13 Forest Hydrology in China

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Abstract

China is a vast nation that has relatively low forest coverage and suffers chronic soil erosion and water shortages due to intensive human activities and natural conditions. Modern forest hydrology research in this populous country started late but has made important advancement during the past 40 years. This chapter provides a summary of the historical development of forest hydrology research in China, highlighting the major research methods, field installation and achievements. We present key research progress in terms of forest canopy interception, evapotranspiration, and the relationships of forests with runoff and soil erosion under the broad background of large-scale ecological restoration campaigns. In addition, we present emerging technologies and techniques such as simulation models and remote sensing, and discussed future opportunities and challenges in forest hydrological research in China.

13.1 Introduction

Traditional Chinese wisdoms value the harmonious relationships between forests and water: known as *Shui Yuan Han Yang* – 'forests retain water' (Sun *et al.*, 2023). However, modern forest hydrology research in China started only around the 1980s in response to the severe lack of knowledge in watershed management for soil erosion control (Ma, 1993; Zhang *et al.*, 2004; Guo *et al.*, 2005). Before the 1980s, limited rigorous studies existed on the role of forests in regulating watershed hydrology in the upper Yellow River basin (Liu and Zhong, 1978) and the upper Yangtze River (Ma, 1993). The last two decades have seen a dramatic increase in Chinese forest hydrology literature, reflecting the tremendous advances in our understanding of the forest–water relationships that are critical to the success of unprecedented ecological restoration in China (Sun *et al.*, 2006, 2023; Wei *et al.*, 2008). Now China has the world's largest plantation forests with total forest coverage reaching more than 24% of the land mass.

This chapter provides a brief summary of the historical development of forest hydrology research in China over the past several decades. Efforts in long-term field study sites and key findings in terms of canopy interception, forest floor interception, forest evapotranspiration

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DOI: 10.1079/9781800625310.0013

(ET), the forest relationship with runoff and soil erosion, emerging technologies and techniques, and future opportunities and challenges are discussed in this chapter.

13.2 Field Studies

13.2.1 National ecosystem research network

Forest ecosystem experimental stations established during the 1950s and 1960s represent much of the early pursuit of forest ecology and hydrology research in China (Zhang *et al*., 2004), particularly on the nutrient and energy flows at ecosystem scales. For instance, the Changbaishan forest ecosystem research station in north-eastern China joined the international Man and the Biosphere (MAB) program in 1979. In 1982, the Chinese Ministry of Forestry started a forest ecosystem study project and provided continuous financial support to 11 long-term stations. In 1988, the Chinese Academy of Sciences established the Chinese Ecosystem Research Network (CERN) (Fu *et al*., 2010; Xia *et al*., 2018). It is a founding member of the International Long-term Ecosystem Research Network (ILTER) and the Global Terrestrial Observation System (GTOS). Since 1998, CERN has conducted long-term observations of typical ecosystems in China in accordance with unified monitoring indicators and technical specifications, obtaining systematic and continuous observation data (e.g. water, soil, atmosphere and biology) and providing shared services. The forestry department in China also gradually established the Chinese Forest Ecosystem Research Network (CFERN) in the 1950s (Niu *et al*., 2013). Currently, CFERN has developed into a network consisting of 73 forest ecological stations spanning 30° in latitude and covering the typical ecological regions of China.

These long-term monitoring stations aim to monitor the changing hydrological patterns and quantify the forest ecosystem services in different regions of China. According to the national standard ‘indicator system for long-term observation of forest ecosystem’ issued in 2017 (Wang *et al*., 2017), important indicators include hydrological processes (e.g. precipitation, throughfall, stemflow, soil moisture, surface runoff, groundwater) and hydrochemical characteristics (e.g. pH, dissolved organic carbon, total nitrogen, total phosphorus). In addition, there are a considerable number of temporary research sites across China for addressing national questions in connection with forestry programs such as the Natural Forests Protection Program, the key shelterbelt system construction projects of ‘Three North’ and the middle and lower reaches of the Yangtze River, and the Grain for Green Program (GFG) (Zhang *et al*., 2004). For example, approximately 180 experimental sites dominated by different forest ecosystems have monitored canopy interception for at least 1 year to understand the hydrological functions of forest canopies in precipitation partitioning (Deng *et al*., 2024).

13.2.2 Hydrometric monitoring at a plot scale

Hydrometric observations at plot scale have been widely used to study hydrological processes, such as canopy interception rate, litter moisture content, soil infiltration and storage capacity, ET and runoff generation. Rain gauges are typically situated at a distance of approximately one to two times the tree’s height from the forest edge, while the open space within the forest should encompass a minimum area of 20 × 20 m. Alternatively, these instruments can be elevated above the observation tower for forest microclimate, maintaining a minimum height of 2m above the forest canopy. The monitoring of throughfall is conducted by five to six cross-shaped or groove-shaped throughfall collectors in the plot (Fig. 13.1a,b). The throughfall collectors are typically positioned beneath the tree canopy and are situated 60 cm above the forest floor. A water outlet connecting to a data collector is incorporated at the base of the throughfall collector.

