Heliyon 9 (2023) e20115

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

The contributions of climate and land use/cover changes to water yield services considering geographic scale

Kai Zhu [a,*], Yufeng Cheng [a], Quan Zhou [a], Zsombor Kápolnai [b], Lóránt Dénes Dávid [c,d,**]

[a] *Faculty of Resources and Environmental Science, Hubei University, Wuhan, 430062, China*
[b] *Doctoral School of Economic and Regional Sciences, Hungarian University of Agriculture and Life Sciences, Godollo, 2100, Hungary*
[c] *Institute of Rural Development and Sustainable Economy, Hungarian University of Agriculture and Life Sciences, Godollo, 2100, Hungary*
[d] *Faculty of Economics and Business, John von Neumann University, Kecskemet, 6000, Hungary*

ARTICLE INFO

Keywords:
Ecosystem service
Water yield services
Climate change
Land use/cover change
Geographic scale
Hanjiang river basin

ABSTRACT

Background: Water yield services are critical for maintaining ecological sustainability and regional economies. Climate change and land use/cover change (LUCC) significantly affect regional water yield, but the spatiotemporal variability of water yield services has been overlooked in previous studies. This study aims to explore the relative contributions of climate and land use/cover changes to water yield services at both grid and subwatershed scales.
Methods: This study employed the InVEST model to calculate the water yield in the study area and employed a multi-scenario simulation approach to investigate the impacts of climate change and LUCC on water yield at both grid and subwatershed scales. Furthermore, the contributions of these two types of changes to water yield were quantified.
Results: Firstly, upstream areas experience significantly lower annual average precipitation, temperature, and potential evapotranspiration than downstream areas, with worsening drought severity. Secondly, urbanization led to significant LUCC, with decreases in farmland and grassland and increases in forest, water, building land, and unused land. Thirdly, the spatial heterogeneity of water yield services remains consistent across different scales, but more pronounced spatial clustering is observed at the subwatershed scale. Fourthly, climate change is the primary factor affecting regional water yield services, surpassing the influence of LUCC. Lastly, LUCC significantly impacts water cycling in watersheds, with vegetation coverage being a critical factor affecting water yield.
Conclusion: These findings highlight the need to consider the complex relationships between climate change, LUCC, and water yield services at multiple scales in water resource management.

1. Introduction

Ecosystem services are defined as the environmental conditions and resources that ecosystems provide to support human survival and development, serving as a fundamental basis for human well-being and closely intertwined with it [1–4]. In recent years,

---

[*] Corresponding author.
[**] Corresponding author.
E-mail addresses: hizhukai@163.com (K. Zhu), david.lorant.denes@uni-mate.hu (L.D. Dávid).

https://doi.org/10.1016/j.heliyon.2023.e20115
Received 24 August 2023; Received in revised form 11 September 2023; Accepted 12 September 2023

ecosystem services have received widespread attention, and there has been an increasing number of studies on ecosystem service assessment [5]. Water resources, in particular, are essential for human society's survival and development and play a crucial role in regional economic and ecological sustainability [6–8]. Providing water resources is a critical ecosystem service function that must be considered in the context of multiple spatial scales, especially given the increasing demand for water resources and the severe water pollution and waste in many regions [9]. Water scarcity will directly affect the sustainable development of regional economies and ecosystems [10–12], and the impact of climate change and land use/cover change (LUCC) caused by human activities on the hydrological elements of surface rainfall interception, infiltration, and evaporation can affect the water yield and availability [13,14]. Therefore, exploring the impact of climate change and LUCC on ecosystem water yield function is of great significance for the rational protection and sustainable use of regional water resources.

The methods for studying ecosystem water yield mainly include the soil water holding capacity method [15], water balance method [16], and annual runoff method [17,18]. Among them, the water balance method is the most commonly used and effective method, as it calculates water yield based on the input and output of water [19,20]. The InVEST model is a tool developed collaboratively by Stanford University, The Nature Conservancy, and the World Wildlife Fund for assessing ecosystem services and associated trade-offs. Its water yield module adopts the principles of the water balance method [21]. The model combines support from relevant disciplines such as remote sensing and geoinformatics and can evaluate the water yield [22]. The InVEST model enables not only the quantification of water yield in the study area but also the characterization of spatial heterogeneity and temporal dynamics of regional water yield [23]. Although ecosystem service quantification methods are prone to unavoidable errors due to data availability constraints, the InVEST model calculates water yield based on precipitation, plant transpiration, surface evaporation, root depth, and soil depth parameters. This method is more straightforward and yields relatively accurate results compared to other methods, which is a valuable balance. Currently, the InVEST model is widely used worldwide and has become an important tool for regional decision-making and resource management due to its strong spatial expression and dynamic evaluation capabilities, as well as its strong scalability.

Studies on water yield services have traditionally provided a single snapshot at a specific time and a limited spatial scale. However, recent research has recognized the importance of multiscale and temporal analyses, given that water yield services vary with time and spatial scales [24–26], and ignoring these scales may lead to misunderstandings of their co-occurrence. At the temporal scale, water yield services may change over time due to factors such as long-term climate change and land use and land cover changes, which have time lags, as well as other time-varying factors that affect water yield services provision [27–29]. Therefore, relying solely on water yield obtained at a single time point may not accurately represent the water yield services provided. In addition to examining the spatial heterogeneity of water yield services, it is crucial to consider changes over time. At the spatial scale, single-scale observations may miss or distort the interactions between different factors and water yield services, highlighting the importance of multiscale analyses [30]. Identifying water yield services at various spatial scales is vital for regional sustainable management [31,32], as water yield services may display different states at different spatial scales [33].

Currently, certain investigations are confined to static evaluations at a singular temporal or spatial scale, thus requiring further integration of the spatiotemporal variability and multiscale characteristics of water yield services with climate and LUCC [33–36].

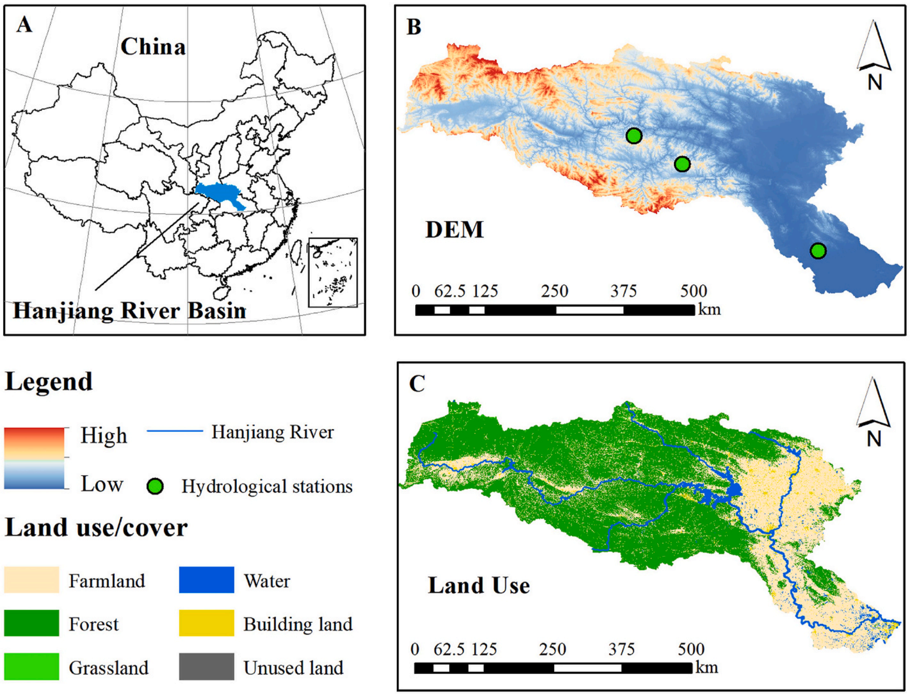


Fig. 1. The (A) location of the target study area, (B) elevation, and (C) land use/cover in 2020.

Such integration is necessary to provide the information required for effective spatial planning, especially in regions undergoing rapid urbanization. Unfortunately, current research in this area remains insufficient, emphasizing the need to narrow this gap. In order to narrow this gap, this study aims to reveal the heterogeneity of the Hanjiang River Basin (HJRB) in central China undergoing rapid urbanization at multiple spatiotemporal scales. The HJRB is the largest subwatershed in the Yangtze River Basin of China, connecting the underdeveloped western region and the relatively developed eastern region. It is the source area of the world's largest inter-basin water transfer project, the South-to-North Water Transfer Project, which aims to solve drought and water shortage problems in northern China. Covering a population of 438 million and a total length of 4350 km, making it a world-renowned huge engineering project. Therefore, this will provide a basis for regional planning and water diversion project management strategies.

The objectives of this study are threefold: (1) to analyze the trends of climate factors and LUCC during the study period; (2) to examine the spatiotemporal heterogeneity of the effects of climate change and LUCC on water yield services at both the grid and sub-watershed scales; and (3) to quantitatively evaluate the contributions of climate and LUCC to water yield services.

2. Data and methods

2.1. Research area overview

As shown in Fig. 1 A-C, the HJRB is located in central China, which is one of the most resource-intensive areas in China and is also the core water source area of the world's largest inter-basin water transfer project, the South-to-North Water Diversion Project (SNWDP) [37,38]. The HJRB has abundant freshwater resources and is also an important producer of commodity grain in China. However, in recent years, with the rapid development of regional agriculture and urbanization, the HJRB has faced huge water resource pressures [39]. Previous studies have shown that climate change and LUCC are the main factors affecting regional water yield [13,14]. Since the late 20th century, with the rapid development of industrialization and urbanization and the implementation of regional ecological engineering protection strategies, the spatial pattern of land use in the HJRB has undergone significant changes [40,41]. Therefore, it is necessary to clarify the impact of climate change and LUCC on the water resources of this region.

2.2. Data source and preprocessing

As shown in Table 1 and Fig. 2, this study mainly used climate, land use/cover, soil data, and DEM. Annual precipitation data were obtained from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/), based on daily observation data from multiple meteorological stations within the study area. Spatial interpolation was performed using ANUSPLIN software to produce the precipitation map (Fig. 2A). The temperature data (Fig. 2B) and solar radiation data were procured from the National Tibetan Plateau Data Center and the China Meteorological Data Service Center (http://data.cma.cn), respectively, and were calculated using an improved Hargreaves formula [42]. Potential evapotranspiration data for the entire study area were obtained through kriging interpolation (Fig. 2C). In accordance with the requirements of the InVEST model, and to maintain consistency with the date of the land-use data and obtain temporally dense results, this study used 5-year averaged climate data as input data. Soil depth and texture data were obtained from the Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences (http://westdc.westgis.ac.cn), and the maximum root depth was estimated based on soil depth data (Fig. 2D). Plant available water (Fig. 2E) was calculated based on soil texture data and previous literature [43]. Land use/cover data (Fig. 2F) were obtained from Wuhan University (https://en.whu.edu.cn/). The data included five periods from 2000 to 2020 with a spatial resolution of 30 m. The accuracy of the data was assessed through sampling surveys, with an accuracy rate of over 94.3% for the first-level classification and over 91.2% for the second-level classification. The overall accuracy was better than that of MCD12Q1, ESACCI_LC, FROM_GLC, and GlobeLand30 [44]. The first-level classification of the data was used in this study, including cultivated land, forest, grassland, water bodies, built-up land, and unused land. DEM data were obtained from the Geographic Spatial Data Cloud (https://www.gscloud.cn/), and sub-watershed data for the HJRB were obtained using the SWAT model (Fig. 2G). For consistency purposes, all raster data with varying spatial resolutions in Table 1 were resampled to a uniform spatial resolution of 100 m × 100 m.

Furthermore, this study used biophysical coefficients, as depicted in Table 2, including ecosystem type, evapotranspiration coefficient, and root depth. The evapotranspiration coefficient was based on the reference values of the Food and Agriculture Organization of the United Nations, while the root depth was estimated based on the standard crop coefficient.

Table 1
The data and sources.

Data	Sources
Precipitation	The National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/)
Temperature	The National Tibetan Plateau Data Center
Solar radiation	China Meteorological Data Service Center (http://data.cma.cn)
Soil depth	Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn)
Soil texture	Cold and Arid Regions Science Data Center
Land use/cover	Wuhan University, Yang et al. (https://en.whu.edu.cn/)
DEM	Geospatial Data Cloud (https://www.gscloud.cn/)

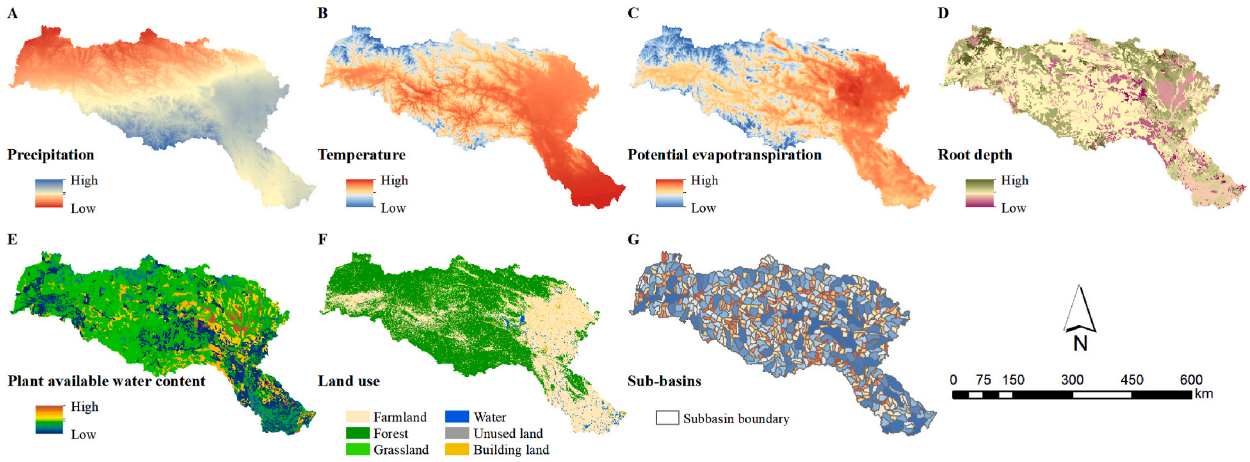


Fig. 2. The input data for the water yield model includes (A) precipitation, (B) temperature, (C) potential evapotranspiration, (D) root depth, (E) plant available water content, (F) land use, and (G) sub-watershed.

Table 2
Biophysical coefficient.

Ecosystem type	Subclassification	Evapotranspiration coefficient	Root depth (mm)
Farmland	Paddy field	0.7	2000
	Dryland	0.5	300
Forest	Forest land	1	3000
	Sparse forest land	0.85	1000
	Other forest land	0.85	1000
Grassland	High coverage grassland	0.65	1700
	Medium coverage grassland	0.5	1300
	Low coverage grassland	0.3	1000
Towns	Urban land	0.3	1
	Rural residential area	0.5	100
	Other building land	0.3	1
Bare ground	Bare land	0.5	10
	Bare rock/gravel ground	0.2	10

2.3. Methods

2.3.1. Water yield model

To calculate the water yield of the study area, we utilized the water yield module from the InVEST model. The water yield module primarily relies on the Budyko water-energy balance hypothesis, which postulates that all water, except for evapotranspiration, can reach the basin outlet [45,46]. The model adopts a yearly time step and a raster cell as the calculation unit. The model's assumptions are based on hydrological processes at the small watershed scale, and the small watershed is utilized as the calculation unit to produce the model results. The formula for computing the annual water yield $Y(x)$ of each raster cell x within the watershed is shown in Equation (1):

$$Y(x) = \left\{1 - \frac{\mathrm{AET}(x)}{P(x)}\right\} \times P(x) \tag{1}$$

where $\mathrm{AET}(x)$ represents the average annual actual evapotranspiration of raster cell x, and $P(x)$ represents the average annual precipitation of raster cell x. Based on previous literature [47], the calculation formulas for vegetation evapotranspiration of different land use/cover types are shown in Equation (2):

$$\frac{\mathrm{AET}(x)}{P(x)} = 1 + \frac{\mathrm{PET}(x)}{P(x)} - \left\{1 + \left\{\frac{\mathrm{PET}(x)}{P(x)}\right\}^{w}\right\}^{\frac{1}{w}} \tag{2}$$

where $\mathrm{PET}(x)$ represents the potential evapotranspiration, and $w(x)$ represents the non-physical parameters of natural climate and soil properties. The calculation formula for $\mathrm{PET}(x)$ is shown in Equation (3).

$$\mathrm{PET}(x) = K_c(l_x) \times \mathrm{ET}_0(x) \tag{3}$$

Table 3
Scenarios of actual conditions, climate change, and LUCC.

