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## Forest effects on runoff under climate change in the Upper Dongjiang River Basin: insights from annual to intra-annual scales

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Zehua Li<sup>1</sup> , Ping Zhou<sup>1</sup>, Xiaogang Shi<sup>2</sup> and Yongkun Li<sup>3</sup><sup>1</sup> Guangdong Open Laboratory of Geospatial Information Technology and Application, Guangzhou Institute of Geography, Guangdong Academy of Sciences, Guangzhou, People's Republic of China<sup>2</sup> School of Interdisciplinary Studies, University of Glasgow, Dumfries, United Kingdom<sup>3</sup> Department of Disaster Prevention and Mitigation, Beijing Water Science and Technology Institute, Beijing, People's Republic of ChinaE-mail: [pzhou@gdas.ac.cn](mailto:pzhou@gdas.ac.cn)**Keywords:** forest effect, climate change, runoff, Upper Dongjiang River Basin**Abstract**

Climate change and large-scale afforestation characterize the conditions in the Upper Dongjiang River Basin (UDRB), which is one of the most important headwater basins in southern China. It is important to understand whether, and to what extent, the observed runoff change can be attributed to forest and/or climate change. Using process- and relation-based methods, we found precipitation in spring (March–May) decreased notably, while precipitation in summer (June–August) showed an increase from the reference period (1961–1990) to the afforestation period (1991–2010). In comparison, annual averaged potential evapotranspiration did not change much. Both of the methods indicated forest had a positive effect while climate change exerted a negative impact on annual averaged runoff in the UDRB. As a result, the observed annual averaged runoff only showed a little decrease from the reference period to the afforestation period. The climate change impact on monthly averaged runoff basically followed the pattern of precipitation change. Except in July and August, climate change exerted negative or little impact on runoff in most of other months. In comparison, the forest effects on monthly averaged runoff change showed a totally different pattern. Except in May and June, forest exerted positive impact on runoff in other months. As a result, the observed monthly averaged runoff in May and June experienced notable reduction, while those in other months experienced increase or no change. The UDRB provides evidence that additional forest cover would not injure but even increase runoff, especially dry season runoff. The study has important implications for sustainable water management and afforestation in this subtropical region and for similar river basins.

**1. Introduction**

In forest-dominated watersheds, forest and climate change have been commonly recognized as two major drivers affecting the hydrologic cycle (Wei and Zhang 2010, Zhang *et al* 2011, Li *et al* 2012, Creed *et al* 2014, Ellison *et al* 2017, Bai *et al* 2020). Although the relationship between forest and water has been extensively studied using paired watershed experiments, the hydrologic responses to forest change and associated mechanisms across multiple spatial scales are not fully understood (Bosch and Hewlett 1982, Stednick 1996, Bruijnzeel 2004, Brown *et al* 2005, Dey and Mishra 2017, Zhang *et al* 2017, Li *et al* 2020a).

As the effects of afforestation or reforestation on water resources have been debated for decades,

numerous studies have been conducted throughout the world to address this concern and concluded that additional forest cover will reduce and removing forests will raise downstream water availability (Trabucco *et al* 2008, Ellison *et al* 2012, Dias *et al* 2015; Liu *et al* 2016). However, some studies, especially in large watersheds, found that afforestation or reforestation have limited effects (Buttle and Metcalfe 2000), no effects (Antonio *et al* 2008), or even positive effects on water resources (Zhou *et al* 2010, Wang *et al* 2011). This issue is becoming increasingly complicated under climate change because shifts in precipitation and temperature can exert a profound impact on the hydrologic cycle and spatio-temporal pattern of water resources (Cuo *et al* 2009, Kang *et al* 2014, Shi *et al* 2015, Li *et al* 2016, Sorribas *et al* 2016, Zhang

*et al* 2018), while increasing carbon dioxide concentration also influences the water and energy balances in land–atmosphere interaction through its effects on plant physiology (Gedney *et al* 2006, Betts *et al* 2007, Mao *et al* 2015, Fowler *et al* 2019). Separating their contributions to hydrologic cycle, especially the runoff process, is essential for understanding and managing interactions between forest and climate change to ensure long-term water availability and ecosystem functions (Liu *et al* 2014; Kang *et al* 2016, Li *et al* 2020a).

As one of several ambitious programs to conserve and expand forest with the goal of mitigating soil erosion, air pollution and climate change in China (Peng *et al* 2014, Chen *et al* 2019), the Guangdong Provincial Government launched a large-scale afforestation program in the 1980s. As part of this program, the land that previously was severely eroded and degraded was planted with forest. As a result of afforestation efforts, forest coverage has increased from approximately 20% in the 1950s to approximately 60% in the 2000s (Zhou *et al* 2010). Satellite imagery shows that, in the period 1989–2009, vegetation cover improved continuously in the Upper Dongjiang River Basin (UDRB) (Peng *et al* 2014). To effectively manage the UDRB, it is important to have an in-depth understanding of how forests have influenced the hydrologic cycle under climate change.

Vegetation restoration is generally positive for watershed health and leads to the reductions in soil erosion and non-point source pollution, enhanced terrestrial and aquatic habitats, and increases in ecosystem carbon sequestration (Sun *et al* 2006). However, the hydrologic responses in the forest coverage of basins may vary by regions (Andreassian 2004). Bosch and Hewlett (1982) conducted basin-scale experiments to determine the influence of vegetation changes on runoff and evapotranspiration, and found the changes in water resources associated with land cover change were highly variable. Jackson *et al* (2005) found that runoff decreased by 227 mm yr<sup>-1</sup> globally because of plantations, and about 13% of streams dried up completely for at least 1 year. Their analyses on 504 annual observations from basins worldwide suggested that runoff decreased dramatically within a few years of planting. The reduction in runoff attributable to afforestation has been explained in the context of the trade-off between forests and water. Using hydrologic models, Sun *et al* (2006) found that the average reductions in runoff ranged from about 50 mm yr<sup>-1</sup> in the semi-arid Loess Plateau region in northern China to about 300 mm yr<sup>-1</sup> in the tropical southern China because of afforestation, and that most areas in Guangdong Province experienced runoff reductions of 20%–30%. However, from the analyses of a 50 year dataset, Zhou *et al* (2010) found that forest recovery from 20% to 57% did not have a significant negative effect on runoff in Guangdong Province. Zhou *et al* (2016) also found that runoff

did not decrease after large-scale afforestation in the Dongjiang River basin. These contradictory results may be due to the complexities of climate change in space and time (Li *et al* 2020a, Niemeyer *et al* 2020). To be specific, although Zhou *et al* (2010) found no significant trends in precipitation over annual, wet or dry season intervals at a regional scale in Guangdong Province, a number of studies have witnessed significant spatio-temporal variability in precipitation across the same region (Wang *et al* 2006, Dong *et al* 2010, Zhou *et al* 2016, Zhang *et al* 2018). Meanwhile, the physiological response of forest to rising CO<sub>2</sub> and its role in regulating evapotranspiration and runoff at the basin scale in this region are also unclear and were rarely studied (Gedney *et al* 2006, Betts *et al* 2007, Fowler *et al* 2019). Therefore, a critical need is highlighted to assess the forest and water relationships under climate change with respects to multiple time scales.