Stemflow measurements typically involve several standard steps. First, all trees within the observation area are categorized based on their diameter at breast height. Subsequently, two or three standard trees are chosen from each diameter class. In the context of studying forest stemflow, at least eight standard trees are

Fig. 13.1. Observation instruments in the Dinghushan Forest Ecosystem Research Station of China: (a) cross-shaped throughfall collector; (b) groove-shaped throughfall collector; (c) stemflow collector; (d) surface runoff plot. Photos courtesy of Xiaodong Liu (2023).

selected per stand. The methodology for observation entails the use of a polyethylene rubber tube with a diameter of 2–3 cm (Fig. 13.1c). The tube is wrapped spirally around the trunk of the sample tree to create an intercepting channel. After two to three revolutions of the trunk, the tube is secured with nails and the joint is sealed. The end of the polyethylene rubber pipe is connected to a collection device such as a water container or an automatic rain gauge that records stemflow continuously.

Forest litter may absorb significant precipitation and affect water available for infiltration into soils. A change in litter moisture and litter interception is an important process of the water cycle (Liu *et al.*, 2022). The assessment of litter interception is commonly conducted using a funnel-type water measuring device, which consists of stainless-steel funnels with a 50 cm diameter, tapering to a diameter of 3–4 cm at the outlet. They are securely affixed with an iron frame positioned 60 cm above the ground. The outlet of each funnel is directed into a water-collection device on the ground, allowing either manual observation or recording through an automatic rain gauge. Litter moisture content is determined by the oven drying method.

Soil moisture measurements are typically conducted next to a runoff plot (Fig. 13.1d). To ensure comprehensive coverage, a minimum of three observation points is established within each sample plot, evenly distributed along the plot's diagonal axis. The measurement depth is determined based on the maximum soil layer depth, facilitating accurate determination of volumetric soil moisture (%) at varying depths when neutron probes are used. Recent advancements in soil moisture monitoring technology and instrumentation have led to the widespread adoption of time-domain reflectometer methods across various forest ecosystem research stations in China. These methods enable real-time and continuous tracking of soil moisture dynamics.

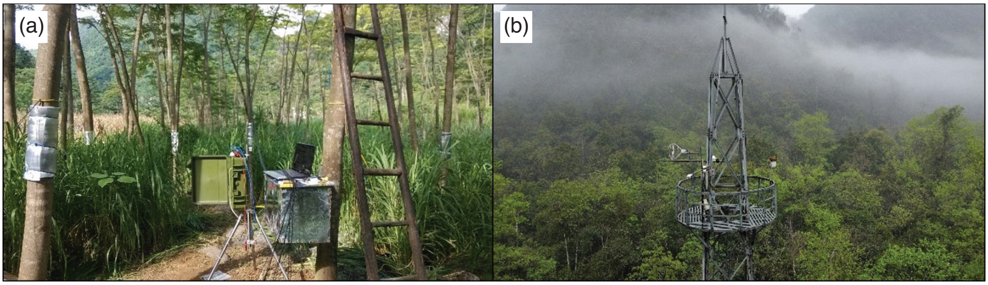

Fig. 13.2. (a) Sap flow probes used to measure tree transpiration and (b) the eddy flux tower used to measure total water and carbon exchange between forests and the atmosphere in the Huanjiang Observation and Research Station for Karst Ecosystems, southern China. Photo courtesy of Meixian Liu (2023).

Forest ET represents the total flux of water vapor transported to the atmosphere by trees, understory vegetation and the soil. Sap-flow methods are commonly used to monitor transpiration through thermal dissipation probes (Fig. 13.2a) (Du *et al.*, 2021). These probes are inserted into the sapwood to measure temperature differentials caused by sap flow, and the rate of temperature change is used to estimate sap-flow rates. Sensors are typically installed at different depths within the sapwood to capture variations in sap-flow rates across the xylem. Typical depths for sensor placement are 1.5, 2.5 and 3.5 cm from the cambium. Observations are carried out on a variety of tree species, sizes and ages to study differences in sap-flow patterns. To measure the combined water loss from both evaporation and plant transpiration, eddy covariance towers are increasingly used to measure ET rates (Fig. 13.2b) (Liu *et al.*, 2013). Standard tower heights typically range from 1.5 to 30m above the canopy, depending on the ecosystem and the specific research objectives. Instrumentation on the eddy covariance tower includes fast-response sensors for measuring air temperature, humidity, wind speed and CO_2 concentration. Additionally, a three-dimensional sonic anemometer measures wind speed and direction at high frequencies. Eddy covariance systems continuously collect high-frequency data (e.g. 10–20 Hz) on vertical wind speed fluctuations and fluctuations in water vapor density. The covariance between vertical wind fluctuations and water vapor density fluctuations is used to calculate latent heat flux, which represents ET rates.

