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# Large-Scale Forestation Aggravates Water Supply Decline: Mounting Challenges to Forest Management in China

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**Key Points:**

- Meta-analysis indicates widespread river flow decline in China during the past four decades due to multiple natural and human stresses
- Forestation is the dominant driver of significant decline in measured river flows for half of the 112 studies in a comprehensive review
- Simulations show climate change dominates the historic water supply decline in 168 large basins during 1980–2020

**Supporting Information:**

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

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**Abstract** The “Nature-based Solutions” strategy for combatting global land degradation and climate change through forestation has drawn increasing concerns regarding its potential tradeoffs with water resources, especially in dry regions. China is “greening up” due to decades of large-scale tree planting and ecological restoration campaigns. However, national-level assessments of the individual and combined effects of forest cover and climate changes on water yield at a fine scale are still lacking. Here, we show several lines of evidence indicating that the unprecedented forestation has exacerbated water availability decline during 1980–2020 amid climate change across China. Meta-analysis identifies forestation as the dominant driver of the observed large declines in river flows for about half of the 112 reviewed watersheds. Scenario simulations using the Budyko framework and a monthly ecohydrological model, WaSSI-CN, all suggest that forestation substantially reduced water yield nation-wide, especially in the humid southern China and during the growing season. Forestation exacerbated the water yield decline caused by climate change of reduction in precipitation and rising air temperature through enhanced evapotranspiration in over 80% of the 168 large basins modeled. Effects of forestation could exert more impacts on water yield than climate change over 17 large basins. Forest management practices such as stand thinning, native tree species planting, and prescribed burning are encouraged to increase forest resilience and improve water supply functions.

**Plain Language Summary** Forests recycle a large amount of water through their enhanced evapotranspiration to provide important ecosystems services, such as flood mitigation, cooling, and carbon sequestration. The Earth is “greening up” due in part to large-scale forest-based ecological restoration campaigns and global warming in many parts of the world. However, increasing concerns exist in that forestation may reduce water yield making local water shortage problems worse, especially in populated arid regions with high water supply stress such as China amid a changing climate. This study offers strong evidence that climate change dominated water supply decline in large basins in the recent decades, but large-scale forestation has exacerbated river flow decline, especially in the growing season when forest and crop water uses are the highest. We derive our conclusions by reviewing published literature on land use change-river flow relations and by conducting two types of ecohydrological modeling to show how changes in forest cover and climate respectively affect annual and seasonal water balances. We offer novel management options (e.g., water-centric afforestation, prescribed burning, thinning of dense plantation forests, promoting native tree restoration) to minimize the negative impacts of forestation on water resources while promoting forest resilience amid increasing water stress in China and elsewhere.

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## 1. Introduction

Forestation is regarded as a major "Nature-based Solutions" (NBS) strategy to achieve eight of the 17 United Nations' Sustainable Development Goals (SDGs) including clean water supply, stable climate, erosion controls, and livelihood (Ingrosso & Pausata, 2024; Lewis et al., 2019; Springgay et al., 2019). Forests sequester a sizable fraction (i.e., 10%–20%) of global $CO_2$ emissions (Bastin et al., 2019; Lewis et al., 2019; Pan et al., 2011) cool the air (Barnes et al., 2023), reduce small to medium floods (Bradshaw et al., 2007), protect air and water quality (Meli et al., 2024), and enhance biodiversity (Hua et al., 2022). However, concerns about how forestation affects water availability are rising as climate change intensifies and water demand by humans increases (Gou et al., 2025), and water is becoming a major limiting factor in large scale forestation (Grant et al., 2013; Yang et al., 2024). Declines in soil moisture (Wang et al., 2024) and water availability in drylands (Feng et al., 2016; van Dijke et al., 2022) negate desirable ecosystem services such as biodiversity conservation (Cao et al., 2011; C. Li et al., 2021; R. Li et al., 2021).

Our knowledge about the forest-water interactions has been mostly derived from small "Paired Watershed Experiments" (Andréassian, 2004; Brown et al., 2005; Farley et al., 2005; H. Zhang et al., 2017; M. Zhang et al., 2017; Creed and van Noordwijk, 2018; Richardson et al., 2023). In general, forest removal or deforestation tends to increase total water yield due to reduction in evapotranspiration and soil degradation (Farley et al., 2005; Zhang et al., 2001). However, the effects of planting trees or forestation are more variable than deforestation at both small watershed and regional scales (Andréassian, 2004; H. Zhang et al., 2017; M. Zhang et al., 2017; Y. Li et al., 2018; Zhang & Wei, 2021; Hou et al., 2023). Background climate, speed and timing of vegetation recovery, pre-forestation land covers (Wei et al., 2013; Zhang & Wei, 2021) and degree of soil degradation (Bruijnzeel, Peña-Arancibia, et al., 2025) all influence hydrologic recovery outcomes. For example, a global review indicates that 60% of watersheds subject to forestation show reduced annual streamflow, but 30% of them exhibit a flow increase (Zhang & Wei, 2021). Detecting the true hydrologic response to vegetation cover change in large basins based on statistics is challenging due to the spatial and temporal variations of climate, watershed properties, and human interferences (Li et al., 2017; Wei et al., 2018).

The inherent tradeoffs between biological carbon gain, erosion controls, and total water yield due to enhanced vegetation water loss are well recognized (Feng et al., 2016; Hua et al., 2022; Jackson et al., 2005; Yang et al., 2022) but the scientific debate about the extent and mechanisms of the tradeoffs continues (Piao et al., 2020; Li C et al., 2021; Li R. et al., 2021; Yang et al., 2022; B. Zhang et al., 2022; J. Zhang et al., 2022; X. Zhang et al., 2022; Y. Yang et al., 2023). The ambiguity prevents land managers and policy makers from developing effective local adaptation strategies for sustainable development as climate change intensifies (Sun et al., 2024; M. Zhang et al., 2022). Research is needed to better understand and separate the individual and combined interactive effects of forestation, climate change, and other anthropogenic factors on water resources (Wei et al., 2013). This is especially important for dryland regions such as African Great Green Wall initiative (Goffner et al., 2019) that consider forestation as a major "green" approach to combat desertification, offset $CO_2$ emission, and meet obligations of carbon neutrality (Briske et al., 2024; Z. Liu et al., 2022; Mallapaty, 2020; Y. Wang et al., 2023; Z. Wang et al., 2023).

China leads the world in forestation (Sarre, 2020), representing a global hot spot of rapid forestation during the past three decades (Chen et al., 2019; Y. Liu et al., 2016; Piao et al., 2020; Xiao, 2014; Zhu et al., 2016). The unprecedented landcover change is largely attributed to national land management policies and governmental investment to ecological restoration programs (Bryan et al., 2018; Fu et al., 2023; J. Liu et al., 2008). An additional increase of 43% in forest area from the current level could offset 7%–14% of China's national $CO_2$ emissions, critical to China's year 2060 "carbon neutrality" goal (Xu et al., 2023). There are many studies and assessments on the hydrological impacts of forest restoration efforts (Y. Liu et al., 2016; Li et al., 2018; C. Li et al., 2021; R. Li et al., 2021; Ma & Yuan, 2024; Wang et al., 2016) and carbon sequestration (Wang et al., 2022; Xiao, 2014), but conclusions are often controversial (Mao et al., 2024). For example, forestation impacts on water yield in a region with a monsoon climate (Xue et al., 2022; Zhang et al., 2021, 2022; Zhou et al., 2010) or in the dry Loess Plateau regions (Yu et al., 2023; B. Zhang et al., 2022; J. Zhang et al., 2022; X. Zhang et al., 2022) seem contradictory due to the compound effects of climatic and human management influences (i.e., dam and reservoir constructions) on watershed hydrology (Teo et al., 2022; Zhou et al., 2021). Scientifically, China's forestation effort serves as a large "land manipulation experiment", providing a rare opportunity to rigorously study how forest cover change can affect water availability at a much larger spatial scale than traditional small watershed vegetation manipulation experiments (Andréassian, 2004; Brown et al., 2005; Wei et al., 2008). More importantly, lessons learned from China can provide much needed guidance to other nations facing similar land management and water resource challenges (Bryan et al., 2018).

Recent studies indicate that China is experiencing widespread streamflow declines during the past three decades due to land use change, climate change, and human interventions (Gou et al., 2025; Wang et al., 2025). The goal of this study was to advance the understanding and quantification of how land cover change and extensive forestation, has affected mean annual and seasonal water yield amid climate change during 1980–2020 at a large basin scale. We focused on two factors: climate and forest cover change. Using meta-analysis and factorial modeling, we examined how river flow declines, observed or predicted, coincided with land cover and socioeconomic transformations. Against the prevailing belief that effects of land use change on water yield in large basins (>1,000 $km^2$) are not detectable or muted (Bi et al., 2014; Kiersch, 2000; Oudin et al., 2008), we show evidence that forestation has substantially amplified the effects of climate change on water yield in large river basins. Scenario simulations reveal how forestation contributes to the decline of river flows in both dry and wet climatic regions through the increase in evapotranspiration. Although climate change dominated forestation in hydrologic effects in most regions across China, forestation overtook climatic influences in over 17 watersheds of the 168 large basins with watershed area >3,000 $km^2$. Based on this study, we provided forest management strategies to mitigate negative effects of forestation on water resources.

## 2. Materials and Methods

### 2.1. Meta-Analysis of Existing Literature

We constructed a database that includes key peer-reviewed journal papers on watershed hydrology in China. The goal was to identify the major factors that could be attributed to the observed change in river flows from the 1980s to date. These factors include climate change (i.e., precipitation and air temperature), forestation/deforestation, human interventions such as water withdrawal for irrigation. We used the following criteria for the literature search: (a) watershed scale studies; (b) measured flow trend data (i.e., not based on model simulations) were used; (c) rigorous statistical methods were used to separate the influences of climate from other human factors; and (d) journal publications in both English and Chinese were included. The Web of Science, the Chinese CNKI platform (https://www.cnki.net/index/), and Google Scholar search engines with keywords of "Forest" AND "Stream flow" AND "China" were used.