Type	Actual conditions					Climate change					LUCC				
	2000	2005	2010	2015	2020	1	2	3	4	5	6	7	8	9	10
Climate change	2000	2005	2010	2015	2020	2005	2010	2015	2020	2020	2000	2005	2010	2015	2000
LUCC	2000	2005	2010	2015	2020	2000	2005	2010	2015	2000	2005	2010	2015	2020	2020

Note: this study calibrated the model using long-term average flow, and captured climate change over a 5-year period. For example, the input climate data for 2005 was the multi-year average from 2001 to 2005.

where $K_c(l_x)$ represents the evapotranspiration coefficient of the land use/cover type in raster cell x, and its value ranges from 0 to 1.5. $\mathrm{ET}_0(x)$ represents the potential evapotranspiration of the reference crop in raster cell x, which is calculated using an improved Hargreaves formula as shown in Equation (4) [42].

$$\mathrm{ET}_0 = 0.0013 \times 0.408 \times \mathrm{RA} \times (T_{\mathrm{av}} + 17) \times (\mathrm{TD} - 0.0123P)^{0.76} \tag{4}$$

where RA represents solar radiation, T_{av} represents the average of the maximum and minimum daily temperatures, TD represents the difference between the maximum and minimum daily temperatures, and P represents monthly precipitation.

The non-physical parameter $w(x)$ is an empirical parameter, which is calculated using a formula proposed by previous scholars in the InVEST model as shown in Equations (5) and (6) [46].

$$w(x) = Z\frac{\mathrm{AWC}(x)}{P(x)} + 1.25 \tag{5}$$

$$\mathrm{AWC}(x) = \mathrm{Min}(Rest.layer.depth, root.depth) \times \mathrm{PAWC} \tag{6}$$

where PAWC represents plant-available water content, which is the difference between field capacity and wilting point, with a value range of 0–1. This is calculated using an empirical formula proposed by previous literature as shown in Equation (7) [43]. Z is a seasonal constant with a value range of 1–30, which effectively improves the error of Budyko curve in simulating runoff [48].

$$\begin{aligned}\mathrm{PAWC} = {} & 54.509 - 0.132\mathrm{SAND} - 0.003(\mathrm{SAND})^2 \\ & -0.055\mathrm{SILT} - 0.006(\mathrm{SILT})^2 - 0.738\mathrm{CLAY} \\ & +0.007(\mathrm{CLAY})^2 - 2.6990\mathrm{OM} + 0.501(\mathrm{OM})^2\end{aligned} \tag{7}$$

where SAND represents the percentage of sand particles in soil, SILT represents the percentage of silt particles in soil, CLAY represents the percentage of clay particles in soil, and OM represents the percentage of organic matter in soil.

2.3.2. Model scenario settings

This study developed virtual scenarios that are more detailed and engaging than those found in previous literature. Previous literature on ecosystem service scenario simulation typically involved creating 2 to 4 development scenarios, such as economic priority, ecological protection, and sustainable development, by restricting the expansion of land use types to model future development. In contrast, our study utilized a novel approach that combined historically accurate climate and land use data to create various virtual scenarios. We then compared the relative contributions of climate and land use changes to water yield services between real and virtual scenarios.

Specifically, this study established three types of scenarios, as presented in Table 3. Firstly, the water yield in the HJRB was calculated using the water yield module in the InVEST model for the years 2000, 2005, 2010, 2015, and 2020, which were designated as the “actual conditions”. Furthermore, to better understand the impact and contribution of climate change and LUCC on regional water yield, this study designed ten sub-scenarios using a scenario analysis method [49].

In the climate change scenarios, the land use/cover was presumed to be constant to assess the effect of climate change on ecosystem water services. To delve deeper into the impact of climate change on ecosystem water services during distinct time periods, this study divided the years 2000–2020 into five periods (2000–2005, 2005–2010, 2010–2015, 2015–2020, and 2000–2020), corresponding to scenarios 1 to 5. For instance, in scenario 1, the climate elements used were from 2005 (the multi-year average data from 2001 to 2005), while the land use/cover data were from 2000. In comparison to the actual conditions in 2000, the land use/cover data in scenario 1 remained unchanged, but the climate elements varied. This study utilized these scenarios to examine the impact and contribution of climate change on regional water yield.

Similarly, in the LUCC scenarios, the climate elements were held constant. This study partitioned the five time periods into scenarios 6 to 10 to explore the influence and contribution of LUCC on regional water yield. Ultimately, through the comparison of these ten sub-scenarios with the five factual conditions, this study exposed the impact and contribution of climate change and LUCC on regional water yield during distinct time periods.

2.3.3. Contribution degree assessment

Based on the changes in water yield under different scenarios, the degree of contribution of climate change and LUCC on regional water yield can be quantified using Equations (8) and (9):

$$R_c = \frac{C}{C+L} \times 100\% \tag{8}$$

$$R_l = \frac{L}{C+L} \times 100\% \tag{9}$$

where R_c represents the contribution rate of climate change to ecosystem water services, R_l represents the contribution rate of LUCC to ecosystem water services, C represents the change in water yield under the climate change scenarios, and L represents the change in water yield under the LUCC scenarios.

2.4. Verification of InVEST

The performance of the InVEST model is related to a parameter called Z, which is an empirical constant that characterizes the regional distribution of precipitation and hydrogeological features [45,50]. To determine the most appropriate value for Z, researchers typically compare the model's simulated water yield with observed runoff data [28,50–53]. In this study, we evaluated the accuracy of the InVEST model by analyzing observed runoff data from three HJRB hydrological stations (Huangjiagang station, Xiangyang station, and Xiantao station) between 2000 and 2020. The data were collected by real-time monitoring systems installed at each station and published by the Hydrology and Water Resources Center of Hubei Province. We performed a linear regression analysis to quantify the relationship between the simulated water yield generated by the InVEST model and the observed runoff data, as shown in Fig. 3. The resulting R value of 0.9067 indicates that the InVEST model is capable of accurately modeling water yield, as the simulated water yield is closest to the observed runoff.

3. Results

3.1. Spatiotemporal variations of climate factors

This study examined the climate change in the HJRB from 2000 to 2020, focusing on annual mean precipitation (PRE), annual mean temperature (TEM), and potential evapotranspiration (PET). The objective of this analysis was to comprehend the continuously changing climate conditions in the basin and their potential impact on the ecosystem [54–56].

The temporal changes of climate factors in the HJRB are presented in Fig. 4. From 2000 to 2020, the annual mean precipitation in the basin exhibited significant variation. The highest precipitation year was 2000, with a value of 1077.44 mm, while the lowest was recorded in 2015, with a value of 948.32 mm. The data indicated that precipitation demonstrated an overall decreasing trend from 2000 to 2015 and an increasing trend from 2015 to 2020. This fluctuation may be attributed to changes in atmospheric circulation patterns and increased climate variability [57,58]. The annual mean temperature in the basin decreased from 13.97 °C in 2000 to 13.49 °C in 2020. The observed trend showed a gradual cooling, with the most significant temperature drop occurring between 2010 and 2015 (from 13.72 °C to 13.39 °C). This cooling trend contradicts the global warming pattern observed during the same period, indicating that regional factors may have an impact on local climate [59]. During the study period, the potential evapotranspiration showed a relatively stable trend. The highest value was recorded in 2000, with 1084.28 mm, while the lowest was seen in 2010, with 1065.06 mm. The potential evapotranspiration decreased from 2000 to 2010 but increased again from 2010 to 2015. The variation in potential evapotranspiration may be linked to fluctuations in temperature and solar radiation levels in the basin [60,61].

Fig. 5 illustrates the spatial variations of climate factors in the HJRB. By comparing the upstream and downstream quantities, it can be observed that the annual mean precipitation, annual mean temperature, and potential evapotranspiration in the upstream region were significantly lower than those in the downstream region during the period from 2000 to 2020, indicating clear and stable spatial differences. In terms of the trend of changes, the annual mean precipitation in the upstream region showed a clear decreasing trend year by year, while the annual mean precipitation in the downstream region exhibited a significant increasing trend in 2015 and 2020. However, no significant trends were observed for the annual mean temperature and potential evapotranspiration in either region. These results suggest that the spatial variations of climate factors in the HJRB display considerable regional differences, and the drought severity in the upstream region is increasingly worsening, while the downstream region is gradually becoming wetter.

The observed trends of precipitation, temperature, and potential evapotranspiration have important implications for the ecosystem in the HJRB. The decrease in precipitation may reduce the availability of water, increase pressure on water storage facilities, and

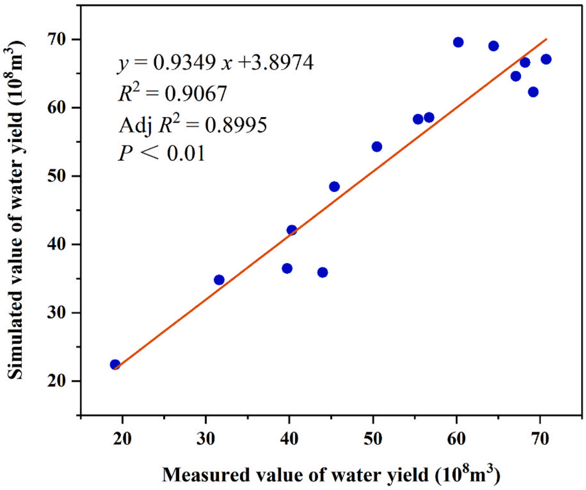


Fig. 3. The water yield simulated by the InVEST model and the observed runoff at hydrological stations.

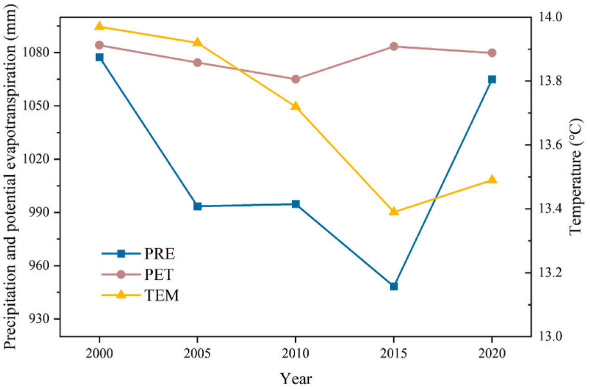


Fig. 4. Temporal changes of climate factors in the HJRB. PRE: precipitation, TEM: temperature, and PET: potential evapotranspiration.

intensify competition for water resources. While the cooling trend of temperature may seem beneficial in the short term, it may have long-term impacts on the stability of regional climate and the ecosystem [62,63].

3.2. Spatiotemporal variations of land use/cover

Fig. 6 depicts the dynamics of land use in the HJRB from 2000 to 2020. The rapid urbanization has resulted in significant changes in land use/cover in the basin [64,65]. Farmland (36.45%) and forest land (58.23%) are the predominant land use types, collectively accounting for approximately 94.68% of the total area. In contrast, grassland (1.08%) and unused land (0.10%) only occupy a small portion of the total area. The period from 2015 to 2020 witnessed the largest changes in land use, with an average change rate of 30.54% for the six land use categories. This period was a window of urbanization in the HJRB, with rapid urban development and an increase in population density, leading to the gradual expansion of building land [49,66,67]. As a result, farmland on the urban fringe has decreased, which may have adverse effects on biodiversity and ecosystem services. To mitigate large-scale human activities such as deforestation and land reclamation, the local government has implemented ecological restoration projects, such as reconverting farmland to forests, lakes, and fields, restoring some ecological lands such as forests and water bodies. However, these actions have also led to a rapid decrease in farmland area [38].

Throughout the entire study period, significant changes in area were observed for all land use types except for unused land. Farmland and grassland exhibited opposite trends compared to other land use types. Specifically, the area of farmland and grassland continuously decreased at rates of −2.84% per year and −27.68% per year, respectively, while the land use changes of other types showed a continuous upward trend (forest land 1.76% per year, water bodies 4.82% per year, building land 11.86% per year). Farmland and forest land are the main land use types in the HJRB, reflecting their importance for the local economy and ecosystem services [68–71]. The proportional area of grassland and unused land is relatively low, indicating limited opportunities for agricultural expansion or natural habitat restoration in the region [72]. The decrease in farmland and grassland area, and the increase in building land and unused land area, may be related to urbanization and infrastructure development, which could have long-term ecological and social consequences. The significant increase in unused land indicates the possibility of forest restoration or habitat restoration.

Fig. 7 A-E portrays the spatial alterations in land use throughout the study period. Farmland was primarily clustered in the southeast and downstream areas of the HJRB, progressively diminishing and converting into forest and building land over time. Forests were predominantly dispersed in the northern, southern, and upstream sectors of the HJRB, gradually extending to the middle reaches of the Hanjiang River. Grasslands were primarily located in the north at higher elevations, with minimal human disturbance. Unused land was sporadically distributed throughout the region. Building land was mainly concentrated in the southeast, particularly in Xiangyang, Nanyang, and Wuhan, and underwent rapid expansion. The water body area was primarily located in the middle reaches of the Hanjiang River, particularly the Danjiangkou Reservoir, and significantly increased with the construction of the SNWDP [37,38].

As depicted in Fig. 8 A-E, this study created land use conversion matrices for different periods to determine the mutual conversion of various land use types. Overall, different land use types underwent mutual conversion during the entire study period. The increase in building land was primarily at the expense of farmland and water bodies, while unused land was mainly utilized by converting it into farmland and building land. Farmland remained the primary land use type in the region, with a transfer rate of 78.89%. However, the transfer rate of building land significantly increased to 67.44%, indicating rapid urbanization in the region. The untransfer rate of grassland was 12.61%, while the untransfer rate of forest was 94.98%, indicating successful conservation efforts in the region. The transfer rate of unused land significantly increased, indicating potential opportunities for ecological restoration and sustainable land use practices in the region [73,74].