In lieu of gauged small watersheds, runoff plots are widely used to measure surface runoff and subsurface runoff in China (Fig. 13.1d). Surface runoff plots are usually 5m wide and aligned parallel to contour lines, with a horizontal projection length of 20m and an area of 100 m^2. Along the slope, upper water-retaining walls are erected in parallel from top to bottom, while left and right water-retaining walls are established to form a quadrilateral framework. Fences, 50 cm deep and 25 cm above ground level, are installed, and a water collection channel is positioned at the lower part of the runoff plot, connecting to a collection pool. This pool gathers all effluents from the plot, enabling sampling of runoff amount and water quality.

13.3 Key Findings of Forest Hydrology Research in China

13.3.1 Canopy interception

A large number of studies on canopy interception have been conducted in China (Q. Zhang *et al.*, 2022). Researchers have employed various data sets, including direct measurements, modeling and remote sensing, to quantify interception loss and understand its role in the overall water balance in forested ecosystems. Wen and Liu (1995) found that the canopy interception of different forest ecosystems in different geographical regions of China fell between 11.4% and 34.3%, with variation coefficients of 6.68–55.05%. Averaged annual interception amounts to 134.0–626.7 mm from north to south. Wei *et al.* (2005) reviewed a series of forest hydrological studies conducted from the mid-1980s to the early 2000s. These studies covered the major types of forest in China, including Korean pine (*Pinus koraiensis*), Chinese fir (*Cunninghamia lanceolata*), oak (*Quercus mongolica*), larch (*Larix gmelinii*), Faber's fir (*Abies fabri*), Chinese pine (*Pinus tabuliformis*), Armand pine (*Pinus armandi*), birch (*Betula platyphylla*) and some tropical forests. These studies revealed that forest canopy interception rates varied from 15% to 30% of total rainfall across the country, and stemflow generally accounted for less than 5%, except for the oak forests in north-east China (15%). Q. Zhang *et al.* (2022) compiled a total of 86 publications from 47 different research sites located in 21 provinces or municipalities in China and found that the dominant type of canopy interception in the southern regions was by trees, while in the north it was shrubs. The canopy interception rate varied significantly across regions (~13.6–34.6%) and species (~12.4–47.6%). The regions with the maximum canopy interception rate were Qinghai (34.6%) and Inner Mongolia (29.5%), while the minimum values were found in Shanxi (13.6%) and Ningxia (14.9%). Across different species, the highest and lowest canopy interception rates were recorded in *Myricaria squamosa* (47.6%) and *Cryptomeria fortunei* (42.7%), and *Populus davidiana* (12.4%) and *Robinia pseudoacacia* (13.6%), respectively.

13.3.2 Forest floor interception

The capacity and storage of water intercepted by litter and understory vegetation influences soil water replenishment and plant water availability. The forest floor is usually more porous than bare soil, and the intercepted water evaporates more easily. Forest floor interception capacity can be two- to four times its own weight (Liu, 1996).

Previous studies have examined various forest types across different climatic zones in China, revealing that forest floor interception can vary considerably depending on forest composition, litter characteristics, understory density and climatic conditions. Key findings from these studies highlighted the role of the forest floor in enhancing soil moisture retention, mitigating surface runoff and regulating water balance in forest ecosystems (Li *et al.*, 2013; Sun *et al.*, 2018; Xia *et al.*, 2019; X. Wu *et al.*, 2021). Moreover, researchers have explored the ecological functions of forest floor interception, such as its impact on nutrient cycling, soil erosion control and ecosystem productivity (Tang *et al.*, 2010; Wang *et al.*, 2021). For example, X. Wu *et al.* (2021) used 1045 observational sites of forest ecosystems across China and a random forest model to estimate the spatial distribution of forest water retention. They concluded that litter maximum water-holding capacity contributed 5.37% to the total forest water retention amount in China, while canopy interception and soil water storage accounted for 21.24% and 73.39%, respectively. Sun *et al.* (2018) found that litter interception varied from 0.9 ± 0.3 to 7.7 ± 0.8 mm between 2008 and 2012 across eight representative sites in China. Stand density, Shannon–Wiener index, litter mass and size ratio showed the largest impacts on litter interception, and litter interception was more correlated to undecomposed litter mass than to total litter mass.

