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Key Points:

- Both precipitation and afforestation explained reduction in runoff for dry basins
- Forest recovery did not result in significant changes in total runoff for two wet basins
- Dry season baseflow in two wet basins had an upward trend

Supporting Information:

Supporting Information may be found in the online version of this article.

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Divergent Hydrological Responses to Forest Expansion in Dry and Wet Basins of China: Implications for Future Afforestation Planning

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Abstract Afforestation to control soil erosion has been implemented throughout China over the past few decades. The long-term hydrological effects, such as total water yield and baseflow, of this large-scale anthropogenic activity remain unclear. Using six decades of hydrologic observations and remote sensing data, we explore the hydrological responses to forest expansion in four basins with contrasting climates across China. No significant change in runoff was found for the period 1970–2012 for the cold and dry Hailar River Basin in northeastern China. However, both forest expansion and reduced precipitation contributed to the runoff reduction after afforestation since the late 1990s. Similarly, afforestation and drying climate since the mid-1990s induced a significant decrease in runoff for the Weihe River Basin in semi-arid northwestern China. In contrast, the two wet basins in the humid southern China, Ganjiang River Basin and Dongjiang River Basin, showed insignificant changes in total runoff during their study periods. However, the baseflow in the winter dry seasons in these two watersheds significantly increased since the 1950s. Our results highlight the long-term variable effects of forest expansion and local climatic variability on basin hydrology in different climatic regions. This study suggests that landuse change in the humid study watersheds did not cause dramatic change in river flow and that region-specific afforestation policy should be considered to deal with forestation-water quantity trade-off. Conclusions from this study can help improve decision-making for ecological restoration policies and water resource management in China and other countries where intensive afforestation efforts are taking place.

1. Introduction

China has played a leading role in global greening efforts over the past few decades (Li et al., 2018; Zhu et al., 2016). Recently, the country sets a goal of achieving peak carbon and carbon neutrality by 2030 and 2060, respectively. This requires a systematic and nature-based strategy to offset anthropogenic carbon dioxide (CO_2) emissions. Enhancing China's carbon sink by planting forests in new areas is an appealing option. Afforestation is generally an effective way to sequester CO_2 and to improve environmental conditions through better water conservation, water quality, sand fixation, and other ecosystem services (Bosch & Hewlett, 1982; Chen et al., 2015; Domke et al., 2020; Piao et al., 2020; Wei et al., 2018; Zhu et al., 2016). Since the early 1950s, China's central government has implemented a series of national policies to address pressing environmental problems. Specifically, to alleviate land degradation and soil erosion, the government has successively implemented multiple nationwide ecosystem restoration programs such as the "Three-North Forest Shelterbelt Program" (since 1979) and the "Grain for Green Program" (GGP; since 1999), particularly in the semiarid and arid northern areas of the country. These programs along with nationwide afforestation efforts have increased China's total forest area from

1.22×10^6 km^2 in the mid-1970s to 2.2×10^6 km^2 to date. As a result, forest coverage has now reached 22.96% of China's land area (National Forestry and Grassland Administration of China, 2018; State Forestry Administration of China, 1977), and the country has the largest area of planted forests in the world (National Forestry and Grassland Administration of China, 2018; Piao et al., 2020; State Forestry Administration of China, 1977; Zhu et al., 2016).

Afforestation or the restoration of croplands or grasslands to forests may have profound effects on the local or regional environment through regulation of the hydrological balance and surface energy exchange (Andréassian, 2004; Bonan, 2008; Piao et al., 2020). The question of how afforestation affects local to regional water yield (i.e., the remaining terrestrial rainwater after losses to the atmosphere via evapotranspiration [*E*]) has attracted growing attention, considering the large area and long duration of the programs implemented across China (Sun et al., 2006). Ecological restoration programs, such as the GGP, have benefited controlling the soil erosion and poverty in the region (Lü et al., 2012). However, large scale reforestation programs in China have caused concerns on water resources-a key ecosystem services, especially for dry regions (Chen et al., 2015; Feng et al., 2016; Y. Liu et al., 2016; M. Zhang et al., 2017). Generally, there are two groups of studies with contrasting conclusions on the effects of afforestation on runoff. One group argues that afforestation has a negative effect on a basin's water yield mainly owing to an enhanced *E* (Andréassian, 2004; Brown et al., 2005; Feng et al., 2016; Swank & Douglass, 1974; Xiao et al., 2020; M. Zhang et al., 2021; Zhao et al., 2021). The other group suggests that forests retain more water through their deep root system via increasing soil water storage (Li et al., 2018; Ward et al., 2021; Yao et al., 2016; W. Zhang et al., 2016; Zhou et al., 2010). Observations support both groups to some extent, indicating that a more detailed exploration of the hydrological response to afforestation is required (Ward et al., 2021; Xiao et al., 2020; J. Zhang et al., 2021; Zhao et al., 2021; Zhou et al., 2010).

The difficulty in establishing the extent to which afforestation affects runoff lies in the complex interactions between the vegetation and hydrological systems. Previous studies showed that water yield responses to afforestation or reforestation are strongly scale-dependent (M. Zhang et al., 2017). For example, afforestation in small basins can substantially reduce runoff, while for large basins the hydrological effects of afforestation are inconsistent and show both positive (increasing runoff) and negative (decreasing runoff) effects (Li et al., 2018; M. Zhang et al., 2017). These inconsistencies are due to the heterogeneity of forest cover, climate, forest types, and geology (Moore & Wondzell, 2005; Vose et al., 2011). Some studies showed that changes in runoff induced by afforestation are dependent upon the local climate and whether the basin is water- or energy-limited (e.g., Li et al., 2018; Liang et al., 2015; Zhou et al., 2010). For example, Zhou et al. (2015) showed that changes in runoff are more sensitive to land cover changes, such as afforestation, in water-limited areas than that in humid energy-limited basins. The *E* and runoff of water-limited basins are relatively low, and the hydrological changes caused by afforestation are thus relatively large (Feng et al., 2016; Zhou et al., 2021). In contrast, in energy-limited areas, where are usually accompanied with plenty of precipitation and large runoff, hydrological response is much less affected by relatively small land cover changes because of pre-existing ample vegetation coverage (Y. Liu et al., 2016; J. Zhang et al., 2022; Zhou et al., 2010). Further, *E* may not change much for the limited atmospheric demand, and thus will have less influence on the runoff (Breil et al., 2021; Li et al., 2018; Williams et al., 2012). Another previous study showed that the sensitivity of runoff to forest change increases with the aridity of the basin, while this depends on the spatial scale of the basin (Zhou et al., 2015). Therefore, extrapolating conclusions from small-scale basins to large-scale basins may be misleading. Another reason for the lack of agreement on the runoff response to afforestation is the absence of high-quality and high-frequency runoff data. Most previous analyses were conducted over a relatively short period, usually less than a decade, while the hydrologic effects may change over time (Andréassian, 2004; Ellison et al., 2012; Wei et al., 2008; M. Zhang et al., 2017).