3.3. Actual conditions

By employing classical ecosystem classification and integrating the actual land use situation of the study area [75,76], the HJRB ecosystem was segregated into six primary types, comprising of farmland, forest, grassland, towns, bare land, and water bodies. The

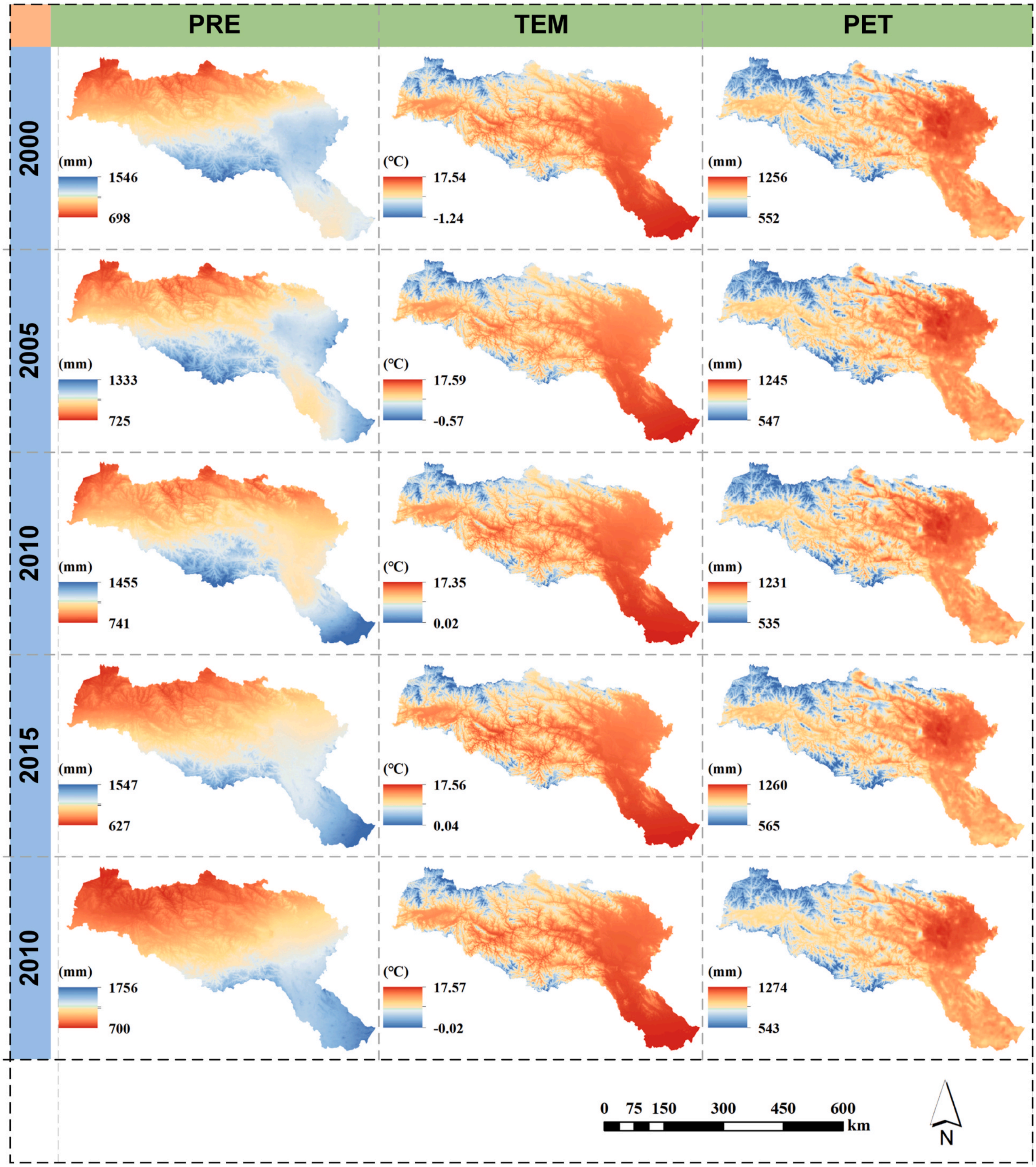


Fig. 5. Spatial changes of climate factors in the HJRB. PRE: precipitation, TEM: temperature, and PET: potential evapotranspiration.

InVEST model was employed to evaluate the regional ecosystem water yield, as illustrated in Fig. 9 A-G. Under the combined influence of climate change and LUCC, the water yield services in the HJRB displayed spatial heterogeneity, but the spatial configuration remained relatively consistent. Specifically, the water yield services exhibited comparable spatial distribution patterns at both the grid and sub-watershed scales, with elevated water yield areas primarily located in the southern mountainous and downstream plain-hilly regions. The gradient pattern of water yield services escalated from northwest to southeast at both scales.

Overall, as depicted in Fig. 9 F-G, the variation rates of the water yield services in actual conditions were similar at both spatial scales, but the variation rates differed at different times. The mean water yield during the periods of 2000–2005 and 2010–2015

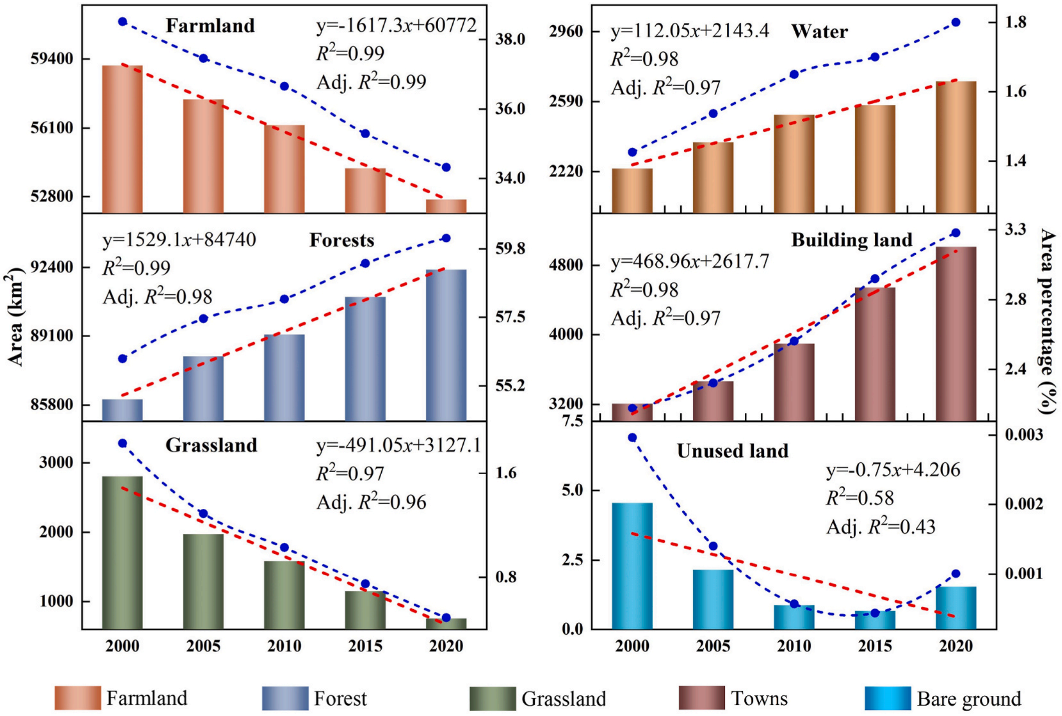


Fig. 6. Analysis of changes in various land use/cover types in the HJRB from 2000 to 2020. The dots represent the area percentage of different land use/cover types and the dashed line represents the linear fit of different land use/cover areas.

showed a decreasing trend, while the mean values during the other two periods showed an increasing trend. It is worth noting that the magnitude of water yield variation during 2005–2010 was small, while the magnitude of variation during 2015–2020 was more significant.

The differences in water yield services at different scales were reflected in the extensiveness and spatial discreteness scales. Compared with the grid scale, the sub-watershed scale showed more obvious changes in the areas with less water yield in the northwest. Specifically, the water yield service function exhibited a clear trend of deterioration, gradually expanding from the northwest to the middle reaches of the basin at the sub-watershed scale.

Fig. 10 displays the mean water yield of distinct ecosystem types in the HJRB under factual conditions from 2000 to 2020. The data reveal that the average water yield of the farmland ecosystem was the highest across all years and demonstrated a noticeable increase from 2005 to 2020. The average water yield of the forest and grassland ecosystems exhibited a declining trend from 2000 to 2015, with the smallest average water yield recorded in 2015. The average water yield of the town ecosystem displayed a fluctuating trend, with the maximum average water yield recorded in 2000 and 2020. The bare land ecosystem had the lowest average water yield among all ecosystem types and fluctuated over time.

The decreasing trend in the average water yield of the forest and grassland ecosystems may indicate a decline in vegetation cover and water-holding capacity, which could be attributed to deforestation, land use change, and other human activities [77]. This trend is particularly concerning because forests and grasslands are vital natural water sources in the region and play a crucial role in maintaining ecological balance. The fluctuating trend in the average water yield of the town ecosystem may reflect changes in urbanization and urban water resource management practices. Accelerated urbanization and increased urban water demand may lead to excessive water resource development and pollution, while improving water resource management practices and enhancing water use efficiency can help alleviate these impacts.

3.4. Climate change scenarios

Alterations in climate factors significantly influence water yield by affecting precipitation and potential evapotranspiration, which are impacted by solar radiation, temperature, and precipitation. This investigation assessed the influence of climate change on water yield while maintaining land use/cover constant. Fig. 11 A-B illustrates the water yield under five climate change scenarios (Scenarios 1–5) at two scales. Specifically, the average water yield under Scenario 2 was 2725.78 mm, which was 124.73 mm (4.38%) lower than the water yield under the 2010 baseline scenario. Data analysis revealed that the water yield services of farmland, towns, and bare land ecosystems were disrupted to varying degrees under climate change scenarios. From a spatial perspective, areas with high water yield were more concentrated in the southern and downstream regions, while areas with decreased water yield slightly expanded. On the other hand, the average water yield under Scenario 4 was 3426.66 mm, indicating significant spatial disparities between the grid scale

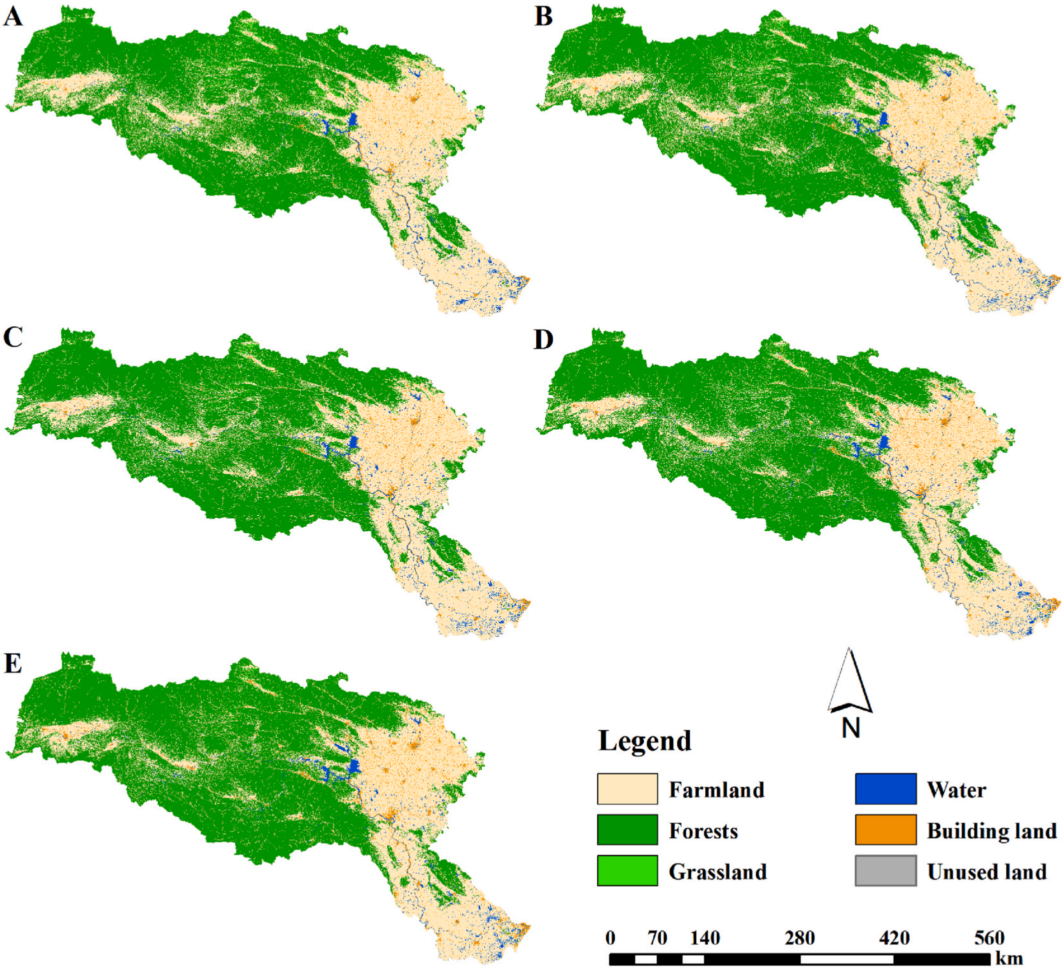


Fig. 7. Lucc in the HJRB in (A) 2000, (B) 2005, (C) 2010, (D) 2015, and (E) 2020.

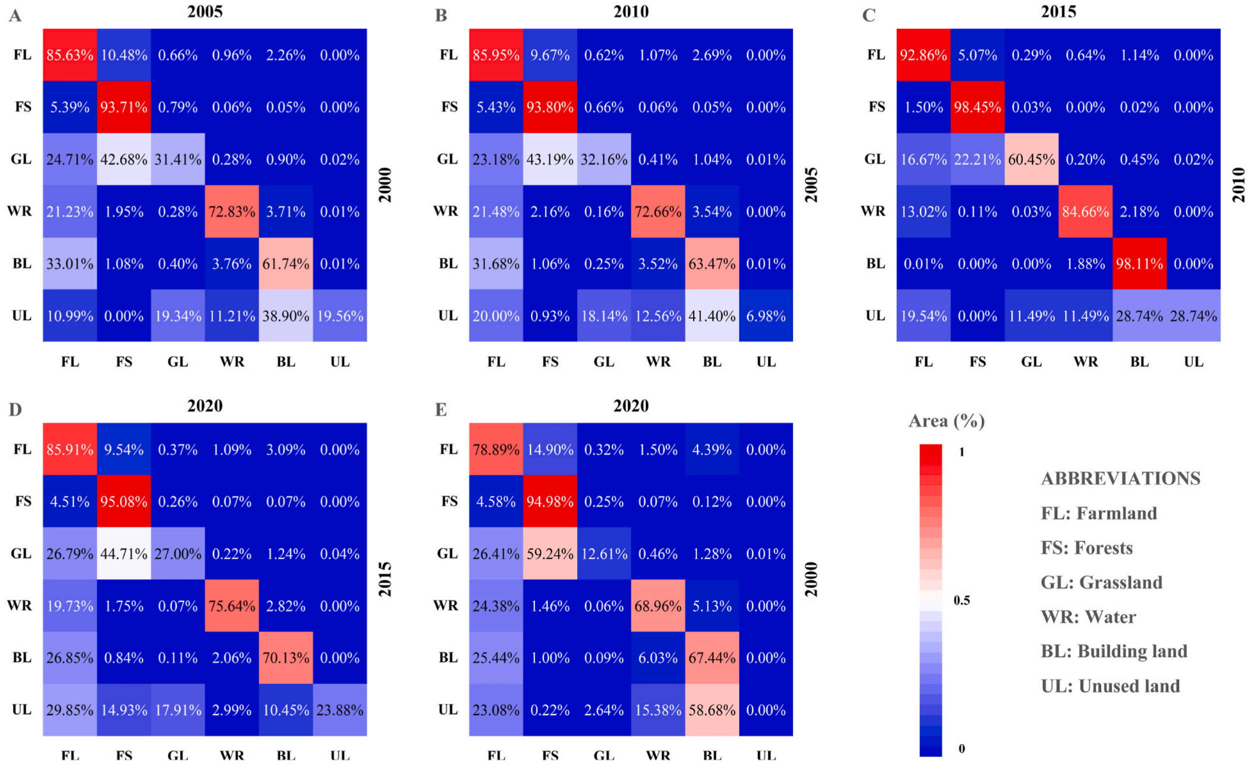
and the sub-watershed scale. The sub-watershed scale manifested a more substantial aggregation effect, with more distinct spatial aggregations of areas with high and low water yield, and the disparities between the upstream and downstream regions were the most prominent.

