EVOLUTION AND INFLUENCING FACTORS OF WATER YIELD AND WATER CONSERVATION SERVICES IN THE YELLOW RIVER SOURCE AREA FROM 2000 TO 2020

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Abstract. The Yellow River Source Area (YRSA) in China is an important water yield and water conservation area in the Yellow River basin. Alterations in climate and landscape patterns have had a significant impact on the water yield and conservation services of the YRSA. In this study, we used a modified parameter water yield module of the InVEST model to calculate water yield and a modified equation to calculate water conservation in order to evaluate the spatiotemporal changes in water yield and water conservation services in the YRSA from 2000 to 2020. The results show that water yield and water conservation in the YRSA increased at rates of 14.72 mm/5a and 10.03 mm/5a, respectively, from 2000 to 2020, and both showed a decreasing pattern from southeast to northwest. Precipitation is the main driving factor of water ecosystem services in the YRSA. An appropriate increase in vegetation coverage is conducive to an increase in water yield and water conservation, and an increase in grassland and forest area has a positive impact on water yield and water conservation services. This study provides insights into high-quality development and water resource protection in the YRSA.
Keywords: *ecosystem service, spatial pattern, climate impact, correlation analysis, InVEST model*

Introduction

The Yellow River Source Area (YRSA) in China is an important area of water production and water conservation in the Yellow River Basin (Ma et al., 2021), and is also sensitive to climate change (Duan et al., 2021). Studies have shown that there has been a significant change in precipitation in the YRSA since the 21st century (Liu et al., 2022b), with a relative change rate of 15.36% (Ma et al., 2021), and it has been showing a sustained increasing trend. The ecosystem in the YRSA is fragile and dynamic. Since 2005, the Chinese government has implemented the Three-River-Source National Park ecological conservation and construction project (Phase I), which includes the implementation of black soil treatment and degraded grassland improvement. The ecological protection and construction have risen to the level of national strategy. Ecological services refer to the benefits that humans directly or indirectly obtain from ecosystems (Li et al., 2021b; Wang et al., 2022b). They are an important foundation for human survival and social development, including supporting, provisioning, regulating, and cultural services (Huang and Yu, 2021). Water yield service refers to the process and capacity of supplying water to the ecosystem and beyond, after deducting actual evapotranspiration from precipitation. Water yield service is a crucial ecosystem provisioning service (Wang et al., 2019), which is commonly quantified by water yield (WY). Water conservation service refers to the process and ability of an ecosystem to keep water resources within the ecosystem in a certain temporal and spatial range. It is an important ecosystem regulating service and plays a crucial role in flood control, soil and water conservation, water purification, and environmental optimization. Water conservation (WC) is commonly used to quantify water conservation service. The water yield service not only provides water within the ecosystem but also provides water outside the ecosystem, while water conservation service focuses on the interception of water, thus retaining water within the ecosystem. In the background of changing climate and landscape patterns, studying the water yield and water conservation services in the YRSA is of great significance for downstream water supply and the stability of the entire ecosystem.

Many studies have focused on the analysis of ecosystem service functions based on climate and land use and land cover changes (Shrestha et al., 2020; Wei et al., 2021; Li et al., 2021; Niu et al., 2022; Yi et al., 2022; Xiang et al., 2022; Wang et al., 2022a). However, research on the relationship between ecosystem service evolution and landscape pattern indices is relatively rare (Lyu et al., 2022). The changes in landscape patterns include changes in patch composition and spatial distribution, which influence the structure and function of ecosystems by altering the biophysical parameters of the land surface (Kindu et al., 2016), thereby affecting the ability of ecosystems to provide ecosystem services (Liu et al., 2022a). For example, changes in landscape patterns can affect water storage and movement between different patches (Yohannes et al., 2021) thereby influencing water yield and water conservation services. Understanding the relationship between ecosystem services and landscape patterns can provide new ideas and approaches from the perspective of landscape optimization to improve the functioning of ecosystem services (Liu et al., 2022a). Quantification of ecosystem services can be done using models, such as the SWAT model is commonly used for assessing hydrological processes (Baker and Miller, 2013), the Multi-scale Integrated Model of Ecosystem Services (MIMES), and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). InVEST model is a specialized tool for ecosystem services (Cong et al., 2020). Wang et al. (2022d) utilized the InVEST model to assess the spatiotemporal variation of water conservation function in the Tibetan Plateau. Nahib et al. (2023) investigated the balance between water supply and demand in the Citarum watershed using the InVEST model. The water yield module in the InVEST model is based on the water balance principle, and uses the Budyko theory (Budyko and Miller, 1974) to describe the water yield in the study area. The model has low requirement and reliable conclusion (Wang et al., 2022c). It has been widely used to evaluate ecosystem services (Kim and Jung, 2020; Chen et al., 2022).