Considering China's ambitious target to achieve carbon neutrality by 2060, afforestation, a nature-based solution, is expected to continue to be encouraged in the coming decades. To achieve a trade-off between carbon sequestration and water yield, especially in dry areas, the elucidation of the hydrological consequences of afforestation is essential to inform the country's greening policy. Here, we focused on four basins in China covering contrasting climates to examine changes in runoff because of changes in forest area over more than three decades. Detailed and long-term runoff data, as well as other auxiliary meteorological data and several remote sensing products, were analyzed to explore runoff changes due to forest expansion. Specifically, we addressed the following research questions: (a) How have forest coverage, climatic variables, and runoff changed in the last three to six decades in

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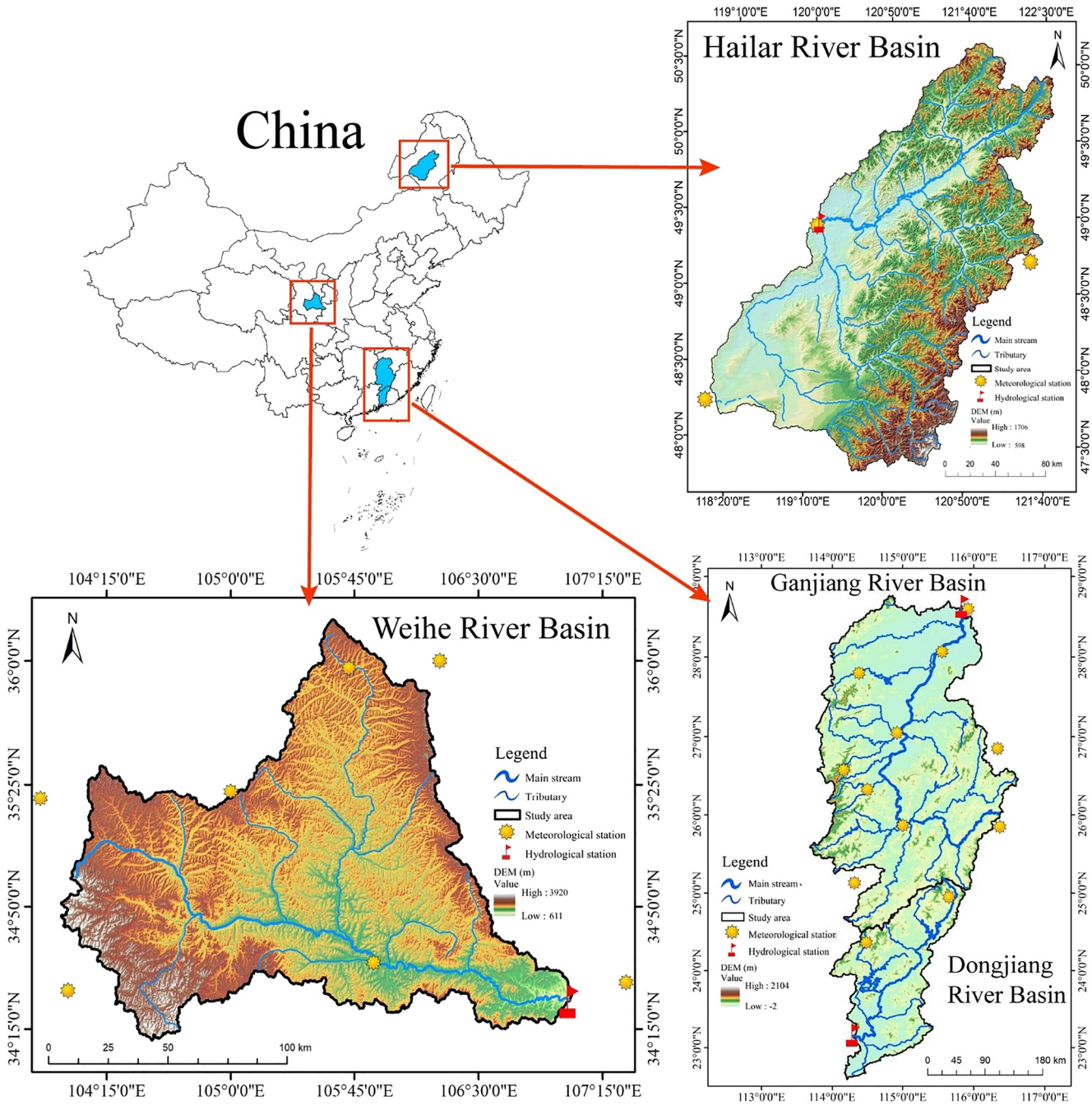

Figure 1. Locations of Ganjiang River Basin (GRB), Dongjiang River Basin (DRB), Weihe River Basin (WRB), and Hailar River Basin (HRB). Two basins are located in northern and two in southern China with dry and wet climates, respectively.

the four basins? (2) What are the relative contributions of climate and forest change to the differences in runoff in these basins? (3) Does the change in forest area have a similar effect on basin hydrology in all four basins?

2. Materials and Methods

2.1. The Study Area

Our study area consists of four basins: (a) Ganjiang River Basin (GRB); (b) Dongjiang River Basin (DRB); (c) Weihe River Basin (WRB); and (d) Hailar River Basin (HRB; Figure 1; Table S1 in Supporting Information S1).

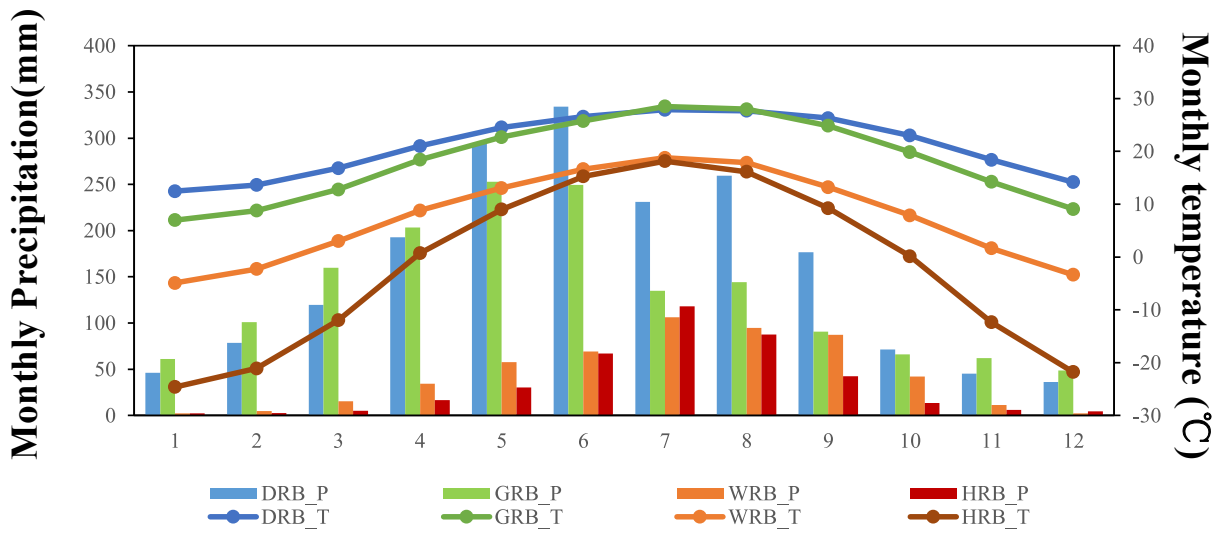

Figure 2. Monthly mean precipitation (P, mm) and temperature (T, °C) for the four basins.

The GRB and DRB are both relatively wet basins (mean annual precipitation of 1,575 and 1,886 mm yr^{-1}, respectively), in southern China. The WRB and HRB are relatively dry basins (mean annual precipitation of 528 and 397 mm yr^{-1}, respectively), located on the Loess Plateau in northern and northeastern China, respectively (Figure 1). The four basins cover areas ranging from ~25 × 10^3 to 81 × 10^3 km^2 with distinct climatic conditions and land covers. The two wet basins (i.e., GRB and DRB) are warmer, and precipitation mainly occurs during the spring and summer (green and blue in Figure 2); in contrast, the two dry basins (i.e., WRB and HRB) are characterized by low temperatures during the winter and contrasting high temperatures during the spring and summer, with precipitation mainly concentrated in summer (orange and red in Figure 2). The HRB and the DRB have the lowest and highest winter temperature, respectively.