### 2.2. National Climate and Land Use Data

We assembled high-resolution spatial data sets that consist of forest cover, meteorological variables (e.g., precipitation and potential ET), and restored natural runoff data sets across China, representing a wide range of physiographical regions from the boreal to the tropical ecotones (Table 1). Areas with annual precipitation less than 300 mm do not support healthy forests, and forestation is assumed not feasible (H. Liu, 2019; Sun et al., 2006), and thus were not included in this modeling analysis. Essentially, this study excluded most of the areas receiving less than 400 mm $yr^{-1}$ of precipitation (i.e., roughly the Heihe-Tengchong Line or Hu Line) (H. Liu, 2019). Tree planting practices to the west of the Hu Line are not recommended, but restoration of grasslands is mostly viable (Zhang et al., 2021).

### 2.3. Model Evaluation With Multiple Data Sources

This study applied two types of modeling methods to assess the individual and combined effects of reforestation and climatic change on water yield for the period of 1980–2020. Change in water yield ($\Delta$WY) was defined as mean water yield during post-forestation period (2000–2020) minus mean water yield during pre-forestation period (1980–1999). We split the study period around 1999 based on the time series of leaf area index (Sun et al., 2008) and the fact that reforestation campaign accelerated end of the 1990s (J. Liu et al., 2008; Lü et al., 2012). The relatively simple Budyko framework was used to examine the mean hydrological response at the annual scale, representing the likely maximum water yield change due to forestation and climate. A more complex process-based water balance model, Water Supply Stress Model (WaSSI)-CN was also applied to have a closer examination at the monthly scale of the seasonal effects of vegetation on water yield. These two modeling approaches, both well validated, offer uncertainty bounds of both direction and magnitude of the likely hydrologic impacts of land cover and climate change in contrasting hydroclimatic regions that have experienced dramatic



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**Table 1**
*Gridded Data Sets for Model Calibration and Validation*

| Data set | Description | Resolution | Time period | Data source references |
|---|---|---|---|---|
| Forest Cover | Long-term forest cover in China by fusing national forest inventory and 20 land use and land cover data sets | 1 × 1 km | 1980–2021 | Xia et al. (2023) |
| Land cover change | Data set from Global Land Surface Satellite program. GLASS15B02.V40 | 0.05° × 0.05° Annually | 1982–2018 | Wang et al. (2019) |
| Monthly precipitation | Based on precipitation monitoring data of more than 2400 meteorological stations; Data used for Budyko mode validation and application | 1 × 1 km | 1960–2020 | Qu et al. (2022) |
| Daily precipitation and temperature | Based on fusion of remote sensing products, reanalysis data sets and in situ station data. Data used for calculating FAO PET, WaSSI-CN model validation | 0.1° × 0.1° | 1979–2018 | He et al. (2020) |
| Potential evapotranspiration | Calculated based on Hargreaves PET method; Used for Budyko and WaSSI-CN modeling applications | 1 × 1 km Monthly | 1990–2022 | Peng, 2022; Peng et al., 2017 |
| China Natural Runoff Data set version 1.0 | Generated using the Variable Infiltration Capacity macroscale hydrological model, which was used to fill in gaps or construct time series of comparable lengths. | 0.25° × 0.25° Daily, monthly, and annual | 1961–2018 | Miao et al., 2022; Gou et al., 2021 |

change in both forest cover and climate during the past four decades. Results from both modeling methods were compared providing confidence in research findings.

### 2.3.1. Budyko Framework Model

We estimated mean annual water yield (WY) as the difference between precipitation (P) and evapotranspiration (ET), assuming change in soil water storage is negligible for a 10-year period, 1980–1999 (pre-forestation) and 2000–2020 (post-forestation). After evaluating commonly used Budyko framework models in studying effects of forestation (van Dijke et al., 2022), we adopted a one-parameter annual mean ET model (Zhang et al., 2001) as a function of annual P and PET calculated by the Hargreaves PET method. This approach has been applied in previous studies to estimate mean potential effects of forestation and deforestation on water yield in China (Sun et al., 2006) and the U.S. (Brown et al., 2008; Sun et al., 2005).

$$\mathrm{ET} = \left( \frac{1 + w\,\frac{\mathrm{PET}}{\mathrm{P}}}{1 + \frac{\mathrm{P}}{\mathrm{PET}} + w\,\frac{\mathrm{PET}}{\mathrm{P}}} \right) \times \mathrm{P} \tag{1}$$

where $\omega$ represents a calibrated ecosystem ET efficiency parameter that is controlled by watershed characteristics. In this study, we used the default parameters for two types of land cover types: fully developed forest lands ($w = 2.0$) and other lands ($w = 0.5$). However, we performed additional model sensitivity simulation using $w = 1.0$ to represent partially recovered forests. It turned out that $w = 1.0$ was more realistic to represent forest recovery conditions and the likely hydrologic responses to forestation at a large basin scale when compared to process-based modeling results from the WaSSI-CN model.

Therefore, the effects of forestation on water yield ($\Delta WY$) is expressed as differences between pre- and post-forestation periods:

$$\Delta \mathrm{WY} = \mathrm{WY}_{\mathrm{post}} - \mathrm{WY}_{\mathrm{pre}} = \mathrm{P}_{\mathrm{post}} - \mathrm{P}_{\mathrm{pre}} + \mathrm{ET}_{\mathrm{pre}} - \mathrm{ET}_{\mathrm{post}} \tag{2}$$

Two forest cover data sets (1 $\mathrm{km}^2$ resolution) in 1980 and 2015 were used to represent the pre- and post- forestation covers, respectively. For a watershed with mixed forests and other land covers, annual mean WY are calculated as difference of between P and weighted ET for forest and other land covers based on their proportions in the watershed:

$$\mathrm{WY} = \mathrm{P} - \mathrm{ET} = \mathrm{P} - \left( \sum \mathrm{ET}_{\mathrm{forest}} \times f_{\mathrm{for}} + \sum \mathrm{ET}_{\mathrm{other}} \times \left(1 - f_{\mathrm{for}}\right) \right) \tag{3}$$

The ET model (Zhang et al., 2001) was assessed with measured mean annual streamflow (WY) in 30 watersheds across China by fitting measured streamflow and modeled WY separately for each of the two time periods to reflect the effects of forestation and human activities on the $w$ parameter. The model was further evaluated with two runoff data streams, the reconstructed China Natural Runoff Data set version 1.0 (CNRD v1.0) based on the VIC model (Miao et al., 2022) and water yield modeled by a process-based ecosystem model (BEPS) (Sun et al., 2022). The VIC model is a general distributed hydrological model that was intensively calibrated in China. BEPS is a remote sensing data-driven model that evolves from a forest ecosystem model that simulates photosynthesis, energy balance, hydrological, and soil biochemical processes. Scatter plots suggest the hydrological model has high accuracy in estimating annual water yield (Figure S1–S3 in Supporting Information S1). We further tested the model's accuracy in predicting the net effects of forestation and climate change on



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**Table 2**
*Four Forest Cover-Climate Combinations Over the 1980–2020 Period for Factorial Analysis*

| Scenarios | $S_1$ | $S_2$ | $S_3$ | $S_4$ |
|---|---|---|---|---|
| Forest cover | 1980 | 1980 | 2015 | 2015 |
| Climate | 1980–1999 | 2000–2020 | 1980–1999 | 2000–2020 |

water yield using published data from 22 large and median sized watersheds and 10 small watersheds across different climate zones (Figure S4 in Supporting Information S1). These evaluations all indicate that the simple model has sufficient accuracy serving as a tool to characterize the hydrologic regime and to estimate mean hydrologic changes due to forest cover change.

### 2.3.2. The WaSSI Model

We applied the revised and validated monthly scale water balance model, WaSSI-CN (Song et al., 2025a, 2025b), originally developed in the U.S. (Sun et al., 2011) for this study as an alternative way to quantify climate change and forestation impacts on water yield at monthly and annual scales. The WaSSI model was substantially modified and parameterized for the Chinese conditions by optimizing the ET algorithms (Song et al., 2025a, 2025b). The core of WaSSI-CN is an empirical monthly ET model that estimates ecosystem ET as a function of potential ET, precipitation, leaf area index (LAI), and limited by soil water availability. PET can be estimated either by the FAO Grass Reference ET model or the temperature based Hamon's PET method or other methods. In this study we used Hargreaves PET method (Table 1). Soil moisture is updated at a monthly scale as the balance of precipitation, ET, and drainage. The WaSSI model has been widely used in several regional and national assessments to quantify water balances in a variety of applications (i.e., land use change, forest thinning, climate change, and urbanization) in the U.S. (Caldwell et al., 2012; Li et al., 2020; Sun et al., 2015), Mexico and West Africa (Bagstad et al., 2018), Australia (N. Liu, 2017), Germany (Pyarali et al., 2026), and China (N. Liu et al., 2013), and most recently in Nepal (Jin et al., 2025) and Türkiye (Peker et al., 2026). Previous calibration and validation of WaSSI-CN against hydrologic data from 193 streamflow gauging stations in China and three global remote sensing ET products indicate that WaSSI captured the large spatial and temporal variability of hydrologic fluxes (mean Nash Sutcliffe Model Efficiency Coefficient = 0.66) (Song et al., 2025b). Therefore, WaSSI-CN is reliable to examine hydrologic responses to climate and land cover change at the national scale. Similar to the modeling exercise using the Budyko framework, we examined water yield change due to land cover and climatic change at both annual and seasonal scales using various scenarios discussed below. The change in water yield ($\Delta$WY) was calculated as the mean WY during 2000–2018 minus mean water yield during 1982–1999. A previous study using WaSSI reports that both ET and gross ecosystem productivity have increased due to expansion of forestlands and increase in precipitation and air temperature in China (Song et al., 2025b).

## 2.4. Attribution of Forestation and Climate Effects

The Budyko modeling approach (Zhang et al., 2001) was implemented to estimate annual water yield using a high-resolution land cover database (1 $km^2$) over 1980–2020. We conducted simulation experiments using four scenarios combining forest covers in 1980 (i.e., pre-forestation) and 2015 (post-forestation) and climates for two corresponding periods (Table 2) to untangle the individual from combined effects (absolute and relative) of forestation and climate change on water yield (Table 3). We assessed the effects of forestation on water yield at multiple scales from 1 $km^2$ pixel, 2nd-level watershed (168 large basins), and 1st level watershed (eight super large basins) scales to illustrate the effects of watershed size on hydrologic responses. The average area of the 168 basins is 33,000 $km^2$, ranging from 3,000 $km^2$ to 150,000 $km^2$.