This study used the water yield modul of the InVEST model to calculate the WY of the YRSA from 2000 to 2020 and adjusted the WY calculation to estimate WC using topographic index, velocity coefficient, and saturated soil hydraulic conductivity parameters. In addition, by evaluating the spatiotemporal characteristics of WY and WC, and analyzing their spatiotemporal correlation with the main driving factors, this study

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explores the main factors influencing water yield and water conservation services in the YRSA. This study aims to (1) assess the water yield and water conservation services in the YRSA from 2000 to 2020; (2) explore the main factors influencing water yield and conservation services; and (3) analyze the impact of different land use types and landscape pattern indices on water yield and water conservation services. The results of this study are beneficial for providing references for the high-quality development of the YRSA and the protection of water resources.

Materials and methods

Study area

The YRSA (*Fig. 1*) is located in the northeast of the Qinghai-Tibet Plateau, China, above the Tangnaihai hydrological station in the Yellow River basin (95.5°E~103.5°E, 32.0°N~36.5°N). It covers an area of 121,972 km^2 and includes 19 counties in three provinces (Qinghai, Sichuan, and Gansu). The YRSA has an average annual precipitation of 421-688 mm, an average annual temperature of -1.7~-3.4℃, and an average elevation of 4,125 m. It is characterized by a high-altitude continental climate, and grassland is the dominant land use type, accounting for 79% of the study area. The soil types in the area are mainly alpine meadow soil and alpine grassland soil. The long-term average runoff at the Tangnaihai station is about 20 billion m^3, accounting for 34.5% of the total runoff in the Yellow River basin. The climate in YRSA is complex and sensitive. Rising temperatures due to climate warming affect water supply. Therefore, it is urgent to study the water yield and water conservation services of YRSA.

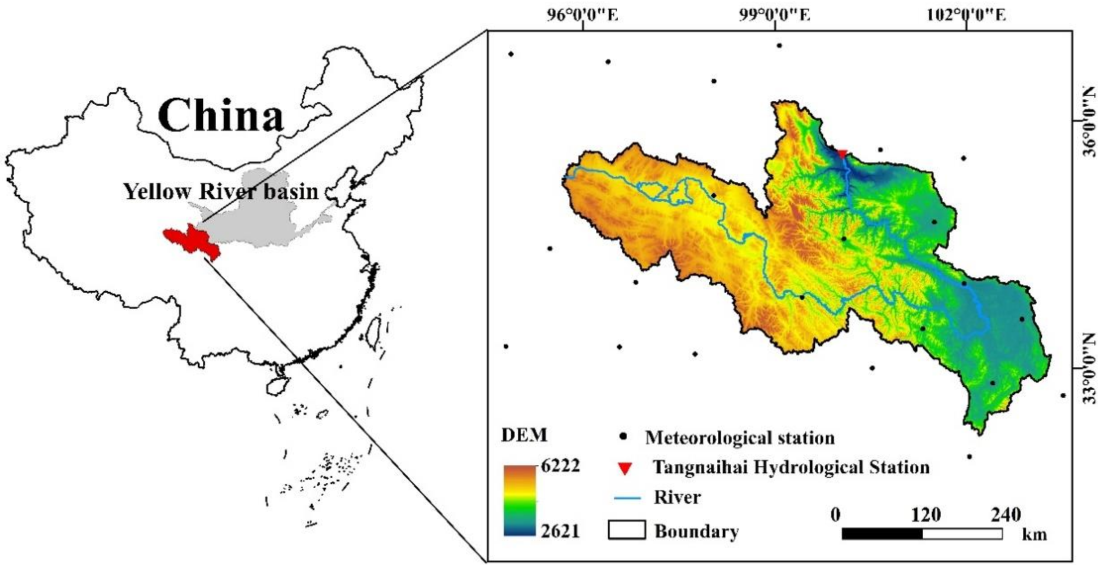

Figure 1. *The location of the YRSA*

Data source

The InVEST model's water yield module requires data inputs including annual precipitation, annual potential evapotranspiration, land use type, biophysical table, plant available water capacity (PAWC), Z coefficient, and biophysical table (Sharp et al., 2016).

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The data inputs required for the modified calculation of water conservation services include topographic index (TI), velocity coefficient (Velocity), and saturated soil hydraulic conductivity (k_{sat}). Further details and sources of the relevant basic data are available in *Table 1*.