Fig. 12 displays the mean water yield of distinct ecosystem types in the HJRB under climate change scenarios. The outcomes indicate that Scenario 4 recorded the highest average water yield among the five scenarios, with the farmland ecosystem having the highest average water yield of 795.77 mm, which was markedly higher than other ecosystem types. This suggests that farmland ecosystems may possess a greater resilience to the impact of climate change on water yield. This may be attributed to the high infiltration capacity of cultivated soils and the potential utilization of irrigation systems. On the other hand, the bare land ecosystem had the lowest average water yield in all five scenarios, with the most substantial reduction in water yield under Scenario 2. This emphasizes the vulnerability of the bare land ecosystem to the impact of climate change on water yield, which may be due to the absence of vegetation cover and impermeable soil layers leading to high surface runoff.

Furthermore, the results indicate that different ecosystem types respond differently to changes in precipitation and potential evapotranspiration, with some ecosystems being more capable of resisting the impact of climate change than others [78,79]. For example, in all five scenarios, the average water yield of grassland ecosystems was higher than that of forest ecosystems, suggesting that grasslands may be more effective in retaining water than forests. Additionally, in all five scenarios, the average water yield of town ecosystems was higher than that of grassland and forest ecosystems, which may be related to the increase in impermeable surfaces and the decrease in infiltration caused by urbanization.

3.5. LUCC scenarios

LUCC can modify the water cycle in a watershed, influencing evapotranspiration, infiltration processes, and water storage models, thus affecting water yield [80]. This investigation assessed the influence of LUCC on water yield while maintaining constant climate conditions. Fig. 13 A-B displays the water yield under five LUCC scenarios (Scenarios 6–10) at two scales, revealing substantial spatial



A

2005

	FL	FS	GL	WR	BL	UL
FL	85.63%	10.48%	0.66%	0.96%	2.26%	0.00%
FS	5.39%	93.71%	0.79%	0.06%	0.05%	0.00%
GL	24.71%	42.68%	31.41%	0.28%	0.90%	0.02%
WR	21.23%	1.95%	0.28%	72.83%	3.71%	0.01%
BL	33.01%	1.08%	0.40%	3.76%	61.74%	0.01%
UL	10.99%	0.00%	19.34%	11.21%	38.90%	19.56%

2000

B

2010

	FL	FS	GL	WR	BL	UL
FL	85.95%	9.67%	0.62%	1.07%	2.69%	0.00%
FS	5.43%	93.80%	0.66%	0.06%	0.05%	0.00%
GL	23.18%	43.19%	32.16%	0.41%	1.04%	0.01%
WR	21.48%	2.16%	0.16%	72.66%	3.54%	0.00%
BL	31.68%	1.06%	0.25%	3.52%	63.47%	0.01%
UL	20.00%	0.93%	18.14%	12.56%	41.40%	6.98%

2005

C

2015

	FL	FS	GL	WR	BL	UL
FL	92.86%	5.07%	0.29%	0.64%	1.14%	0.00%
FS	1.50%	98.45%	0.03%	0.00%	0.02%	0.00%
GL	16.67%	22.21%	60.45%	0.20%	0.45%	0.02%
WR	13.02%	0.11%	0.03%	84.66%	2.18%	0.00%
BL	0.01%	0.00%	0.00%	1.88%	98.11%	0.00%
UL	19.54%	0.00%	11.49%	11.49%	28.74%	28.74%

2010

D

2020

	FL	FS	GL	WR	BL	UL
FL	85.91%	9.54%	0.37%	1.09%	3.09%	0.00%
FS	4.51%	95.08%	0.26%	0.07%	0.07%	0.00%
GL	26.79%	44.71%	27.00%	0.22%	1.24%	0.04%
WR	19.73%	1.75%	0.07%	75.64%	2.82%	0.00%
BL	26.85%	0.84%	0.11%	2.06%	70.13%	0.00%
UL	29.85%	14.93%	17.91%	2.99%	10.45%	23.88%

2015

E

2020

	FL	FS	GL	WR	BL	UL
FL	78.89%	14.90%	0.32%	1.50%	4.39%	0.00%
FS	4.58%	94.98%	0.25%	0.07%	0.12%	0.00%
GL	26.41%	59.24%	12.61%	0.46%	1.28%	0.01%
WR	24.38%	1.46%	0.06%	68.96%	5.13%	0.00%
BL	25.44%	1.00%	0.09%	6.03%	67.44%	0.00%
UL	23.08%	0.22%	2.64%	15.38%	58.68%	0.00%

2000

ABBREVIATIONS
FL: Farmland
FS: Forests
GL: Grassland
WR: Water
BL: Building land
UL: Unused land

Fig. 8. Land use/cover transformation (A) from 2000 to 2005, (B) from 2005 to 2010, (C) from 2010 to 2015, (D) from 2015 to 2020, and (E) from 2000 to 2020 in the HJRB. FL: Farmland; FS: Forests; GL: Grassland; WR: Water; BL: Building land; UL: Unused land. The numbers in the column indicate the area percentages of a particular land use/cover type in that column that are converted to other corresponding types in the rows within a period, which sums to 100%.

heterogeneity. The spatial change trend can be roughly divided into two patterns. Under Scenarios 6–8, the spatial heterogeneity gradually diminishes, and although the disparity in water yield services between upstream and downstream areas remains significant, the magnitude of the difference gradually lessens. However, under Scenarios 9–10, the spatial heterogeneity significantly intensifies, and this trend is more pronounced at the sub-watershed scale. Additionally, the study discovered that under Scenario 10, the water yield services in the downstream area experienced a significant degradation, with some areas exhibiting a rapid decline in precipitation. This suggests that the impact of LUCC on the water cycle in the watershed may lead to the deterioration of water yield services in the downstream area and a decrease in precipitation, potentially posing a threat to the ecosystem.

Fig. 14 displays the mean water yield of distinct ecosystem types in the HJRB under LUCC scenarios. Under different LUCC scenarios, the average water yield of distinct ecosystem types varies. The data reveal that vegetation cover is positively associated with water yield. Farmland and forests typically exhibit higher water yields than grasslands, towns, and bare land because they possess higher vegetation cover. However, the data also demonstrate that the relationship between vegetation cover and water yield is not always straightforward. For instance, in Scenario 9, the water yield of towns is higher than that of grasslands, despite having lower vegetation cover. This may be attributed to towns having a higher proportion of impervious surfaces, which can increase surface runoff and thus lead to higher water yield.

Furthermore, the data also indicate that different LUCC scenarios can lead to significant changes in water yield for different ecosystem types. For example, bare land has the lowest average water yield in all scenarios, with the highest water yield in Scenario 6 at 809.54 mm. This may be due to the low vegetation cover and low water holding capacity of bare land, resulting in lower water yield. In Scenario 10, farmland has the highest water yield, reaching 748.86 mm. This may be because farmland is often irrigated, increasing the available water for crops and thus raising water yield. This highlights the complex and dynamic relationship between LUCC and water yield.

The average water yield of forests ranked second in all scenarios, with the highest water yield in Scenario 6 at 607.54 mm. This may be due to forests having a higher interception rate, which can reduce surface runoff and increase water yield. Grasslands have a moderate average water yield in all scenarios, with the highest water yield in Scenario 8 at 571.93 mm. This may be because grasslands have a lower interception rate compared to forests, but still have the ability to retain soil moisture and increase water yield. The implications behind these changes are that LUCC can alter the water cycle by affecting factors such as evapotranspiration, infiltration processes, and water holding models, leading to changes in water yield [81,82]. The determination of water yield may be influenced by various factors, such as vegetation cover and impervious surfaces, among others. Understanding these complex relationships is

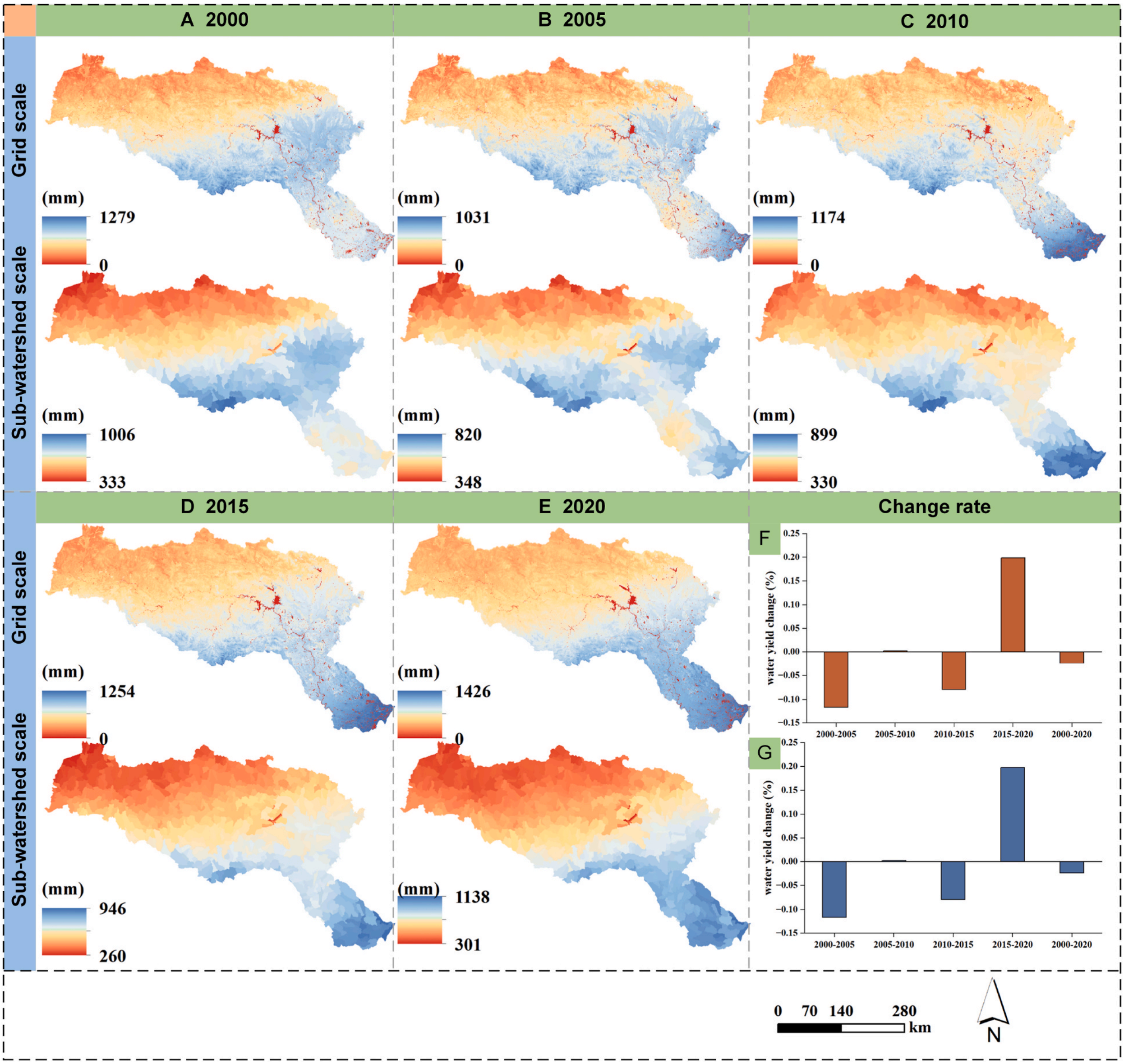


Fig. 9. The spatial-temporal patterns and variability of water yield under actual conditions, the spatial-temporal pattens of water yield at the grid scale and the sub-watershed scale in (A) 2000, (B) 2005, (C) 2010, (D) 2015, and (E) 2020, (F) the change rate of water yield at the grid scale, and (G) the change rate of water yield at the sub-watershed scale.

imperative to develop efficient water resource management strategies in the HJRB and other similar regions.

3.6. Contribution of climate and LUCC

Table 4 provides a quantitative analysis of the impacts of climate change and LUCC on water yield services in the HJRB. The outcomes demonstrate that climate change has played a significant role in shaping the water yield services of the HJRB, while the contribution of LUCC is relatively minor. Climate change is the primary factor influencing water yield services, and its contribution has increased over time, from 97.75% in 2000–2005 to 99.13% in 2015–2020. Conversely, the contribution of LUCC decreased from 2.25% in 2000–2005 to 0.87% in 2015–2020. This suggests that the management measures implemented for LUCC in the HJRB may have, to some extent, mitigated their negative impact on water yield services.

The increasing contribution of climate change to water yield services aligns with global climate change predictions, which indicate that the frequency and severity of extreme weather events, including floods and droughts, will intensify in numerous regions [83,84]. Climate change driven by global warming and related changes in precipitation patterns has had a significant impact on water yield

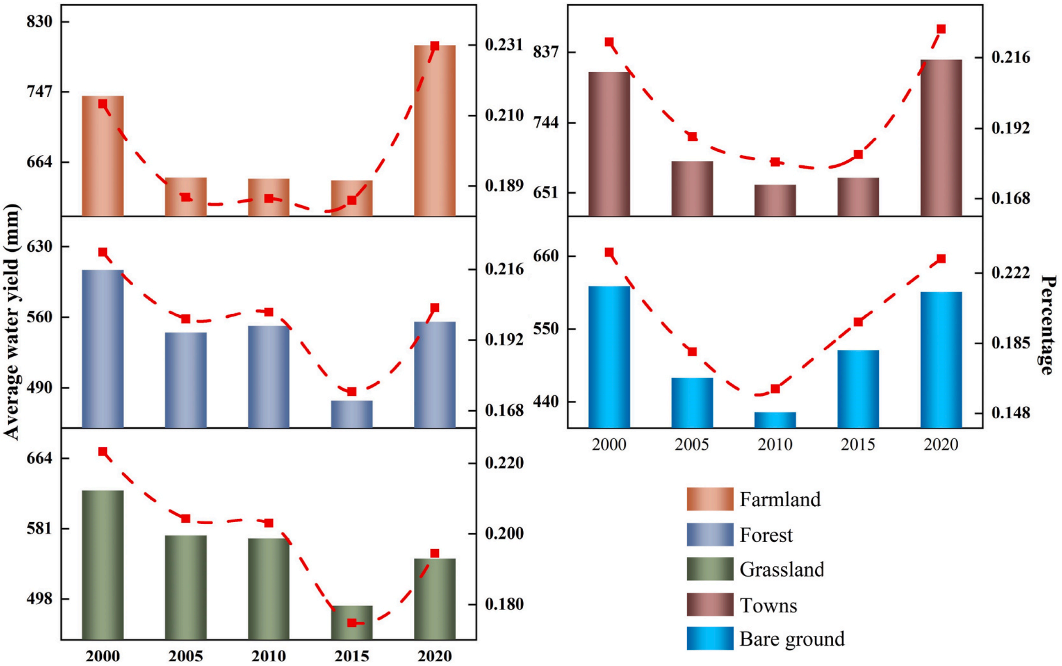


Fig. 10. Average water yield and their proportions of different ecosystem types in the HJRB under actual conditions.

services in the HJRB, surpassing the impact of LUCC, which is primarily driven by human activities such as urbanization, deforestation, and agricultural expansion. It is expected that the HJRB will experience more frequent and severe droughts, which may lead to reduced water yield and negative impacts on agricultural production, energy generation, and other industries [85,86].

The reduction in the contribution of LUCC to water yield services may reflect successful efforts to manage LUCC in the HJRB. These efforts may include policies promoting sustainable land management practices, reducing deforestation, and limiting urbanization in sensitive areas. Nevertheless, it is also possible that LUCC has reached a saturation point, and subsequent alterations have a reduced impact on water yield services.