13.3.3 Forest ET

Evapotranspiration is the key process in forest hydrology to understand forest influence on water yield and carbon cycles. Common methods adopted in China to measure forest ET include hydrological, micrometeorological and vegetation physiology methods (Tie *et al.*, 2018). Hydrological methods include the water balance method and the lysimeter method, with the former estimating ET by the difference between precipitation and water yield at catchment scales, and the latter usually directly measuring ET beneath forest canopies. Micrometeorological methods include the aerodynamic method, eddy covariance, Bowen's ratio energy balance method and large-aperture scintillometry (S.M. Liu *et al.*, 2011, 2013). These methods are based on the assumption that the coefficients for turbulent diffusion of momentum, energy and water vapor are equivalent, necessitating specific atmospheric and underlying surface conditions (Tang and Wang, 2022). The vegetation physiology methods are mainly the sap-flow method (Du *et al.*, 2021) and stoma meter method, which monitor the transpiration of individual plants or leaves (Wang and Ma, 2002).

The study of forest ET in China has progressed significantly in recent years along with the increasing applications of remote-sensing and eddy covariance flux data sets (Li *et al.*, 2014). Data collected from flux observations across China have shown that annual ET generally declines with increasing latitude. Such latitudinal dependency of ET is controlled by the latitudinal decline in annual temperature and precipitation and the resulting decline in growing season length (Xiao *et al.*, 2013). Recent research emphasizes the impact of vegetation characteristics and changes in climate and land use on ET rates. Synthesized data sets indicate that a multi-decadal and accelerating rise in global ET has been apparent since the 1980s. These changes are largely related to vegetation greening (revealed by increasing leaf area index), while increased precipitation and enhanced atmospheric evaporative demand have secondary roles (Yang *et al.*, 2023). China leads the world in greening through ambitious land-use management programs to conserve and expand forests, aiming to achieve the goals of mitigating land degradation, air pollution and climate change (Chen *et al.*, 2019). A recent assessment using products from the Global Land Evaporation Amsterdam Model (GLEAM), Global Land Data Assimilation System (GLDAS) and Noah Land Surface Model (NOAH) suggest that annual ET increased in 84.82% (52.75% with $P<0.01$) of China's land surface with a countrywide rate of 1.27 ± 0.12 mm/year ($P<0.01$) during 1982–2017 (Yao *et al.*, 2023). Although the greening trends generally had positive effects on ET at the large river basin and national scales, large diversity and fluctuation were also found across the heterogeneous climate and landscapes in China (Li *et al.*, 2017; Ma *et al.*, 2024).

13.3.4 Forest–water yield relationship

The relationship between forests and runoff/streamflow has long been an important research interest in China (Sun *et al.*, 2008; Wei *et al.*, 2008). Forest removal or deforestation generally increases surface runoff and total water yield due to decreased ET and soil degradation (Wang *et al.*, 2008, 2011). However, the effects of increasing vegetation greenness, particularly afforestation, are more complex, uncertain or even controversial than deforestation across basins and spatial scales due to the various climate and basin characteristics, such as topography, soil properties, pre-forestation land cover, tree species and stand structure (Zhou *et al.*, 2010; Zhang and Wei, 2021; B. Zhang *et al.*, 2022a). For example, Sun *et al.* (2006) conducted a national modeling experiment and concluded that average water yield reduction due to forestation may vary from about 50 mm/year (50%) in the semi-arid Loess Plateau region in northern China to about 300 mm/year (30%) in the tropical southern region. Although empirical data are rare and regular streamflow change is influenced by many human influences (e.g. hydraulic engineering, urbanization), Zhou *et al.* (2010) argued that forest recovery in the Guangdong Province of southern China may play a positive role in redistributing water from the wet season to the dry season and thus increase water yield in the dry season. Xue *et al.* (2022) contrasted two dry and two wet basins in China, and found that afforestation explained parts of runoff reduction for dry basins but did not result in significant changes in the total runoff for the two wet basins. Annual runoff is usually more sensitive to forest cover change in water-limited watersheds than in energy-limited watersheds. Given the water shortage in northern China and the negative effects of large-scale vegetation greening on water yield, there are increasing concerns that revegetation programs in semi-arid regions such as the Loess Plateau have caused substantial streamflow reduction that has consequently approached regional sustainable water resource limits (Feng *et al.*, 2016). These studies suggest that afforestation efforts should perhaps focus on southern China with a larger water supply and that a region-specific afforestation policy is crucial to deal with forestation–water quantity tradeoff (Y. Liu *et al.*, 2016; Xue *et al.*, 2022).

Using global or regional land–climate-coupled models at a relatively coarse spatial resolution, recent studies have also explored the potential feedback from vegetation changes on regional precipitation and consequent impacts on the hydrological cycle (Y. Li *et al.*, 2018; Teo *et al.*, 2022). Model simulations incorporating the precipitation response to vegetation increases suggest that increased precipitation could offset some of the negative vegetational impacts on soil moisture and water yield. For example, Y. Li *et al.* (2018) coupled the Laboratoire de Météorologie Dynamique atmospheric general circulation model with zoomed capability (LMDZ, version 5, v2076) and the ORganizing Carbon and Hydrology in Dynamic EcosystEms model (ORCHIDEE, v3035) to investigate vegetation biophysical feedback to regional hydrology in China, and found that the increased precipitation from vegetation greening and the increased forest area supplied enough water to cancel out enhanced ET in North and South-east China in the past three decades. Teo *et al.* (2022) coupled the International Centre for Theoretical Physics (ICTP) Regional Climate Model version 4.7 to the Common Land Model version 4.5 (RegCM4.7-CLM4.5) and concluded that reforestation would increase both ET and precipitation and resulted in a statistically significant increase in water yield for the Loess Plateau–North China Plain, Yangtze Plain and South-east China under future representative concentration pathway scenarios.