Similarly, using the scenario simulation designs in Tables 2 and 3, we applied the improved and validated WaSSI model, WaSSI-CN (Song et al., 2025a, 2025b) to examine how climate and land cover change has affected water yield at both monthly and annual scales. Due to limitations in monthly climatic data availability, our analysis

**Table 3**
*Simulation Scenarios to Examine the Combined and Separate Effects of Climate and Forestation on Mean Annual Water Yield Under Four Climate-Forest Combinations, S1–S4, in Table 2*

| Different factors | Forest cover | | Climate | | Both |
|---|---|---|---|---|---|
| Simulation scenarios | A | B | C | D | E |
| Absolute water yield change (mm $yr^{-1}$) | $S_3-S_1$ | $S_4-S_2$ | $S_2-S_1$ | $S_4-S_3$ | $S_4-S_1$ |
| Relative water yield change (%) | $(S_3-S_1)/S_1$ | $(S_4-S_2)/S_2$ | $(S_2-S_1)/S_1$ | $(S_4-S_3)/S_3$ | $(S_4-S_1)/S_1$ |



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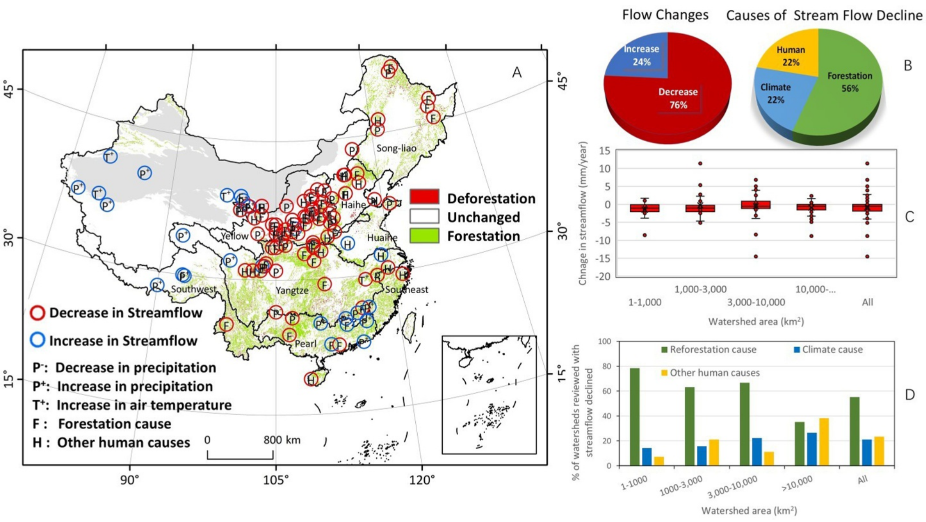


**Figure 1.** A meta-analysis study on long-term mean annual river streamflow patterns over the period of 1980–2020 in China. (a) identified flow trend and causes of flow decline for 85 watersheds; the directions and the causes of change in flow are color and letter symbol coded, respectively; the base map shows forest change at 1-km scale from 1980 to 2015, (b) Percentage of watersheds showing a decrease or increase in annual streamflow and causes of streamflow decline, (c) Reported flow change by watershed size, and (d) Percentage of watersheds with a decrease in flow due to three key causes by watershed size. A list of watersheds reviewed is in Supporting Information S2.

focused on the period from 1982 to 2018, compatible with the period of 1980–2020 used by the Budyko modeling. The same precipitation and PET data sets were used by the two modeling approaches.

## 3. Results

### 3.1. Widespread Decline in River Flow

The 91 empirical studies on river flow change encompassed 112 diverse watersheds with a total catchment area of more than 5 million km$^2$ across a large climatic gradient in China (Figure 1a) (Supporting Information S2). Most watersheds were found in the dry northern hilly regions, headwaters of the Yellow River, where water shortage and sediment problems are most acute. The majority (i.e., 85 or 76% of the total) of the watersheds exhibited a declining trend in river flow, regardless of climatic regions, dry or wet. The other 27 watersheds (i.e., 24% of the total) show an increasing trend and are found in the alpine mountains on the Qinghai-Tibetan Plateau region or urbanizing areas in southern China (Figures 1b and 1c). About 82% of watersheds with a size less than 1,000 km$^2$ had a decline trend in flow, and 24 large watersheds (>1,000 km$^2$) (21% of total) showed an increasing trend in streamflow.

Forestation was registered as the main factor causing flow decrease in over half of those 85 watersheds that showed flow decline trends (Figures 1b and 1d). Forestation was identified as the dominant reason causing flow decline in all the relatively small watersheds (<1,000 km$^2$) (Figures 1c and 1d). For large river basins with area >1,000 km$^2$ each, besides forestation, a decrease in precipitation was also identified as a major factor in 24 watersheds. In addition, increased ponds and reservoirs to support water use for irrigation were determined as key human factors responsible for flow decline in large basins (>1,000 km$^2$) (Figure 1d). The commonly cited reasons for the decrease in water yield by forestation are the increase in water loss through ET as forest area expands (Feng et al., 2012; Li et al., 2014; W. Liu et al., 2015) and/or vegetation leaf area recovery (Y. Liu et al., 2018; Yu et al., 2023). Small bioengineering methods such as terraces, "fish scale pits," and check dams that are often used in forest-based forestation to control soil erosion. These measures also increase water retention (Chen et al., 2020; X. Wei et al., 2021; W. Wei et al., 2021), enhance tree transpiration (H. Zhang et al., 2017; M. Zhang et al., 2017), soil evaporation (Y. Liu et al., 2026), deep soil desiccation (L. Yang et al., 2014), and water yield reduction (Yu et al., 2010; Zhang et al., 2008) at the watershed scale.

Increase in precipitation (Yang et al., 2022) and thawing soils and melting glaciers due to rising air temperature (Wang et al., 2021) in the Qinghai-Tibetan Plateau region, and urbanization in populated eastern regions (Hao



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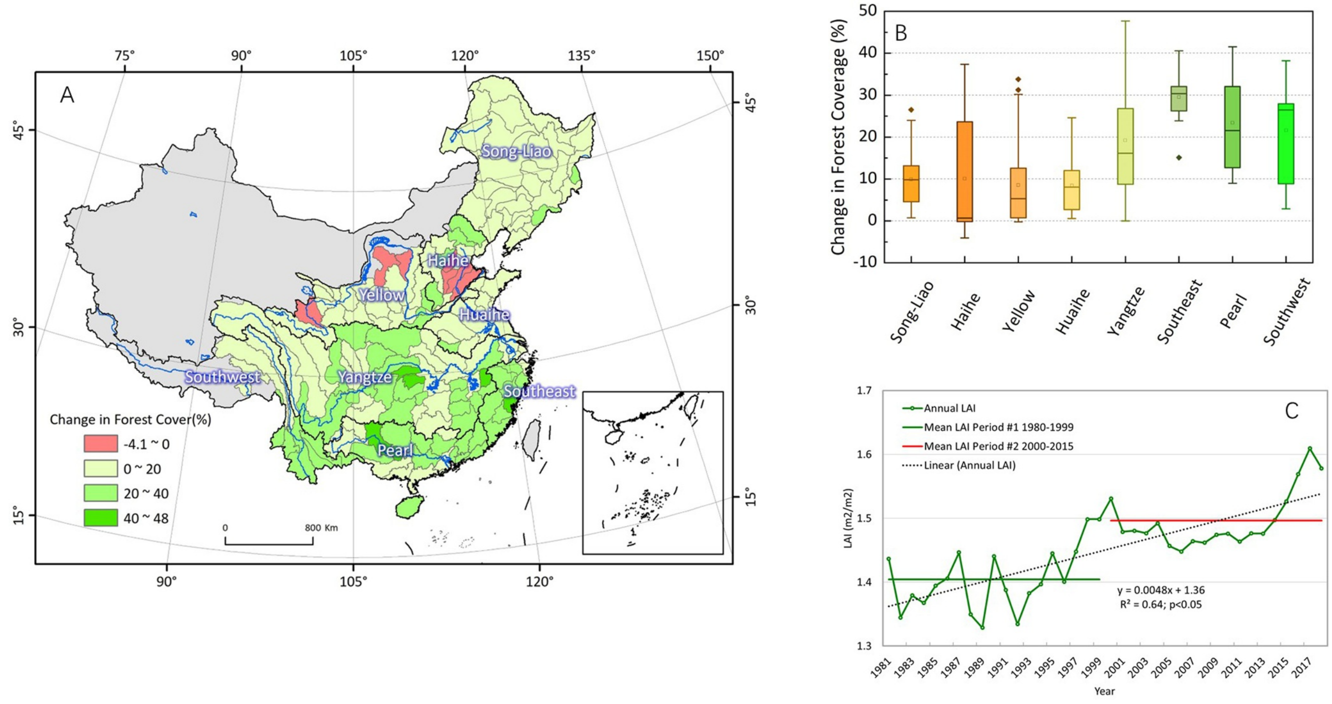


**Figure 2.** Changes in forest covers and "greening up" across China. (a) Absolute increase in forest coverage (forest area/total watershed area in %) across 168 watersheds, and (b) eight first level large basins, and (c) significant increase in mean leaf area index (LAI) across vegetated areas in China from 1981 to 2018. The forest coverage data in (a) and (b) are upscaled from forest cover data with a 1 $km^2$ resolution.

et al., 2015) were responsible for the increase in flow for 14 basins (1,000–10,000 $km^2$) and those larger than 10, 000 $km^2$ (Figure 1d). Increase in precipitation in some regions might have masked the negative effects of forestation on river flow. The offsetting effects were demonstrated by several studies on the Yangtze River in southern China (B. Zhang et al., 2022; J. Zhang et al., 2022; X. Zhang et al., 2022) where water yield is known to be less sensitive to vegetation change compared to the northern dry regions (Xue et al., 2022; Zhou et al., 2021). The Yangtze River Basin as a whole (B. Zhang et al., 2022; J. Zhang et al., 2022; X. Zhang et al., 2022) or other large basins (Ganjian River and Dongjiang River with area of 35,000 $km^2$ and 112,000 $km^2$, respectively) (Xue et al., 2022) in the humid regions did not show significant decreases in flow although forest area and leaf area index have appreciably increased. Other studies reported that water yield significantly decreased in small watersheds (<10 $km^2$) (Ouyang et al., 2018; Sun et al., 2008) and large watersheds (95,000 $km^2$) (B. Zhang et al., 2022; J. Zhang et al., 2022; X. Zhang et al., 2022) in the Yangtze River Basin due to vegetation recovery.