To address this problem, we adopted a process-based method, combined with a relation-based method, to evaluate the effects of forest on runoff under climate change in the UDRB, southern China. The major objectives of this study are (a) to identify the differences in precipitation and potential evapotranspiration (PET) between the reference period (1961–1990) and afforestation period (1991–2010); (b) to simulate the basin runoff process in the UDRB; and (c) to quantify the effects of changing forest on runoff under climate change from annual to intra-annual scales.

## 2. Materials and methods

### 2.1. Study area

The Dongjiang River is one of three main tributaries of the Pearl River Basin in southern China (figure 1). The upper reaches of the Dongjiang River Basin (upstream of the hydrometric gauge at Longchuan) have a drainage area of 7932 km<sup>2</sup>. Water availability in the Dongjiang River Basin is key to sustainable social and economic development of the East Wing of Guangdong-Hong Kong-Macao Greater Bay Area, which comprises the cities of Guangzhou, Shenzhen, Dongguan, Huizhou, and Hong Kong Special Administrative Region.

The forest coverage in the UDRB has increased rapidly since the afforestation program was implemented in Guangdong Province. During the period 1989–2009, the forest coverage in the UDRB increased from 51.0% to 63.3% (table 1) (Peng *et al* 2014). On this basis, the study period of 1961–2010 was divided into a reference period of 1961–1990 and an afforestation period of 1991–2010 for comparative analyses in our study.

### 2.2. Data used

Monthly averaged discharge data for the period 1961–2010 were obtained from the hydrometric

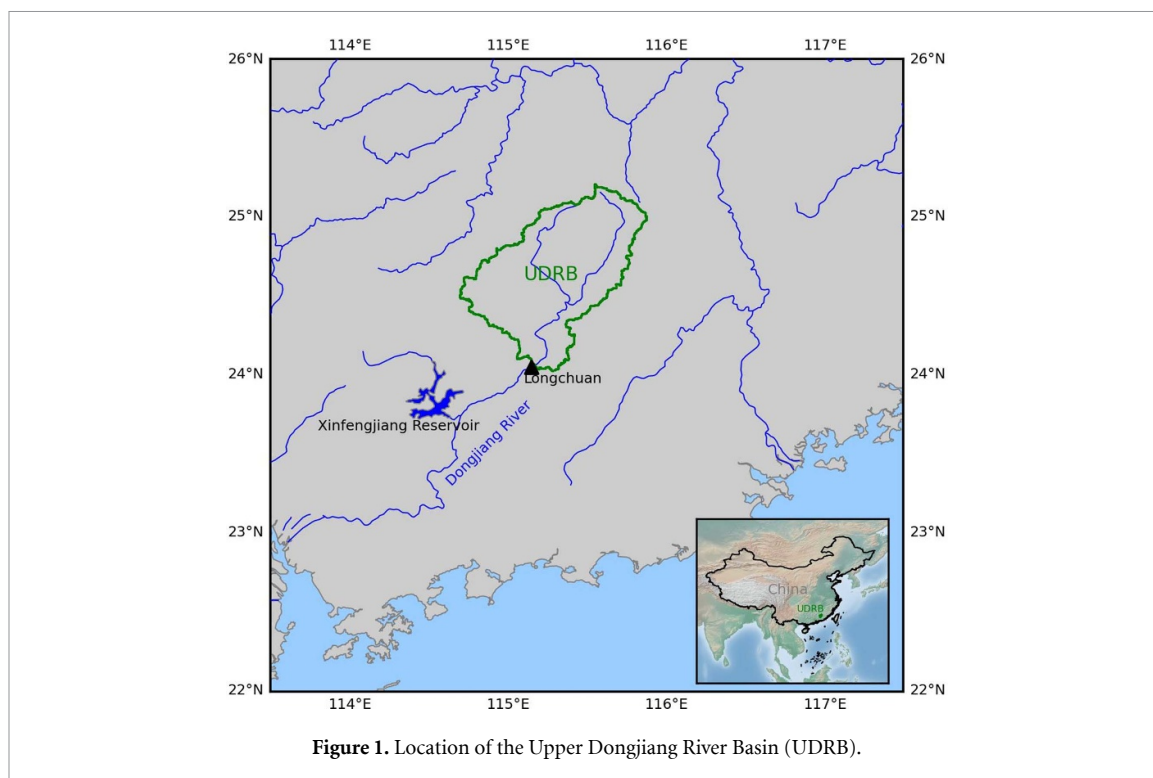


Figure 1. Location of the Upper Dongjiang River Basin (UDRB).

Table 1. Land use/cover of the UDRB in 1989 and 2009.

Year	Arable land	Garden	Pasture	Forest	Urban	Water area	Unused land
1989	8.0%	20.4%	6.0%	51.0%	7.7%	1.0%	6.0%
2009	16.8%	9.5%	1.3%	63.3%	7.2%	0.6%	1.3%

gauge at Longchuan, then monthly averaged runoff time series were generated for the UDRB (upstream of Longchuan). The annual averaged runoff over the UDRB for the study period is  $803 \text{ mm yr}^{-1}$ . Monthly precipitation datasets, gridded using the methods outlined in Wu and Gao (2013), were based on an interpolation from over 2400 observation stations in China. The annual averaged precipitation over the UDRB for the period is  $1624 \text{ mm yr}^{-1}$ . Monthly averaged PET estimates were extracted from the Global Land Data Assimilation System forcing data provided by the United States National Aeronautics and Space Administration (Rodell *et al* 2004). The annual averaged PET over the UDRB for the study period is  $1407 \text{ mm yr}^{-1}$ .

## 2.3. Methods

### 2.3.1. Process-based method

The process-based method adopted in this study is based on the conceptual rainfall-runoff (CRR) model called SIXPAR, which uses two soil layers to represent the subsurface. The upper zone extends from the surface to the bottom of rootzone, while a lower zone represents ground water storage. The percolation process links the upper and lower zones, simulating the effects of gravity and downward suction (Brazil and Hudlow 1980). In this study, we used a modified SIXPAR (Gupta and Sorooshian 1983, Duan *et al*

1992) to simulate river runoff at monthly time steps, with precipitation as the input to the upper zone. The actual evapotranspiration is calculated based on maximum soil water capacity, actual soil water content and PET (Zhao 1992, Li *et al* 2020b). In this study, the model was further modified to include a linear reservoir scheme for routing different runoff components (Zhao 1992). Therefore, the model parameters include: upper and lower zone maximum storage capacities (UM and LM), upper and lower zone recession constants (UK and LK), constants to fit the percolation equation ( $A$  and  $X$ ), and upper and lower zone linear reservoir constants (UR and LR).

