP = 1.28, 1.31, and 1.29, respectively) and dry lands to urban areas (VIP = 0.92, 1.29, and 1.30, respectively). The patterns of paddy fields to urban areas and dry lands to urban areas had positive RCs (Table 7). As expected, transformation from paddy

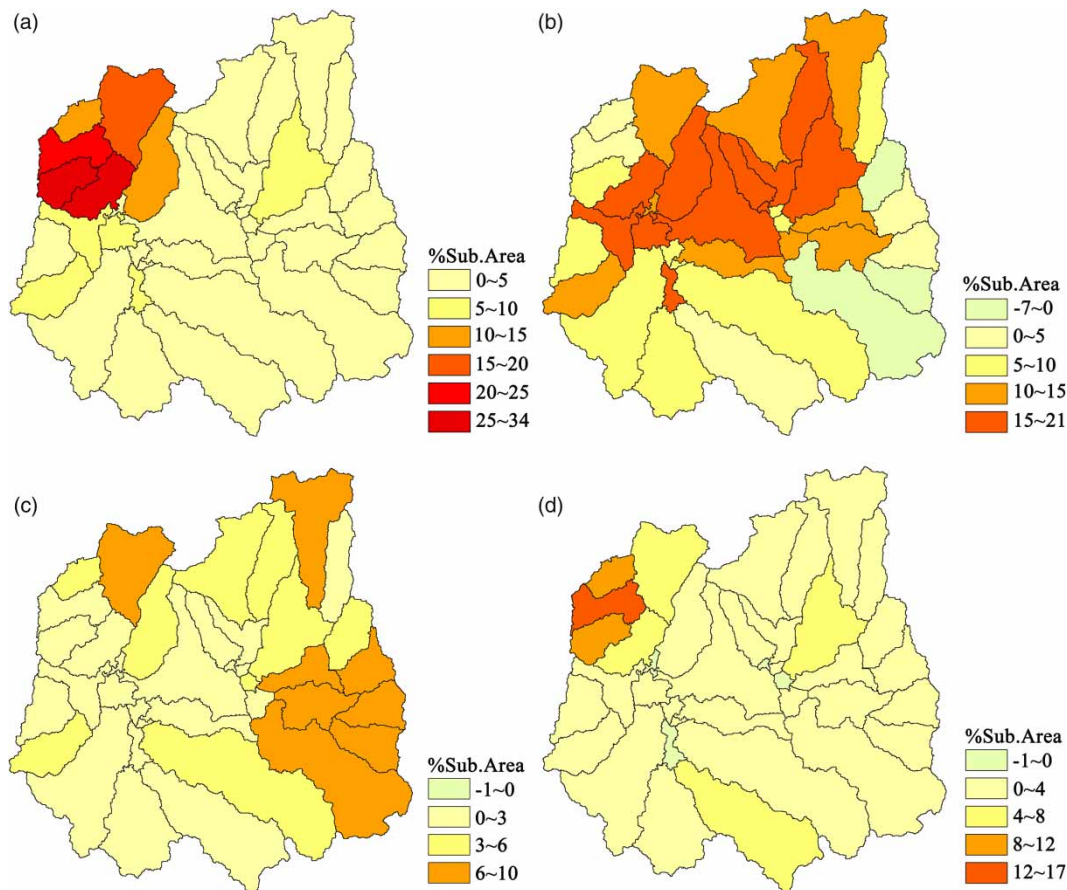


Figure 6 | Spatial variations of each land-use change pattern between 1994 and 2009 in the QRB. (a) Paddy field to urban area, (b) paddy field to dry land, (c) forest to dry land, and (d) land to urban area.