### 3.2. Changes in Forest Coverage and Climate

#### 3.2.1. Forest Cover Change

The forest coverage increased dramatically from 19 ± 18% in 1980 to over 34 ± 26% in 2015 (Figure 2a) across 168 watersheds representing the 2nd level by the Chinese basin delineation schemes. The forest cover change represented a 1.9 ± 2.5 folds expansion in forest land area (or an increase of 1.2 million $km^2$, about the land mass size of South Africa). The largest absolute increase in forest coverage was found in the hilly humid South China wherein regional climate favored forest reestablishment (Figure 2b). The Southwest, Southeast, the Yangtze River Basin, and the Pearl River Basin benefited from the large ecological restoration programs such as the Natural Forest Protection Program and the Grain for Green Program (Liu et al., 2008). The largest relative changes in forest areas (2–3 folds) were found in the headwaters of the Haihe, Huaihe, and the Loess Plateau dry regions in northern China traditionally dominated by croplands. From 1981 to 2018, the mean leaf area index (LAI) ($m^2$ $m^{-2}$) across China's vegetated areas increased significantly ($p < 0.05$) by 15% in the study watersheds (Figure 2c). The mean LAI during the post-reforestation period (2000–2015) was 1.5 compared to 1.4 for the pre-forestation period (1980–1999) (Figure 2c), representing a 7% increase. The Huaihe basin in central China saw the



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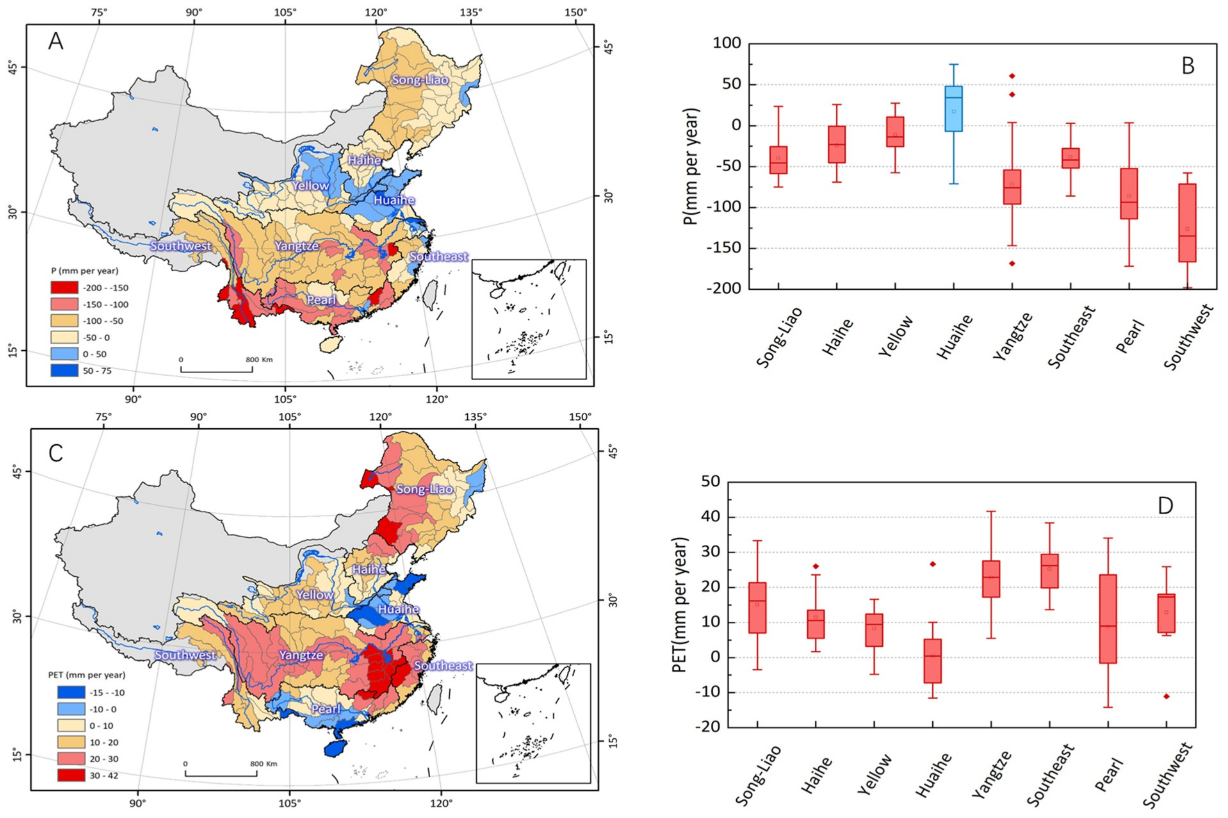


**Figure 3.** Climate change (2000–2020 vs. 1980–1999) data sets scaled from 1*1 $km^2$ resolution for 168 watersheds, showing a decrease in annual precipitation (P) but an increase in annual potential evapotranspiration (PET). (a–b) spatial distribution of change in annual precipitation, and (c–d) change in PET from 1980–1999 to 2000–2020. Box plots show variability among watersheds with each first level large basin.

largest annual increase in LAI (0.01 $m^2\ m^{-2}\ y^{-1}$) which coincided with the largest relative change (3.3 times) in forest coverage.

#### 3.2.2. Climate Change

Over the period of 1980–2020, about 82% of the watersheds experienced a decline in annual precipitation (62 ± 42 mm) with the southwestern region being the most pronounced (Figures 3a and 3b). There was a significant ($p < 0.05$) warming trend of 0.025°C $y^{-1}$ from 2000 to 2020 in China, primarily in watersheds located in the southwestern, northern, and southeastern China (Sun et al., 2022). Annual potential ET (PET) increased 17 ± 9 mm, as much as 41 mm in more than 88% of the watersheds due to global warming (Figures 3c and 3d). A severe decrease in precipitation coupled with increase in air temperature and PET caused widespread hydrologic drought in the southwestern regions and middle reaches of the Yangtze River Basin during the study period (Sun et al., 2017, 2022). The drought was reported to result in reduced increase in LAI due to water stress in the Southwest comparing to the general rising trend in southern China (Sun et al., 2022).

### 3.3. Water Yield Change Attributions: Forestation versus Climate Change

#### 3.3.1. The Budyko Modeling Framework

The water balance model based on the Budyko framework (Zhang et al., 2001) ($w = 2.0$, 0.5 used for forest and other land uses, respectively) performed reasonably well without calibration (Figures S1-S3 in Supporting Information S2). Most of the model bias came from the mismatch of periods and land cover data used. The model was then applied with a varying $w$ parameter to examine various scenarios (Tables 2 and 3) to quantify the individual and combined effects of forestation and climate on water yield at the 1-$km^2$ spatial resolution (FigureS S5 and S6 in Supporting Information S1). The results were then scaled up to two spatial scales, 2nd level 168 watersheds and eight 1st level large basins (Figure 4).



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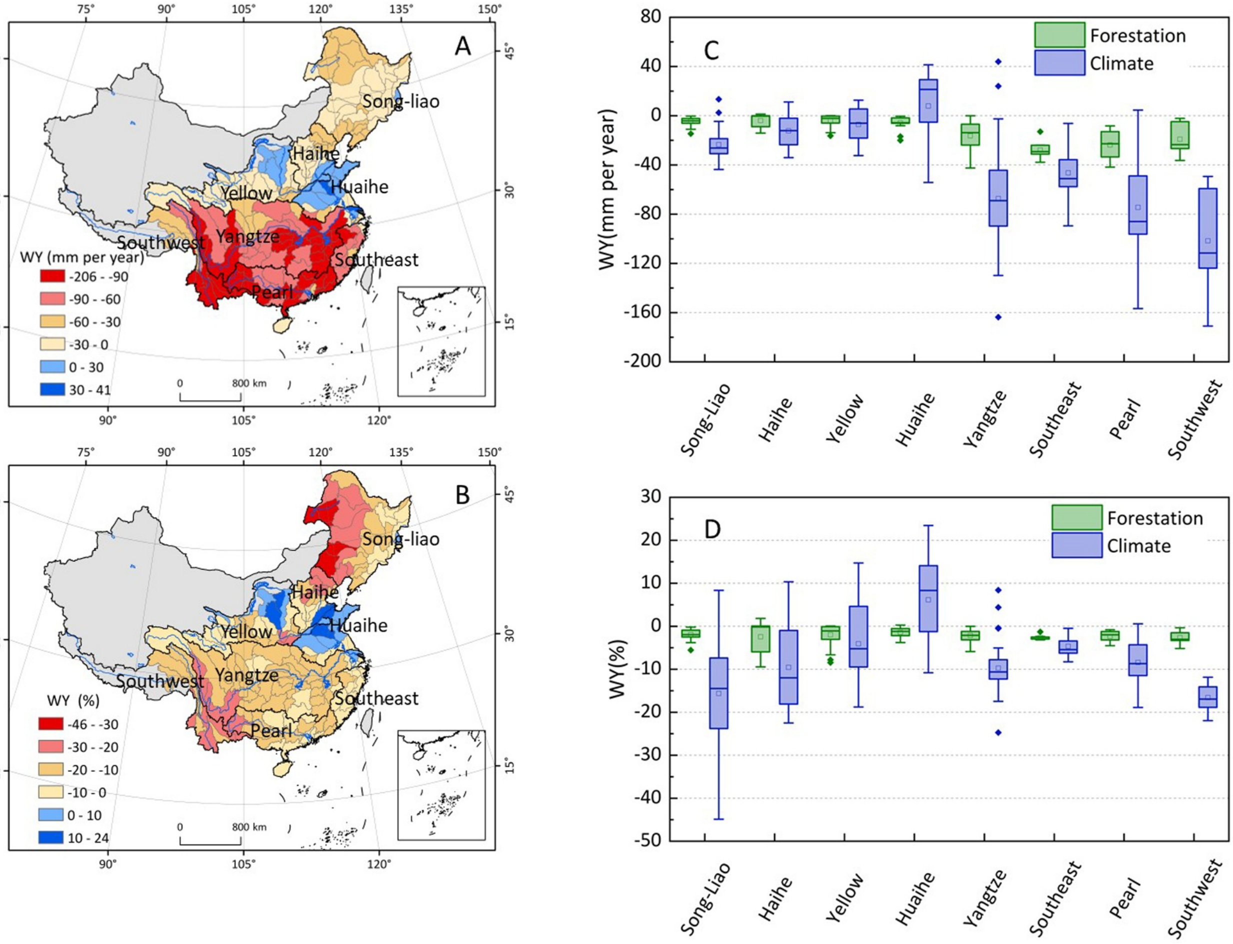


**Figure 4.** Simulated effects of forestation and climate change from around 1980 to 2020 on water yield (WY) using $w = 1.0$ for post-forestation and $w = 0.5$ for pre-forestation in the Zhang et al. (2001) Budyko model. Results scaled to the second level watershed (total = 168 watersheds) and 1st level (eight basins). (a) Spatial distribution of absolute change in water yield (mm $yr^{-1}$), (b) Spatial distribution of relative change in water yield (WY) (%), (c–d) Attribution of change in water yield (WY) by the 1st level eight large basins.