In this study, the Multi-objective Shuffled Complex Evolution Metropolis (MOSCEM) algorithm was used for model calibration (Vrugt *et al* 2003). This algorithm is an improvement over the Shuffled Complex Evolution Metropolis (SCEM) global optimization algorithm, which uses an improved concept of Pareto dominance to evolve the initial population of points toward a set of solutions stemming from a stable distribution (Pareto solution set) (Shi *et al* 2008). The MOSCEM algorithm is used to calibrate eight model parameters as mentioned above (as shown in table 2). The criterion used for model calibration and validation to ensure an optimal model performance with respect to both observed annual and monthly time series of runoff is based on

the Nash–Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe 1970), defined as:

$$\text{NSE} = 1 - \frac{\sum (R_{\text{obs}} - R_{\text{sim}})^2}{\sum (R_{\text{obs}} - \bar{R}_{\text{obs}})^2} \quad (1)$$

with simulated ( $R_{\text{sim}}$ ) and observed runoff ( $R_{\text{obs}}$ ) for the calibration period of 1961–1980, and the validation period of 1981–1990, respectively.

Then, the relative contributions of forest and climate change to annual/monthly averaged runoff were estimated. The total change in annual/monthly averaged runoff can be defined as:

$$\Delta R = \Delta R^c + \Delta R^f \quad (2)$$

where  $\Delta R$  for the total change in annual/monthly averaged runoff can be calculated as:

$$\Delta R = R_{\text{oa}} - R_{\text{or}} \quad (3)$$

where  $R_{\text{oa}}$  and  $R_{\text{or}}$  represent the observed annual/monthly averaged runoff in the afforestation period and reference period, respectively.  $\Delta R^f$  and  $\Delta R^c$  represent the change in annual/monthly averaged runoff attributed to forest and climate change, respectively. As the model parameters are invariant through the reference period and the afforestation period, climate change would take effect solely on runoff in model simulation, and  $\Delta R^c$  can be estimated as:

$$\Delta R^c = R_{\text{sa}} - R_{\text{sr}} \quad (4)$$

where  $R_{\text{sa}}$  and  $R_{\text{sr}}$  represent the model simulated annual/monthly averaged runoff in the afforestation period and the reference period, respectively. Once  $\Delta R$  and  $\Delta R^c$  are estimated,  $\Delta R^f$  can be calculated by equation (2).

### 2.3.2. Relation-based method

On the basis of phenomenological considerations, Fu (1981) described the Budyko hypothesis as partial differential equations. Through a combination of dimensional analysis and mathematical reasoning, one analytical solution for annual averaged evapotranspiration was derived (Fu 1981, Zhang et al 2004, Yang et al 2008), and has been analyzed and validated using globally published data (Zhou et al 2015, 2018). Based on the theoretical study by Fu (1981), the dependence of the ratio of annual averaged runoff to annual averaged precipitation ( $R/P$ ) on the wetness index ( $P/\text{PET}$ ) and watershed characteristics ( $m$ ) can be estimated as:

$$\frac{R}{P} = \left( 1 + \left( \frac{P}{\text{PET}} \right)^{-m} \right)^{\frac{1}{m}} - \left( \frac{P}{\text{PET}} \right)^{-1} \quad (5)$$

which also can be written as:

$$R = P \left( 1 + \left( \frac{\text{PET}}{P} \right)^m \right)^{\frac{1}{m}} - \text{PET} \quad (6)$$

with  $R$  for the annual averaged runoff,  $P$  for the annual averaged precipitation,  $\text{PET}$  for the annual averaged potential evapotranspiration, and  $m$  for the watershed characteristics. The values of  $m$  can be determined by the observed  $R$ ,  $P$ , and  $\text{PET}$  in the reference period. Similar to the process-based method, the relative contributions of forest and climate change to annual averaged runoff can be estimated using equations (2)–(4). The relation-based method is used here at annual scale for mutual corroboration with the process-based method.

## 3. Results

### 3.1. Changes in precipitation and PET

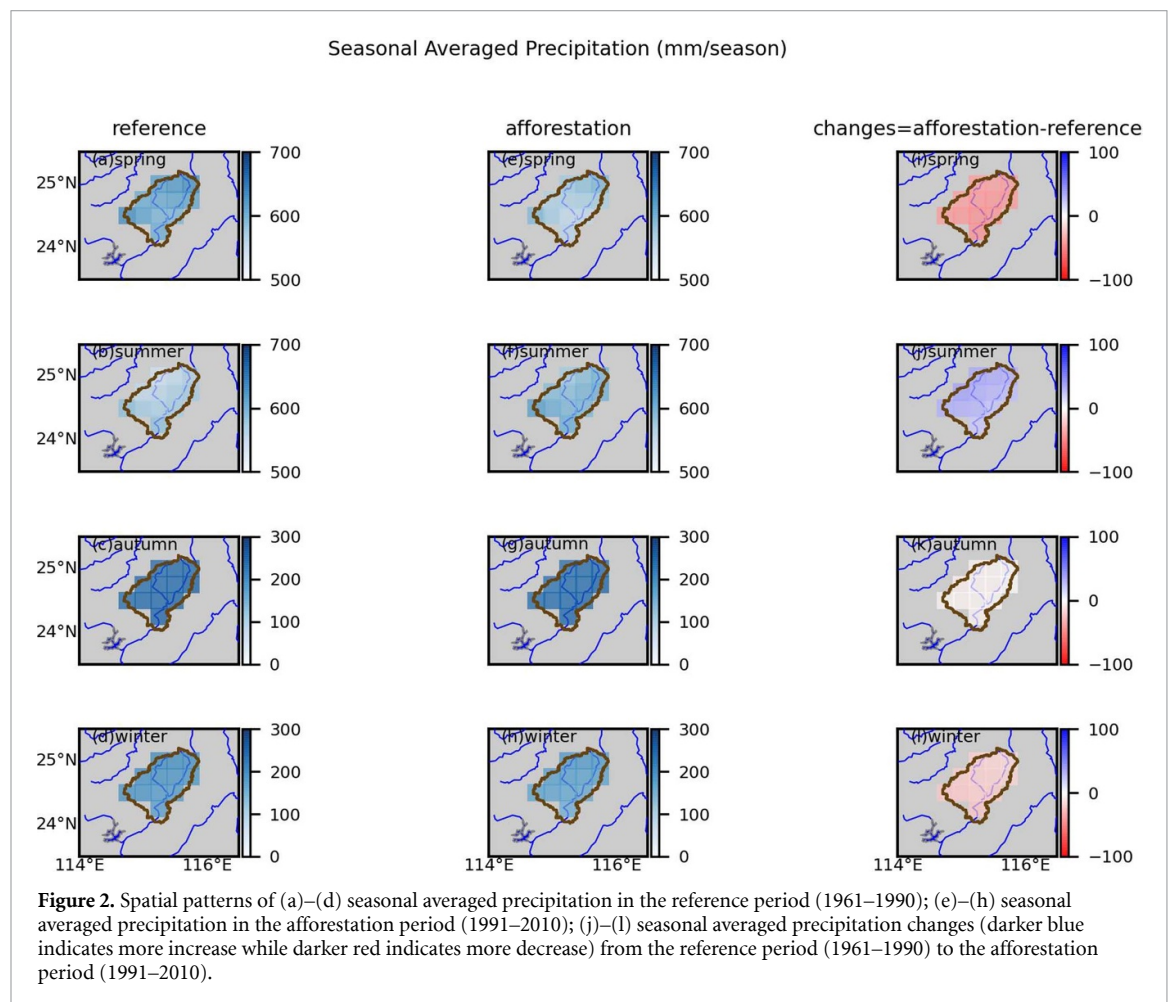
In figure 2, the left and middle series of panels show the spatial distribution of the seasonal averaged precipitation of the UDRB in the reference period and the afforestation period, respectively. The precipitation in spring (March–May) and summer (June–August) is much greater than that in autumn (September–November) and winter (December–February). The right panel in figure 2 presents the spatial distribution of changes in seasonal averaged precipitation from the reference period to the afforestation period. It clearly shows that precipitation in spring decreased notably, while precipitation in summer showed an obvious increase. In comparison, precipitation in autumn and winter did not change much. In figure 3, the upper and lower panel present the annual time series of precipitation and monthly averaged precipitation in the UDRB. The annual averaged precipitation was 1630 mm yr<sup>-1</sup> in the reference period and 1614 mm yr<sup>-1</sup> in the afforestation period, respectively. That means the annual averaged precipitation did not change much in the UDRB. When looking into the monthly scale, however, the intra-annual distribution of precipitation showed notable difference in these two periods. Specifically, the seasonal averaged precipitation in spring (March–May) decreased from 625 mm season<sup>-1</sup> in the reference period to 582 mm season<sup>-1</sup> in the afforestation period, while the seasonal averaged precipitation in summer (June–August) increased from 576 mm season<sup>-1</sup> in the reference period to 645 mm season<sup>-1</sup> in the afforestation period.