2.2. Meteorological Variables

The climatic variability is represented by precipitation (P, mm) and potential evapotranspiration (E_p, mm day^{-1}). Annual P was calculated as the sum of the daily P within a year, which was obtained from the China Meteorological Administration (http://data.cma.cn/) and collected by stations located in each basin and its surrounds. The number of dry days ($P = 0$ mm) and the number of days with little P ($P < 10$ mm) were also analyzed to explore the seasonal change in P, following a previous study (Zhou et al., 2011). Meanwhile, the meteorological data of daily mean air temperature (T, °C), relative humidity (%), daytime length (hr), and wind speed (m s^{-1}) were also collected to calculate E_p. These data were spatially interpolated using the thin plate spline method (Dubrule, 1984) to generate gridded data sets with a spatial resolution of 10 km × 10 km that covered each of the four basins. E_p was calculated from the Penman equation (Penman, 1948) as follows:

$$E_p = \frac{\Delta \cdot R_n + \gamma \cdot 6.43 \cdot (1 + 0.536 \cdot U_2)(e_s - e_a)}{\lambda \cdot (\Delta + \gamma)} \tag{1}$$

where λ is the latent heat of vapourization (MJ kg^{-1}), Δ is the slope of the saturated vapor pressure curve (kPa °C^{-1}), R_n is the net radiation (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa °C^{-1}), u_2 is wind speed (m s^{-1}), and e_s and e_a are saturated and actual vapor pressure (kPa), respectively.

To explore the interannual changes in actual evapotranspiration (E) f, we obtained four global E data products derived by various methods (Table S2 in Supporting Information S1). These included: E from the research group of Zhang et al. (2010) (hereafter Zhang, http://www.ntsg.umt.edu/); E from the Global Land Evaporation Amsterdam Model (hereafter GLEAM, https://www.gleam.eu/): E from FLUXNET modeling by Jung et al. (2011; hereafter Jung, https://www.bgc-jena.mpg.de/); and E from the ECMWF Reanalysis v5 (ERA5; hereafter ERA, https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). These data cover the global land surface

Table 1
Basin Characteristics and Long-Term Average Precipitation (P, mm), Actual Evapotranspiration (E, mm), Potential Evaporation (E_p, mm), Runoff (R, mm), and Elasticity for the Four Basins

Basin		P	E_p	Q	E	n	ε_P	ε_{Ep}	ε_n
Ganjiang River Basin (GRB)	**All (1954–2014)**	**1,568**	**1,189**	**844**	**724**	**1.11**	**1.49**	**−0.49**	**−0.53**
	Period I (1954–1983)	1,578.8	1,210.4	846.2	732.5	1.1085	1.4961	−0.4961	−0.5329
	Period II (1984–2014)	1,558.4	1,168.0	842.7	715.7	1.1135	1.4922	−0.4922	−0.5189
Dongjiang River Basin (DRB)	**All (1959–2011)**	**1,914.5**	**1,372.0**	**939.0**	**975.4**	**1.4198**	**1.64**	**−0.64**	**−0.4872**
	Period I (1959–1983)	1,925.4	1,372.0	988.4	937	1.3023	1.5769	−0.5769	−0.4873
	Period II (1984–2011)	1,905.1	1,371.9	896.8	1,008.3	1.5347	1.7009	−0.7009	−0.4853
Hailar River Basin (HRB)	**All (1970–2012)**	**394.7**	**855.9**	**75.7**	**319.1**	**1.3842**	**2.0759**	**−1.0759**	**−1.7301**
	Period I (1970–1999)	407.0	849.8	84.4	322.6	1.3527	2.0311	−1.0311	−1.6474
	Period II (2000–2012)	366.4	869.8	55.5	310.9	1.4865	2.2136	−1.2136	−1.9694
Weihe River Basin (WRB)	**All (1961–2009)**	**522.7**	**1,033.0**	**65.6**	**457.1**	**1.856**	**2.5355**	**−1.5355**	**−1.9806**
	Period I (1961–1993)	532.7	1,017.8	83.1	449.6	1.6968	2.3531	−1.3531	−1.7936
	Period II (1994–2009)	503.7	1,061.5	32.6	471.2	2.3666	3.1173	−2.1173	−2.5448

areas with differing spatial resolutions and temporal coverages. For each product, E was spatially averaged over each basin to examine the temporal changes for the four basins.

2.3. Interannual Changes of Forest Area

Information on forest area was obtained from a remote sensing land cover data product developed by H. Liu et al. (2020). This product provides the yearly change in land cover area of the major land cover classes, including forests, from 1982 to 2015 at a relatively high spatial resolution of 5 km (Figure S1 in Supporting Information S1). The product has been validated and has high consistency (H. Liu et al., 2020). We extracted the grid cells classified as forests within each basin from 1982 to 2015 to examine year-to-year temporal changes in forest area.

2.4. Attribution of Runoff Changes

Long-term runoff data (Q) from hydrological stations were obtained from the Hydrological Year Books published by the Ministry of Water Resources of the People's Republic of China. Combined with the remote sensing yearly product of forest area, the overall long-term runoff data were divided into two periods: pre- and post-forest change (Table 1). In detail, for basins with a break point in runoff, we used the year when the break point was found as the dividing point; while for basins without break point, the year when vegetation plan was implemented was used. Thus, since no break point was found in the total runoff for the GRB and DRB (Pettitt test, $p > 0.05$), we selected 1984 as the start year of the post-afforestation period. This year was selected on the basis that the afforestation in these two basins was intensively launched during the mid-1980s (e.g., Zhou et al., 2010) and that remote sensing forest cover data were also available. Similarly, 2000 was selected as the dividing year for the HRB because the "Grain to Green" project was launched in 1999. In contrast, a break point in total runoff in 1994 (Pettitt test, $p < 0.05$) was found for the WRB and this year was thereby selected as the dividing year for this basin. The baseflow was calculated as follows using the digital filtering method (Lyne & Hollick, 1979; Nathan & McMahon, 1990) to examine whether changes in forest area had a significant effect on baseflow in dry years:

$$q_t = \alpha \cdot q_{t-1} + \frac{1+\alpha}{2}(Q_t - Q_{t-1}) \tag{2}$$

$$b_t = Q_{t-1} - q_t \tag{3}$$

where q_t and q_{t-1} are the filtered quickflow at time step t and $t-1$, respectively; Q_t and Q_{t-1} are the total runoff at time step t and $t-1$; b_t is the filtered baseflow; α is the filter parameter, ranging from 0.9 to 0.95 with the optimal value being 0.925 as proposed by Nathan and McMahon (1990).

The attribution of runoff changes to climate and land surface changes (forest area change, in our case) was explored using the Budyko framework (Budyko, 1974). Runoff elasticity was estimated theoretically via an analytical form of the Budyko theorem (i.e., the Choudhury–Yang equation, Choudhury, 1999; H. Yang et al., 2008) based on climatic and land surface conditions in the four basins (H. Yang & Yang, 2011). The Budyko framework is a widely used method to analyze long-term watershed water and energy balances (Helman, Lensky, Yakir, & Osem, 2017; Xue et al., 2020; L. Zhang et al., 2001). The Budyko method relates the evaporative index (*EI*, i.e., the ratio of *E* to *P*) to the dryness index (*DI*, i.e., the ratio of E_p to *P*) for both wet ($DI < 1$) and dry ($DI > 1$) basins, where *EI* and *DI* represent the water supply and atmospheric demand, respectively. Several analytical equations have been developed for the Budyko curve (e.g., Pike, 1964; L. Zhang et al., 2001) and here we used the Choudhury-Yang equation (Choudhury, 1999; H. Yang et al., 2008):

$$E = \frac{P \cdot E_p}{\left[P^n + E_p{}^n\right]^{1/n}} \tag{4}$$

where *n* is a parameter of basin characteristics (e.g., soil properties, topographic slope, and vegetation cover; H. Yang et al., 2008). Because soil properties and topography do not change over such short periods, *n* can be assumed to be mainly affected by vegetation cover (i.e., changes in forest area, in our case). Having the long-term averages of P, *Q*, and E_p, allows for the estimation of the parameter *n* through Equation 4, where *E* is estimated from the long-term catchment water balance of each basin as $E = P - Q$, assuming a negligible change in water storage for long periods of time (Budyko, 1974).