Table 1. *Data name, description, and source used in this study*

Name	Description	Source
DEM	Digital Elevation Model with a spatial resolution of 30m.	NASADEM (https://www.earthdata.nasa.gov/esds/competitive-programs/measures/nasadem)
Precipitation	Interpolation was performed on 23 meteorological stations to obtain a 1km precipitation dataset for the period from 2000 to 2020.	National Meteorological Science Data Center of China（http://data.cma.cn/）
Temperature	Interpolation was performed on 23 meteorological stations to obtain a 1km temperature dataset for the period from 2000 to 2020.	National Meteorological Science Data Center of China（http://data.cma.cn/）
Potential evapotranspiration	A dataset of potential evapotranspiration at 1km resolution for each year from 2000 to 2020.	National Tibetan Plateau Data Center（https://data.tpdc.ac.cn/）
Land use and land cover change	2000, 2005, 2010, 2015, and 2020 datasets were used with a spatial resolution of 30 m, and were reclassified into dryland, woodland, high, middle and low coverage grassland, water body, artificial land, unused land, permanent snow and glacier, wetland.	Resource and Environment Science and Data Center（https://www.resdc.cn/）
Runoff observations	Annual streamflow data at the Tangnaihai station from 2000 to 2020.	Yellow River Water Resources Bulletin
SD	Soil Depth, Spatial resolution of 1km.	Harmonized World Soil Database (https://www.fao.org/soils-portal/)
k_{sat}	Soil saturated hydraulic conductivity, Spatial resolution of 1km.	Calculated using the SPAW software.
Velocity	Velocity coefficient, Spatial resolution of 1km.	Referred to relevant research (Wang, et al., 2019) and model manuals
PAWC	Plant Available Water Capacity, Spatial resolution of 1km.	The soil parameters provided by Harmonized World Soil Database(HWSD) are calculated using empirical equations.

Research methods

Technical workflow

In order to explore the spatiotemporal variation characteristics and influencing factors of water yield and water conservation services in the YRSA, this study collected basic data to evaluate the spatiotemporal evolution characteristics of WY and WC and conducted a driving factor analysis of WY and WC. The specific technical process is shown in *Figure 2*.

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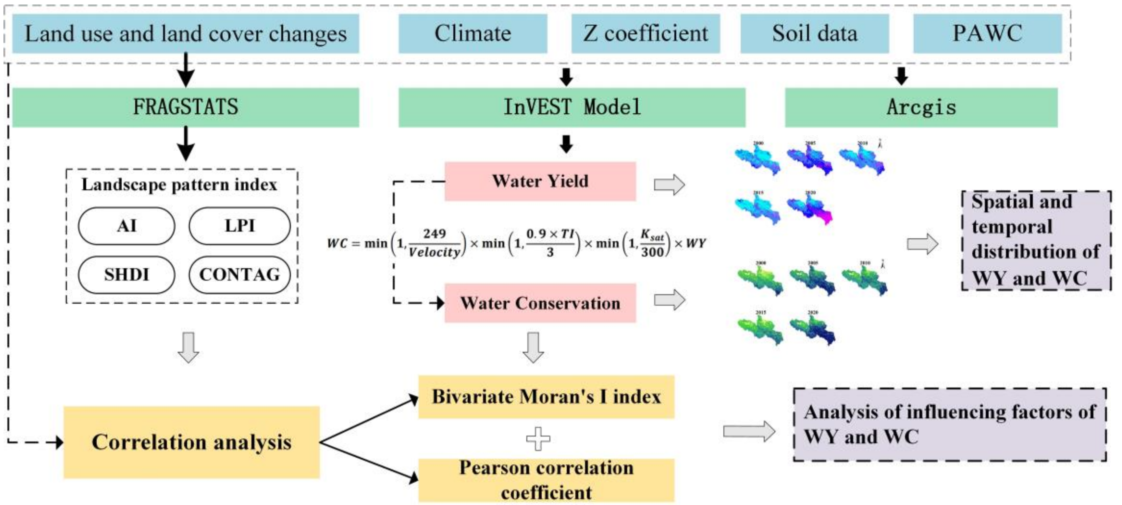

Figure 2. *The technical workflow of this study*

Calculation of water yield

The InVEST model's water yield module is based on the principle of water balance (Li et al., 2021a,c) and can calculate the WY for each grid cell. The specific formula is shown below:

$$WY_{jx} = \left(1 - \frac{AET_{xj}}{P_x}\right) P_x \quad \text{(Eq.1)}$$

$$\frac{AET_{xj}}{P_x} = \frac{1+\omega_x R_{x_j}}{1+\omega_x R_{x_j}+\frac{1}{R_{x_j}}} \quad \text{(Eq.2)}$$

$$\omega_x = Z\frac{AWC_x}{P_x} \quad \text{(Eq.3)}$$

$$R_{x_j} = \frac{kc_{jx} \cdot ET_{0x}}{P_x} \quad \text{(Eq.4)}$$

where WY_{jx} represents the annual water yield(mm)on grid cell x for land use type j, P_x represents the mean annual precipitation (mm), and AET_{xj} represents the mean annual actual evapotranspiration (mm). ω_x represents the ratio of annual water demand to annual precipitation for land use type x, and R_{x_j} is the Budyko aridity index for grid cell x on land use type j, defined as the ratio of potential evapotranspiration to precipitation. Z is a seasonal constant with a value range of 1-30 (Wang et al., 2021). AWC_x represents the soil available water content of grid cell.ET_{0x} represents the potential evapotranspiration (mm), and kc_j is the vegetation evapotranspiration coefficient of grid cell x for land use type j.