4. Discussion

This study demonstrates that climate change has a more substantial effect on ecosystem water yield services, while the influence of LUCC is relatively minor, consistent with prior research [14,87,88]. Climate factors are primarily governed by natural conditions, and human activities have a relatively small impact on precipitation. LUCC is more influenced by human activities, but its impact on water yield is smaller, likely due to the complex change process, and the transfer between different land use/cover types can either augment or diminish water yield, resulting in an overall non-significant effect.

4.1. Impacts of climate factors on water yield services

The water yield module is based on the Budyko water-heat coupling balance hypothesis, which treats evapotranspiration as water loss [45,50,89]. Generally, there is a strong correlation between precipitation and potential and actual evapotranspiration, which can be considered as direct driving factors that affect water yield. However, the HJRB's vast spatial span, topography, and altitude differences result in substantial climatic variations among different regions. Therefore, although precipitation is a direct driving factor, it exhibits differences in sub-basin variations.

The impact of climate change on water yield services has critical implications for both human well-being and ecological health [90,91]. Various climate factors significantly influence regional ecosystem water yield services, including precipitation, temperature, and evapotranspiration. These impacts can be observed from various perspectives, such as changes in precipitation patterns, temperature, and evapotranspiration. These changes can result in variations in the timing, quantity, and quality of water available for various uses such as agriculture, industry, and domestic purposes [92,93].

In areas with high precipitation, water yield services are typically more abundant, while in areas with low precipitation, water supply may be insufficient to meet demand. Moreover, changes in precipitation patterns, such as long-term droughts or floods, can also significantly impact water yield services. For example, long-term droughts may lead to water supply shortages, while floods may cause water quality issues and damage water facilities [94,95].

Temperature is another critical climate factor that affects water yield services by directly influencing the water cycle. High temperatures can increase evapotranspiration, which is the process by which soil and vegetation lose water to the atmosphere. This could

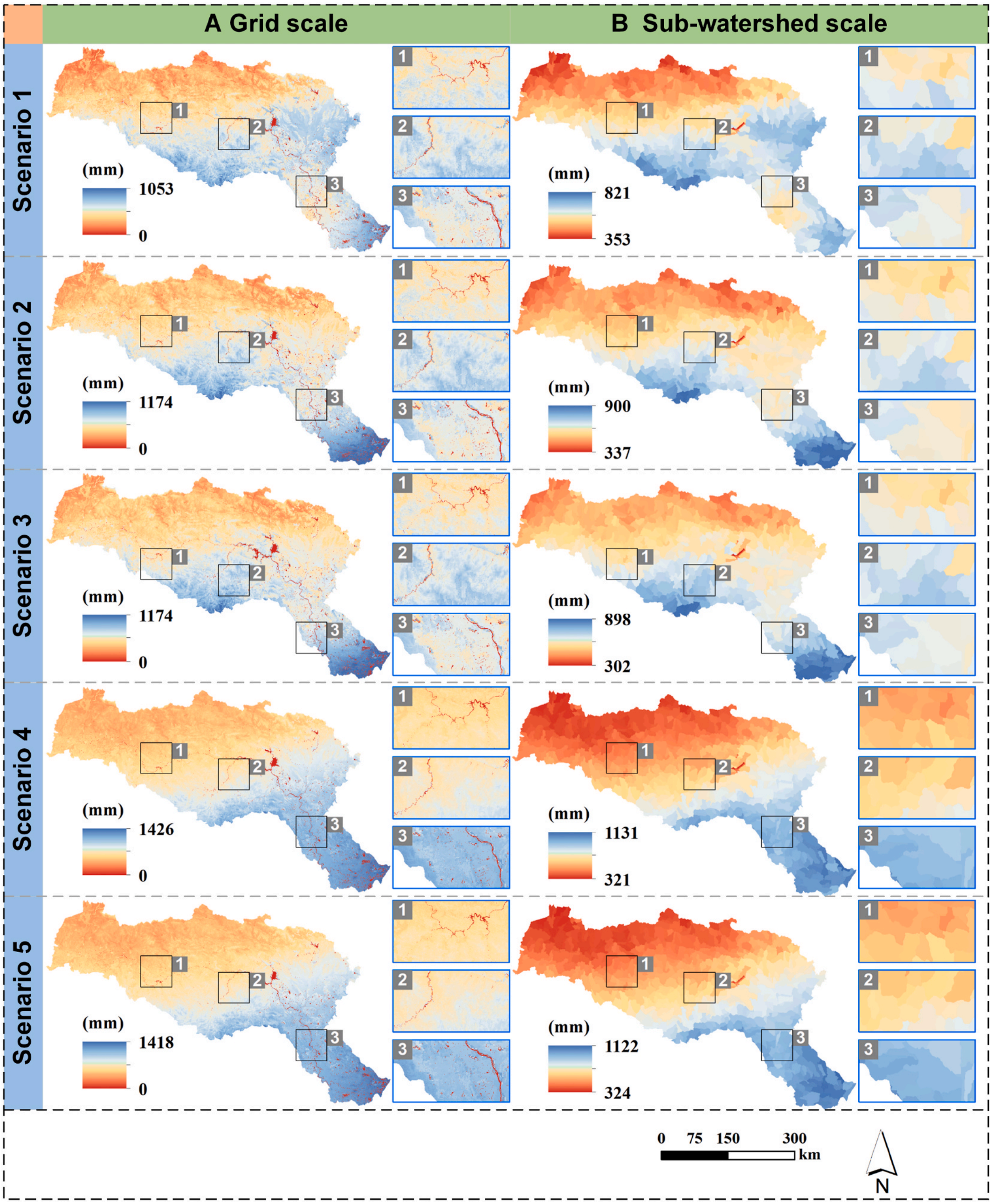


Fig. 11. The spatial-temporal patterns and variability of water yield under climate change scenarios, (A) the spatial-temporal patterns of water yield at the grid scale, (B) the spatial-temporal patterns of water yield at the sub-watershed scale.

potentially decrease the availability and quality of water resources, especially in areas with low precipitation but high temperature [94,96]. Furthermore, temperature regulates both rainfall and evapotranspiration and constrains variations in surface vegetation biomass and soil water-holding capacity, thereby impacting plant and soil water utilization. Temperature variations can also impact water quality by modifying the thermal characteristics of water bodies and increasing the risk of harmful algal blooms.

Evapotranspiration is influenced by two factors: precipitation and temperature [97,98]. In areas with high evapotranspiration rates, water resources may be lost to the atmosphere before being utilized, reducing the availability and quality of water resources, especially in areas with limited water resources [99,100].

Climate change has the potential to worsen water scarcity and amplify the frequency and intensity of droughts, floods, and other extreme weather events. This has significant impacts on freshwater ecosystems, which are crucial for maintaining biodiversity and ecological functions [101]. Furthermore, climate change may exacerbate existing water resource management challenges such as

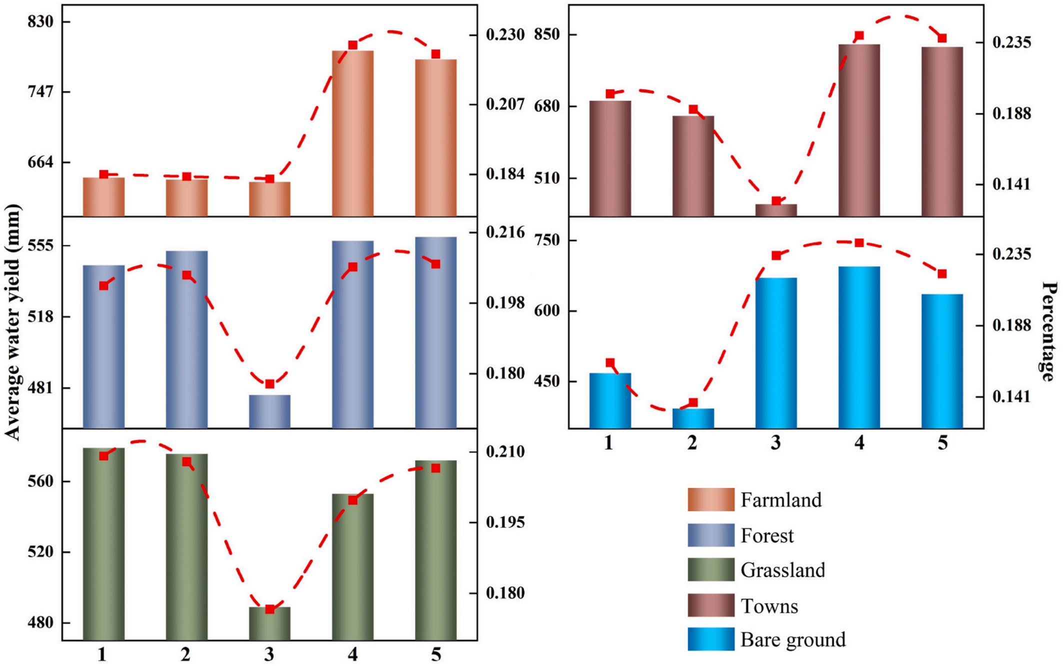


Fig. 12. Average water yield and their proportions of different ecosystem types in the HJRB under climate change scenarios.

water scarcity, water pollution, and water allocation conflicts. This may lead to increased competition for water resources and potential social and economic impacts, particularly in areas already vulnerable to water resource pressures [102,103].

4.2. Impact of land use/cover on water yield services

Land use changes in the HJRB are closely linked to regional urbanization, human activities, and policies. This study highlights the importance of ecosystem types in water yield services, with towns and farmland ecosystems having higher water yield services compared to forest, grassland, and bare land ecosystems, which have lower water yield services, consistent with previous literature [104]. Over the years, the area of building land in the HJRB has been increasing, whereas the areas of farmland and grassland have been decreasing. The influence of forest and water areas on water yield is diverse. Specifically, forests, as a typical vegetation type, play a critical role in the major ecological restoration process in the HJRB. Actions such as afforestation, returning farmland to forests, ecological forest protection, and returning fields to lakes have important impacts on the transfer of forests and water areas. Although vegetation restoration has improved the efficiency of water resources utilization in the basin, the results indicate a slight downward trend in the water yield capacity of forests. This finding demonstrates that the role of land ecological restoration policies in the HJRB is not yet clear. From the perspective of land use, the HJRB still faces the problem of uneven distribution of water yield space and increasing heterogeneity between river basins. This situation necessitates a scientifically reasonable approach to water resources regulation and land use allocation in the future.

The water yield of a river basin is a reflection of the coordination between water source conservation and human activities, and there are significant variations in water yield among different land types. Research findings indicate that the average water yield of land types in the HJRB is ranked in the following order from high to low: building land, farmland, grassland, forest, and unused land. These characteristics have reference significance for maintaining ecosystem services, ecological functional zoning, and different land use patterns across different geographic regions of the HJRB. Nevertheless, due to differences in land use allocation, the HJRB continues to encounter the problem of uneven distribution of water yield function space and increasing heterogeneity between river basins. Thus, future water resource regulation and land use allocation should be more scientifically reasonable to achieve the goals of ecological protection and sustainable development.

The water yield of different ecosystems is primarily influenced by evapotranspiration, infiltration processes, and water retention models [14]. Forests regulate water yield by intercepting rainfall, increasing infiltration, and reducing runoff, thereby redistributing rainfall. Moreover, they help maintain soil moisture and regulate river flow, providing benefits to downstream ecosystems and human communities [27,105,106]. Similarly, grasslands increase water yield by increasing infiltration and reducing runoff, particularly if sustainably managed with grazing practices. Overgrazing can lead to soil compaction and erosion, which can ultimately decrease water yield and quality [107–109]. The mechanism regulating rainfall in farmland ecosystems is similar to that of forests and grasslands [110]. However, the regulation effect of farmlands may be less than that of forests and grasslands due to factors such as plant density and root depth, resulting in lower infiltration but relatively higher water yield [111].

In contrast, town ecosystems have impermeable surfaces such as concrete, asphalt, and cement that quickly generate runoff when

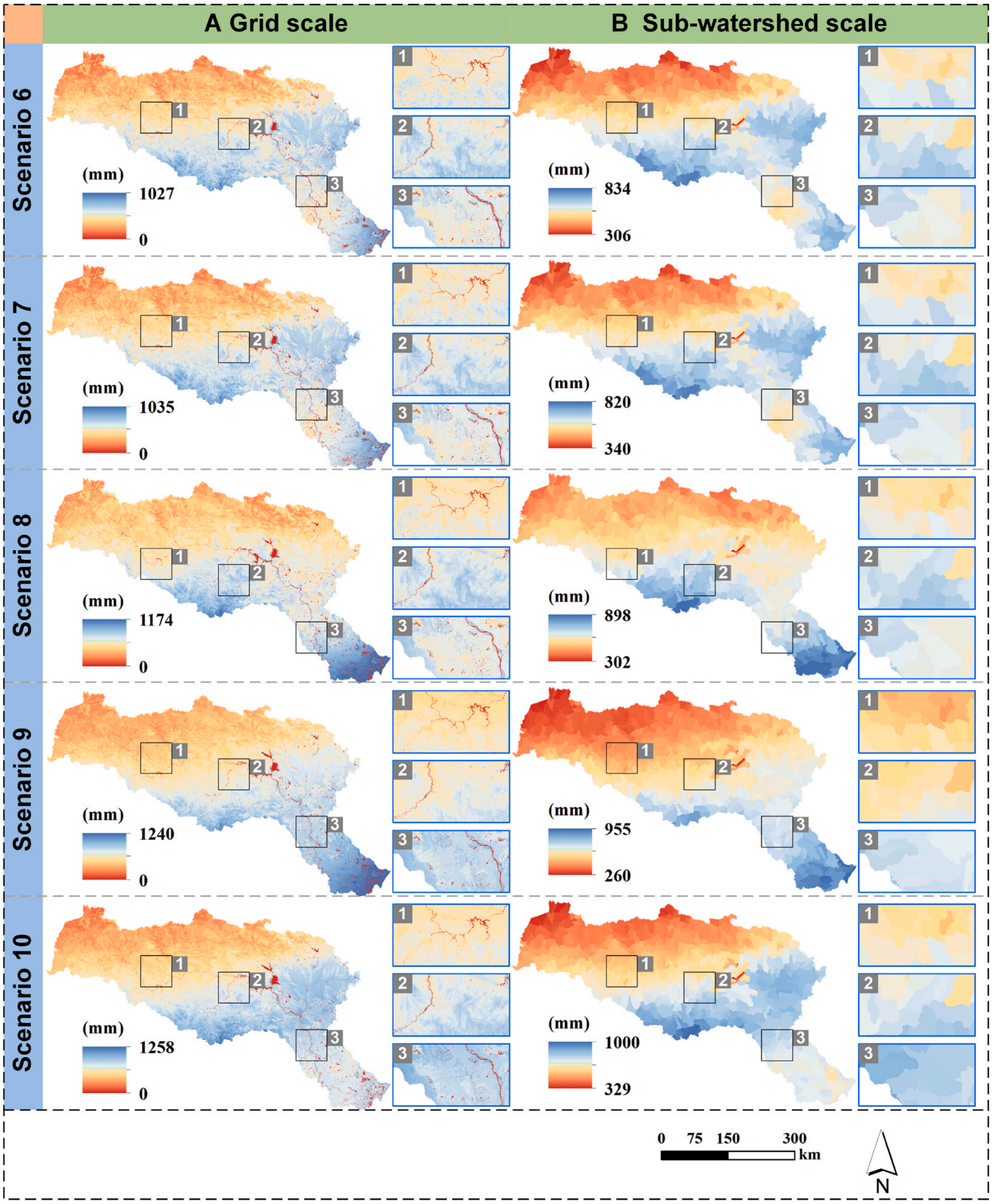


Fig. 13. The spatial-temporal patterns and variability of water yield under LUCC scenarios, (A) the spatial-temporal patterns of water yield at the grid scale, (B) the spatial-temporal patterns of water yield at the sub-watershed scale.

precipitation reaches the ground. This reduces water infiltration and leads to high levels of water yield [112,113]. Additionally, town ecosystems have minimal evapotranspiration, resulting in higher water yield than other ecosystem types. Consequently, transitioning from other ecosystem types to town ecosystems leads to an increase in water yield. Urbanization also leads to an expansion of the area covered by town ecosystems, further increasing water yield. However, due to the impermeable surfaces of towns, most precipitation that reaches the ground enters the city's drainage system and is difficult to use for human purposes [114,115]. Areas with bare ground or limited vegetation cover may have a negative impact on water yield, as they increase runoff and reduce infiltration, leading to soil erosion and decreased groundwater recharge.