13.3.5 Forests and soil erosion

Forest plantations can mitigate soil erosion by reducing surface runoff and river peak flow (Gong *et al.*, 2022). Guo *et al.* (2015) analyzed soil loss rates of five water erosion regions in China based on 2823 plot-year data from 73 different sites, and found small regional differences in the soil loss rate of forest, shrub and grasslands, which were 0–1.89, 0.28–8.06 and 3.98–1.57 t/ha/year, respectively. Meanwhile, the soil loss rate was 30.87–107.44 t/ha/year on fallow land and 7.65–49.38 t/ha/year on farmland under conventional tillage, showing large regional differences across the country.

Dams and reservoirs have played a dominant role in reducing sediments in major Chinese rivers in the second half of the 20th century (Chu *et al.*, 2009; T. Li *et al.*, 2018). Since 1999, China's vegetation cover has increased and the water erosion area began to decrease significantly. The country's water erosion area decreased from 1.83×10^6 km^2 in 1996 to 1.29×10^6 km^2 in 2011 according to the first national water census (T. Li *et al.*, 2018). In the Loess Plateau in particular, the average vegetation coverage of the 12 main Yellow River subcatchments increased from 25% in 1978 to 29% in 1998, and then to 46% in 2010. Between 1980–1999 and 2000–2010, a decrease of 26% in water yield and 21% in sediment concentration could be attributed to vegetation restoration, and about 57% (0.23 Gt/year) of the reduction in average sediment transport between these two time periods resulted from the increased vegetation coverage (Wang *et al.*, 2015). As a result of the restoration of soil-stabilizing forests and grasslands on barren or farmed land, sediment discharge into the Yellow River declined to levels close to those estimated for the agriculture period of the Tang dynasty in 740 AD (Chen *et al.*, 2015).

13.4 Emerging Technologies and Techniques

13.4.1 Forest hydrology modelling tools

Various models have been used in China ranging from simple water balance equations (Wang *et al.*, 2011) to more complex landscape distributed models (Zhang *et al.*, 2008; Zhou *et al.*, 2011) with different assumptions, spatiotemporal scales, structural complexities, parameter transferability and data requirements. The Budyko framework is widely used to explain the large-scale, long-term hydrological response to climate and watershed characteristics across China (Zhou *et al.*, 2021). Models including SWAT (Zhou *et al.*, 2011), MIKE-SHE (Zhang *et al.*, 2008; Wang *et al.*, 2012), TOPOG (Yu *et al.*, 2010), GBHM (Gao *et al.*, 2015), RHESSys (Peng *et al.*, 2016), HSPF (Zhou *et al.*, 2017) and WaSSI (J. Zhang *et al.*, 2021; X. Wang *et al.*, 2022) have also been applied in different basins to study the forest water mechanism. As well as process-based ecohydrological models, watershed-scale hydrological models with improvements in vegetation and terrain representations are increasingly used to address hydrological responses to climate and land-cover changes in the hydrology communities (Gao *et al.*, 2015; Zhou *et al.*, 2017).

13.4.2 Remote sensing of precipitation

In contemporary times, the detection of regional precipitation relies heavily on weather radar and satellite-based remote sensing. Weather radar uses the principle of backscattering to detect and quantify precipitation in the atmosphere. When the emitted electromagnetic wave pulse from a weather radar encounters precipitation particles, a fraction of its energy is scattered in various directions. Through empirical and physical models correlating echo power, radar parameters and target characteristics, the radar system can be used to analyze the intensity, location and type of precipitation from the back-scattered signals. Besides conventional radar, Doppler weather radars not only gauge precipitation intensity but also track the radial velocity of target objects along its path. Compared with traditional rain gauges, radar-based precipitation measurement offers substantial advantages in terms of scale (up to kilometer-level coverage), high resolution and real-time performance. This translates into the provision of more comprehensive, precise and timely precipitation data. China has taken significant strides in this realm, establishing a national Doppler weather radar network comprising 236 radar stations as of 2022 (http://en.weather.com.cn/radar/; accessed 9 May 2025). These radar stations, operating on S-band, C-band and X-band frequencies, are strategically spaced approximately 150–300 km apart based on terrain, precipitation characteristics and radar capabilities. S-band radars are predominantly deployed in areas susceptible to intense convective weather, while C-band radars cover arid and semi-arid regions. X-band radars fill the coverage gaps left by the aforementioned radar types.