In figure 4, the left and middle panel show the spatial distribution of seasonal averaged PET of the UDRB in the reference period and afforestation period, respectively. The right panel in figure 4 indicated the spatial distribution of changes in seasonal averaged PET from the reference period to the afforestation period. We found that the PET did not change much for most of the year, except that PET in autumn showed a slight increase. This was also evident from figure 5, the upper and lower panels of which present the annual time series of PET and monthly averaged PET in the upper reaches of DRB.

**Table 2.** Testing significant differences in precipitation, PET and runoff from annual to monthly scale between the reference period and afforestation period (when Z statistic >1.64 or <-1.64, the significant level is  $p < 0.05$  (one sided)).

Differences between the two periods	Mann–Whitney <i>U</i> -test Z statistic		
	Precipitation	Potential evapotranspiration	Runoff
Annual	-0.17	-0.70	-0.60
January	-0.98	0.88	-2.05 <sup>a</sup>
February	-0.74	-0.24	-2.96 <sup>a</sup>
March	-0.57	-0.34	-1.07
April	-0.44	-0.68	-0.39
May	2.32 <sup>a</sup>	-1.38	2.08 <sup>a</sup>
June	-0.69	1.33	1.16
July	-0.40	-1.04	-1.11
August	-0.96	0.04	-0.60
September	0.13	-0.91	-1.00
October	1.94 <sup>a</sup>	-2.17 <sup>a</sup>	-0.18
November	1.29	-1.20	-0.25
December	-0.99	-0.67	-0.94

<sup>a</sup> Significant at  $p = 0.05$ .



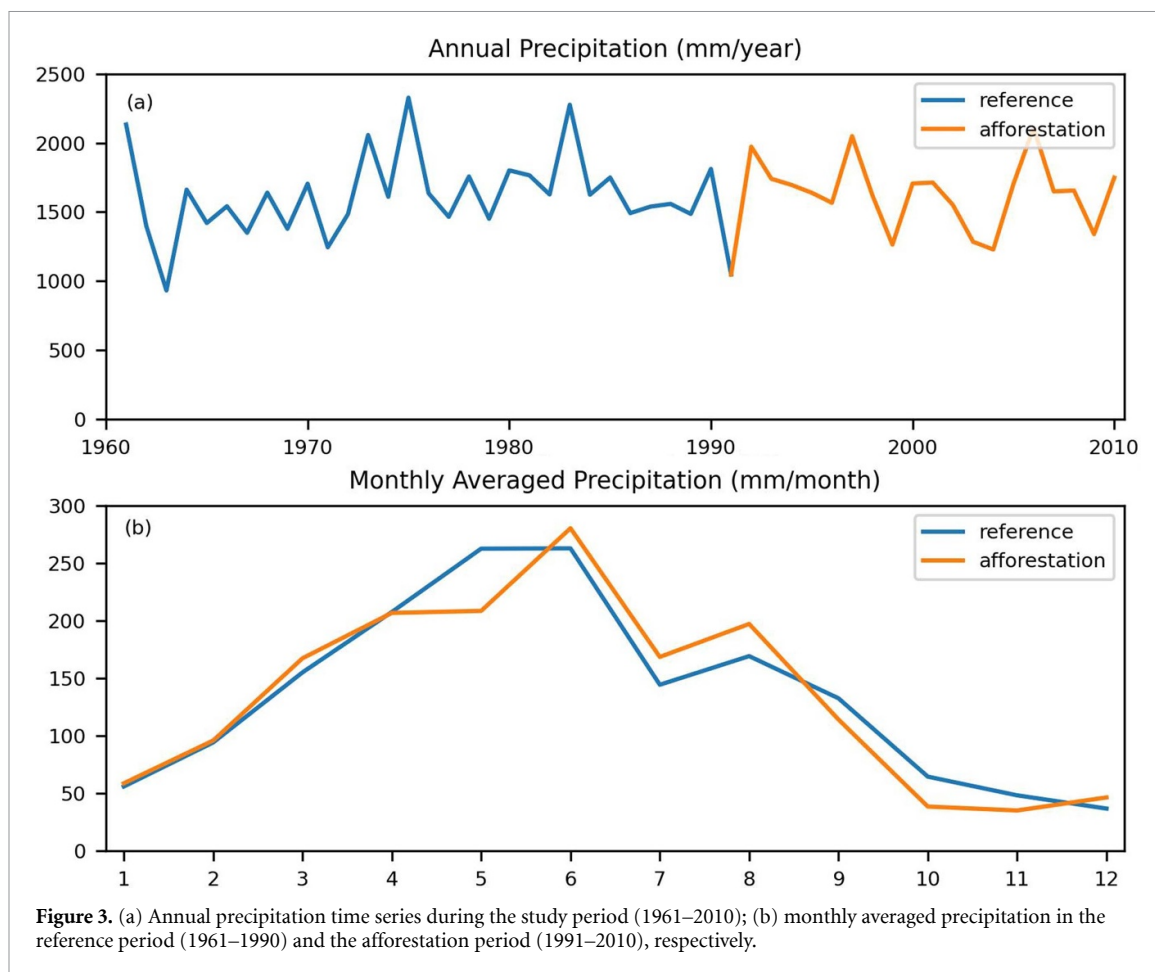
**Figure 2.** Spatial patterns of (a)–(d) seasonal averaged precipitation in the reference period (1961–1990); (e)–(h) seasonal averaged precipitation in the afforestation period (1991–2010); (i)–(l) seasonal averaged precipitation changes (darker blue indicates more increase while darker red indicates more decrease) from the reference period (1961–1990) to the afforestation period (1991–2010).