$$AWC_x = Min(SD, root.depth) \cdot PAWC \quad \text{(Eq.5)}$$

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$$PAWC = 54.509 - 0.132sand - 0.003(sand)^2 - 0.055slit - 0.006(slit)^2 - 0.738clay + 0.007(clay)^2 - 2.699om + 0.501(om)^2 \quad \text{(Eq.6)}$$

where SD represents soil depth. Root depth refers to the depth at which 95% of the root biomass of a vegetation type occurs. PAWC is calculated using empirical formula (Li, et al., 2021b) based on soil parameters provided by the HWSD.

Calculation of water conservation

After calculating the WY using the InVEST model, WC is estimated by correction equation 7. WC refers to the amount of water that is intercepted and retained by vegetation and soil and is equal to the difference between precipitation and the sum of evapotranspiration and surface runoff. The calculation of the specific equation is as follows (Li et al., 2021b):

$$WC = \min\left(1, \frac{249}{Velocity}\right) \times \min\left(1, \frac{0.9 \times TI}{3}\right) \times \min\left(1, \frac{K_{sat}}{300}\right) \times WY \quad \text{(Eq.7)}$$

where WC represents water conservation capacity (mm). Velocity is the dimensionless velocity coefficient. TI represents the dimensionless terrain index. K_{sat} is the saturated soil hydraulic conductivity(mm/d).

Landscape pattern index

Landscape pattern index succinctly summarizes landscape pattern information and effectively reflects the composition and configuration of the landscape (Qin and Chen, 2023). To avoid redundancy among landscape indices, typical indices are generally selected to represent landscape patterns (Clement et al., 2017), four classic landscape pattern indices were selected to investigate the influence of landscape patterns on water yield and water conservation services: Shannon's Diversity Index (SHDI), Aggregation Index (AI), Largest Patch Index (LPI), Contagion Index (CONTAG). In this study, the moving windows method was used to calculate landscape pattern indices using Fragstats 4.2 software. The formulas for each landscape pattern index and their ecological significance are shown in *Table 2*.

Table 2. *Landscape pattern indices and their ecological significance*

Landscape pattern index	Ecological significance
SHDI	SHDI reflects landscape heterogeneity, with a higher value indicating greater landscape heterogeneity.
AI	AI reflects the degree of aggregation and expansion trend of patches. The larger the AI value, the more concentrated the patches.
LPI	LPI reflects the percentage of the total area represented by the largest patch within the landscape, which helps to determine the main type of landscape.
CONTAG	CONTAG reflects the spreading trend of different patch types in the landscape. A high contagion value indicates that a dominant patch type in the landscape has formed a good physical connectivity.

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Correlation analysis

(1) Spatial analysis

The bivariate Moran's I index is used to characterize the spatial dependence between two variables (Wang et al., 2022b) and is commonly used to analyze the spatial relationships between ecosystem services and influencing factors (Zalasiewicz et al., 2010). The calculation was performed using the GeoDa software, and the specific formula for the calculation is shown below:

$$\mathrm{I_{wo}} = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} \mathrm{W_{ij}} \left(\frac{y_{\mathrm{i,w}} - \overline{\mathrm{y}}_{\mathrm{w}}}{\sigma_{\mathrm{w}}} \right) \left(\frac{y_{\mathrm{i,o}} - \overline{\mathrm{y}}_{\mathrm{o}}}{\sigma_{\mathrm{o}}} \right)}{(\mathrm{n}-1) \sum_{i=1}^{n} \sum_{j=1}^{n} \mathrm{W_{ij}}} \qquad \text{(Eq.8)}$$

where $\mathrm{I_{wo}}$ is the bivariate global Moran's index measuring the spatial autocorrelation between ecosystem services and influencing factors. $\mathrm{W_{ij}}$ refers to the spatial weights between sub-basin i and j, σ represents the variance, n represents the number of sub-basins, $y_{\mathrm{i,w}}$ and $y_{\mathrm{i,o}}$ respectively denote the values of WY and WC and other variables at sub-basin i, and $\overline{y}_w$ and $\overline{y}_o$ represent the average values of WY or WC and other variables, respectively. $\mathrm{I_{wo}}$ ranges from -1 to 1, and the closer its absolute value is to 1, the greater the spatial correlation between ecosystem services and influencing factors. A value greater than 0 indicates positive correlation, less than 0 indicates negative correlation, and equal to 0 indicates no spatial correlation.