Regardless of the $w$ parameters (1.0 or 2.0) used, the multi-scenario simulations indicated that forestation and climate change together substantially altered water yield for a large portion of the country from 1980 to 2020 (Figures S5 and S6 in Supporting Information S1). At the 1 $km^2$ scale, water yield decreased as much as −978 mm $yr^{-1}$ (−832 mm $yr^{-1}$) in an absolute term and as much as 80% (70%) in a relative term when the $w$ parameter of 2.0 (1.0) was used (Figures S5b and S6b in Supporting Information S1). Flow increased as high as 100 mm $yr^{-1}$ or 400% for limited areas (Figures S5c and S6c in Supporting Information S1). The majority (>70%) of the study areas were projected to have a decline in water yield in the range of 0–100 mm $yr^{-1}$ when $w = 2.0$ was used or 60% of the areas was predicted to decrease up to 50 mm $yr^{-1}$ when $w = 1.0$ was used. Climate change alone was responsible for water yield decrease as high as −200 mm $yr^{-1}$ and an increase up to 100 mm $yr^{-1}$ (Figures S5e and S6e in Supporting Information S1). In contrast, forestation alone caused a decrease in water yield across the country with a small area showing a large decrease (up to −200 mm $yr^{-1}$ or −300 mm $yr^{-1}$ when $w = 1.0$ or 2.0 was used) due to an increase in ET (Figures S5f and S6f in Supporting Information S1).

At the watershed scale, when $w = 1.0$ was used, the mean change in water yield was estimated as $-52 \pm 52$ mm $yr^{-1}$. Among the 168 watersheds, 127 (or 76%) showed a decrease in water yield (up to −206 mm $yr^{-1}$ or −46%), and the rest showed an increase (up to 41 mm, or 25%) (Figures 4a and 4b). Forestation alone decreased watershed yield by up to −44 mm $yr^{-1}$ (mean $-12 \pm 12$ mm) in all of the watersheds except one. Climate change resulted in a mean change of water yield of $-40 \pm 43$ mm $yr^{-1}$, ranging from −171 mm to +44 mm $yr^{-1}$ with 85% of the watersheds having a decrease in water yield. Regionally across the eight large



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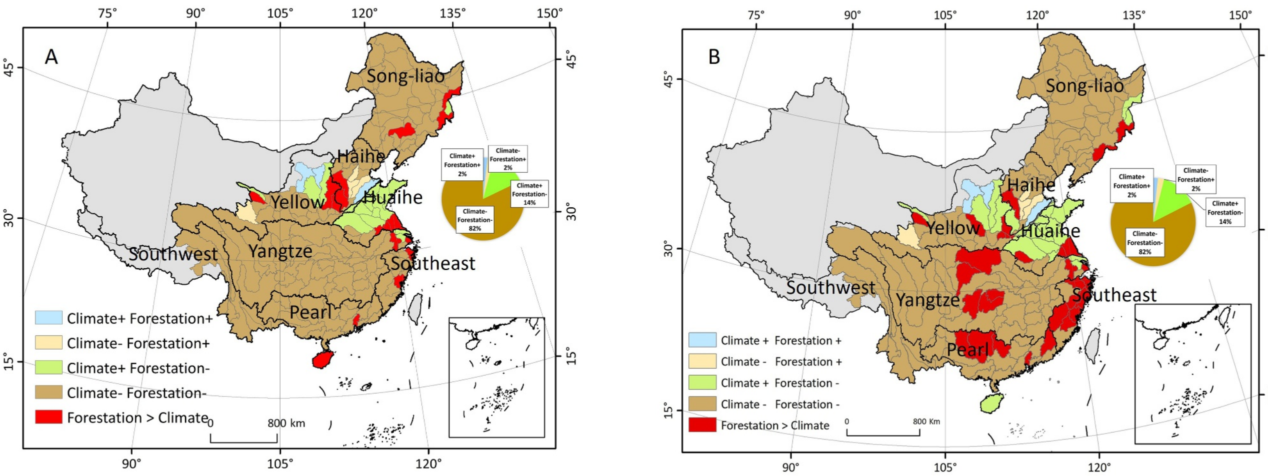


**Figure 5.** Simulated additive (same signs) and offsetting (opposite signs) effects on water yield over the 1980–2020 period using Zhang et al. (2001) Budyko framework. (a) $w = 1.0$ and (b) $w = 2.0$ for post-forestation and $w = 0.5$ for pre-forestation. The negative sign represents a decline in water yield and positive represents an increase in water yield (e.g., Climate$^-$ Forestation$^-$ represents both climate and forestation cause reduction in water yield). The watersheds in red indicate that forestation effects exceed climate change effects. The inset figure represents proportion of each of the four combined effects on water yield, indicating negative effects of forestation and climate change dominate water yield change at the national level (brown).

basins, large decreases (i.e., 120 mm yr$^{-1}$) in water yield were found in southwestern and southeastern China (Figures 4a and 4c), a region with a relatively high forest coverage and precipitation. The large (i.e., >20%) relative decreases (Figures 4c and 4d) were found in northern China with lower forest coverage and precipitation, and in southwestern China where severe droughts occurred during the study period (Figure 4c). Both forestation and climate change had the highest decrease impacts on water yield in the Pearl River and Southeast basins (−46 to −120 mm yr$^{-1}$) (Figure 4c). Water yield increased 2 ± 6 mm yr$^{-1}$ in the Huaihe River Basin due to a large increase in precipitation.

Compared to the simulations using $w = 1.0$, the predicted spatial patterns of hydrological responses to forestation and climate change were similar to these when the parameter $w = 2.0$ was used (Figure S7 in Supporting Information S1) with a mean change in flow of −67 ± 65 mm yr$^{-1}$, somewhat higher in magnitude. Using $w = 2.0$, the effects of forest recovery on water yield (−27 ± 29 mm yr$^{-1}$) were much higher than under $w = 0.1$ conditions (−12 ± 12 mm yr$^{-1}$) and were most pronounced in humid regions (Figures S7 and S8 in Supporting Information S1). In this case, 150 (89%) of the 168 watersheds exhibited a decrease in water yield up to −268 mm yr$^{-1}$. Climatic effects were almost identical to the simulation case using $w = 1.0$. Therefore, estimated hydrological responses to the combined effects of climate and forestation were sensitive to the choice of the $w$ parameter.

The combined effects of forestation and climate change resulted in the complex spatial patterns of water yield responses that were dominated by an overall decline trend (Figure 5). When $w = 1.0$ was used (moderate forest recovery), 87% (13%) of watersheds showed a decrease (increase) in water yield. Forestation and climate change accounted for 23% (−12 ± 12 mm) and 77% (−40 ± 44 mm) of the total water yield impacts (−52 ± 52 mm), respectively. Water yield was negatively impacted by both climate and forestation (i.e., Climate$^-$ + Forestation$^-$) in about 83% of the watersheds (Figure 5a). Forestation reduced flow by −14 ± 12 mm yr$^{-1}$, in 82% of the 168 watersheds. This greatly exacerbated the negative climate change effects (i.e., −52 ± 39 mm yr$^{-1}$) by 22%. Moreover, effects of forestation exceeded climate change and variability in 17 watersheds by up to 25 mm yr$^{-1}$ or 2% to over 100% (Figures 5c and 55d).

Comparing to estimates using $w = 1.0$ (Figures S5 in Supporting Information S1), similar spatial patterns but higher magnitude of change in water yield were found when $w = 2.0$ was used (Figure 5b) Forestation and climate change accounted for 21% (−28 ± 29 mm) and 79% (−40 ± 43 mm) of the total impacts (−67 ± 65 mm) on water yield, respectively. A total of 138 watersheds (or 82%) showed a decline in water yield caused by both climate and forestation (i.e., Climate$^-$ + Forestation$^-$) (Figure 5b). Forestation substantially exacerbated the water yield decline due to climate change (−51 ± 39 mm yr$^{-1}$) by −32 ± 30 mm yr$^{-1}$ (or 36%). Negative effects of