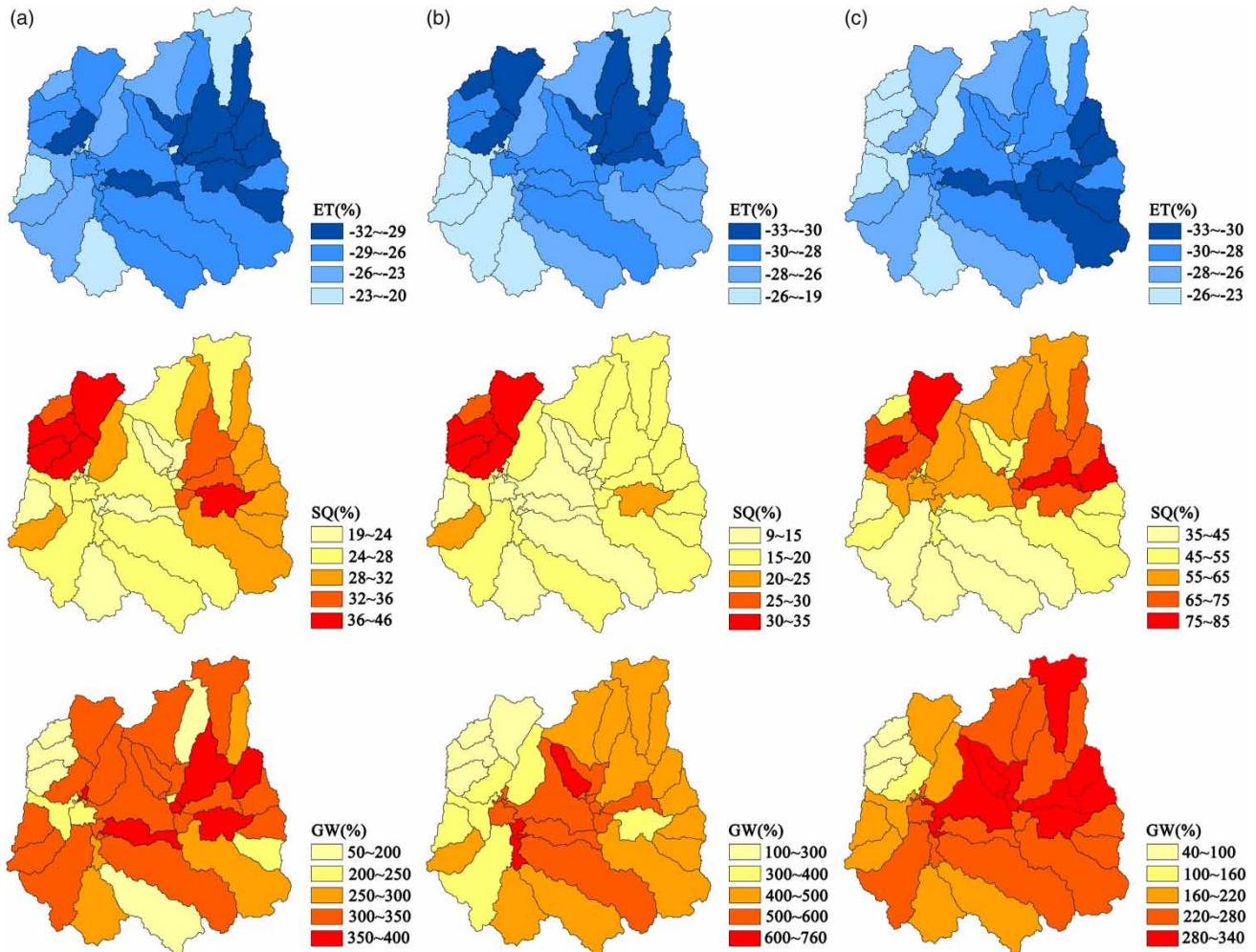


Figure 7 | Spatial distribution of changes in annual and seasonal actual evapotranspiration (ET), surface runoff (SQ), and baseflow (BF) for land-use maps between 1994 and 2009 in the QRB. (a) Annual, (b) flood season, and (c) non-flood season.

fields and dry lands to urban areas encouraged greater surface runoff. For all BF models, the more important predictors were forest to dry lands (VIP = 1.50, 1.60, and 1.60, respectively) and paddy fields to dry lands (VIP = 0.97, 1.05, and 1.05, respectively). The transformations of paddy fields and forest to dry lands also had positive RCs and significantly increased baseflow in the QRB.