Satellite-based remote sensing of precipitation involves using satellites equipped with sensors (e.g. visible light or reflected infrared sensors, thermal infrared sensors and microwave sensors) to detect and measure various parameters related to precipitation (Y.B. Liu *et al.*, 2011). China's achievements in this domain include the launch of 20 Fengyun (FY) meteorological satellites since the 1970s, such as geostationary satellite FY-4B and polar orbit satellite FY-3E. Notably, the successful launch of FY-3G satellite in April 2023 marked a significant milestone. Equipped with a dual-frequency active precipitation-measurement radar, combined with passive microwave and optical remote-sensing capabilities, this satellite offers enhanced monitoring of precipitation-formation processes. It can detect relevant atmospheric factors such as clouds, water vapor, aerosols and wind fields, accurately sensing precipitation-intensity changes as subtle as 0.2 mm/h (N. Li *et al.*, 2018; Xue *et al.*, 2021; H. Wang *et al.*, 2022).

13.4.3 The stable isotope method in ET partitioning

Stable isotope techniques have been increasingly applied to study ET partitioning in forest ecosystems in China (Liu and Li, 2008; Wu *et al.*, 2014). This involves using isotopic signatures to differentiate between soil/canopy evaporation and plant transpiration.

The isotopic compositions of water are typically characterized by the relative deviation of their isotope ratio (R, the ratio of deuterium:hydrogen (D:H) or ^{18}O:^{16}O) from that of the Vienna Standard Mean Ocean Water (V-SMOW) reference standard. These deviations are commonly expressed as:

$$\delta = \left[R_{Sample}/R_{V-SMOW} - 1\right] \times 1000\% \quad (13.1)$$

where $R_{V\text{-}SMOW} = 0.0020052$ for ^{18}O:^{16}O and 0.00015576 for D:H (Zhang *et al.*, 2010). Differences in isotopic compositions ($\delta^{18}O$ and δD) of water fluxes from foliage and soil water are used to partition the ecosystem ET (Liu *et al.*, 2017; Han *et al.*, 2022; Ren *et al.*, 2022). For example, Peng *et al.* (2020) used the Craig–Gordon model, isotope steady-state assumption and the Keeling plot model to partition ET within the Qinghai spruce forest ecosystem; Y.X. Wu *et al.* (2021) employed the Keeling curves alongside the Craig–Gordon model, incorporating both isotopic steady-state and non-steady-state models to simulate ET, evaporation and transpiration water vapor $\delta^{18}O$ in the *Platycladus orientalis* ecosystem, thereby comparing the ET classification outcomes derived from these two models. The stable isotope method provides a promising alternative for accurate partitioning of ET components, requiring only small water samples. However, isotope analysis equipment and data-processing tools can be costly, and field campaigns involving isotopic sampling and modeling require significant labor and resources.

13.4.4 Contactless technology in discharge monitoring

Traditional discharge monitoring relies on stream gauges that convert water level to discharge with an established stage-discharge curve, or information on stable cross-sections and flow velocity obtained from various flow velocimeters, such as a rotor current meter, acoustic Doppler current profiler, radar velocimeter and other ultrasonic devices (Kasuga *et al.*, 2003). However, these approaches require substantial investment in equipment implementation, personnel training with specialized expertise and ongoing maintenance (Yorke and Oberg, 2002; Fujita *et al.*, 2007; Czuba *et al.*, 2017). To overcome the limitations of traditional methods, a few image-based approaches have been introduced for water stage, flow velocity and discharge measurement in rivers (Leduc *et al.*, 2018; Noto *et al.*, 2022). Image-based approaches rely solely on capturing digital images of streams using inexpensive commercial cameras, presenting a promising alternative for continuous, non-invasive and low-cost streamflow monitoring. These methods usually assume that the surface characteristics of a river mirror the motion pattern of its water body and utilize image-processing techniques to analyze river-surface images for flow measurement. The velocity–area method is then used to indirectly deduce discharge after identifying the stage and average velocity. Image-based approaches or algorithms such as large-scale particle image velocimetry, particle tracking velocimetry, space–time image velocimetry and optical tracking velocimetry have increasingly been implemented (Zhang *et al.*, 2024). For example, the AiFlow system developed by the Intelligent Water Research Institute of Wuhan University and Wuhan Dashuiyun Technology Co. have been applied for stage and streamflow monitoring in over ten hydrological stations across China, while Fang *et al.* (2024) developed a procedure to extract information on flow patterns and volumes from high-frequency RGB (red, green, blue) images with deep convolutional neural networks and achieved satisfactory accuracy in discharge measurement at a steep mountain stream in southern China.