Assuming *P*, E_p and *n* are independent variables in Equation 4, the total differential change in *Q* can be calculated as (Milly & Dunne, 2002):

$$\Delta Q = \frac{\partial f}{\partial P}\Delta P + \frac{\partial f}{\partial E_p}\Delta E_p + \frac{\partial f}{\partial n}\Delta n \tag{5}$$

where ΔP, ΔE_p, and Δn are changes in precipitation, potential evapotranspiration, and the parameter *n*, respectively. Then, on the basis of the definition of runoff elasticity ($\varepsilon_x = \frac{\Delta Q/Q}{\Delta x/x}$, e.g., Schaake, 1990), we can rewrite Equation 5 as follows:

$$\frac{\Delta Q}{Q} = \varepsilon_P \frac{\Delta P}{P} + \varepsilon_{E_P} \frac{\Delta E_p}{E_p} + \varepsilon_n \frac{\Delta n}{n} \tag{6}$$

where ε_P, ε_{Ep}, and ε_n are the runoff elasticities of *P*, E_p, and *n*, respectively. According to the definition of elasticity, a positive (negative) value of ε_x indicates how much 1% of an increase in *x* will induce a corresponding percentage of increase (decrease) in runoff equal to the ε_x absolute magnitude. The percent increase (decrease) in runoff is relative to the long-term average *Q*. As the absolute magnitude of ε_x increases (more positive or negative), the effect of *x* on the runoff increases (Schaake, 1990).

Specifically, the runoff elasticities of *P*, E_p, and *n* can be given as follows (H. Yang & Yang, 2011):

$$\varepsilon_P = \frac{1 - \left[\frac{(E_p/P)^n}{1+(E_p/P)^n}\right]^{1/n+1}}{1 - \left[\frac{(E_p/P)^n}{1+(E_p/P)^n}\right]^{1/n}} \tag{7}$$

$$\varepsilon_{E_p} = \frac{1}{1-(E_p/P)^n} \frac{1}{1 - \left[\frac{(E_p/P)^n}{1+(E_p/P)^n}\right]^{1/n}} \tag{8}$$

$$\begin{aligned} \varepsilon_n &= \frac{A - B}{\left[1 + (P/E_p)^n\right]^{1/n} - 1} \\ A &= \frac{P^n \ln P + E_p{}^n \ln E_p}{P^n + E_p{}^n} \\ B &= \frac{\ln(P^n + E_p{}^n)}{n} \end{aligned} \tag{9}$$

For a given basin, we assumed that changes in runoff between the pre- and post-afforestation periods were mainly induced by climate change and land surface changes as such:

$$\Delta Q = Q_2 - Q_1 \tag{10}$$

$$\Delta Q = \Delta Q_P + \Delta Q_{E_p} + \Delta Q_n \tag{11}$$

where "2" and "1" represent the post- and pre-afforestation periods for each basin and according to elasticity theory, the change in Q caused by the individual element (P, E_p, or n) is calculated as:

$$\Delta Q_x = \varepsilon_x \frac{Q}{x}(x_2 - x_1) \tag{12}$$

3. Results

3.1. Changes in Forest Area in the Four Basins Over the Past Three Decades

Forest area substantially increased in the four basins between 1982 and 2015 (Figure 3; Figure S1 in Supporting Information S1). In HRB and WRB (the dry basins), forest cover changes from 12% to 24% and from 28% to 43%, respectively, were recorded. The wet basins (GRB and DRB) had larger initial forest area than HRB and WRB (by over 50% in 1982, Figure 3a). The increasing trend in forest area was steeper after 2000, which was the year in which the "Grain to Green" project started in WRB and HRB. The forest area change was observed mostly in the middle and lower reaches of the river systems in GRB and DRB and mostly in the upper reaches of WRB and HRB (Figures 3b–3d).

3.2. Long-Term Trends in Air Temperature, Precipitation, and Potential Evapotranspiration

There was no significant trend in P for all the four basins during their corresponding study periods (Figure 4). In contrast, the number of dry days ($P = 0$) increased, while the number of days with little P ($P < 10$ mm) decreased in DRB and HRB, displaying a more concentrated P among seasons (Figure S2 in Supporting Information S1). P was found to decline in the dry autumn and winter seasons in DRB (Figure S2b in Supporting Information S1), while the decline was mostly during the wet summer season in HRB (Figure S2c in Supporting Information S1). The annual temperature was observed to increase significantly in all basins, with the greatest increase of 0.4°C decade^{-1} observed in HRB (Figure 4). Further, there was a significant decrease in E_p in GRB, indicating a decline in evaporative demand for this wet basin.

3.3. Long-Term Trends in Annual and Seasonal Runoff

No significant trends were found for Q, Q_b, and Q_q for three basins: GRB, DRB, and HRB (Figure 5). In contrast, WRB showed a significant decrease in all three runoff components for 1961–2009, with a more pronounced decline after the mid-1990s, which concurred with a decline in precipitation (Figure 5d; $p < 0.001$). Seasonal variations in Q_b showed large differences among the four basins (Figure 6; Figures S3–S5 in Supporting Information S1). During winter, Q_b in WRB significantly decreased (Figure 6d) while in the other three basins, including the dry basin of HRB, Q_b increased (Figures 6a–6c). The decrease in Q_b in WRB occurred not only during the winter, but also throughout the summer (Figure S4 in Supporting Information S1). In contrast, Q_b significantly increased in GRB and DRB during the autumn and spring but did not change during the summer (Figures S2–S4 in Supporting Information S1).

3.4. Influences of Forest Area Changes on Water Balance Components

The influences of climate and forest area changes on the hydrology of the basins are shown through the Budyko space (Figures 7 and 8, Table 1). Figure 7 shows that in three of the four basins (i.e., DRB, WRB, and HRB), there was an increase in atmospheric demand (i.e., E_p/P increased through warming/drying), which reduced the water yield of the basin (the amount of rainwater remaining in the basin after losses via E) from period I (prior to the change in forest area) to period II (following the increase in forest area). There was a decline in atmospheric demand in period II only in GRB, a wet basin. This decline did not affect the water yield such that E/P remained almost constant (Figure 7a).