DISCUSSION

The Qinhui River basin (QRB) is a region where land use has changed dramatically during the rapid urbanization process over the past three decades. We found that land-use

change played a dominant role in the increases in annual and seasonal runoff. However, the impacts of climate and land-use changes on seasonal runoff were different. Specifically, the effect of climate change increased flood seasonal runoff by 58.5 mm, with a positive contribution of 44.9%, while it decreased non-flood seasonal runoff by 5.2 mm, with a negative contribution of -4.8%. These different effects of climate change are mainly attributed to the change trends of precipitation in the two seasons. It should be noted that the flood seasonal precipitation had a significant increase from 579.1 mm of the baseline period (1986–2001) to 675.2 mm of the change period (2002–2015), while the non-flood seasonal precipitation had a small decrease of 25 mm from the baseline period to the

Table 7 | Summary of the PLSR models of the annual and seasonal hydrological components for the Qinhuai River basin

	Response variable Y	R ²	R ² _{cross}	Component	% of explained variability in Y	R ² _{cum}
Annual	ET	0.84	0.69	1	73	0.61
				2	84	0.69
	SQ	0.98	0.97	1	95	0.92
				2	98	0.97
BF	0.80	0.61	1	67.2	0.50	
			2	80	0.61	
Flood Season	ET	0.88	0.76	1	77	0.67
				2	88	0.76
	SQ	0.98	0.97	1	95	0.91
				2	98	0.97
	BF	0.81	0.63	1	69	0.52
				2	81	0.63
Non-flood season	ET	0.81	0.62	1	69	0.55
				2	81	0.62
	SQ	0.99	0.97	1	95	0.92
				2	99	0.97
	BF	0.80	0.59	1	66	0.48
				2	80	0.59

Table 8 | List of VIP and RCs for the hydrological components of the PLSR models in the QRB

Response variables		Predictors							
		Paddy fields to urban areas		Paddy fields to dry lands		Woodlands to dry lands		Dry lands to urban areas	
		VIP	RCs	VIP	RCs	VIP	RCs	VIP	RCs
Annual	ET	0.52	-0.16	1.02	-0.32	1.45	-0.46	0.77	-0.24
	SURQ	1.28	0.50	0.67	0.01	0.53	0.14	0.92	0.50
	BF	0.65	-0.15	0.97	0.37	1.50	0.73	0.64	0.05
Flood season	ET	0.58	-0.19	1.06	-0.34	1.38	-0.44	0.79	-0.26
	SURQ	1.31	0.43	0.59	0.20	0.52	0.17	1.29	0.43
	BF	0.23	0.08	1.05	0.34	1.60	0.53	0.54	0.18
Non-flood season	ET	0.46	-0.15	0.97	-0.31	1.51	-0.47	0.74	-0.23
	SURQ	1.29	0.43	0.58	0.19	0.55	0.18	1.30	0.43
	BF	0.23	0.07	1.05	0.34	1.60	0.52	0.54	0.17

VIP values > 0.8, which are shown in bold, indicate that the independent variable are significant in explaining the corresponding variables.

change period. Moreover, we found that the relative contribution of land-use change to non-flood seasonal runoff was larger than that to flood seasonal runoff, indicating that runoff in the non-flood season was more sensitive to land-use change than during the flood season. This is mainly related to the fact that the high intensity and large volume of rainfall in the flood season caused the natural surface to saturate quickly and behave like an impervious surface. Therefore, the relative influence of the land-use change

will decrease in the flood season. Some previous studies also found that the contributions of climate change and human activities to runoff change were not consistent over different time scales (Wei & Zhang 2010; Zhang *et al.* 2016). For example, Zeng *et al.* (2014) quantitatively evaluated the impacts of climate change and human activities on runoff changes at annual, seasonal, and monthly time scales in the Zhang River basin, suggesting that climate change had a stronger effect than human activities on

annual and wet seasonal runoff changes, while in the dry season human activities was the dominant factor for runoff change. Hence, it should be emphasized that different times testified different degrees of effects of climate and land-use changes on runoff change. A quantitative differentiation of the climate-induced and land-use-induced variation in runoff at different time scales has been investigated to enhance our understanding of runoff change under the influence of climate and land-use changes. Such quantitative evaluation will be important for regional water resource management and the mitigation of influence of climate and land-use changes on water resource.