(2) Pearson correlation analysis

This study employed the Pearson correlation analysis method to investigate the correlation between ecosystem services and influencing factors, reflecting the degree of correlation between the influencing factors and WY and WC during the study period. Pearson correlation analysis is an effective method for exploring "one-to-one" relationships (Liu et al., 2023), and the calculation formula is shown below.

$$R = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{j=1}^{n}(y_i - \overline{y})^2}} \qquad \text{(Eq.9)}$$

where x_i represents the value of ecosystem service, y_i represents the value of influencing factor. R is the correlation coefficient between ecosystem services and influencing factors. When $R>0$, it indicates a positive correlation, when $R<0$, it indicates a negative correlation, and when $R=0$, there is no correlation. The larger the absolute value of R, the stronger the correlation between the influencing factors and the ecosystem services.

Results

Spatial and temporal distribution of water yield and water conservation

Spatial and temporal distribution of water yield

The overall trend of WY in the study area from 2000 to 2020 was an increase of 14.72 mm/5a (*Fig. 3a*), and the spatial distribution showed a gradual increase from north to south and from west to east (*Fig. 4*). Although there were significant inter-annual

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variations in WY, the spatial distribution remained relatively consistent. In 2005, the WY depth reached 251 mm, and the spatial distribution of water yield was relatively dispersed. The WY decreased in 2010 and 2015 and reached the highest level in 2020 (262.1 mm), with more pronounced spatial differences in WY. High water yield areas were located in the southeastern part of the YRSA, where the annual average precipitation exceeded 600 mm, leading to high runoff after precipitation. Low-yield areas were distributed near the Zaling Lake and Eling Lake, and at the Tangnaihai outlet station. The area near the Tangnaihai outlet station mainly collected water from upstream, and the lakes mainly collected water rather than generating it.

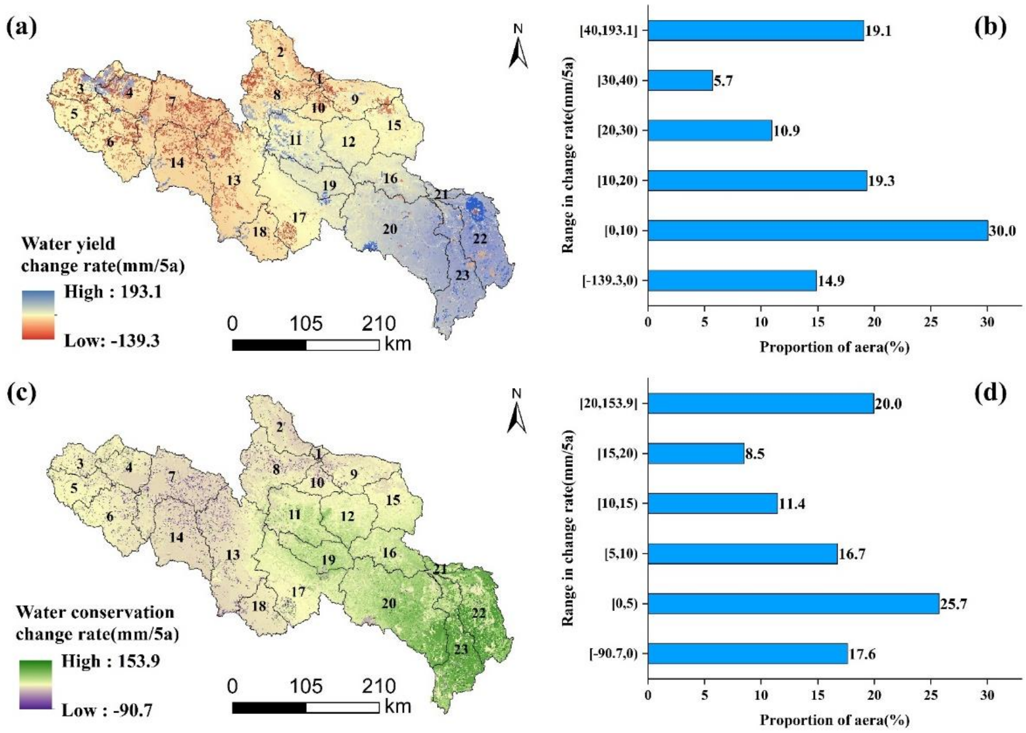

Figure 3. *(a) The change rate of water yield from 2000 to 2020;(b) Frequency distribution of the range of changes in water yield;(c) The change rate of water conservation from 2000 to 2020;(d) Frequency distribution of the range of changes in water conservation; Numbers (1–23) represent the serial number of these sub-watersheds*

In order to improve the accuracy of the WY simulation results, we compared the simulation results with the observation data from the Yellow River Basin Water Resources Bulletin and adjusted the Z parameter repeatedly. Finally, when the Z value was set to 5, the average relative error (MRE) was 1.92%, and the R^2 reached 0.93. Therefore, we set the Z value equal to 5 as the input parameter for the model.