According the results from Mann–Whitney *U* test, there was no significant ( $p < 0.05$ ) difference in annual averaged precipitation, PET or runoff between the reference period and afforestation period (table 2). Our results also highlighted the differences at monthly scale. To be specific, the precipitation had significant differences in May and October, while the runoff had significant differences in January,

February and May. Besides, the PET had significant differences only in October.

### 3.2. CRR model calibration and evaluation

Annual and monthly NSE were used for model calibration to ensure an optimal model performance with respect to both observed annual and monthly time series of runoff. Figure 6 illustrates the concept of



**Figure 3.** (a) Annual precipitation time series during the study period (1961–2010); (b) monthly averaged precipitation in the reference period (1961–1990) and the afforestation period (1991–2010), respectively.

**Table 3.** Method parameters with values and units.

Methods	Parameters	Values	Units
Process-based	UM	25.75 ~ 46.59	mm
	LM	32.03 ~ 69.95	mm
	UK	0.10 ~ 0.24	—
	LK	0.08 ~ 0.16	—
	A	0.53 ~ 0.70	—
	X	4.31 ~ 21.32	—
	UR	0.54 ~ 0.76	—
	LR	0.987 ~ 0.990	—
Relation-based	$m$	1.86	—

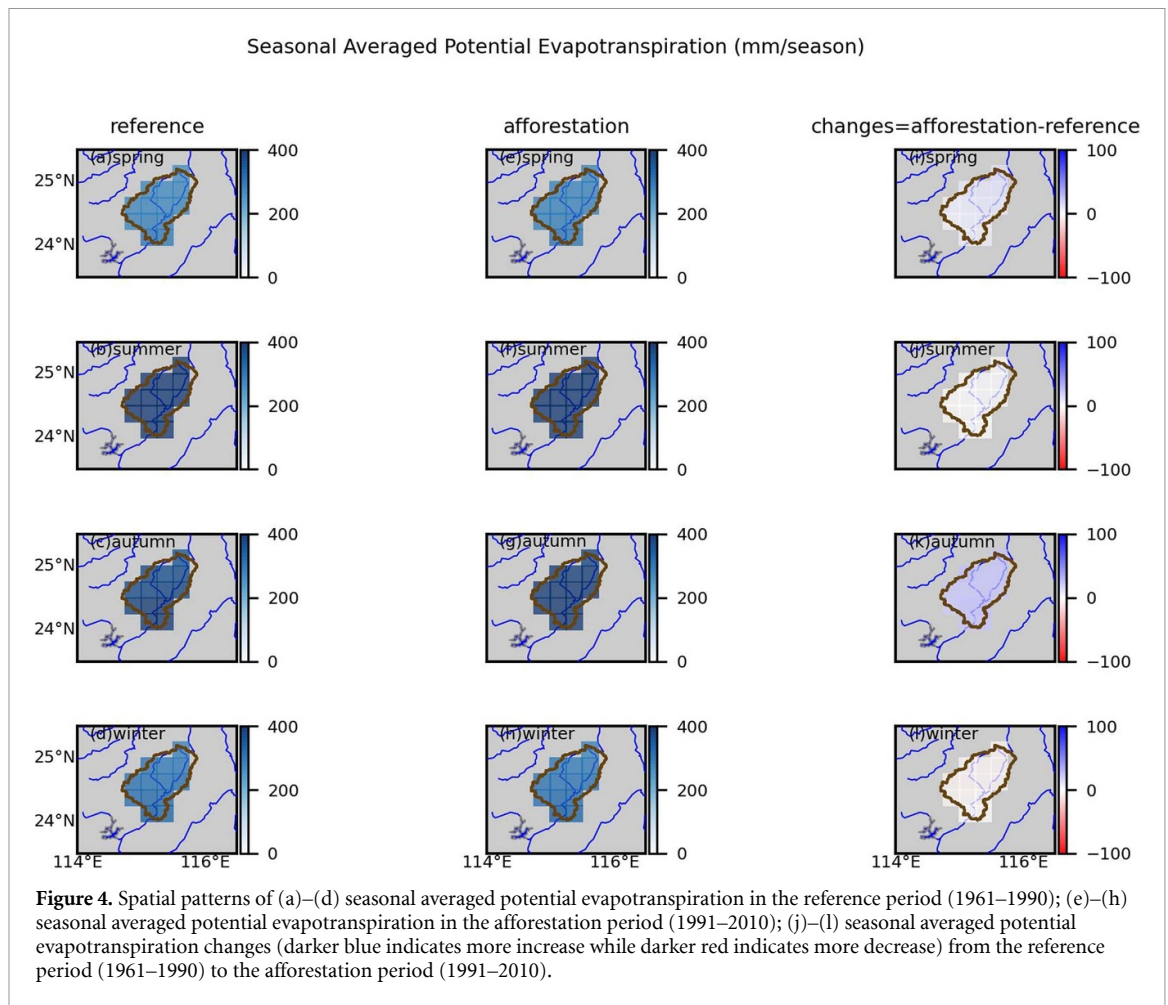
Pareto dominance to evolve the initial population of points (grey dots) toward a set of solutions stemming from a stable distribution (Pareto solutions, black dots), with respect to observed annual and monthly time series of runoff (annual and monthly NSE). The resulting Pareto sets are then selected as the optimal solutions for further evaluation and analysis. The selected parameters are listed in table 3.

The simulated uncertainty ranges of runoff (shaded area) associated with the Pareto solution set estimated using the MOSCEM algorithm are displayed in figure 7, with the observed runoff are indicated with solid line for comparison (Vrugt *et al* 2003). As mentioned above, the model parameters

(representing the underlying surface characteristics) in the process-based method were kept invariant through the reference period and afforestation period, in order to separate the contributions of forest and climate change to runoff change. From the simulation results (table 4), we can see that the model consistently had a better performance simulating the runoff changes in the reference period (with higher NSE values) than in the afforestation period (with lower NSE values). The difference of NSE values between the two periods witnessed that the forest had exerted a great influence on the hydrologic cycle in the UDRB, through altering the underlying characteristics in response to the changing environment.