13.4.5 Unmanned aerial vehicle technology

Recent developments in unmanned aerial vehicle (UAV) technologies have drawn the attention of many researchers in the ecohydrology community. UAV-based remote sensing stands out due to its agility, operational flexibility, ability to carry multiple payloads and high-resolution surveying accuracy (J.X. Zhang *et al.*, 2021). Typically, UAVs are outfitted with visible light sensors, LiDAR (light detection and ranging) and hyperspectral sensors, each serving distinct purposes. UAVs equipped with visible light sensors are prevalently employed in terrain analysis and related domains such as soil erosion, surface rock outcrop examination, and land-use and vegetation categorization owing to their prowess in capturing high-resolution topographical data. Meanwhile, UAVs integrated with LiDAR are instrumental in geological and forestry surveys, canopy structure analysis, understory vegetation monitoring and vegetation biomass quantification due to their high structural measurement accuracy and the penetrability of laser scanning beams. Furthermore, UAVs with hyperspectral sensors are extensively utilized in vegetation growth monitoring and crop pest detection. In forest hydrology studies, UAV applications encompass the monitoring of ET and soil moisture (Luo *et al.*, 2019), soil erosion (Li *et al.*, 2024), forest canopy structure (e.g. leaf area index) (Lu *et al.*, 2020), topography (Du *et al.*, 2023), biomass (Mao *et al.*, 2023) and runoff (Yang *et al.*, 2021). For example, Q. Liu *et al.* (2016) used UAV-borne LiDAR and hyperspectral sensors to delineate the types and height profiles of dominant tree species in subtropical forests of Hubei Province, while Yang *et al.* (2021) developed a new UAV-based method for river flow estimation employing the high-precision Digital Orthophoto Map, the Digital Surface Model and the classic Manning formula river flow algorithm.

13.5 Unique Opportunities and Challenges Brought by Massive Reforestation

Zhang and Song (2006) characterized the change of forest cover in China into three stages: (i) the transition stage in 1949–1981; (ii) the slow-increase stage in 1982–1993; and (iii) the rapid-increase stage after 1994. In the 20th century, intensive deforestation and land reclamation on steep slopes and sandy lands caused severe soil erosion and environmental damage in China. The government has since heavily invested in various ecological restoration projects, such as the Three North Shelterbelt Program, the GFG, and rocky desertification control projects across the country (Shao *et al.*, 2022). In 1999, the Returning Farmland to Forest Program was launched in the provinces of Sichuan, Shaanxi and Gansu in north-eastern and south-western China. This initiative marked the beginning of the world-renowned GFG program. From 1999 to 2008, the GFG program covered a total of 26.9 million ha of land, including 9.3 million ha of reforestation on farmland and 17.6 million ha of afforestation on bare lands. Alongside the GFG program, the Ministry of Water Resources launched the Soil and Water Conservation Ecological Restoration Program. The first demonstration plots, initiated in 2002, covered a total area of 58.9×10^3 km^2 across 27 provinces. The second demonstration plots, initiated in 2006, covered 95 counties in 28 provinces. The main objective of this program is to increase vegetation cover to a rate higher than 75%, and to convert all sloping farmland with gradients higher than 25°, as well as regions prohibited from cultivation, to forest or grassland.

Over the past 20 years, China has continued to introduce policies and regulations to further promote ecological restoration and ecological civilization construction. Since 2016, the government has invested approximately 10 billion Chinese Yuan (approximately US$1.4 billion) annually in the implementation of 51 'Integrated Protection and Restoration Projects for Mountains, Rivers, Forests, Fields, Lakes, Grasslands, and Sand' across the country. It is projected that from 2021 to 2030, the total investment will exceed 250 billion Chinese Yuan and revitalize 10 million ha of land. China's planted forests in 2020 had a total area of 0.77 million km^2, accounting for 31.30% of the world's total planted forests (Cheng *et al.*, 2023). Over three-quarters (77.45 %) of China's planted forests were located in the eastern, center-south and south-western regions (Tong *et al.*, 2023).

China's massive forestation effort serves as a giant 'land manipulation experiment,' providing a rare opportunity to rigorously study how forest cover change can affect hydrological processes and water balance at a much bigger spatial level than traditional paired-watershed experiments (Sun *et al.*, 2006; Wei *et al.*, 2008). In the past four decades, water and carbon fluxes in China have exhibited an overall increasing trend, with significant growth in ET and gross primary productivity, and divergent changes in runoff (Fig. 13.3). Besides the generally warming and wetting climate, researchers have shown that vegetation greening played a dominating role in enhancing ET (Yang *et al.*, 2023; Yao *et al.*, 2023), altering the magnitudes and seasonality of water yield (Zhou *et al.*, 2010; Teo *et al.*, 2022; Xue *et al.*, 2022), and reducing soil erosion and sediment discharges (Chu *et al.*, 2009; T. Li *et al.*, 2018).