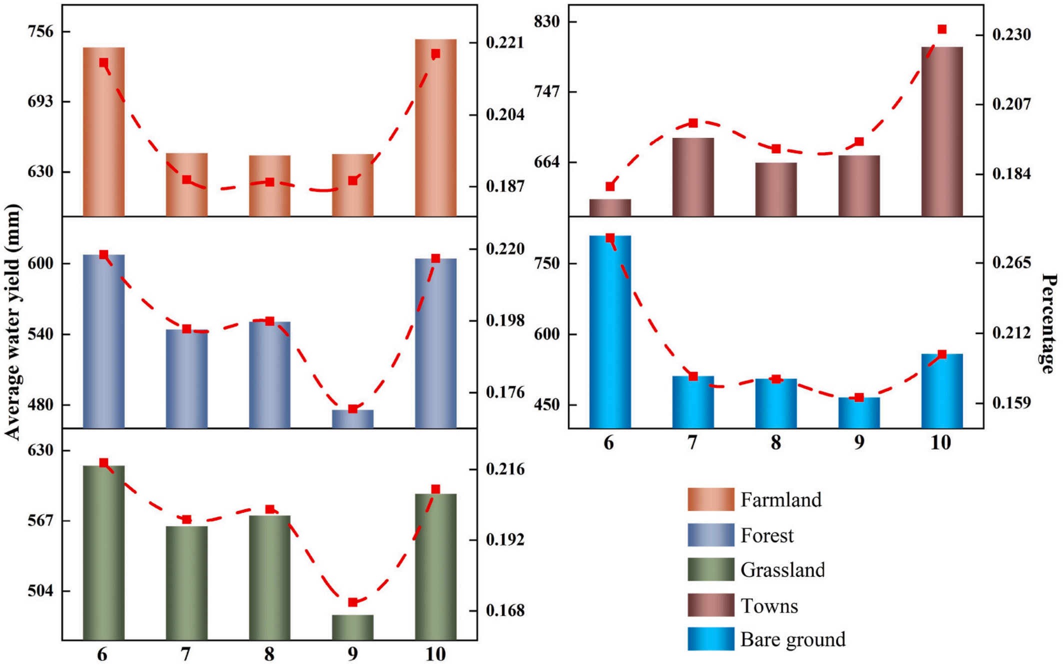


Fig. 14. Average water yield and their proportions of different ecosystem types in the HJRB under LUCC scenarios.

Table 4
The contribution of climate change and LUCC to water yield services in the HJRB from 2000 to 2020.

Type	2000–2005	2005–2010	2010–2015	2015–2020	2000–2020
Climate change	97.75%	69.75%	97.64%	99.13%	67.50%
LUCC	2.25%	30.25%	2.36%	0.87%	32.50%

4.3. Spatial scale effects

Successful management of ecosystem services requires consideration of spatial scale effects [116]. In this study, different spatial resolution data were aligned to a 100 m resolution for consistency and compared and analyzed at both the grid and sub-watershed scales. This may slightly reduce the dissimilarity between different scale models, as results presented at the coarse grid scale lack physical meaning in terms of displaying pathways and may lose some physical information, while the sub-watershed scale may cause confusion in flow direction and slope, leading to discontinuous pathways. However, from the results of this study, the spatial heterogeneity of water yield services at different scales has not fundamentally changed, but the sub-watershed scale shows more pronounced spatial clustering.

This study investigates the impacts of climate change and LUCC on water yield at both the grid and sub-watershed scales. The study emphasizes the importance of prioritizing different scales while maintaining coordination between them to achieve effective water resource management. While the results at the grid scale may provide more detailed insights, larger sub-watershed scale studies remain crucial rather than redundant. China's national spatial planning aims to establish a harmonious coexistence between humans and nature, optimizing production, living, and ecological spaces across multiple levels. However, different spatial scales variations in climate change and LUCC require interconnected spatial planning with distinct directions and priorities. Resolving conflicts between spatial planning at different scales poses a long-term and challenging problem in China's spatial planning system [117–119]. This research highlights the necessity of prioritizing multi-scale research and provides insights into the complexities of spatial planning at different scales. Therefore, it is crucial to consider the interactions between different sub-basins and to plan and balance their functional positioning to regulate the water yield function in the HJRB. This approach can enhance the implementation efficiency of regional and macro policies in the future by taking into account the variations in water yield among different sub-basins and balancing reasonable water resource functional zoning.

4.4. Recommendations for regional governance

The HJRB is a crucial ecological and economic region in China, known for its location and natural environment that serve as a significant agricultural, industrial, and ecological resource base in the central region [37,120]. Nevertheless, the intensifying effects of climate change and LUCC have led to increasing pressure on the water resources situation in the basin. The impacts of these changes on water yield are complicated and multifaceted, necessitating a comprehensive understanding of the underlying factors. Effective strategies must be developed to adapt to and mitigate the effects of climate change on water resources, and sustainable water resource management practices must be promoted to ensure long-term access to water resources for future generations.

The HJRB has undergone diverse and complex changes that have significant implications for water resources management. Climate change, driven by a range of factors including greenhouse gas emissions, land use changes, and natural climate variability, is a major contributor to these changes. Meanwhile, human activities such as urbanization, deforestation, and agricultural expansion have been the primary drivers of land use and cover change in the region [39]. Given the complexity of these interactions, effective water resource management in the HJRB requires a deep understanding of the complex interplay among these factors and their impacts on water provisioning services. Without such an understanding, efforts to manage water resources in the region are likely to fall short of their intended goals.

Effective water resource management in the HJRB requires policy recommendations based on observed trends and impacts. To this end, mitigating the impacts of climate change on water provisioning services should be prioritized, including measures to adapt to more frequent and severe droughts. Sustainable land management practices should also be promoted to limit the negative impacts of LUCC on water provisioning services. Ongoing research is needed to better understand the complex interactions among climate change, LUCC, and water provisioning services to identify driving forces behind trends and develop effective management strategies. Such strategies will be critical for mitigating potential negative impacts on regional water resources and ecosystems, including the HJRB and other similar regions.

4.5. Limitations and future work

LUCC is a crucial driver of changes in ecosystem services and has been increasingly studied. Most ecosystem services assessment research is based on LUCC [104]. While LUCC is a primary cause of changes in ecosystem services, it may not always be the result of such changes. Alterations in land use can lead to changes in ecosystem types, which, in turn, can impact ecosystem services. However, modifications in ecosystem services may not solely be due to changes in land use types but could also be attributed to changes in ecosystem quality.

In this study, the InVEST model's water yield module was used to conduct research. Several factors can affect the accuracy of ecosystem services estimates. If a longer time period, such as 10 years, could be used to capture some climate changes as input climate data for the model that is consistent with the date of the land use/cover map, it may lead to more accurate model results. Some of the input data in the model, such as plant-available water content and potential evapotranspiration, are calculated based on empirical formulas. However, selecting different empirical formulas can lead to different results. The seasonal constant Z is compared and adjusted based on the actual water resources in the local area, and the optimal fitting effect is used as the input parameter. Different regions may have different Z values. Model input data, such as precipitation and potential evapotranspiration, are obtained through spatial interpolation, and using different interpolation methods can also cause some errors. For different study areas, the optimal empirical formula and the interpolation method with the smallest error should be selected based on local conditions, and model parameters should be optimized to improve the model's simulation accuracy. Additionally, this study used the InVEST model's annual water yield module, which is based on the water balance principle and easy to use. However, it attributes runoff changes to the influences of climate and watershed changes, which is not very precise. Although the error can be reduced by calibrating the parameter Z, there is always some residual between observed and estimated runoff changes. In future research, the Complementary Method or the Total Differential Method can be used to address this gap [89].

5. Conclusion

This study focused on the HJRB, the location of the world's largest inter-basin water transfer project, as the study area. We simulated and analyzed the water yield services of different climate factors and land use types under actual conditions, virtual scenarios, and different spatial scales. The main conclusions are as follows:

The upstream area experiences significantly lower annual average precipitation, temperature, and potential evapotranspiration than the downstream area. Drought severity in the upstream area is progressively worsening, while the downstream area is becoming wetter. Urbanization has led to changes in land use/cover. During the study period, forests, water bodies, building land, and unused land increased, while cultivated land and grassland areas decreased. Farmland and grassland showed opposite trends.

The impacts of actual conditions, climate change scenarios, and LUCC scenarios on the spatial distribution pattern of water yield services were evaluated at both grid and basin scales, taking into account the responses of different ecosystem types. The results revealed that the spatial heterogeneity of water yield at different scales did not fundamentally change, but the sub-watershed scale exhibited more obvious spatial clustering.

The provision of water yield services is primarily impacted by climate change, surpassing the influence of LUCC. Climate change can disrupt water yield by affecting precipitation and potential evapotranspiration, with varying impacts on different ecosystem types. Farmland ecosystems are more resistant to climate change impacts on water yield, while bare land ecosystems are more vulnerable. Grassland ecosystems yield more water than forest ecosystems, and town ecosystems have the highest average water yields. LUCC significantly affects the water cycle and ecosystems, particularly vegetation cover, which is a critical factor in water yield. Different LUCC scenarios can result in significant changes in water yield for various ecosystem types. Additionally, towns with a higher proportion of impermeable surfaces can experience greater surface runoff and contribute to higher water yield.

Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Author contribution statement

Kai Zhu: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Yufeng Cheng and Quan Zhou: Conceived and designed the experiments; Performed the experiments.

Zsombor Kápolnai and Lóránt Dénes Dávid: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was supported by the Hungarian University of Agriculture and Life Sciences and the Doctoral School of Economic and Regional Sciences (MATE), Hungary.

References

[1] R. Seppelt, C.F. Dormann, F.V. Eppink, S. Lautenbach, S. Schmidt, A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead, J. Appl. Ecol. 48 (2011) 630–636, https://doi.org/10.1111/j.1365-2664.2010.01952.x.

[2] C. Kremen, Managing ecosystem services: what do we need to know about their ecology? Ecol. Lett. 8 (2005) 468–479, https://doi.org/10.1111/j.1461-0248.2005.00751.x.

[3] E.M. Bennett, G.D. Peterson, L.J. Gordon, Understanding relationships among multiple ecosystem services, Ecol. Lett. 12 (2009) 1394–1404, https://doi.org/10.1111/j.1461-0248.2009.01387.x.

[4] S.L.R. Wood, S.K. Jones, J.A. Johnson, K.A. Brauman, R. Chaplin-Kramer, A. Fremier, E. Girvetz, L.J. Gordon, C.V. Kappel, L. Mandle, M. Mulligan, P. O'Farrell, W.K. Smith, L. Willemen, W. Zhang, F.A. DeClerck, Distilling the role of ecosystem services in the sustainable development goals, Ecosyst. Serv. 29 (2018) 70–82, https://doi.org/10.1016/j.ecoser.2017.10.010.

[5] P.A. Harrison, R. Dunford, D.N. Barton, E. Kelemen, B. Martín-López, L. Norton, M. Termansen, H. Saarikoski, K. Hendriks, E. Gómez-Baggethun, B. Czúcz, M. García-Llorente, D. Howard, S. Jacobs, M. Karlsen, L. Kopperoinen, A. Madsen, G. Rusch, M. van Eupen, P. Verweij, R. Smith, D. Tuomasjukka, G. Zulian, Selecting methods for ecosystem service assessment: a decision tree approach, Ecosyst. Serv. 29 (2018) 481–498, https://doi.org/10.1016/j.ecoser.2017.09.016.

[6] L. Pejchar, H.A. Mooney, Invasive species, ecosystem services and human well-being, Trends Ecol. Evol. 24 (2009) 497–504, https://doi.org/10.1016/j.tree.2009.03.016.

[7] J.K. Summers, L.M. Smith, J.L. Case, R.A. Linthurst, A review of the elements of human well-being with an emphasis on the contribution of ecosystem services, Ambio 41 (2012) 327–340, https://doi.org/10.1007/s13280-012-0256-7.

[8] B. Wang, Q. Zhang, F. Cui, Scientific research on ecosystem services and human well-being: a bibliometric analysis, Ecol. Indicat. 125 (2021), 107449, https://doi.org/10.1016/j.ecolind.2021.107449.

[9] Q. Wang, S. Li, R. Li, Evaluating water resource sustainability in Beijing, China: combining PSR model and matter-element extension method, J. Clean. Prod. 206 (2019) 171–179, https://doi.org/10.1016/j.jclepro.2018.09.057.

[10] G. Gao, Q. Shen, Y. Zhang, N. Pan, Y. Ma, X. Jiang, B. Fu, Determining spatio-temporal variations of ecological water consumption by natural oases for sustainable water resources allocation in a hyper-arid endorheic basin, J. Clean. Prod. 185 (2018) 1–13, https://doi.org/10.1016/j.jclepro.2018.03.025.

[11] B. Fu, X. Wu, Z. Wang, X. Wu, S. Wang, Coupling human and natural systems for sustainability: experience from China's Loess Plateau, Earth Syst. Dynam. 13 (2022) 795–808, https://doi.org/10.5194/esd-13-795-2022.

[12] C. Su, B. Fu, Y. Wei, Y. Lu, G. Liu, D. Wang, K. Mao, X. Feng, Ecosystem management based on ecosystem services and human activities: a case study in the Yanhe watershed, Sustain. Sci. 7 (2012) 17–32, https://doi.org/10.1007/s11625-011-0145-1.

[13] H. Pei, M. Liu, Y. Shen, K. Xu, H. Zhang, Y. Li, J. Luo, Quantifying impacts of climate dynamics and land-use changes on water yield service in the agro-pastoral ecotone of northern China, Sci. Total Environ. 809 (2022), 151153, https://doi.org/10.1016/j.scitotenv.2021.151153.

[14] Y. Lang, W. Song, Y. Zhang, Responses of the water-yield ecosystem service to climate and land use change in Sancha River Basin, China, Phys. Chem. Earth, Parts A/B/C 101 (2017) 102–111, https://doi.org/10.1016/j.pce.2017.06.003.

[15] D. Wang, A new probability density function for spatial distribution of soil water storage capacity leads to the SCS curve number method, Hydrol. Earth Syst. Sci. 22 (2018) 6567–6578, https://doi.org/10.5194/hess-22-6567-2018.

[16] W. Liu, L. Wang, J. Zhou, Y. Li, F. Sun, G. Fu, X. Li, Y.-F. Sang, A worldwide evaluation of basin-scale evapotranspiration estimates against the water balance method, J. Hydrol. 538 (2016) 82–95, https://doi.org/10.1016/j.jhydrol.2016.04.006.

[17] M. Li, Y. Zhang, J. Wallace, E. Campbell, Estimating annual runoff in response to forest change: a statistical method based on random forest, J. Hydrol. 589 (2020), 125168, https://doi.org/10.1016/j.jhydrol.2020.125168.

[18] S. Chen, M. Ren, W. Sun, Combining two-stage decomposition based machine learning methods for annual runoff forecasting, J. Hydrol. 603 (2021), 126945, https://doi.org/10.1016/j.jhydrol.2021.126945.