Spatial and temporal distribution of water conservation

From 2000 to 2020, the average WC in the YRSA increased at a rate of 10.03 mm/5a (*Fig. 3c*), indicating an increase in water conservation service. 17.6% of the study area showed a decreasing trend in WC (*Fig. 3d*), with the decreasing areas mainly distributed in the northwest region of the YRSA, while the southeastern region showed the largest increase in WC. The spatial distribution of WC in the study area was similar to that of

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WY, showing a decreasing trend from southeast to northwest (*Fig. 5*). The central and southeastern parts of the YRSA are mostly covered by forests and grasslands with high coverage, and the terrain is relatively flat, which is conducive to the infiltration of precipitation into the soil.

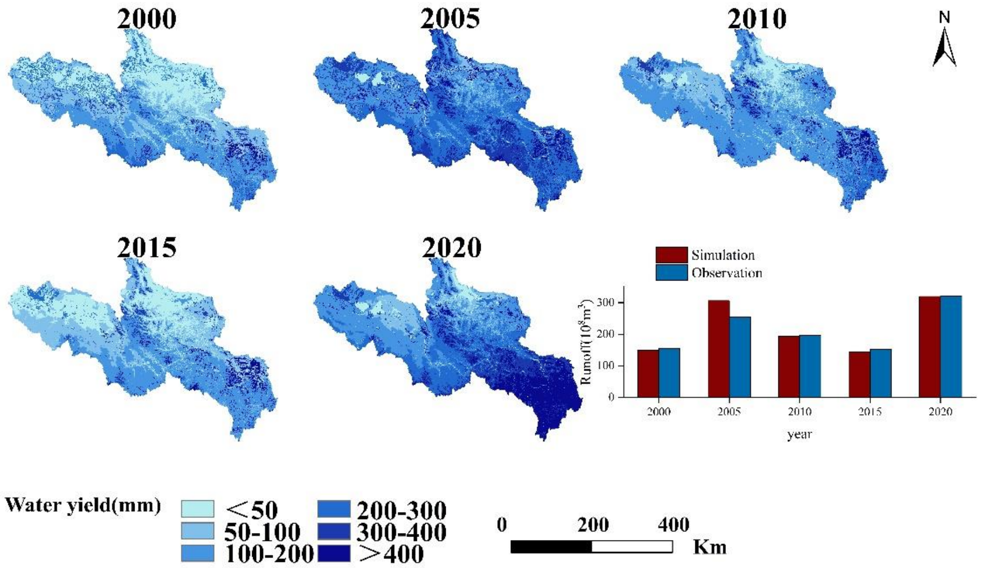

Figure 4. *Spatial distribution and verification of water yield in 2000, 2005, 2010, 2015, and 2020*

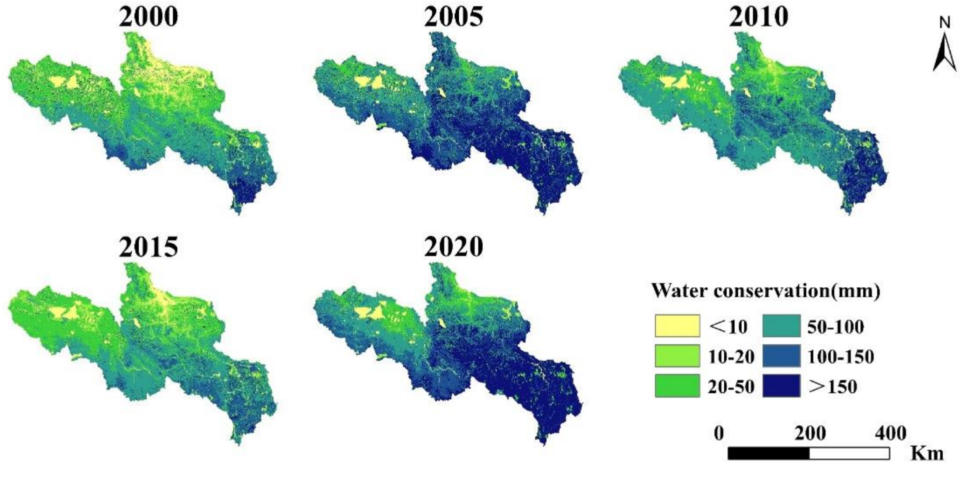

Figure 5. *Spatial distribution of water conservation in 2000, 2005, 2010, 2015, and 2020*

Correlation analysis between water yield, water conservation and influencing factors

Spatial correlation analysis

To analyze the spatial driving relationship of climate and landscape pattern on WY and WC, this study calculated the global bivariate Moran's index between the average values of WY and WC in 23 sub-basins and climate and landscape pattern indices

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(*Table 3*) and performed 999 random permutations to calculate the corresponding p-values.