Recent vegetation expansion in China has also raised concerns on the inherent tradeoffs between water yield, ecosystem carbon sequestration, soil erosion controls and sediment delivery (Chen *et al.*, 2015; Feng *et al.*, 2016; Yu *et al.*, 2024). Although these tradeoffs are well recognized, our understanding of their extent and mechanisms is still limited. It is particularly challenging for China to balance the conflicting demands for water between the ecosystem and humans in fragile ecosystems such as the Loess Plateau. The changing climate and extensive afforestation have reduced water availability for humans due to enhanced vegetation ET. Meanwhile, the changing climate and

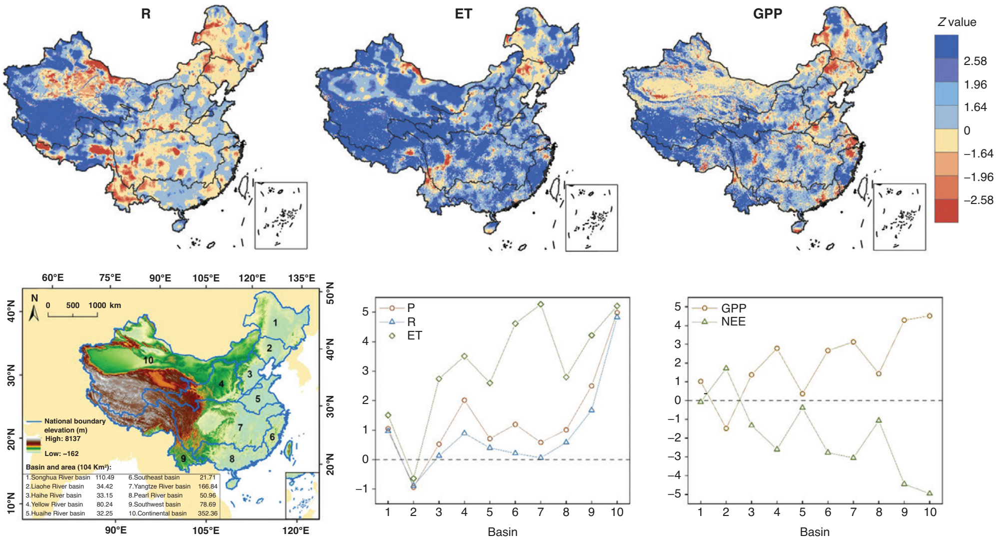

Fig. 13.3. Trends in water and carbon fluxes in the ten basins of China in 1982–2018 derived from the WaSSI model. Trends in precipitation (P), evapotranspiration (ET), runoff (R), gross primary productivity (GPP) and net ecosystem exchange (NEE) were evaluated by the *Z* value of the Mann–Kendall method. Positive and negative *Z* values indicate increasing and decreasing trends, respectively.

afforestation have used up much of the Loess Plateau's limited water and reduced soil moisture, which has made the fragile loess soil more vulnerable to wind and water erosion and has caused vegetation degradation in some areas (Fu *et al.*, 2017). The reduction in total sediment flux delivered to the sea, driven by soil erosion control and reservoir operation, has also resulted in challenges for the sustainable management of river deltas (Chu *et al.*, 2009).

13.6 Conclusions

Although forest hydrology research in China had a late start, great progress has been made in understanding forest–water relationships in the past decades thanks to the large investments in ecological restoration and relevant studies. The 21st century has seen a dramatic rise of Chinese forest hydrology literature, reflecting our advances in understanding the role of forests in water yield regulation, flood/drought mitigation, soil erosion control and ecosystem conservation.

The developments in forest hydrology research have largely relied on the advancements in data acquisition and processing technology. Continuous satellite monitoring of underlying characteristics and the water cycle since the early 1980s has facilitated the development of long-term high-resolution data sets of forest resources and key ecohydrological processes such as ET. The integration of multiple data sources based on on-site observations, physical algorithms, machine learning and remote sensing has provided new opportunities to enhance our understanding of forest hydrology. Nevertheless, evidence derived from multi-source data highlights the uncertainty in the effects of increasing vegetation greenness across basin characteristics, spatial scales and plant species.

The lessons learned from China can provide much-needed guidance to other developing countries or regions with similar challenges in the management of water and land resources. However, challenges remain for scientists and decision makers to fully understand the complexities of forest–water relationships in the face of climatic changes and intensive anthropogenic disturbances. The long-lasting debates over the role of forests or forestation in reducing floods and water yield across the country's different hydro-climatic and geophysical regions remain due to the lack of long-term experimental research and the ambiguity in scale effects. Stable support for basic forest ecosystem research with long-term commitment is crucial to fill the gaps between China's forest hydrological research and that of other developed countries. Rigorous data quality control and further interdisciplinary research are needed to better understand the individual and combined effects of forest management, climate change and other anthropogenic factors (e.g. reservoir regulation, water withdrawal, irrigation) on water resources and ecosystem functions.

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