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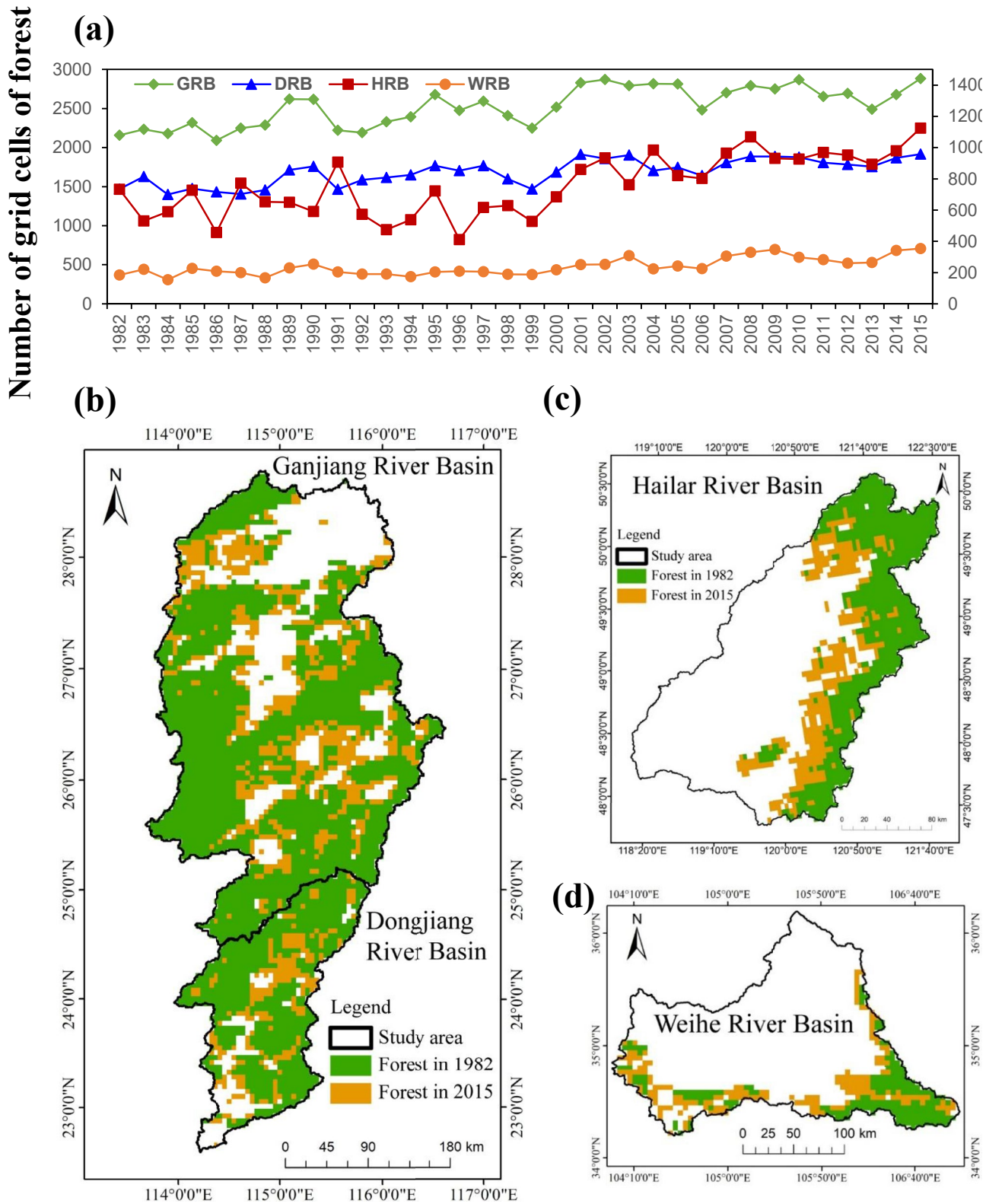

Figure 3. (a) Temporal changes in the area of forests for the four basins and the spatial patterns of forest area increments from 1982 to 2015 for (b) Ganjiang River Basin and Dongjiang River Basin, (c) Hailar River Basin, and (d) Weihe River Basin. The annual forest areas are defined based on the number of grid cells classified as forest for each basin.

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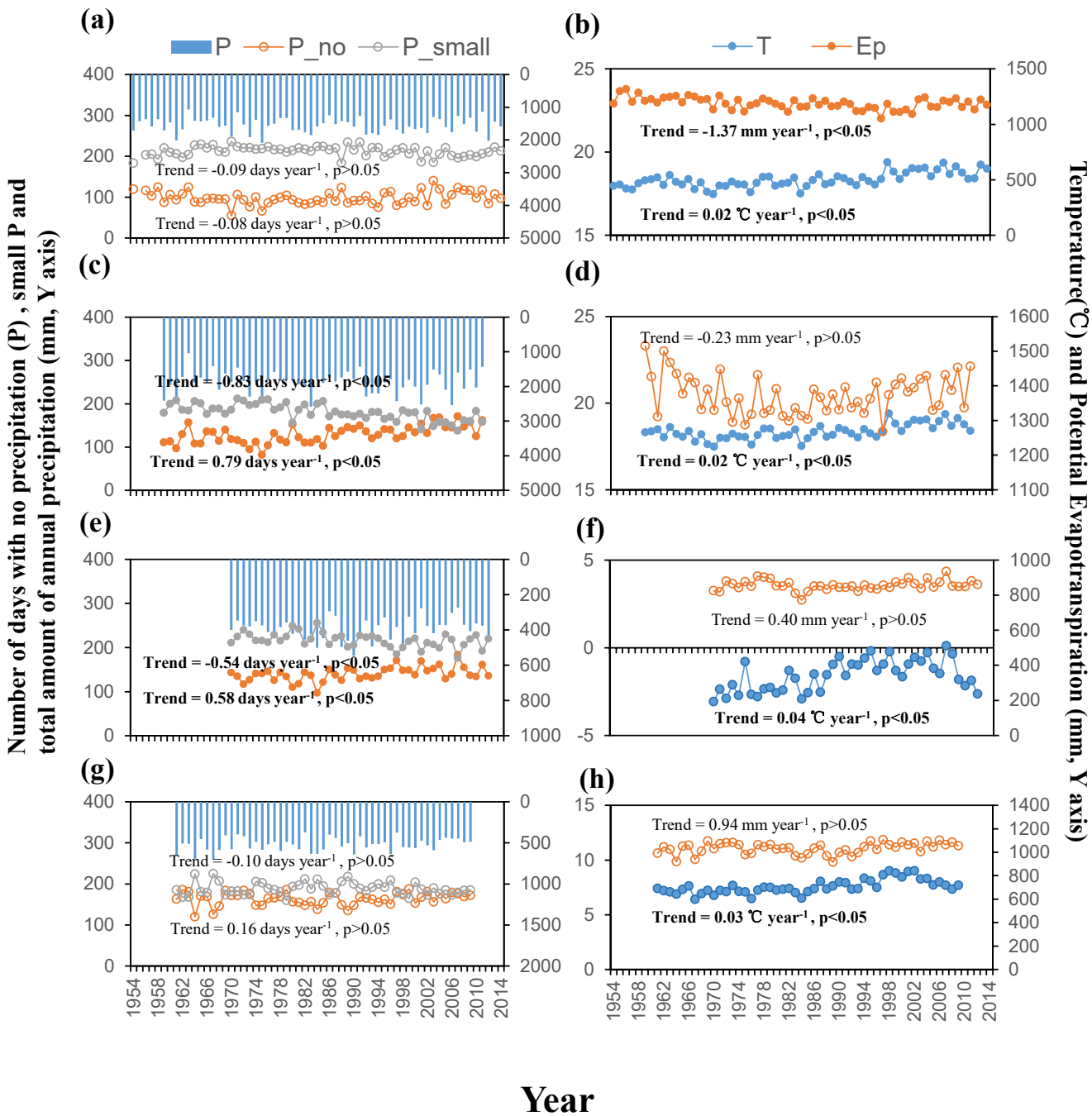

Figure 4. Temporal changes in precipitation, temperature and potential evapotranspiration. Left column: temporal changes in the number of dry days ($P = 0$ mm; P_no) and days with very little P ($P < 10$ mm; P_small) and the annual precipitation (P, mm; right axes); right column: annual temperature (°C) and potential evapotranspiration (E_p, mm; right axes) in (a and b) Ganjiang River Basin, (c and d) Dongjiang River Basin, (e and f) Hailar River Basin, and (g and h) Weihe River Basin. Data with significant (non-significant) changes are shown by solid (hollow) points.