Table 3. *Bivariate Moran's I of water yield, water conservation and influencing factors*

Variable	Precipitation	Temperature	SHDI	AI	LPI	CONTAG
Water yield	0.720**	0.377**	0.168	0.110	0.008	0.353**
Water conservation	0.794**	0.457**	0.271*	0.228	0.122	0.427**

**p-value<0.01
* p-value<0.05

The results indicate that at the spatial scale, precipitation has a significant spatial dependence on WY and WC ($p<0.01$), followed by temperature. The spatial correlation between landscape pattern indices and WC is more significant than that of WY, and WC is more affected by the spatial relationship of landscape pattern. The diversity index SHDI of landscape pattern shows a significant positive spatial correlation with WC and a non-significant positive spatial correlation with WY, indicating that WC is more driven by the spatial pattern of landscape heterogeneity than WY. The contagion index CONTAG shows a significant positive spatial correlation with both WY and WC, indicating that WY and WC are both driven by the spatial layout of connectivity between patches.

Pearson correlation analysis

Unlike spatial analysis, Pearson correlation analysis focuses more on explaining the degree of correlation between two variables over time. We calculated the Pearson correlation coefficients between WY, WC, and influencing factors for 23 watersheds during five study periods (*Table 4*). As consistent with the spatial analysis, the CONTAG shows a significant positive correlation with both WY and WC ($p<0.01$). Landscape contagion promotes water yield and water conservation services by enhancing the connectivity between dominant patches, which is favorable for increasing the amount of WY and WC. There is no significant correlation between WY, WC, and other landscape pattern indices.

Table 4. *Pearson correlation coefficient of water yield, water conservation and influencing factors from 2000 to 2020*

Variable	Precipitation	Temperature	SHDI	AI	LPI	CONTAG
Water yield	0.687**	0.257**	0.116	-0.043	-0.121	0.293**
Water conservation	0.775**	0.342**	0.177	0.049	0.033	0.325**

**p-value<0.01
* p-value<0.05

Water yield and water conservation services are the result of multi-factor driving, and climate affects the water ecosystem services of the YRSA by influencing the two important water cycle pathways of precipitation and evaporation (Che et al., 2022).The correlation results show that precipitation and temperature are significantly positively correlated with WY and WC ($p<0.01$), indicating that climate is the main driving factor for water yield and water conservation services, which is consistent with the spatial analysis and previous research results (Wang et al., 2021; Yang et al., 2021).

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The impact of land types on water yield and water conservation services

Impact of different land types on water yield

Different land types respond differently to water ecosystem services (*Fig. 6*). On average, the depth of WY from different land use types is ranked from high to low as follows: wetland (414.63 mm) > unused land (315.81 mm) > artificial land (247.66 mm) > high coverage grassland (204.34 mm) > permanent glacier and snow (197.56 mm) > dry land (182.87 mm) > low coverage grassland (155.88 mm) > medium coverage grassland (155.23 mm) > forest land (115.77 mm) > water body (53.46 mm). Wetlands are mainly distributed in the southeast of the YRSA where there is abundant precipitation and have good water yield performance. Artificial land has a non-permeable surface, so rainfall quickly forms runoff after reaching the ground. Unused land and dry land have poor infiltration but good water yield performance. Permanent glaciers and snow are distributed in high altitude areas, where the large vertical temperature difference and the small actual evapotranspiration plus snowmelt have certain water yield capacity. Water bodies mainly refer to lakes and rivers, which mainly collect water from the slope and upstream instead of producing water.