### 3.3. Effects of forest on runoff under climate change

As listed in table 5, the estimated contribution of climate change to annual averaged runoff change from the reference period to the afforestation period ranged from  $-50 \text{ mm yr}^{-1}$  to  $-25 \text{ mm yr}^{-1}$ , as compared with  $+21 \sim +47 \text{ mm yr}^{-1}$  attributed to forest effects in the UDRB based on the results of process-based method. The relation-based method (parameters listed in table 2) provided similar estimates, with the estimated contribution ( $-21 \text{ mm yr}^{-1}$ ) of climate change to annual averaged runoff change from



**Table 4.** CRR model performance with respect to annual and monthly NSE.

Period		Annual NSE	Monthly NSE
Reference period (1961–1990)	Calibration period (1961–1980)	0.92 ~ 0.97	0.87 ~ 0.89
	Validation period (1981–1990)	0.82 ~ 0.87	0.69 ~ 0.73
Afforestation period (1991–2010)		0.76 ~ 0.81	0.64 ~ 0.68

**Table 5.** Changes in runoff from the reference period to the afforestation period attributed to forest and climate change at the annual scale.

Method	$\Delta R^c$ (mm yr <sup>-1</sup> )	$\Delta R^f$ (mm yr <sup>-1</sup> )	$\Delta R$ (mm yr <sup>-1</sup> )
Process-based	-50 ~ -25	+21 ~ +47	
Relation-based	-21	+18	-3

the reference period to the afforestation period, compared with +18 mm yr<sup>-1</sup> attributed to forest effects. Both methods indicated that forest had a positive effect while climate change exerted a negative impact on runoff in the UDRB. As a result, the observed annual averaged runoff only showed a little reduction (-3 mm yr<sup>-1</sup>) from the reference period to the afforestation period.

Furthermore, the process-based method could help us look inside the forest effects at the intra-annual scale. The estimated contributions of forest and climate change to monthly averaged runoff change from the reference period to the afforestation period based on the process-based method results are listed in table 6. The estimated contribution of climate change to monthly averaged runoff basically followed the pattern of precipitation change. Except in July and August, climate change exerted negative or little impact on runoff during the year. The spring (March–May) became the season in which the runoff experienced the largest negative impact by climate change. In comparison, the estimated contribution of forest effects to monthly averaged runoff showed a totally different pattern. Except in May and June, forest exerted positive or little impact on runoff during the year, while the winter (December–February) experienced the largest positive impact on runoff.



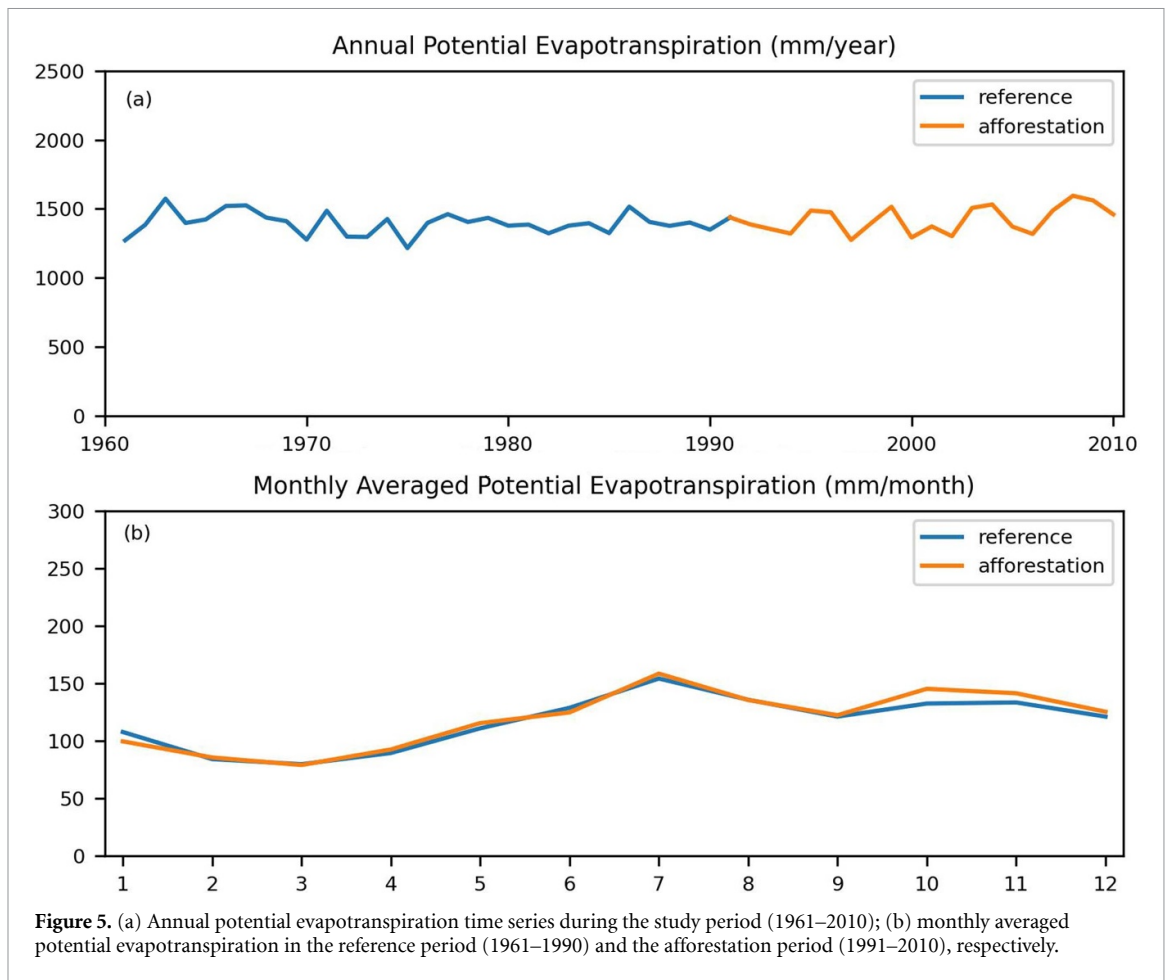


Figure 5. (a) Annual potential evapotranspiration time series during the study period (1961–2010); (b) monthly averaged potential evapotranspiration in the reference period (1961–1990) and the afforestation period (1991–2010), respectively.