Both E_p and the vegetation parameter (n) negatively affected the runoff in all basins. However, P had a positive effect based on the corresponding elasticity of Q to changes in E_p, P, and n (Table 1). WRB had the most negative ε_n value ($\varepsilon_n = -1.98$), indicating that for every 1% of an increase in n there was almost a 2% decrease in total runoff. In contrast, DRB had the least negative ε_n ($\varepsilon_n = -0.49$), meaning that the runoff in this basin was the least influenced by n (i.e., in our case, by forest expansion). In general, the magnitude of ε_n was much larger for the

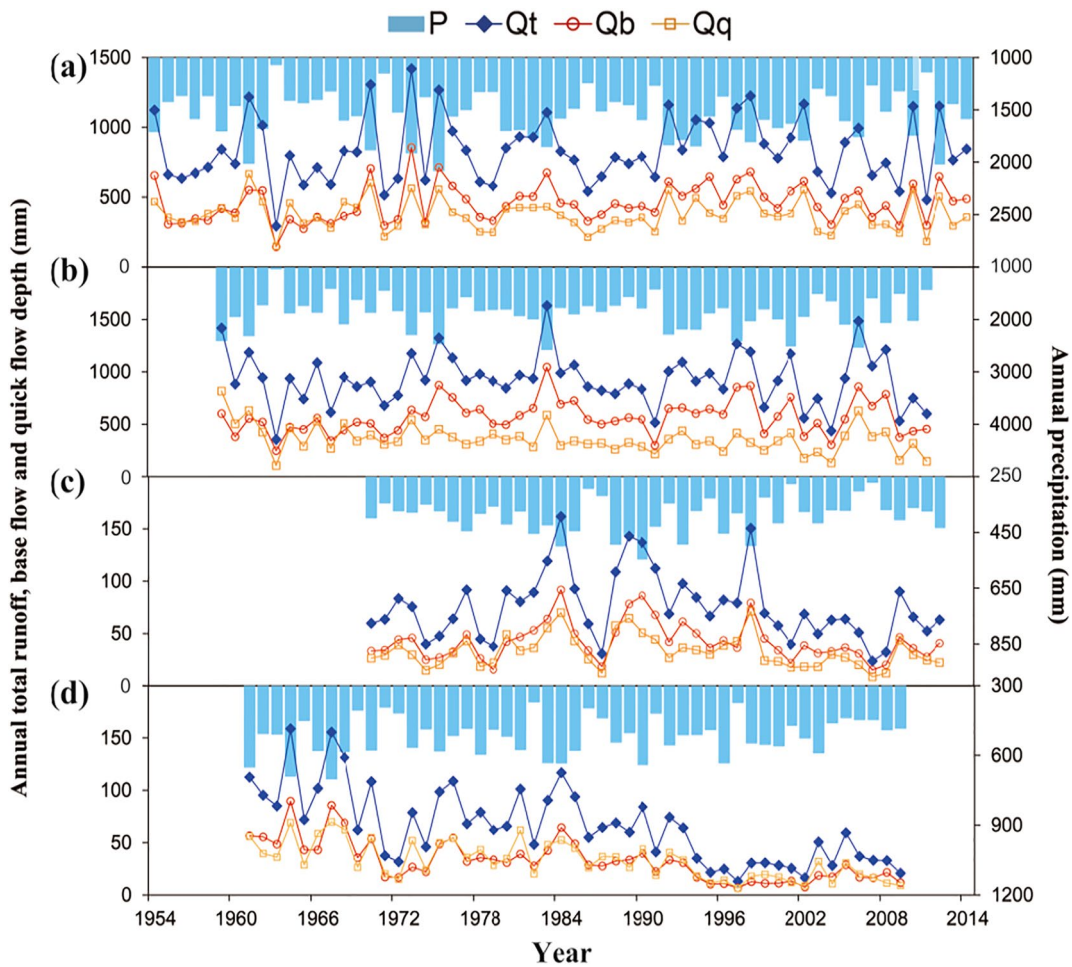

Figure 5. Temporal changes in total runoff (Q_t, mm), baseflow (Q_b, mm), and quickflow (Q_q, mm) for (a) Ganjiang River Basin, (b) Dongjiang River Basin, (c) Hailar River Basin, and (d) Weihe River Basin. Significant changes were only found in Weihe River Basin for Q_t, Q_b, and Q_q.

two dry basins (WRB and HRB) than that of the wet basins (DRB and GRB), indicating that the runoff in the dry basins was more sensitive to changes in n (i.e., forest expansion).

ε_n was more negative than ε_{Ep} except for DRB, a dry basin, which means that n was a more important factor in changing the basin's runoff than the evaporative demand. As expected, precipitation had the largest effect on runoff, especially in the dry basins. On average, the decrease of precipitation from period I to period II for the four basins induced a 13 mm decrease in runoff (mean of ΔRp for all basins, Figure 8). The change in n (i.e., increased forest area) had an average impact on the runoff by decreasing its amount by −35 mm (mean of ΔRn for all basins). This effect, however, was much more significant in DRB and WRB (Figure 8), which were the two basins with the largest forest area and rate of forest increase (Figure 3).

4. Discussion

4.1. Contrasting Characteristics of Runoff Changes Among the Four Basins

The effects of forest cover change on water yield are complex and variable and are often confusing for scientists and land managers (e.g., Brown et al., 2005; Feng et al., 2016; Li et al., 2018; Ward et al., 2021; M. Zhang & Wei, 2021; Zhou et al., 2010). Here, we selected four typical basins in China to investigate the hydrological changes resulting from forest area change, which provide insights into the potential influences of future afforestation efforts. The selected basins are located in northern and southern China and have contrasting climates as

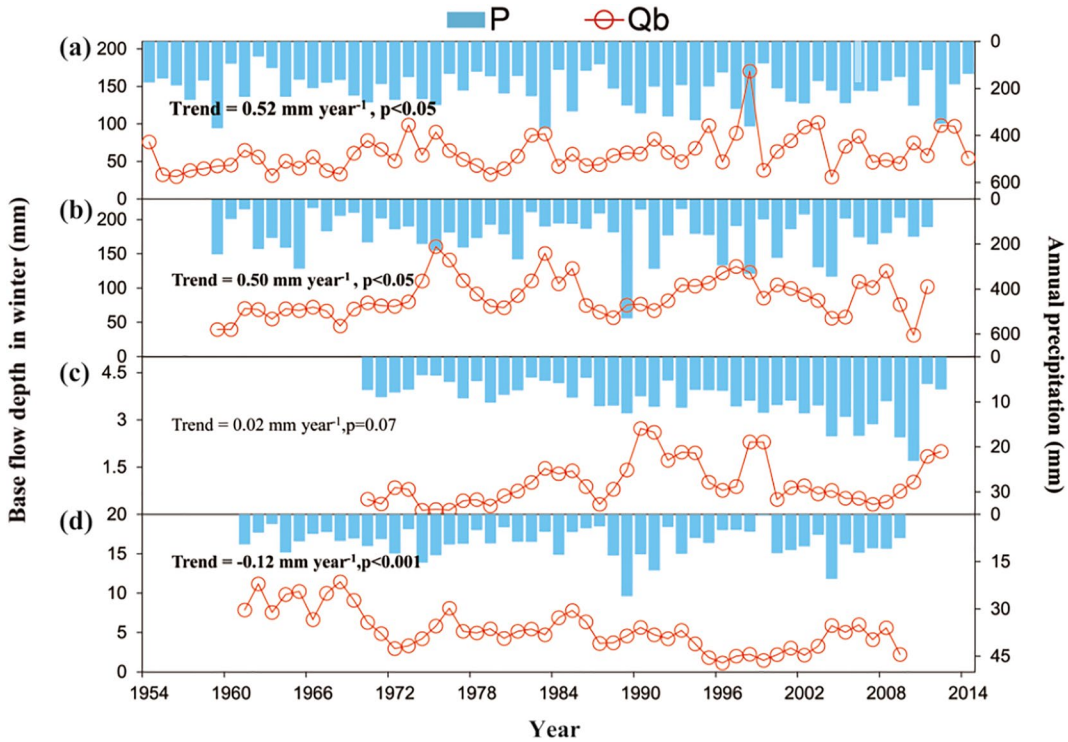

Figure 6. Temporal changes in baseflow (Q_b, mm) in winter for (a) Ganjiang River Basin, (b) Dongjiang River Basin, (c) Hailar River Basin, and (d) Weihe River Basin.