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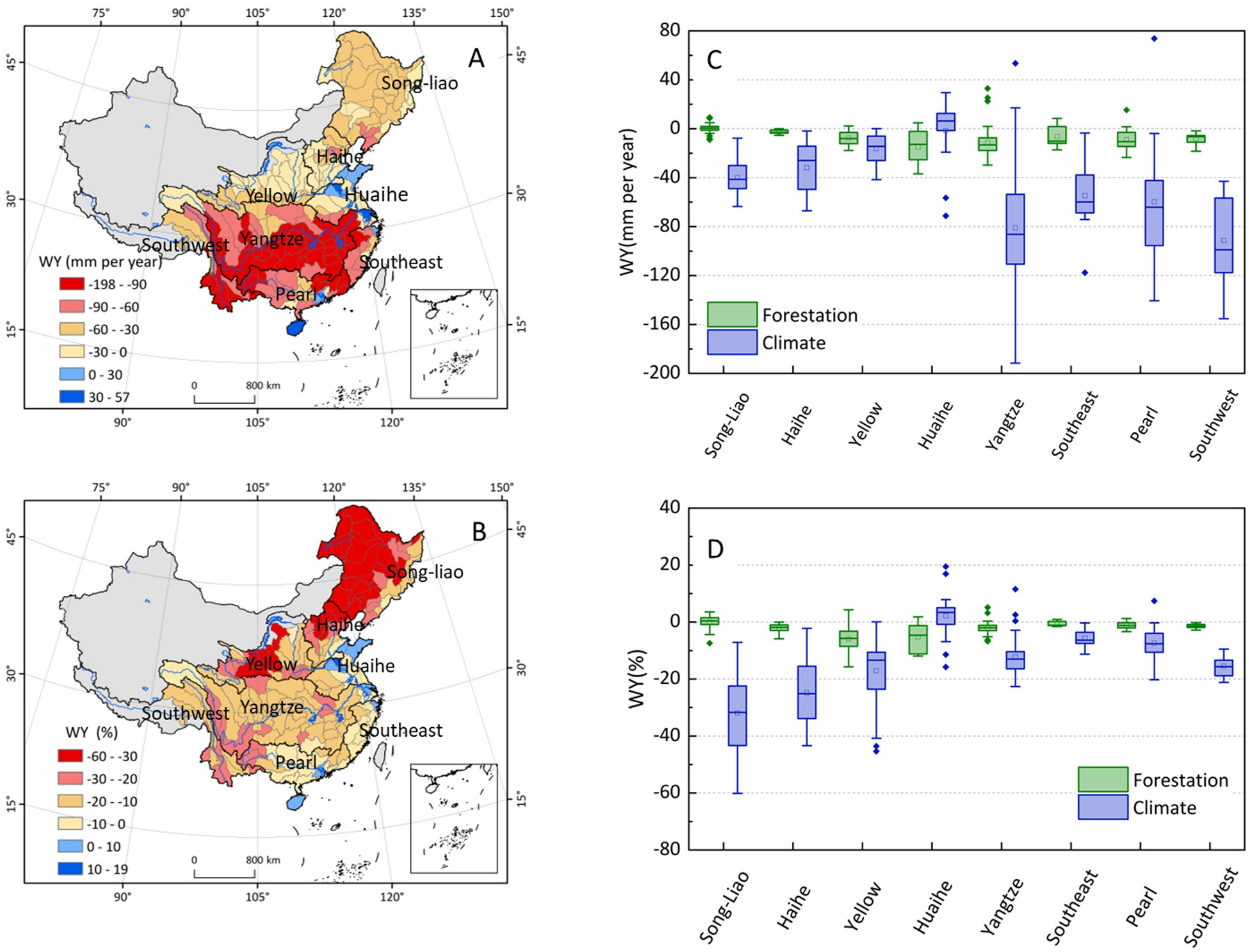


**Figure 6.** WaSSI-CN simulated effects of forestation and climate change on water yield across the 168 watersheds and eight first-level basins from 1982 to 2018. (a) Spatial distribution of absolute change in water yield (mm $yr^{-1}$), (b) Spatial distribution of relative change in water yield (%), (c) Attribution of change in water yield (WY) (mm $yr^{-1}$) by eight first level large basins, and (d) Attribution of relative change (%) in WY by the eight large basins.

forestation ($-50 \pm 32$ mm $yr^{-1}$) surpassed climate effects ($-26 \pm 26$ mm $yr^{-1}$) in 38 watersheds (or 23% of the total number of watersheds examined).

The most pronounced areas with additive effects of forestation were in southern China (Figure 5). In heavily forested areas such as the Southeast and Pearl river basins, effects of forestation on water yield even exceeded those of climate change as much as 24 mm $yr^{-1}$ ($w = 1.0$) (Figure 5a) and 86 mm $yr^{-1}$ ($w = 2.0$) (Figure 5b). In dry areas with little change in forest coverage (e.g., northern China's lower Yellow River and Huaihe River Basins), or areas with large increase in precipitation in the southeast such as the Yangtze River Bain, the impacts of increased precipitation overwhelmed the negative effects of forestation, resulting in a significant net increase in water yield up to 44 mm $yr^{-1}$ (9%).

### 3.3.2. Annual Water Yield Response Simulated by the WaSSI Model

Similar to the modeling results by the Budyko framework presented above, WaSSI-CN simulations at the $0.1° \times 0.1°$ grid spatial scale suggest that forestation and climate change together substantially altered water yield for a large portion of the country from 1982 to 2018 (Figure S10 in Supporting Information S1). Across the 168 watersheds (Figure 6), on average, water yield was projected to decrease $-57 \pm 47$ mm $yr^{-1}$. Climate change of decrease in precipitation contributed to ($-49 \pm 44$ mm $yr^{-1}$) while forestation explained $-8 \pm 10$ mm $yr^{-1}$. The Yangtze River Basin, Southwest, and Pearl River basins showed the highest decline up to $-197$ mm $yr^{-1}$ (Figure 6a). The highest impact of forestation was $-37$ mm $yr^{-1}$ in a watershed in the Huaihe River Basin while the climate change caused the largest decline of $-192$ mm $yr^{-1}$ in the Yangtze River Basin. The largest relative



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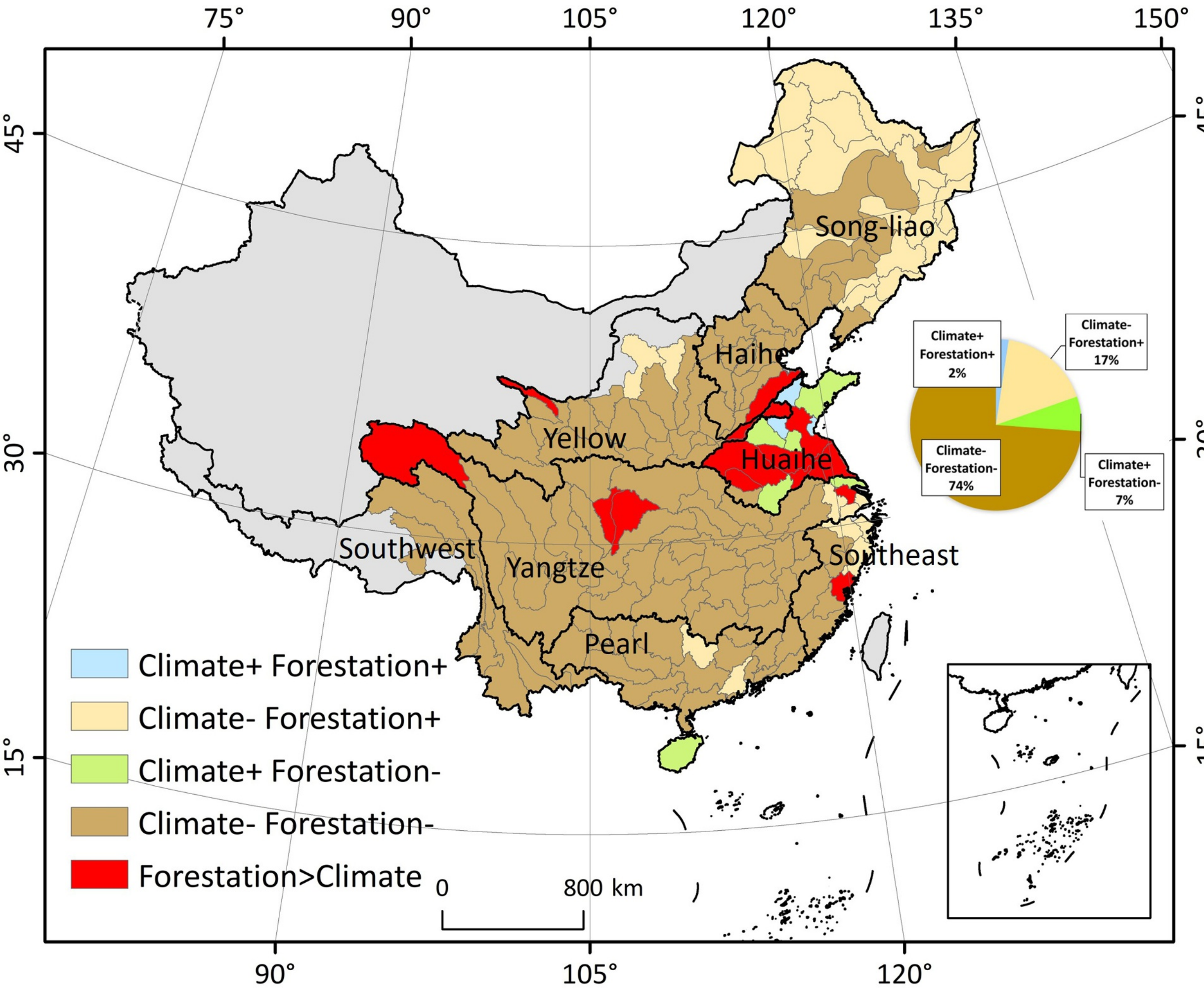


**Figure 7.** WaSSI-CN model simulated additive (same signs) and offsetting (opposite signs) effects of land use change or climate change on water yield over the 1982–2018 period. The negative sign represents a decline in water yield and positive represents an increase in water yield (e.g., Climate$^-$ and Forestation$^-$ represents both climate and land use change cause reduction in water yield). The watersheds in red indicate that negative effects of land cover change exceed climate change effects. The inset figure indicates that negative effects of land use change and climate change dominate water yield change at the national level.

water yield decrease (up to −30%–60%) was found in the dry northern China (Figures 6b and 6d) (Song-liao, Haihe, Yellow). It appears that the WaSSI-CN simulations on hydrological responses had similar magnitude and directions with the Budyko modeling results (Figure 4).

WaSSI-CN exhibited similar water yield responses to climate and land use change (Figures 6 and 7, and Figure S9 in Supporting Information S1) to those determined by the Budyko framework (Figure 5). The WaSSI-CN modeled water response, a decrease (93% of total number of 168 basins) or an increase (7% of total), was dominated by climate change (87% of mean total change) (Figure S10 in Supporting Information S1; Figure 6). A total of 128 basins (76%) showed additive effects (124 both negative and 4 both positive) of climate change and land use change (inset of Figure 7). Majority of the watersheds were negatively affected by climate and land use change. The negative additive effects (88% of total change of $-63 \pm 44$ mm) dictated the magnitude of water yield decline (Figures 6c and 6d). Climate change effects were offset by land use change on water yield in 40 (or 24%) watersheds (inset of Figure 7). The magnitude of effects of land use change (negative or positive) exceeded the influence of climate change in 19 basins (11%) by $11 \pm 8$ mm yr$^{-1}$. These basins were mostly found in Huaihe and Yangtze river basins in central and southern China (Figure 7).