[19] B. Xue, L. Wang, X. Li, K. Yang, D. Chen, L. Sun, Evaluation of evapotranspiration estimates for two river basins on the Tibetan Plateau by a water balance method, J. Hydrol. 492 (2013) 290–297, https://doi.org/10.1016/j.jhydrol.2013.04.005.

[20] S.K. Dingre, S.D. Gorantiwar, Determination of the water requirement and crop coefficient values of sugarcane by field water balance method in semiarid region, Agric. Water Manag. 232 (2020), 106042, https://doi.org/10.1016/j.agwat.2020.106042.

[21] C. Caro, J.C. Marques, P.P. Cunha, Z. Teixeira, Ecosystem services as a resilience descriptor in habitat risk assessment using the InVEST model, Ecol. Indicat. 115 (2020), 106426, https://doi.org/10.1016/j.ecolind.2020.106426.

[22] S. Nedkov, S. Campagne, B. Borisova, P. Krpec, H. Prodanova, I.P. Kokkoris, D. Hristova, S. Le Clec'h, F. Santos-Martin, B. Burkhard, E.S. Bekri, V. Stoycheva, A.G. Bruzon, P. Dimopoulos, Modeling water regulation ecosystem services: a review in the context of ecosystem accounting, Ecosyst. Serv. 56 (2022), 101458, https://doi.org/10.1016/j.ecoser.2022.101458.

[23] K.L. Vigerstol, J.E. Aukema, A comparison of tools for modeling freshwater ecosystem services, J. Environ. Manag. 92 (2011) 2403–2409, https://doi.org/10.1016/j.jenvman.2011.06.040.

[24] H. Xia, S. Yuan, A.V. Prishchepov, Spatial-temporal heterogeneity of ecosystem service interactions and their social-ecological drivers: implications for spatial planning and management, Resour. Conserv. Recycl. 189 (2023), 106767, https://doi.org/10.1016/j.resconrec.2022.106767.

[25] A.F. Cord, B. Bartkowski, M. Beckmann, A. Dittrich, K. Hermans-Neumann, A. Kaim, N. Lienhoop, K. Locher-Krause, J. Priess, C. Schröter-Schlaack, N. Schwarz, R. Seppelt, M. Strauch, T. Václavík, M. Volk, Towards systematic analyses of ecosystem service trade-offs and synergies: main concepts, methods and the road ahead, Ecosyst. Serv. 28 (2017) 264–272, https://doi.org/10.1016/j.ecoser.2017.07.012.

[26] M. Dallimer, Z.G. Davies, D.F. Diaz-Porras, K.N. Irvine, L. Maltby, P.H. Warren, P.R. Armsworth, K.J. Gaston, Historical influences on the current provision of multiple ecosystem services, Global Environ. Change 31 (2015) 307–317, https://doi.org/10.1016/j.gloenvcha.2015.01.015.

[27] X. Zhang, G. Zhang, X. Long, Q. Zhang, D. Liu, H. Wu, S. Li, Identifying the drivers of water yield ecosystem service: a case study in the Yangtze River Basin, China, Ecol. Indicat. 132 (2021), 108304, https://doi.org/10.1016/j.ecolind.2021.108304.

[28] J.W. Redhead, C. Stratford, K. Sharps, L. Jones, G. Ziv, D. Clarke, T.H. Oliver, J.M. Bullock, Empirical validation of the InVEST water yield ecosystem service model at a national scale, Sci. Total Environ. (2016) 1418–1426, https://doi.org/10.1016/j.scitotenv.2016.06.227, 569–570.

[29] P.J. DennedyFrank, R.L. Muenich, I. Chaubey, G. Ziv, Comparing two tools for ecosystem service assessments regarding water resources decisions, J. Environ. Manag. 177 (2016) 331–340, https://doi.org/10.1016/j.jenvman.2016.03.012.

[30] Y. Wang, H. Wang, G. Liu, J. Zhang, Z. Fang, Factors driving water yield ecosystem services in the Yellow River Economic Belt, China: spatial heterogeneity and spatial spillover perspectives, J. Environ. Manag. 317 (2022), 115477, https://doi.org/10.1016/j.jenvman.2022.115477.

[31] S. Chacko, J. Kurian, C. Ravichandran, S.M. Vairavel, K. Kumar, An assessment of water yield ecosystem services in periyar tiger reserve, southern western ghats of India, Geology, Ecology, and Landscapes 5 (2021) 32–39, https://doi.org/10.1080/24749508.2019.1699988.

[32] Y. Zou, D. Mao, Analysis of water yield service of Lianshui River Basin in China based on ecosystem services flow model, Water Supply 22 (2021) 335–346, https://doi.org/10.2166/ws.2021.265.

[33] R. Spake, R. Lasseur, E. Crouzat, J.M. Bullock, S. Lavorel, K.E. Parks, M. Schaafsma, E.M. Bennett, J. Maes, M. Mulligan, M. Mouchet, G.D. Peterson, C.J. E. Schulp, W. Thuiller, M.G. Turner, P.H. Verburg, F. Eigenbrod, Unpacking ecosystem service bundles: towards predictive mapping of synergies and trade-offs between ecosystem services, Global Environ. Change 47 (2017) 37–50, https://doi.org/10.1016/j.gloenvcha.2017.08.004.

[34] E. Gomes, M. Inácio, K. Bogdzevič, M. Kalinauskas, D. Karnauskaitė, P. Pereira, Future land-use changes and its impacts on terrestrial ecosystem services: a review, Sci. Total Environ. 781 (2021), 146716, https://doi.org/10.1016/j.scitotenv.2021.146716.

[35] X. Wang, X. Dong, H. Liu, H. Wei, W. Fan, N. Lu, Z. Xu, J. Ren, K. Xing, Linking land use change, ecosystem services and human well-being, A case study of the Manas River Basin of Xinjiang, China, Ecosystem Services 27 (2017) 113–123, https://doi.org/10.1016/j.ecoser.2017.08.013.

[36] W. Song, X. Deng, Land-use/land-cover change and ecosystem service provision in China, Sci. Total Environ. 576 (2017) 705–719, https://doi.org/10.1016/j.scitotenv.2016.07.078.

[37] K. Zhu, Y. Zhang, M. Wang, H. Liu, The ecological compensation mechanism in a cross-regional water diversion project using evolutionary game theory: the case of the Hanjiang River Basin, China, Water 14 (2022) 1151, https://doi.org/10.3390/w14071151.

[38] Y. Wang, K. Zhu, X. Xiong, J. Yin, H. Yan, Y. Zhang, H. Liu, Assessment of the ecological compensation standards for cross-basin water diversion projects from the perspective of main headwater and receiver areas, Int. J. Environ. Res. Publ. Health 20 (2023) 717, https://doi.org/10.3390/ijerph20010717.

[39] K. Zhu, Q. Liu, X. Xiong, Y. Zhang, M. Wang, H. Liu, Carbon footprint and embodied carbon emission transfer network obtained using the multi–regional input–output model and social network analysis method: a case of the Hanjiang River basin, China, Frontiers in Ecology and Evolution 10 (2022), https://doi.org/10.3389/fevo.2022.941520.

[40] H. Dadashpoor, P. Azizi, M. Moghadasi, Land use change, urbanization, and change in landscape pattern in a metropolitan area, Sci. Total Environ. 655 (2019) 707–719, https://doi.org/10.1016/j.scitotenv.2018.11.267.

[41] E. Kalnay, M. Cai, Impact of urbanization and land-use change on climate, Nature 423 (2003) 528–531, https://doi.org/10.1038/nature01675.

[42] P. Droogers, R.G. Allen, Estimating reference evapotranspiration under inaccurate data conditions, Irrigat. Drain. Syst. 16 (2002) 33–45, https://doi.org/10.1023/A:1015508322413.

[43] W. Zhou, G. Liu, J. Pan, X. Feng, Distribution of available soil water capacity in China, J. Geogr. Sci. 15 (2005) 3–12, https://doi.org/10.1007/BF02873101.

[44] J. Yang, X. Huang, The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019, Earth Syst. Sci. Data 13 (2021) 3907–3925, https://doi.org/10.5194/essd-13-3907-2021.

[45] W. Cong, X. Sun, H. Guo, R. Shan, Comparison of the SWAT and InVEST models to determine hydrological ecosystem service spatial patterns, priorities and trade-offs in a complex basin, Ecol. Indicat. 112 (2020), 106089, https://doi.org/10.1016/j.ecolind.2020.106089.

[46] R.J. Donohue, M.L. Roderick, T.R. McVicar, Roots, storms and soil pores: incorporating key ecohydrological processes into Budyko's hydrological model, J. Hydrol. 436 (437) (2012) 35–50, https://doi.org/10.1016/j.jhydrol.2012.02.033.

[47] L. Zhang, K. Hickel, W.R. Dawes, F.H.S. Chiew, A.W. Western, P.R. Briggs, A rational function approach for estimating mean annual evapotranspiration, Water Resour. Res. 40 (2004), https://doi.org/10.1029/2003WR002710.

[48] L. Zhang, W.R. Dawes, G.R. Walker, Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water Resour. Res. 37 (2001) 701–708, https://doi.org/10.1029/2000WR900325.

[49] K. Zhu, Y. Cheng, W. Zang, Q. Zhou, Y. El Archi, H. Mousazadeh, M. Kabil, K. Csobán, L.D. Dávid, Multiscenario simulation of land-use change in Hubei province, China based on the markov-FLUS model, Land 12 (2023) 744, https://doi.org/10.3390/land12040744.

[50] Y. Wang, A. Ye, D. Peng, C. Miao, Z. Di, W. Gong, Spatiotemporal variations in water conservation function of the Tibetan Plateau under climate change based on InVEST model, J. Hydrol.: Reg. Stud. 41 (2022), 101064, https://doi.org/10.1016/j.ejrh.2022.101064.

[51] W. Qi, H. Li, Q. Zhang, K. Zhang, Forest restoration efforts drive changes in land-use/land-cover and water-related ecosystem services in China's Han River basin, Ecol. Eng. 126 (2019) 64–73, https://doi.org/10.1016/j.ecoleng.2018.11.001.

[52] D. Yang, W. Liu, L. Tang, L. Chen, X. Li, X. Xu, Estimation of water provision service for monsoon catchments of South China: applicability of the InVEST model, Landsc. Urban Plann. 182 (2019) 133–143, https://doi.org/10.1016/j.landurbplan.2018.10.011.

[53] M. Yang, X. Wang, G. Pang, G. Wan, Z. Liu, The Tibetan Plateau cryosphere: observations and model simulations for current status and recent changes, Earth Sci. Rev. 190 (2019) 353–369, https://doi.org/10.1016/j.earscirev.2018.12.018.

[54] Y. Malhi, J. Franklin, N. Seddon, M. Solan, M.G. Turner, C.B. Field, N. Knowlton, Climate change and ecosystems: threats, opportunities and solutions, Phil. Trans. Biol. Sci. 375 (2020), 20190104, https://doi.org/10.1098/rstb.2019.0104.

[55] S.C. Doney, M. Ruckelshaus, J. Emmett Duffy, J.P. Barry, F. Chan, C.A. English, H.M. Galindo, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, J. Polovina, N. N. Rabalais, W.J. Sydeman, L.D. Talley, Climate change impacts on marine ecosystems, Ann. Rev. Mar. Sci 4 (2012) 11–37, https://doi.org/10.1146/annurev-marine-041911-111611.

[56] G.B. Bonan, S.C. Doney, Climate, ecosystems, and planetary futures: the challenge to predict life in Earth system models, Science 359 (2018), eaam8328, https://doi.org/10.1126/science.aam8328.

[57] S.L. Grotch, M.C. MacCracken, The use of general circulation models to predict regional climatic change, J. Clim. 4 (1991) 286–303, https://doi.org/10.1175/1520-0442(1991)004<0286:TUOGCM>2.0.CO, 2.

[58] W.L. Gates, The use of general circulation models in the analysis of the ecosystem impacts of climatic change, Climatic Change 7 (1985) 267–284, https://doi.org/10.1007/BF00144171.

[59] A. Dai, Increasing drought under global warming in observations and models, Nat. Clim. Change 3 (2013) 52–58, https://doi.org/10.1038/nclimate1633.

[60] K.L. Bristow, G.S. Campbell, On the relationship between incoming solar radiation and daily maximum and minimum temperature, Agric. For. Meteorol. 31 (1984) 159–166, https://doi.org/10.1016/0168-1923(84)90017-0.

[61] X. Liu, X. Mei, Y. Li, Q. Wang, J.R. Jensen, Y. Zhang, J.R. Porter, Evaluation of temperature-based global solar radiation models in China, Agric. For. Meteorol. 149 (2009) 1433–1446, https://doi.org/10.1016/j.agrformet.2009.03.012.

[62] A.S.A. Johnston, A. Meade, J. Ardö, N. Arriga, A. Black, P.D. Blanken, D. Bonal, C. Brümmer, A. Cescatti, J. Dušek, A. Graf, B. Gioli, I. Goded, C.M. Gough, H. Ikawa, R. Jassal, H. Kobayashi, V. Magliulo, G. Manca, L. Montagnani, F.E. Moyano, J.E. Olesen, T. Sachs, C. Shao, T. Tagesson, G. Wohlfahrt, S. Wolf, W. Woodgate, A. Varlagin, C. Venditti, Temperature thresholds of ecosystem respiration at a global scale, Nat Ecol Evol 5 (2021) 487–494, https://doi.org/10.1038/s41559-021-01398-z.

[63] F.C. García, E. Bestion, R. Warfield, G. Yvon-Durocher, Changes in temperature alter the relationship between biodiversity and ecosystem functioning, Proc. Natl. Acad. Sci. U.S.A. 115 (2018) 10989–10994, https://doi.org/10.1073/pnas.1805518115.

[64] J.S. Deng, K. Wang, Y. Hong, J.G. Qi, Spatio-temporal dynamics and evolution of land use change and landscape pattern in response to rapid urbanization, Landsc. Urban Plann. 92 (2009) 187–198, https://doi.org/10.1016/j.landurbplan.2009.05.001.

[65] U. Chatterjee, S. Majumdar, Impact of land use change and rapid urbanization on urban heat island in Kolkata city: a remote sensing based perspective, Journal of Urban Management 11 (2022) 59–71, https://doi.org/10.1016/j.jum.2021.09.002.

[66] G. Zhao, R. Liang, K. Li, Y. Wang, X. Pu, Study on the coupling model of urbanization and water environment with basin as a unit: a study on the Hanjiang Basin in China, Ecol. Indicat. 131 (2021), 108130, https://doi.org/10.1016/j.ecolind.2021.108130.

[67] Y. Cheng, K. Zhu, Q. Zhou, Y. El Archi, M. Kabil, B. Remenyik, L.D. Dávid, Tourism ecological efficiency and sustainable development in the Hanjiang River Basin: a super-efficiency slacks-based measure model study, Sustainability 15 (2023) 6159, https://doi.org/10.3390/su15076159.

[68] A.P. GarcíaNieto, M. GarcíaLlorente, I. IniestaArandia, B. MartínLópez, Mapping forest ecosystem services: from providing units to beneficiaries, Ecosyst. Serv. 4 (2013) 126–138, https://doi.org/10.1016/j.ecoser.2013.03.003.

[69] W. Mengist, T. Soromessa, Assessment of forest ecosystem service research trends and methodological approaches at global level: a meta-analysis, Environ Syst Res 8 (2019) 22, https://doi.org/10.1186/s40068-019-0150-4.

[70] S.M. Swinton, F. Lupi, G.P. Robertson, S.K. Hamilton, Ecosystem services and agriculture: cultivating agricultural ecosystems for diverse benefits, Ecol. Econ. 64 (2007) 245–252, https://doi.org/10.1016/j.ecolecon.2007.09.020.