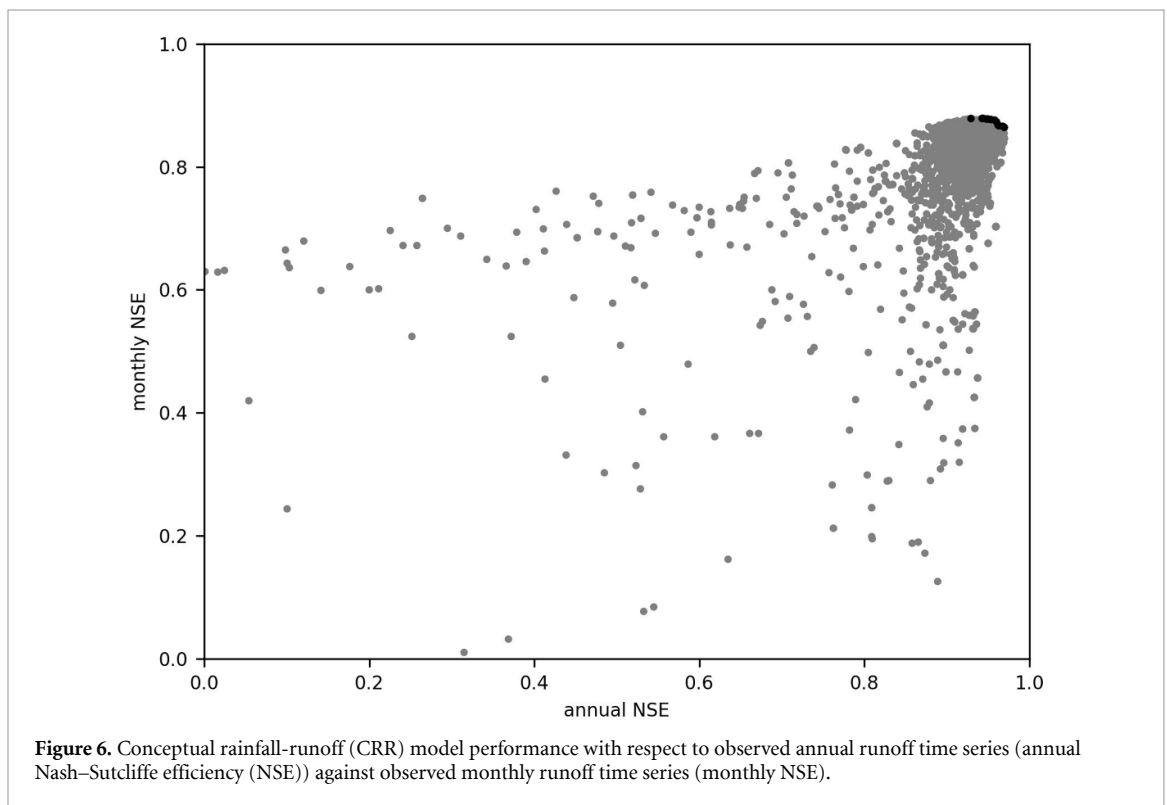
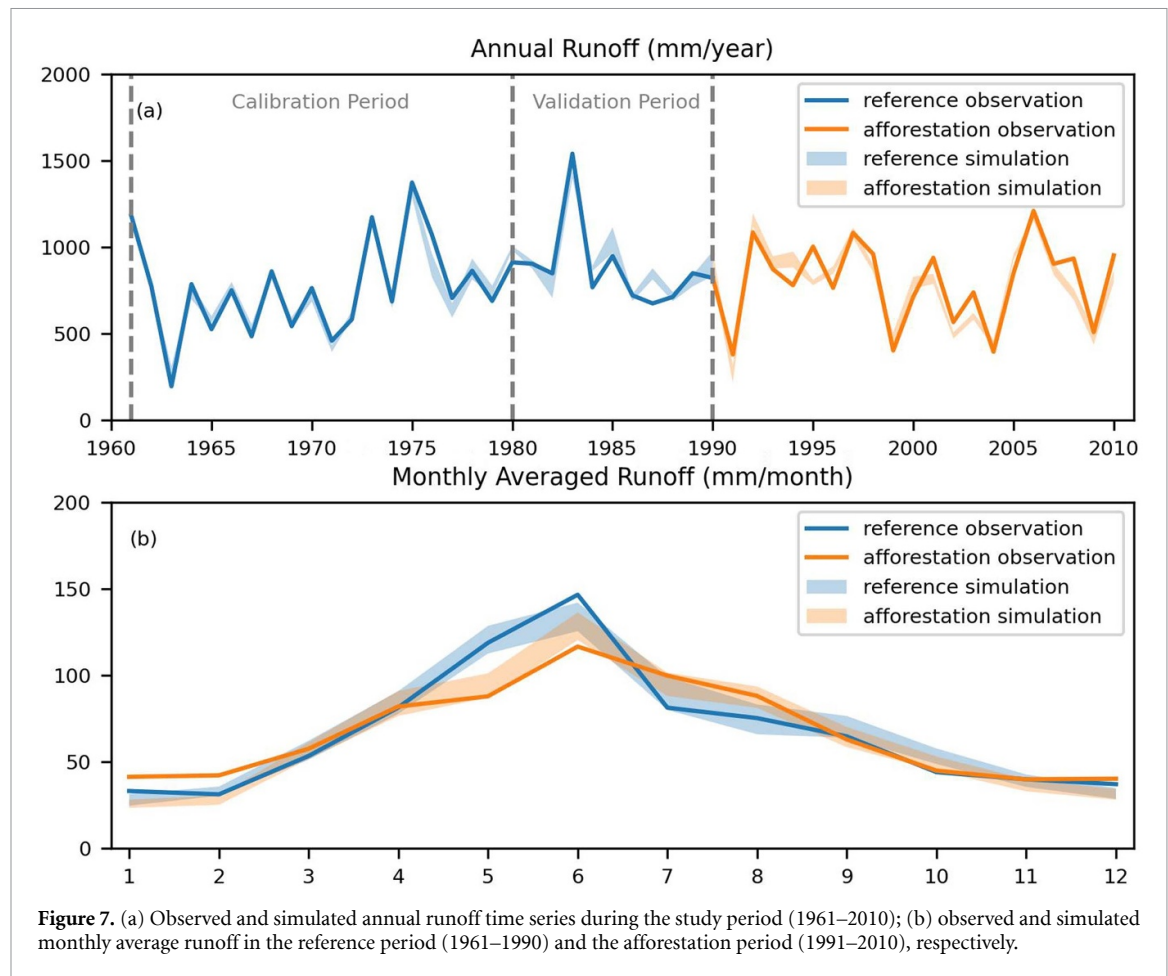


Figure 6. Conceptual rainfall-runoff (CRR) model performance with respect to observed annual runoff time series (annual Nash–Sutcliffe efficiency (NSE)) against observed monthly runoff time series (monthly NSE).

As a result, the observed monthly averaged runoff in May and June experienced notable reduction, while those in other months experienced increase or no

change. The UDRB provides evidence that additional forest cover would not injure but even increase runoff, especially dry season runoff.



**Table 6.** Changes in runoff from the reference period to the afforestation period attributed to forest and climate change at the monthly scale.