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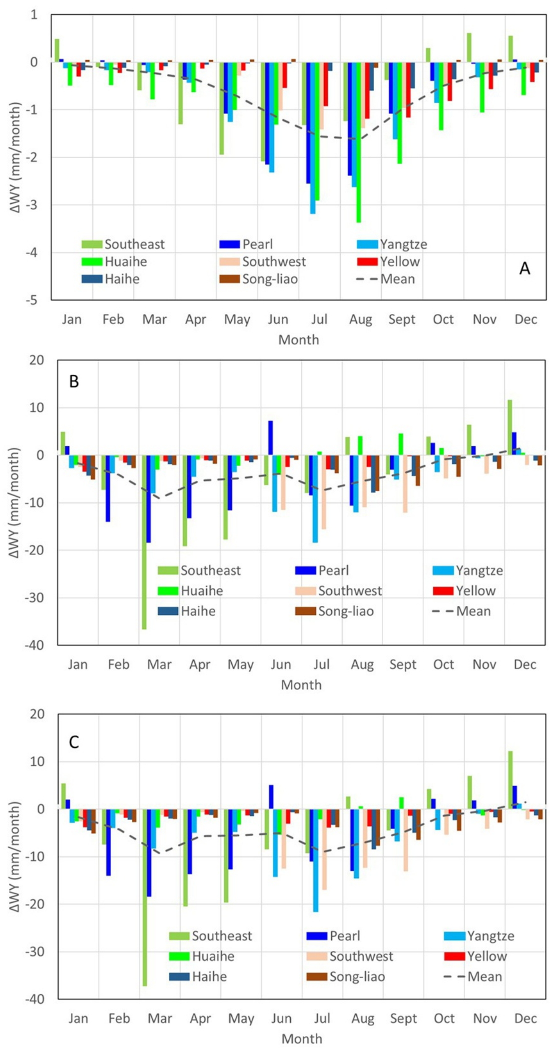


**Figure 8.** WaSSI-CN simulated effects of climate (a), land use change (b), and the combined effects of climate and landuse change (c) on monthly water yield across eight first level river basins in China for the period of 1980–2018 by an ecohydrological model (WaSSI-CN).

### 3.3.3. Water Yield Response at the Monthly Scale Simulated by the WaSSI Model

As expected, water yield response to vegetation change was projected to be most pronounced in the peak growing season in the summer months when most of the watersheds received the largest portion of the annual precipitation and energy (i.e., PET) under a monsoon climate in China (Figure 8a). These are especially true for the Huaihe, Yangtze, and Pearl river basins in southern China where the absolute change in water yield is the highest in July and August (Figure 8a). In contrast, climate change impacts were much larger than vegetation effects (Figure 8b), and were much more variable intra-annually, a pronounced decline in the spring months (March, April) but a large increase in the summer monsoon season (June–September) (Figure 8b). This pattern appears to be most obvious for the southern regions (Yangtze, Pearl River basins).

Overall, at the national scale, the combined effects of change in land cover ($-0.6 \pm 0.6$ mm mon$^{-1}$) (Figure 8a) and climate ($-3.7 \pm 3.1$ mm mon$^{-1}$) (Figure 8b) resulted in a water yield decline ($-4.4 \pm 3.4$ mm mon$^{-1}$) (Figure 8c). As expected, land cover effects were most pronounced during the summer growing seasons (June-August) (Figure 8a) corresponding to the peaks in both water availability and plant growth across China that is dominated by a monsoon climate. Climatic effects were more variable among regions. Notably, the Southeast showed a large decrease in water yield (up to $-37$ mm mon$^{-1}$) during the spring months due to a decrease in precipitation (Figure 8b). In contrast, climatic effects were most pronounced in the summer months in Yangtze, Pearl, and Southwest river basins. Overall, at the eight large basin scale, effects of land cover change were muted compared to climatic change influences during the study period from 1980 to 2018.

## 4. Discussion

### 4.1. Water Yield Declines Due To Multiple Stressors

Taking advantage of the observations of the unpresented large-scale changes in forest cover and long-term river flow records, this comprehensive analysis offers new insights into the effects of forestation. We found substantial change in water yield at multiple scales across China during the past four decades. Overall, findings from this study are in line with recent national-scale comprehensive assessments that show river flow has been declining in many parts of China due to land use change charterized as "greening up," climate change, and human water extractions (Bai et al., 2020; Song et al., 2023). For example, Wang et al. (2025) show that streamflow has declined across more than 70% of the 1046 stations over the past six decades in China. They found that land use and land cover change exacerbated streamflow decline caused by water abstraction, diversion, and regulation in the dry northern China, but climate change and variability dominate the increases in streamflow primarily in the wet southeastern China. Similarly, Gou et al. (2025) found that increased human water withdrawal by agricultural, domestic, and industrial sectors, and climate warming reduced surface water persistence resulting in an increase in length of intermittent rivers from 13% to 50% in China from 1961 to 2020. An et al. (2025) reported that forestation in China increased annual ET by 1.71 mm resulting in annual water yield decrease in 0.46 mm when atmospheric moisture redistribution was considered during 2001–2020.

In contrast to recent long-term national studies discussed above, the present work specifically quantified the effects of land use change/forestation amid climate change by meta-analysis and simulation experiments using two types of models at both annual and monthly scales. Our study contributes to better understanding of the forest-water relations across a large climatic gradient and at a large spatial scale over a period that witnessed dramatical forest cover and climate change. The methods adopted here contrast to traditional small "paired watershed" studies that are challenged to address forestation-water nexus issues at a large scale (Andréassian, 2004; Brown



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et al., 2005). In fact, the lack of creditable "Paired Watershed Experiment" has been considered as one of the key reasons of the lasting debate (Sun et al., 2006, 2023a, 2023b) on the hydrologic change associate with forestation (Bi et al., 2014; Y. Liu et al., 2016) in China. Therefore, results from this study filled considerable knowledge gaps.

Our meta-analysis and factorial simulations by two distinct modeling strategies all suggest climate change dominated water yield change during the past four decades. Also, the results support the notion that forestation generally decreases annual water yield at a watershed scale (X. Wei et al., 2021; W. Wei et al., 2021; H. Zhang et al., 2017; M. Zhang et al., 2017; Zhang & Wei, 2021). However, we found that river flows are often subject to multiple stresses and separating the sole impacts of forestation on water yield from those by climate change and anthropogenic influences in large basins is challenging. Almost all the studied watersheds in China have experienced a decrease in streamflow that coincided with large-scale forestation and widespread "greening up" (Li et al., 2018; Sun et al., 2022). At the same time, decreases in precipitation (i.e., southwestern China), a rise in atmospheric water demand, and increase in human water demand have occurred. Therefore, forestation has additive effects on water yield decline, aggravating the diminishing river flow caused by climate change and human water use in China. This is especially important in the dry northern China in the growing seasons when water use by forests and humans are the highest.

The negative effects of forestation on water yield could be masked by the increase in precipitation and hydraulic alterations (i.e., dams) in certain regions (B. Zhang et al., 2022; J. Zhang et al., 2022; X. Zhang et al., 2022). For example, Huaihe River Basin in eastern China experienced an increase in precipitation (Figures 3a and 3b) and an increase in water yield (Figures 4 and 6). However, forestation could moderate the expected increase in water yield in regions dominated by a summer monsoon climate (i.e., southern China). Similarly, the negative impacts of forestation might be amplified by climate change (e.g., PET increase or/and Precipitation decrease). Impacts of forestation on water yield can be more complicated especially for large basins. Most of the watersheds examined in this study were larger than 10,000 $km^2$. Additionally, these watersheds had mixed land use change and were subject to considerable modifications for water resource management (e.g., flood control, flow diversion, inter-basin transfers), and other flow alterations. For large basins, the proportion of forest cover changes can be relatively small, resulting in a minor change in flow. Research suggests that there is a threshold of 15%–25% of forest cover change to have a measurable change in water yield (Stednick, 1996; X. Wei et al., 2021; W. Wei et al., 2021; Hou & Wei, 2024). The fate of forest ET to become precipitation downwind is rather variable and uncertain (Gao et al., 2025; Tian et al., 2022; Yan et al., 2025). For example, a study by An et al. (2025) suggest that forest expansion in China elevated ET and reduced water availability overall, but the impacts were spatially variable when considering atmospheric moisture recycling: an increase in the Tibetan Plateau (0.38 mm $yr^{-1}$), but a decrease in the Eastern Monsoon Region (−0.59 mm $yr^{-1}$) and Northwestern Arid Region (−1.14 mm $yr^{-1}$). Studies also suggest that the actual forestation effects on regional precipitation are often too small to alleviate water shortage for dry regions (Briske et al., 2024) and local watersheds (Haas et al., 2024).

### 4.2. Implications for Forest Management for Water

The United Nation declared 2021–2030 as the "Decade on Ecosystem Restoration" that aims at slowing down desertification and recovering the ecosystem services diminished due to deforestation. This study may offer important guidance to such endeavors. First, planting trees has the potential to appreciably reduce water availability (Mao et al., 2024; Yang et al., 2022), especially in regions that are suffering from climatic warming and reduced precipitation (e.g., southwestern China). Increased climatic variability with intense storm, more dry spells, or longer growing season can also result in river flow decrease (Wu et al., 2024). Even in traditionally wet regions such as the southeastern U.S. and southeastern China, the rise in forest ET in headwater watersheds may reduce water supplies to downstream communities (Z. Liu et al., 2022; Wu et al., 2025). Our results align with a global modeling study that cautions about unwanted local and regional reductions in water availability from ecological restoration projects (Benedict et al., 2024). Second, global climate change-induced drought stress to trees may become a barrier to large scale forestation efforts (M. Zhang et al., 2022; Sun et al., 2024). Innovative silvicultural practices are needed in managing future forests (FAO et al., 2021). Native rather than exotic tree species are encouraged in forestation to reduce tree water use and increase resilience to drought and insect diseases outbreaks and promote biodiversity (Hua et al., 2022; Jones et al., 2022; Meli et al., 2024). Degraded forests that have been subjected to fire suppression and mesophication, thinning and prescribed burning that reduce tree density and understories may help reduce total forest water consumption, and thus benefit water yield

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especially during dry periods (Sun et al., 2015). Restoring forest litter layers or adding mulch may enhance soil water infiltration, reduce soil moisture loss through surface evaporation, and improve forest health (Bruijnzeel, 2004; Grant et al., 2013) in degraded forests that were overgrazed or burned. Forestation should follow the basic ecohydrological principles of "greening China naturally" (Cao et al., 2011), and forestation plans should be based on site water carrying capacity—"*Planting the right tree in the right place for the right purposes*" (Creed and van Noordwijk, 2018). For example, forestation on natural grassland or range lands (e.g., some areas in Inner Mongolia and the Loess Plateau) that do not support forests can negatively affect water related ecosystem services. In such cases, forestation is not a natural climate solution (Briske et al., 2024; Zhou et al., 2021).