[71] C. Comberti, T.F. Thornton, V. Wyllie de Echeverria, T. Patterson, Ecosystem services or services to ecosystems? Valuing cultivation and reciprocal relationships between humans and ecosystems, Global Environ. Change 34 (2015) 247–262, https://doi.org/10.1016/j.gloenvcha.2015.07.007.

[72] P. Sikorski, B. Gawryszewska, D. Sikorska, J. Chormański, A. Schwerk, A. Jojczyk, W. Ciężkowski, P. Archiciński, M. Łepkowski, I. Dymitryszyn, A. Przybysz, M. Wińska-Krysiak, B. Zajdel, J. Matusiak, E. Łaszkiewicz, The value of doing nothing – how informal green spaces can provide comparable ecosystem services to cultivated urban parks, Ecosyst. Serv. 50 (2021), 101339, https://doi.org/10.1016/j.ecoser.2021.101339.

[73] X. Chen, L. Yu, Z. Du, Y. Xu, J. Zhao, H. Zhao, G. Zhang, D. Peng, P. Gong, Distribution of ecological restoration projects associated with land use and land cover change in China and their ecological impacts, Sci. Total Environ. 825 (2022), 153938, https://doi.org/10.1016/j.scitotenv.2022.153938.

[74] H. Yang, S. Mu, J. Li, Effects of ecological restoration projects on land use and land cover change and its influences on territorial NPP in Xinjiang, China, Catena 115 (2014) 85–95, https://doi.org/10.1016/j.catena.2013.11.020.

[75] L.E. Stevens, E.R. Schenk, A.E. Springer, Springs ecosystem classification, Ecol. Appl. 31 (2021), e2218, https://doi.org/10.1002/eap.2218.

[76] J.S. Rowe, Land classification and ecosystem classification, Environ. Monit. Assess. 39 (1996) 11–20, https://doi.org/10.1007/BF00396131.

[77] P. Luo, M. Zhou, H. Deng, J. Lyu, W. Cao, K. Takara, D. Nover, S. Geoffrey Schladow, Impact of forest maintenance on water shortages: hydrologic modeling and effects of climate change, Sci. Total Environ. 615 (2018) 1355–1363, https://doi.org/10.1016/j.scitotenv.2017.09.044.

[78] S.R. Verón, J.M. Paruelo, M. Oesterheld, Grazing-induced losses of biodiversity affect the transpiration of an arid ecosystem, Oecologia 165 (2011) 501–510, https://doi.org/10.1007/s00442-010-1780-4.

[79] R. MataGonzález, T. McLendon, D.W. Martin, The inappropriate use of crop transpiration coefficients (Kc) to estimate evapotranspiration in arid ecosystems: a review, Arid Land Res. Manag. 19 (2005) 285–295, https://doi.org/10.1080/15324980590951469.

[80] L. Zhang, L. Cheng, F. Chiew, B. Fu, Understanding the impacts of climate and landuse change on water yield, Curr. Opin. Environ. Sustain. 33 (2018) 167–174, https://doi.org/10.1016/j.cosust.2018.04.017.

[81] M. Liu, H. Tian, G. Chen, W. Ren, C. Zhang, J. Liu, Effects of land-use and land-cover change on evapotranspiration and water yield in China during 1900-20001, JAWRA Journal of the American Water Resources Association 44 (2008) 1193–1207, https://doi.org/10.1111/j.1752-1688.2008.00243.x.

[82] X. Yang, W. Sun, P. Li, X. Mu, P. Gao, G. Zhao, Integrating agricultural land, water yield and soil conservation trade-offs into spatial land use planning, Ecol. Indicat. 104 (2019) 219–228, https://doi.org/10.1016/j.ecolind.2019.04.082.

[83] M.R. Allen, P.A. Stott, J.F.B. Mitchell, R. Schnur, T.L. Delworth, Quantifying the uncertainty in forecasts of anthropogenic climate change, Nature 407 (2000) 617–620, https://doi.org/10.1038/35036559.

[84] S. Hsiang, R.E. Kopp, An economist's guide to climate change science, J. Econ. Perspect. 32 (2018) 3–32, https://doi.org/10.1257/jep.32.4.3.

[85] Y. Xu, X. Zhang, X. Wang, Z. Hao, V.P. Singh, F. Hao, Propagation from meteorological drought to hydrological drought under the impact of human activities: a case study in northern China, J. Hydrol. 579 (2019), 124147, https://doi.org/10.1016/j.jhydrol.2019.124147.

[86] M. Jehanzaib, S.A. Shah, J. Yoo, T.-W. Kim, Investigating the impacts of climate change and human activities on hydrological drought using non-stationary approaches, J. Hydrol. 588 (2020), 125052, https://doi.org/10.1016/j.jhydrol.2020.125052.

[87] N. Pessacg, S. Flaherty, L. Brandizi, S. Solman, M. Pascual, Getting water right: a case study in water yield modelling based on precipitation data, Sci. Total Environ. 537 (2015) 225–234, https://doi.org/10.1016/j.scitotenv.2015.07.148.

[88] W. Nie, Y. Yuan, W. Kepner, M.S. Nash, M. Jackson, C. Erickson, Assessing impacts of Landuse and Landcover changes on hydrology for the upper San Pedro watershed, J. Hydrol. 407 (2011) 105–114, https://doi.org/10.1016/j.jhydrol.2011.07.012.

[89] S. Zhou, B. Yu, L. Zhang, Y. Huang, M. Pan, G. Wang, A new method to partition climate and catchment effect on the mean annual runoff based on the Budyko complementary relationship, Water Resour. Res. 52 (2016) 7163–7177, https://doi.org/10.1002/2016WR019046.

[90] W.N. Adger, Climate change, human well-being and insecurity, New Polit. Econ. 15 (2010) 275–292, https://doi.org/10.1080/13563460903290912.

[91] W.F. Lamb, J.K. Steinberger, Human well-being and climate change mitigation, WIREs Climate Change 8 (2017) e485, https://doi.org/10.1002/wcc.485.

[92] G.T. Pecl, M.B. Araújo, J.D. Bell, J. Blanchard, T.C. Bonebrake, I.-C. Chen, T.D. Clark, R.K. Colwell, F. Danielsen, B. Evengård, L. Falconi, S. Ferrier, S. Frusher, R.A. Garcia, R.B. Griffis, A.J. Hobday, C. Janion-Scheepers, M.A. Jarzyna, S. Jennings, J. Lenoir, H.I. Linnetved, V.Y. Martin, P.C. McCormack, J. McDonald, N. J. Mitchell, T. Mustonen, J.M. Pandolfi, N. Pettorelli, E. Popova, S.A. Robinson, B.R. Scheffers, J.D. Shaw, C.J.B. Sorte, J.M. Strugnell, J.M. Sunday, M.-N. Tuanmu, A. Vergés, C. Villanueva, T. Wernberg, E. Wapstra, S.E. Williams, Biodiversity redistribution under climate change: impacts on ecosystems and human well-being, Science 355 (2017), https://doi.org/10.1126/science.aai9214 eaai9214.

[93] T. Kjellstrom, A.J. McMichael, Climate change threats to population health and well-being: the imperative of protective solutions that will last, Glob. Health Action 6 (2013), 20816, https://doi.org/10.3402/gha.v6i0.20816.

[94] X. Gong, H. Zhang, C. Ren, D. Sun, J. Yang, Optimization allocation of irrigation water resources based on crop water requirement under considering effective precipitation and uncertainty, Agric. Water Manag. 239 (2020), 106264, https://doi.org/10.1016/j.agwat.2020.106264.

[95] F. HuiMean, Z. Yusop, F. Yusof, Drought analysis and water resource availability using standardised precipitation evapotranspiration index, Atmos. Res. 201 (2018) 102–115, https://doi.org/10.1016/j.atmosres.2017.10.014.

[96] P.H. Gleick, Climate change, hydrology, and water resources, Rev. Geophys. 27 (1989) 329–344, https://doi.org/10.1029/RG027i003p00329.

[97] M.C. Anderson, R.G. Allen, A. Morse, W.P. Kustas, Use of Landsat thermal imagery in monitoring evapotranspiration and managing water resources, Rem. Sens. Environ. 122 (2012) 50–65, https://doi.org/10.1016/j.rse.2011.08.025.

[98] J.B. Fisher, F. Melton, E. Middleton, C. Hain, M. Anderson, R. Allen, M.F. McCabe, S. Hook, D. Baldocchi, P.A. Townsend, A. Kilic, K. Tu, D.D. Miralles, J. Perret, J.-P. Lagouarde, D. Waliser, A.J. Purdy, A. French, D. Schimel, J.S. Famiglietti, G. Stephens, E.F. Wood, The future of evapotranspiration: global

requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources, Water Resour. Res. 53 (2017) 2618–2626, https://doi.org/10.1002/2016WR020175.
[99] J.R. Mecikalski, W.B. Shoemaker, Q. Wu, M.A. Holmes, S.J. Paech, D.M. Sumner, High-resolution GOES insolation–evapotranspiration data set for water resource management in Florida: 1995–2015, J. Irrigat. Drain. Eng. 144 (2018), 04018025, https://doi.org/10.1061/(ASCE)IR.1943-4774.0001312.
[100] O. Moses, W.L. Hambira, Effects of climate change on evapotranspiration over the Okavango Delta water resources, Phys. Chem. Earth, Parts A/B/C 105 (2018) 98–103, https://doi.org/10.1016/j.pce.2018.03.011.
[101] J. Horne, C. Tortajada, L. Harrington, Achieving the Sustainable Development Goals: improving water services in cities affected by extreme weather events, Int. J. Water Resour. Dev. 34 (2018) 475–489, https://doi.org/10.1080/07900627.2018.1464902.
[102] P. Li, H. Qian, Water resources research to support a sustainable China, Int. J. Water Resour. Dev. 34 (2018) 327–336, https://doi.org/10.1080/07900627.2018.1452723.
[103] M.M.Q. Mirza, Climate change and extreme weather events: can developing countries adapt? Clim. Pol. 3 (2003) 233–248, https://doi.org/10.3763/cpol.2003.0330.
[104] J. Gao, F. Li, H. Gao, C. Zhou, X. Zhang, The impact of land-use change on water-related ecosystem services: a study of the Guishui River Basin, Beijing, China, J. Clean. Prod. 163 (2017) S148, https://doi.org/10.1016/j.jclepro.2016.01.049. –S155.
[105] A.F. Mark, K.J. Dickinson, Maximizing water yield with indigenous non-forest vegetation: a New Zealand perspective, Front. Ecol. Environ. 6 (2008) 25–34, https://doi.org/10.1890/060130.
[106] M. Sharafatmandrad, A. Khosravi Mashizi, Temporal and spatial assessment of supply and demand of the water-yield ecosystem service for water scarcity management in arid to semi-arid ecosystems, Water Resour. Manag. 35 (2021) 63–82, https://doi.org/10.1007/s11269-020-02706-1.
[107] R.F. Young, Managing municipal green space for ecosystem services, Urban For. Urban Green. 9 (2010) 313–321, https://doi.org/10.1016/j.ufug.2010.06.007.
[108] J. Shen, H. Lu, Y. Zhang, X. Song, L. He, Vulnerability assessment of urban ecosystems driven by water resources, human health and atmospheric environment, J. Hydrol. 536 (2016) 457–470, https://doi.org/10.1016/j.jhydrol.2016.03.004.
[109] D.M. Alderson, M.G. Evans, E.L. Shuttleworth, M. Pilkington, T. Spencer, J. Walker, T.E.H. Allott, Trajectories of ecosystem change in restored blanket peatlands, Sci. Total Environ. 665 (2019) 785–796, https://doi.org/10.1016/j.scitotenv.2019.02.095.
[110] S. Yang, Y. Bai, J.M. Alatalo, H. Wang, B. Jiang, G. Liu, J. Chen, Spatio-temporal changes in water-related ecosystem services provision and trade-offs with food production, J. Clean. Prod. 286 (2021), 125316, https://doi.org/10.1016/j.jclepro.2020.125316.
[111] J.F. Weltzin, M.E. Loik, S. Schwinning, D.G. Williams, P.A. Fay, B.M. Haddad, J. Harte, T.E. Huxman, A.K. Knapp, G. Lin, W.T. Pockman, R.M. Shaw, E. E. Small, M.D. Smith, S.D. Smith, D.T. Tissue, J.C. Zak, Assessing the response of terrestrial ecosystems to potential changes in precipitation, Bioscience 53 (2003) 941–952, https://doi.org/10.1641/0006-3568(2003)053, 0941:ATROTE]2.0.CO;2.
[112] D. Haase, N. Larondelle, E. Andersson, M. Artmann, S. Borgström, J. Breuste, E. Gomez-Baggethun, Å. Gren, Z. Hamstead, R. Hansen, N. Kabisch, P. Kremer, J. Langemeyer, E.L. Rall, T. McPhearson, S. Pauleit, S. Qureshi, N. Schwarz, A. Voigt, D. Wurster, T. Elmqvist, A quantitative review of urban ecosystem service assessments: concepts, models, and implementation, Ambio 43 (2014) 413–433, https://doi.org/10.1007/s13280-014-0504-0.
[113] J. Langemeyer, M. Camps-Calvet, L. Calvet-Mir, S. Barthel, E. Gómez-Baggethun, Stewardship of urban ecosystem services: understanding the value(s) of urban gardens in Barcelona, Landsc. Urban Plann. 170 (2018) 79–89, https://doi.org/10.1016/j.landurbplan.2017.09.013.
[114] T. Ding, J. Chen, Z. Fang, J. Chen, Assessment of coordinative relationship between comprehensive ecosystem service and urbanization: a case study of Yangtze River Delta urban Agglomerations, China, Ecol. Indicat. 133 (2021), 108454, https://doi.org/10.1016/j.ecolind.2021.108454.
[115] J. Zeng, J. Xu, W. Li, X. Dai, J. Zhou, Y. Shan, J. Zhang, W. Li, H. Lu, Y. Ye, L. Xu, S. Liang, Y. Wang, Evaluating trade-off and synergies of ecosystem services values of a representative resources-based urban ecosystem: a coupled modeling framework applied to panzhihua city, China, Rem. Sens. 14 (2022) 5282, https://doi.org/10.3390/rs14205282.
[116] J.P. Rodríguez, T.D. Beard, E.M. Bennett, G.S. Cumming, S.J. Cork, J. Agard, A.P. Dobson, G.D. Peterson, Trade-offs across space, time, and ecosystem services, Ecol. Soc. 11 (2006), https://doi.org/10.5751/ES-01667-110128.
[117] Y. Liu, Y. Zhou, Territory spatial planning and national governance system in China, Land Use Pol. 102 (2021), 105288, https://doi.org/10.1016/j.landusepol.2021.105288.
[118] M. Chen, L. Liang, Z. Wang, W. Zhang, J. Yu, Y. Liang, Geographical thoughts on the relationship between 'Beautiful China' and land spatial planning, J. Geogr. Sci. 30 (2020) 705–723, https://doi.org/10.1007/s11442-020-1751-6.
[119] J. Cheng, J. Turkstra, M. Peng, N. Du, P. Ho, Urban land administration and planning in China: opportunities and constraints of spatial data models, Land Use Pol. 23 (2006) 604–616, https://doi.org/10.1016/j.landusepol.2005.05.010.
[120] K. Zhu, Q. Zhou, Y. Cheng, Y. Zhang, T. Li, X. Yan, A. Alimov, E. Farmanov, L.D. Dávid, Regional sustainability: pressures and responses of tourism economy and ecological environment in the Yangtze River basin, China, Frontiers in Ecology and Evolution 11 (2023), https://doi.org/10.3389/fevo.2023.1148868.