well as forest area and total basin sizes. Overall, the dry basins, which have a smaller forest area, have a faster increase in forest area for the study period (Figure 3). Despite the large increase in forest area, this change did not affect the runoff in those basins except the WRB (Figure 4). The reasons for this may lie partly in the different climates of these basins, with the dry basins being more susceptible to land cover changes (Table 1). The WRB was the only basin that showed a significant decrease in total runoff, which can be attributed to both climate variability and forest expansion following the "Grain to Green" afforestation project. Though E_p did not show a significant increase for the whole period ($p = 0.05$, Figure 4h), it increased since 1980, which might have played an essential role in decreasing runoff. Meanwhile, the E derived from various remote sensing products showed an increasing trend after the mid-1990s for WRB (Figure S6 in Supporting Information S1). Furthermore, it was found that the WRB had the most intensive land cover change and the largest increasing rate in forest area (Table S1 in Supporting Information S1). This was likely a major factor contributing to the high hydrological sensitivity of WRB (Zhou et al., 2015). For HRB, runoff was less influenced by forest cover change most likely because E was mainly driven by water supply (i.e., P) and less by evaporative demand in this basin (Table 1). The increase in the number of dry days was accompanied by a decline in the total rainfall amount during the wet season, which likely limited the rate of E in this basin (Figure S2c in Supporting Information S1). As such, an increase in forest area would not affect runoff because the basin was still limited by water supply for HRB (Budyko, 1974; H. Yang et al., 2008). On the other hand, the absolute forest area was relatively small for WRB and HRB (Table 1), and therefore other land use changes such as agricultural practices and urbanization may also contribute to the runoff changes (e.g., Feng et al., 2016; Liang et al., 2020). Thus, exploration of the individual influences by these factors in future research can benefit from better understanding of the hydrological response for these two basins.

Annual E in the two wet basins was high, and significantly increased following the expansion in forest area (Figure S6 in Supporting Information S1). However, the increased E did not translate into a reduction in runoff in the two wet basins (Figure 5) likely due to energy limitation (Zhou et al., 2015). Moreover, total precipitation amounts were large in these areas with surplus water provided for the increasing E.

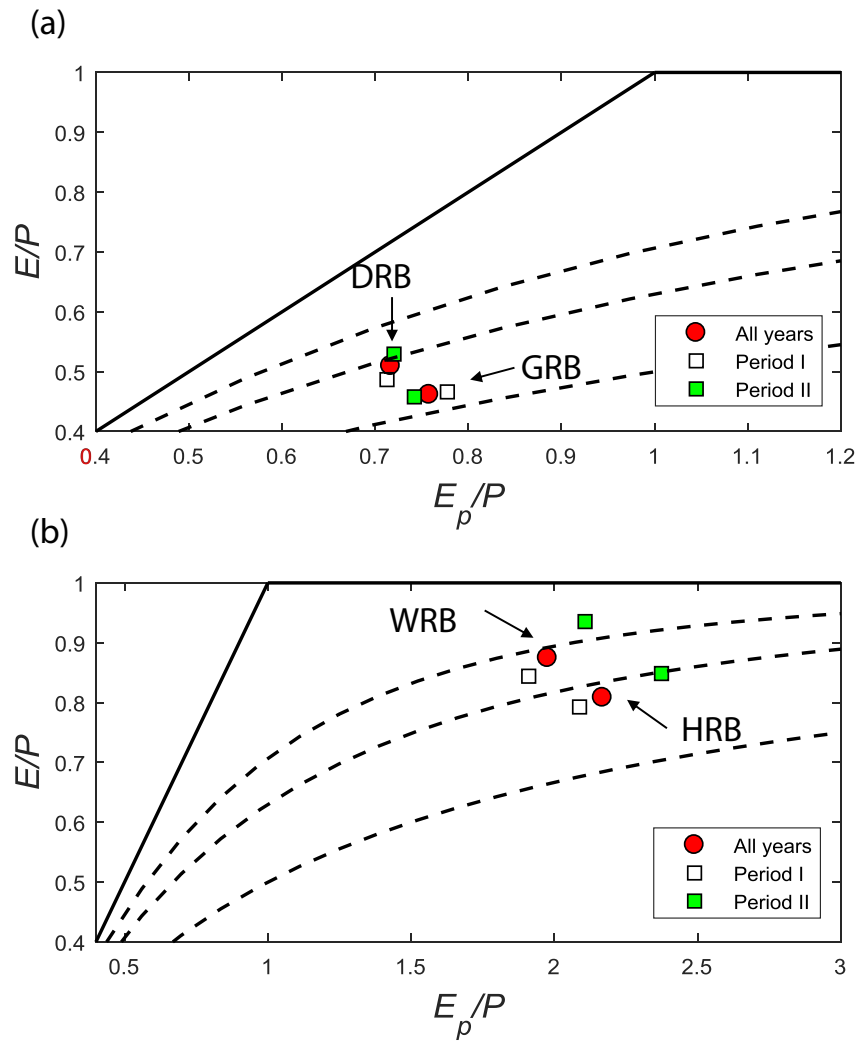

Figure 7. Trajectories from period I (before the change point) to period II (after the change point) in the Budyko framework for (a) wet and (b) dry basins, respectively. Circles indicate the location of each basin within the Budyko space for all the years. Rectangles indicate the locations for Period I (hollow) and Period II (solid), respectively.

4.2. Effects of Forest Change on Water Yield

Many studies have suggested that afforestation would dramatically reduce water yield because forests have larger *E* than other vegetation types and bare land (Bosch & Hewlett, 1982; Brown et al., 2005; Malmer et al., 2010; Qiu, 2010; L. Zhang et al., 2001). Our results suggest otherwise. Early studies were generally conducted via small watersheds scale with several square kilometers. Although the conclusions drawn from these pioneering studies significantly improved our knowledge of forest-water relationships, caution should be taken when they are applied to other places with different climates and basin characteristics (e.g., basin area, soil retention capacity, and land use). These watersheds have abrupt vegetation changes while the vegetation in our study is gradual. Small basins of less than several hundred square kilometers are much more responsive to land cover and/or climate change (M. Zhang et al., 2017; Zhou et al., 2015). At the same time, the net effect of a land cover change may be detected only beyond the basin area (Ellison et al., 2012; Li et al., 2018; Spracklen et al., 2012; van der Ent et al., 2010).

The net "positive" effect of an increase in forest area on dry season baseflow that was found in the GRB and DRB can be partly attributed to both climate and gradual change in land use changes (e.g., vegetation and reservoirs). Previous studies using modeling and remote sensing data showed that the effect of forest expansion on water yield was strongly dependent on spatial scale, and contrasting conclusions may be drawn from studies conducted on different spatial scales. For example, Y. Liu et al. (2016) explored the effect of afforestation using

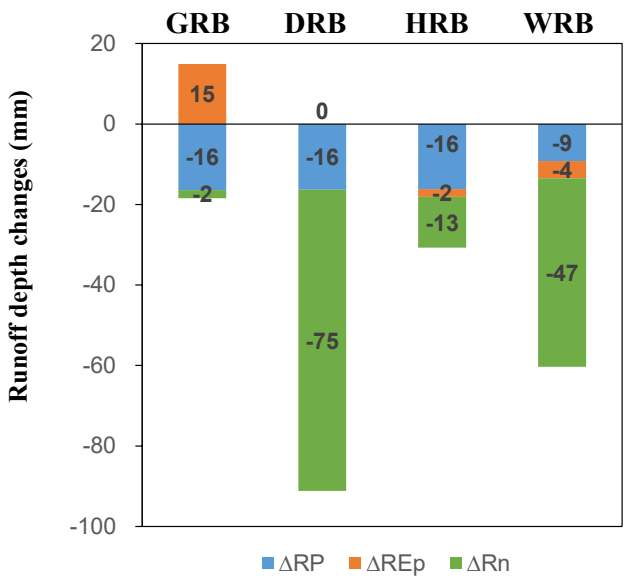

Figure 8. Runoff changes from period 1 to period 2 attributed to changes in precipitation (ΔR_P, mm), potential evapotranspiration (ΔR_{Ep}, mm), and afforestation (ΔR_n, mm). The division of the two periods for each basin were based either on the break point of runoff or the time of afforestation implemented.