Y. Liu et al. (2025) provided a list of adaptive forest management options (e.g., reducing tree stocking, maintaining forest litter, improving riparian zones) to enhance forest ecosystem resilience and water supplies. This is especially important for regions where annual precipitation is close or less than potential evapotranspiration such as northern and southwestern China where streamflow is sensitive to vegetation change. Active forest management practices that restore native forest ecosystems and control invasive plants in the humid regions such as southeastern and southern China can improve forest structure and health and may also benefit dry season low flows while mitigating floods and periodic drought threats. Globally, forestation campaigns such as the African Great Wall initiative for combating desertification and change climate must be carried out carefully factoring in local water availability sustaining ecosystems and people's livelihood (Goffner et al., 2019). Even in "water rich" monsoon-dominated regions such as the Lesser Himalayas, innovative forest management (i.e., Community Forestry) guided by forest hydrological sciences is important to rural communities that rely on spring water supplies in dry seasons (Bruijnzeel, Mulligan, & Zhang, 2025; Jin et al., 2025). Implementing these measures in ecological restoration has been challenged by "trade offs" of multifaceted ecosystem services, policies, and governances beyond water resources (Lü et al., 2012).

Forestation influences the water cycle at multiple spatial and temporal scales (Jones et al., 2022). The current study focused on mean seasonal and annual water yield for large basins to provide useful information to national level water resource managers and policy makers. This study represents a rare opportunity to examine forestation effects on water yield across a large climatic gradient over a 40-year period of land use and climate change (e.g., drought and warming). Our results show hydrologic responses to forest ecosystem restoration are site specific (Wei et al., 2025), largely depending on local conditions such as climate, soils, forest structure, and vegetation recovery status (Hou et al., 2023; Jones et al., 2022; Tian et al., 2021). We present water yield response at 1-km and large basin scales with former scale showing much pronounced response. Water yield response at one particular climate regime can change over time. For example, there has been a wetting and warming trend in northwestern China during the past few years that coincided with the observed land greening upand flow recovery in some watersheds on the Loess Plateau (Tian et al., 2026). The fluctuations of climatic wetting pattern have benefitted forest reestablishment and growth, and water yield. However, this climatic shift may further elevate forest water demand and deplete soil moisture (Wang et al., 2024). Therefore, forests are playing a more important role in moderating hydrologic response shaping water resources as China's young forests mature (Y. Wang et al., 2023; Z. Wang et al., 2023).

### 4.3. Uncertainty, Limitations, and Future Studies

Impacts of forestation on water yield, climate, carbon, and socioeconomics have been well-studied in China, and the ecosystem service tradeoffs of forest-based restoration activities are being recognized. The present study represents a synthesis of what we know about the relative influences of landcover change, forestation in this case, on water yield over a period of 40 years among many stressors that affect river flow in China. This study took an integrated approach by combining meta-analysis and two independent water balance models validated with the most complete published runoff data sets in China that incorporated forest cover change and climatic variability and change. However, given the complex interactions between forests and water across a large physiographical gradient and timing, separating the individual effects of forest cover change from climate change and variability across China is challenging. Uncertainty remains in the study results that require to be resolved in future studies.

Samples for meta-analysis may favor studies that show large changes in river flows and regions or large river basins with better and long flow records. Data scarce regions or gaged streams that have not seen detectable flow changes may be missed in this study. The modeling results using the Budyko or WaSSI-CN do not always agree with meta-analysis in particular watersheds. For example, rather than a decrease in water yield, Figure 1a shows that several watersheds in the southern China (Pearl, Yangtze) have an increased flow due to either deforestation or increase in precipitation. This obvious discrepancy is likely caused by the mismatch of study periods and local climatic conditions or land use change (i.e., urbanization) that are not adequately described in the input data of the models.

Despite the advantages of diverse modeling methods, which appear to be consistent in results, and insights gained in this study, some modeling limitations require additional work. For example, the Budyko modeling approach ignored the effects of forest structure and age and land surface characteristics of prior land cover on water use, thus ET and water yield projections under forestation can result in errors. Soil characteristics (e.g., depth and hydraulic properties) can play an important role in hydrologic recovery in areas subject to ecological restoration (Bruijnzeel, Peña-Arancibia, et al., 2025). Therefore, the modeling results on water yield are best viewed as the mean effects of forestation under current climate. Although the WaSSI-CN model considered both climate change and changes in land cover types, thus better represented the reality of forestation than the Budyko approach, the dynamics of forest vegetation and soil recovery and their influences on ET and soil water storage have not been described.

Another limitation of this continental scale modeling study is that it did not explicitly consider precipitation recycling effects (Cao et al., 2024; Cui et al., 2022; Gao et al., 2025; B. Zhang et al., 2022; J. Zhang et al., 2022; X. Zhang et al., 2022; Zhang & Hao, 2025; Yan et al., 2025; An et al., 2025; Zhang et al., 2026) on water yield in watersheds downwind. However, we argue that this study used locally measured precipitation thus partially incorporated the effects of forestation on precipitation if such effects did exist. In addition to addressing large-scale precipitation recycling downwind (Naik & Abiodun, 2016; van Dijke et al., 2022), future studies should address fine scale hydrologic processes such as peakflow and baseflow, groundwater recharge (Bruijnzeel, Peña-Arancibia, et al., 2025) to fully assess the effects of forestation on climate and water resources on degraded watersheds that are subject to ecological restoration. The connections between observed rise of winter dry season baseflow in China and ecological restoration of large, heavily disturbed watersheds remain to be controversial due to limitations of research method and data availability (Zhou et al., 2010; B. Zhang et al., 2022; J. Zhang et al., 2022; X. Zhang et al., 2022; Xue et al., 2022; Zhou et al., 2025).

Existing forest hydrological modeling has inherent uncertainty (Sun et al., 2024). This study tested a rather simplified approach using a single parameter model (Zhang et al., 2001) to provide a likely hydrologic response bound under pre- and post- forestation conditions that are represented by two values (2.0 or 1.0) of the $w$ parameter. Although our model validation experience suggested an uncalibrated model with a fixed $w$ parameter across China provided reasonable estimates of water yield, a variable $w$ is desirable to account for variability of forestation processes and may reduce errors in projection of change in water yield. Local calibration of the parameter would also improve prediction accuracy. Similarly, although the process-based WaSSI-CN modeling used more sophisticated ET and soil hydrological algorithms and parameters than the Budyko approach, uncertainty of model parameters (e.g., change in soil physical properties) can be large. Also, regional land surface models (e.g., CLM) (Duarte et al., 2025) should be explored to compare the simple approach adopted by this study. However, these physically based models with both water and energy constraints should be properly parameterized (e.g., biophysical controls on plant stomatal conductance) and validated with both ET and streamflow data to fully realize their capacity to describe the effects of forest cover change on the hydrological cycles across watershed boundaries (Sun et al., 2024). Finally, the split of study period for pre-forestation (1980–1999) and post-forestation (2000–2015) was based on general land use change pattern and policy shift in China, thus can be somewhat arbitrary for individual basins or regions. Alternative categorization of pre- and post-forestation periods may result in different conclusions given the large temporal variability of climate and timing of implementing ecological restoration policies across China.

## 5. Conclusions

This study demonstrates that climate dominated the recent water yield decline and large-scale forestation aggravated the trend in local watersheds in China. Climate change and human water use will likely continue to be the major stress to river flows in the future (Gou et al., 2020; Sun et al., 2024). Therefore, active forest management will become more important for sustaining water supply security as China's young forests increasingly mature accelerating water use amid global warming during the next few decades (Y. Wang et al., 2023; Z. Wang et al., 2023). This study emphasizes that climate change must be factored in national forest management plans that



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should be designed to enhance forest ecosystem resilience to drought. In the meantime, forestation, an increasingly accepted "Nature-based Solutions" for mitigating desertification and climate changes, must consider its water needs. Managing existing forests to adapt to climate change and its induced impacts on water-related services merits a high priority in forest management in China. Adaptive novel forest management options through tree species conversion (i.e., using native species), stand thinning (S. Liu et al., 2025; Y. Liu et al., 2025), and prescribed burning (Zhang et al., 2025) may provide multiple benefits including enhancing water availability and forest resilience amid climate change (Wei et al., 2025) and increasing human water demands.

## Conflict of Interest

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

## Availability Statement

Key data sets used for this study were obtained from several published sources: The forest cover data can be accessed via China National Ecosystem Data Science Center at Xia et al., 2023. https://cstr.cn/15732.11.nesdc.ecodb.rs.2023.015. The land cover change data can be accessed from Wang et al. (2019); http://wdcrre.data.ac.cn/list/land_use. The monthly precipitation data for China can be accessed from the published data archive by Qu et al., 2022; https://www.scidb.cn/en/cstr/31253.11.sciencedb.01607 or He et al. (2020) from https://data.tpdc.ac.cn/en/data/8028b944-daaa-4511-8769-965612652c49/. Potential evapotranspiration data for estimating actual evapotranspiration can be accessed at Peng, 2022 through the National Earth System Science Data Center http://wdcrre.data.ac.cn/data/9a074. Natural runoff data for model validation are available at Miao et al., 2022. https://data.tpdc.ac.cn/en/data/8b6a12c7-c8f9-465a-b449-852fbff51853/. All data sets may be downloaded free of charge after user registrations.

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