Furthermore, we also quantitatively analyzed the effects of land-use change on major hydrological components. The results indicated that the ET significantly decreased and surface runoff and baseflow increased at annual and seasonal scales over the study period, which were likely attributed to the dramatic land-use changes by urbanization in the QRB. Our findings were consistent with an earlier study of the same basin by Hao *et al.* (2015), who found that the reduction in ET and increase in streamflow could be largely attributed to the expansion of urban areas and shrinkage of paddy fields. There were some evidence suggesting that ET of paddy fields was close to the PET under less water stress, while urban areas were generally characterized by impervious surfaces with low ET and high runoff. Thus, transformation of paddy fields to relatively 'dry' urban areas was expected to dramatically reduce ET and increase surface runoff, which were coincident with some previous studies (Zhou *et al.* 2013; Maina *et al.* 2014). Moreover, we further analyzed the influence of each land-use transformation pattern on hydrological components, and found that baseflow had a significant increase in the study basin, which somewhat contradicted the general view that urbanization with an increase in the impervious surface likely reduces infiltration and baseflow (Price *et al.* 2011; Kalantari *et al.* 2017; Wang & Stephenson 2018a). We argued that the increase of baseflow in the QRB was due to the large reduction in ET attributed to the transformation from paddy field and forest to dry land. Some previous studies indicated that baseflow variation was strongly controlled by vegetation cover and the reduction of perennial vegetation, especially forest, which could decrease ET, increase groundwater recharge, and thus increase baseflow

(Zhang & Schilling 2006; Boggs & Sun 2011; Zomlot *et al.* 2015). Thus, conversion of paddy fields and forest to dry lands not only decreases the ET, but also allows infiltration and groundwater exchange. In this way, it is credible that replacing paddy fields and forest with dry lands plays a key role in the increase of baseflow during urbanization in the QRB. Future studies should examine the mechanism of baseflow change during the urbanization to confirm the influence of the dry land expansion on baseflow and groundwater change, which will be explored to enhance our understanding of hydrological response to land-use change in a highly urbanized basin.

CONCLUSIONS

This study quantified the effects of climate and land-use changes on annual and seasonal runoff in the QRB, a highly urbanized region in the Yangtze River Delta. The good performance of the SWAT model indicated that the SWAT model could be used to evaluate the contributions of climate and land-use changes to runoff change at annual and seasonal time scales by simulating hydrological processes of the study basin. Moreover, the PLSR method was adopted to evaluate the influence of the individual pattern of land-use change on major hydrological components. From the results of this study, the main conclusions are as follows:

- (1) The predominant directions of land-use change were converting paddy fields and forest to urban areas and dry lands. The diminishing portion of paddy fields (decrease of 13.9%) and forest (decrease of 7%) contributed to the expansion of urban areas (increase of 9.3%) and dry lands (increase of 9.1%) over the study period.
- (2) The results of the M-K test indicated that the flood seasonal precipitation series, all temperature series, and runoff series had significant rising trends. The abrupt change point in the year 2001 was detected for annual and seasonal runoff series by the Pettitt test.
- (3) The climate and land-use changes increased runoff of the QRB with different degrees of effects during different time scales. The contributions of climate and land-use changes to annual runoff changes are 22.4 and 77.6%, respectively. In addition, the contributions of land-use

change to runoff changes in the flood and non-flood seasons were 55.1 and 104.8%, respectively, while the contributions of climate change were 44.9 and -4.8%, respectively. It was apparent that the land-use change was the main driving factor of the increase in runoff for annual and seasonal periods in the QRB.

- (4) Due to the dramatic variations of land use in the QRB, the ET decreased 203.6, 96.4, and 107.2 mm for annual, flood seasonal, and non-flood seasonal periods; the surface runoff increased 100.8, 41.2, and 59.6 mm, respectively, and the baseflow increased 92, 33.8, and 58.2 mm, respectively. According to the results of the PLSR models, the decreases of ET and the increase of baseflow were mainly attributed to the transformations from paddy fields and forest to dry lands, while the increases of surface runoff were mainly attributed to the transformations from paddy fields and dry lands to urban areas.

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CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest with the work presented here

DATA AVAILABILITY STATEMENT

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

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