remote sensing data and a modeling approach, and showed that vegetation greening, caused by both climate change and afforestation, induced a larger *E* and thus a reduction in water yield at the local scale. At the national scale, their results showed no significant trends in *E* or water yield because the greening area accounted for a small fraction of the whole country and the larger *E* was offset by other factors (such as vegetation browning) in other areas of the country. The results from Y. Liu et al. (2016) may partly explain the relatively constant runoff in the GRB and DRB because these two basins cover a relatively large area. Similarly, Zhou et al. (2010) observed no significant change in runoff after forest recovery in Guangdong Province, Southern China, which has a similar climate to the GRB and DRB, using a water budget method. Meanwhile, the precipitation in the dry or wet seasons showed no significant changes in DRB (Figures S3–S5 in Supporting Information S1) while the number of dry days during the dry season increased in this basin (Figure S2b in Supporting Information S1). These results indicate that the continuous increase in baseflow may not be fully explained by climatic change in this wet basin. Forest expansion and other disturbances such as landuse change may also have contributed to the observed increase in baseflow. Furthermore, some studies showed that reservoirs may change the hydrological regimes and increase runoff in the dry season (Barbarossa et al., 2020; Y. Yang et al., 2017). Thus, the increase of baseflow during dry seasons may also be partly attributed to the reservoir construction in our wet basins (Figure 5). The quantification of the individual contributions of baseflow increase by forest expansion, reservoirs and other human activities, such as urbanization, is a great challenge due to the data availability and the complex interactions among these factors. A previous study showed that reservoirs made a relatively small contribution to the increase of baseflow in southern China (Zhou et al., 2010), which might be the case for our two wet basins. Previous studies have shown that afforestation could shift the available water in the wet season to the dry season through water retention by forest soils (W. Zhang et al., 2016; Zhou et al., 2010). This may be the case for the GRB and DRB. The redistribution of excess water from the wet season to the dry season is thought to occur through large soil infiltration in forested areas that recharges the ground water reservoir (Bruijnzeel, 2004; Li et al., 2018; Zhou et al., 2010). Forest expansion, in this case, plays an essential role in reducing flood events during the wet season and enhancing the runoff during the dry season (Ferreira & Ghimire, 2012; Laurance, 2007; Preti et al., 2011).

Afforestation may have positive effects on large scale hydrological cycles by strengthening *E* and increasing summer atmospheric water vapor. Both modeling results and observations suggested that afforestation can regulate the hydrological cycle via changes in *E* and *P* (e.g., Li et al., 2018; J. Liu et al., 2018; Y. Liu et al., 2018; Spracklen et al., 2012; Sun et al., 2006). Previous studies focused on a relatively short period using small "paired watershed" vegetation manipulation experiments (e.g., Bosch & Hewlett, 1982; Brown et al., 2005). The long-term observations of runoff over the past several decades for the four basins provided a valuable opportunity to explore this hydrologic effect through the separation of total runoff into quickflow and baseflow recharges (Zhou et al., 2010). Our results highlight the complex combined effects of climate, vegetation, and soil change on river flow, especially in basin with human activities (e.g., dam construction and urbanization). We recognize that it is perhaps too early to attribute the observed increase in baseflow to soil improvement from forest recovery and ecological restoration in the two wet watersheds. The percentage of forest cover change in HRB (from period 1 of 12% to period 2 of 24%), rather than forest structure change, may not be a good indicator of functional change in evapotranspiration. The restoration of soil properties, such as soil water storage capacity and groundwater recharge, may take decades to recover or regenerate after a change in the forest area has occurred (Diochon et al., 2009; Parotta et al., 1997; Shi et al., 2015; Yao et al., 2016). Therefore, detecting biophysical or biogeochemical changes in a basin requires long-term observations or exploration of runoff variations. Meanwhile, the close interactions between *P* and *E*, especially the positive feedbacks of forest change to *P*, should be considered. A recent study using 30-yr simulations showed that soil drying from increased *E* could be canceled out by increased precipitation from vegetation greening (Li et al., 2018).

4.3. Implications for Afforestation and Forest Management

Although the eco-hydrological environment in China has improved because of the large-scale ecological projects, some studies argued that planting trees in semiarid and arid regions in northern China may increase ecosystem carbon sequestration at the cost of water (Gao et al., 2014; Jackson et al., 2005; Yao et al., 2016). The large *E* required to sustain forest ecosystems in drylands is of great concern. Our results indicate that the influences of forest expansion (i.e., afforestation) on runoff in drylands may be overestimated. Conclusions on runoff changes can be biased owing to the spatiotemporal scale of the analysis (M. Zhang et al., 2017), runoff data availability (Brown et al., 2005), and the method used to analyze the data (Li et al., 2018).

We suggest that climate, besides forest area change, should be fully explored as one of the main drivers of runoff change, particularly in drylands. Additionally, our results in the HRB indicate that afforestation may not necessarily induce a significant reduction in runoff in cold and dry areas. Furthermore, long-term runoff observations over a large basin are needed to quantitatively explore the feedbacks of biophysical changes (e.g., in soil properties and precipitation) resulting from afforestation on the hydrological cycle. Effects of different strategies afforestation in water-limited areas of northern China should be carefully studied. A recent study showed that arid basins with vegetation that had a larger leaf area index were more vulnerable to climatic changes such as drought and warming (Xue et al., 2021). Our results indicate that afforestation should be focused in water-surplus areas such as the GRB and DRB (Li et al., 2018; Y. Liu et al., 2016). In these areas, evapotranspiration is more dependent on available energy rather than vegetation area and water yield is less sensitive to vegetation cover change. Therefore, the goals for enhancing the carbon sink without negatively affecting water resources can be achieved in the wet regions of the country. More attention should also be paid to vegetation types and/or species planted in dry areas (e.g., Chechina & Hamann, 2015; Chen et al., 2019; J. Liu et al., 2018; Y. Liu et al., 2018; Zhou et al., 2021). Tradeoffs between carbon gain, groundwater recharge, and water consumption should be fully considered in dry lands (Helman, Osem, Yakir, & Lensky, 2017) and as well as humid regions. In addition, evaluating the effects of forest recovery on soil physical properties is important to fully understand the role of vegetation in influencing baseflow (Bruijnzeel, 2004). Afforestation may change the biogeochemical properties of soil and thus soil hydrology (J. Liu et al., 2018; Y. Liu et al., 2018).

5. Conclusions

Afforestation has been implemented throughout China for the past few decades. How this will change the hydrology of the country in the long term is still under debate. Using long-term hydrological observations and remote sensing data, we explored the hydrological responses of four large basins to forest expansion across contrasting climate. Our results highlight the different response of watershed hydrology to landuse and climate change under different climatic regimes. In contrast to a semi-arid region, forest expansion apparently did not cause dramatic change in total water yield in the wet region in southern China. Future study should examine the upward trend of baseflow in the humid region under a monsoon climate and how this trend is related to land use change. Our study suggests that afforestation policy should be region-specific and that large scale afforestation should be encouraged mainly in wet areas and afforestation in water-limited areas must be carefully implemented. Conclusions from this study can help improve decision-making for ecological restoration and water resource management in China as well as other countries, where intensive afforestation efforts are taking place.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The meteorological data are available at http://data.cma.cn/. The evapotranspiration (*E*) data from the research group of K. Zhang et al. (2010) are available at http://www.ntsg.umt.edu/; *E* from the Global Land Evaporation Amsterdam Model are available at https://www.gleam.eu/: *E* from FLUXNET modeling by Jung et al. (2011) are available at https://www.bgc-jena.mpg.de/; and *E* from the ECMWF Reanalysis v5are available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. The global land cover data are available at https://essd.copernicus.org/articles/12/1217/2020/.

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