Month	$\Delta R^c$ (mm month <sup>-1</sup> )	$\Delta R^f$ (mm month <sup>-1</sup> )	$\Delta R$ (mm month <sup>-1</sup> )
January	-2 ~ -1	+10 ~ +11	+8
February	-6 ~ -4	+15 ~ +17	+11
March	-1 ~ +1	+3 ~ +5	+4
April	-1 ~ 0	0 ~ +1	+1
May	-29 ~ -25	-6 ~ -2	-31
June	-9 ~ -4	-26 ~ -21	-30
July	0 ~ +10	+9 ~ +19	+19
August	+9 ~ +17	-4 ~ +4	+13
September	-9 ~ -4	+2 ~ +7	-2
October	-5 ~ -4	+5 ~ +6	+1
November	-4 ~ -2	+2 ~ +4	0
December	-1 ~ 0	+3 ~ +5	+3

## 4. Discussion

### 4.1. Precipitation and PET change

This study provided an insight of climate change and large-scale afforestation impacts on runoff from annual to intra-annual scale in the UDRB during the past decades. Our results indicated there was almost no change in the annual averaged precipitation. However, precipitation in spring decreased notably, while that in summer showed an obvious increase from the reference period to the afforestation period. This finding agreed with previous studies (Zhou *et al*

2010, 2016). The reasons for the precipitation change might be complicated. It is well known that the climate has been changing with the changed hydrologic cycle, including the precipitation patterns globally and regionally (Ellison *et al* 2017). In addition, forest also plays an active role in regulating atmospheric moisture fluxes and precipitation patterns (Ellison *et al* 2017). Our results also indicated that the PET did not change much during the year, except for a slight increase in autumn, similar to the findings in Zhou *et al* (2010). We also understand that forests play a large role in regulating fluxes of atmospheric moisture

**Table 7.** Forest effects on runoff under climate change in basins experiencing afforestation/reforestation with different initial forest coverage.

Study area	Forest coverage in the 1980s	Forest effects on runoff under climate change	Reference
Duero River Basin (Spain)	50%	Runoff increase	Antoio <i>et al</i> (2008)
Guangdong Province (China)	30%	No effect	Zhou <i>et al</i> (2010)
Adjungbilly Creek Catchment (Australia)	20%	Runoff reduction	Zhang <i>et al</i> (2011)
Poyang River Basin (China)	30%	Runoff reduction	Liu <i>et al</i> (2014)
Heihe River Basin (China)	50%	Runoff increase	Wu <i>et al</i> (2015)
Yellow River Basin/Loess Plateau (China)	25%	Runoff reduction	Wang <i>et al</i> (2016)
Upper Dongjiang River Basin (China)	51%	Runoff increase	This study

and rainfall patterns over land (Ellison *et al* 2017). However, as this issue is well beyond our research scope, as well as our framework and methodology, we would rather attribute the precipitation change to the changing climate and put the focus on the direct forest effects on runoff.

#### 4.2. Separation of the impacts of forest and climate change on runoff

Climatic variability and land cover/use changes are commonly recognized as two major drivers for hydrologic regimes. The methods, namely process- and relation-based methods, were used in this study to separate the impacts of forest and climate change on runoff. The relation-based method derived from Fu's equation (Fu 1981), had been confirmed as a valid framework for quantifying the effects of land cover and climate on hydrology (Zhang *et al* 2004, Yang *et al* 2008). According to the recent works based on Fu's equation on global runoff pattern (Zhou *et al* 2015, 2020), afforestation can increase runoff in large watersheds ( $m > 2$ ) or humid regions ( $P/PET > 1$ ). The UDRB with a drainage area of 7932 km<sup>2</sup> ( $m \approx 1.86$ ) and  $P/PET \approx 1.15$  provides evidence that additional forest cover would not injure but even increase runoff at annual scale. At monthly scale, our process-based method results witnessed that afforestation would increase dry season flows where improvements in soil infiltration capacity and groundwater recharge exceed increased evapotranspiration (Bruijnzeel 2004, Zhou *et al* 2010, Ellison *et al* 2017).

#### 4.3. The importance of physiological responses of forest to rising CO<sub>2</sub> on runoff

Regarding to the basins experiencing afforestation/reforestation, the forest effects can be divided into two parts, namely the initial and additional forest coverages. The results of previous studies on the relationship between forest and water are

highly variable, especially in the basins experiencing afforestation/reforestation. We found some new findings regarding the initial forest coverage of those basins (table 7). For the basins with smaller initial forest coverage (e.g. lower than 30%), the runoff showed decreasing trends after afforestation/reforestation (Zhang *et al* 2011, Liu *et al* 2014, Wang *et al* 2016). In contrast, the runoff in the basins (e.g. UDRB) with larger initial forest coverage (e.g. higher than 30%) was found with no or increasing trends after afforestation/reforestation (Antonio *et al* 2008, Zhou *et al* 2010, Wu *et al* 2015). We understand that the physiological responses of forest to rising CO<sub>2</sub> may reduce plant transpiration through stomatal closure (Gedney *et al* 2006, Betts *et al* 2007, Fowler *et al* 2019). From a hydrologic perspective at the basin scale, the importance of physiological responses of forest to rising CO<sub>2</sub> on evapotranspiration and runoff directly depended on the initial forest coverage, and potentially explained the different runoff responses of those basins experiencing afforestation/reforestation. To be specific, as climate change progresses and CO<sub>2</sub> rises, the basins with larger initial forest coverage would result in more transpiration reduction from the initial forest cover than the basins with smaller initial forest coverage, then would be more likely to offset or even surpass the transpiration increase from the additional forest cover and sustain more runoff in comparison.

#### 4.4. Implications for future work

The effects of forest on runoff have been debated for a long time. This issue would become more complicated involving deforestation, afforestation or reforestation. Numerous studies have been conducted throughout the world to address this concern. By using a combination of process- and relation-based methods, this study revealed that the balance of forest and climate change has resulted in a slight reduction in runoff in the UDRB over the past decades. Our results provided new evidence that additional forest

cover would not injure but even increase runoff, especially dry season runoff (Sun *et al* 2006, Ellison *et al* 2017, Bai *et al* 2020). Limited to the framework and methodology, our study attributed the precipitation change completely to the changing climate and cut off the linkage between the forests and the precipitation. However, forests-driven evapotranspiration contributes to the availability of atmospheric moisture vapor and its transport locally and regionally, raising the likelihood of precipitation events and increasing runoff (Ellison *et al* 2012, 2017). And this mechanism is becoming more complicated under the changing climate and rising CO<sub>2</sub> concentration (Fowler *et al* 2019). Therefore, more efforts are needed to improve the understanding of water-energy balance and associated biophysical processes between land-atmosphere interactions in forest-dominated watersheds.

## 5. Conclusions

Using process- and relation-based methods, we have investigated the forest and climate change effects on runoff in the UDRB during the last few decades from annual to intra-annual scales. Our key findings are (a) precipitation in spring (March–May) decreased notably, while precipitation in summer (June–August) showed an obvious increase from the reference period (1961–1990) to the afforestation period (1991–2010). In comparison, annual averaged PET did not change much; (b) both of the process- and relation-based methods indicated forest had a positive effect while climate change exerted a negative impact on annual averaged runoff in the UDRB. As a result, the observed annual averaged runoff only showed a little reduction from the reference period to the afforestation period; (c) the climate change on monthly averaged runoff basically followed the pattern of precipitation change. Except in July and August, climate change exerted negative or little impact on runoff. In comparison, the forest effects on monthly averaged runoff change showed a totally different pattern. Except in May and June, forest exerted positive impact on runoff. As a result, the observed monthly averaged runoff in May and June experienced notable reduction, while those in the other months experienced increase or no change. The UDRB provides evidence that additional forest cover would not injure but even increase runoff, especially dry season runoff.

## Data availability statement


The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.7910/DVN/6JQ5Y3>.

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