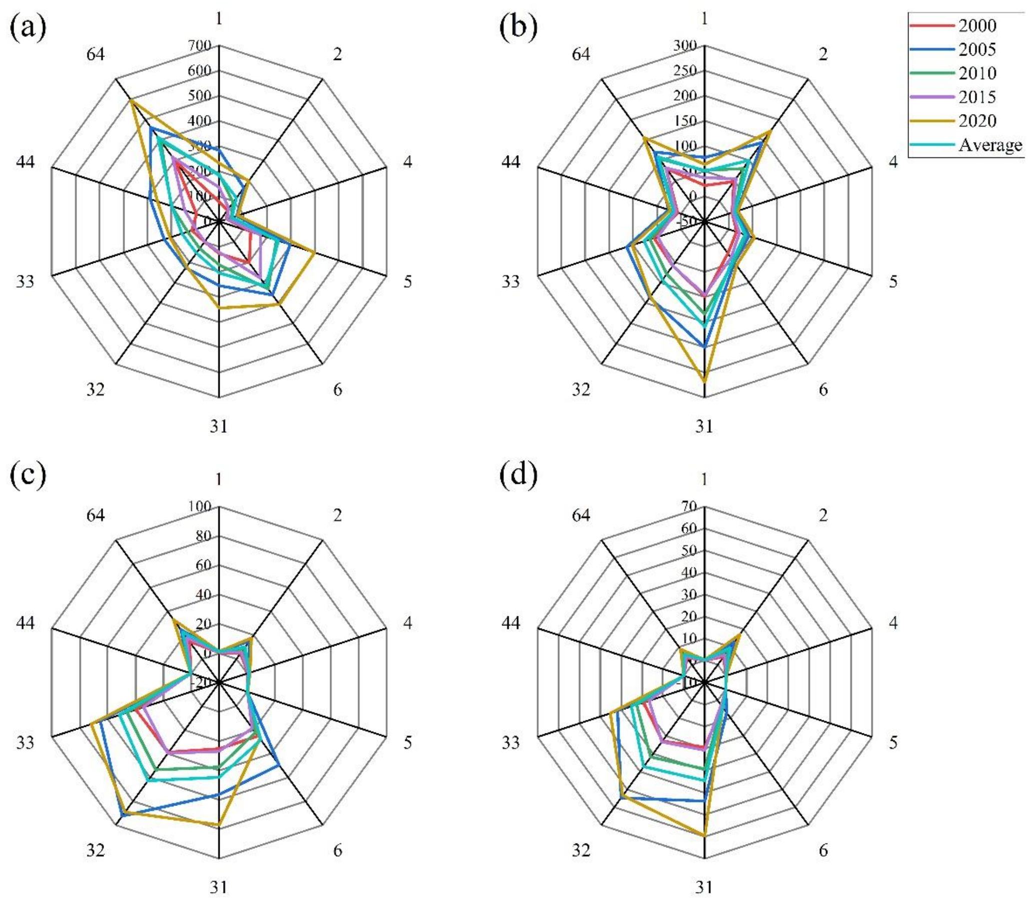

Figure 6. *Average water yield depth (mm) for different land uses; (b) Average water conservation depth (mm) for different land uses; (c) Total water yield (10^8 m^3) for different land uses; (d) Total water conservation (10^8 m^3) for different land uses; codes: 1 = Dry land; 2 = Woodland; 4 = Water body; 5 = Artificial land; 6 = Unused land; 31 = High coverage grassland; 32 = Medium coverage grassland; 33 = Low coverage grassland; 44 = Permanent snow and glacier; 64 = Wetland*

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The low water yield of forest land is due to the fact that water interception by vegetation, roots, and soil is effective in achieving water conservation. In terms of total WY (*Fig. 6c*), grasslands with different coverage levels have the highest average WY, reaching 15.87 billion m^3, accounting for 71.3% of the total WY in the YRSA, followed by unused land, while the other land types have less water yield.

Impact of different land types on water conservation

Land type is an important factor that affects the nature, processes, and components of ecosystems, and it is also a key driving factor that affects water conservation service (Li et al., 2021b). Our research findings indicate that there is a positive correlation between grassland coverage and WC (*Fig. 6b*). Grassland, forestland, and wetland have better water conservation effects. The water conservation capacity of dryland, artificial land, unused land, water bodies, and permanent glaciers and snow is relatively poor.

The WC depths of different land types, ranked from high to low, are high coverage grassland (159.6 mm) > forest land (108.8 mm) > wetland (100.2 mm) > medium coverage grassland (93.3 mm) > low coverage grassland (76.9 mm) > dry land (50.3 mm) > unused land (44.6 mm) > artificial land (34.3 mm) > permanent glaciers and snowfields (15.4 mm) > water bodies (12.9 mm). The main reason for the differences in water conservation capacity among different land uses is their own WC and interception efficiency. In terms of total WC volume (*Fig. 6d*), grassland with different coverage levels has the highest water retention capacity, with an average WC volume of 9.68 billion m^3, followed by forest land at 950 million m^3. Grassland and forest land account for 91.1% of the total WC volume in the YRSA, indicating their enormous value in providing water conservation services.

Discussion

Spatial and temporal evolution characteristics of water yield and water conservation services

From 2000 to 2020, the WY and WC in the YRSA increased at rates of 14.72 mm/5a and 10.03 mm/5a, respectively, indicating that the area has become more humid in the past 20 years. The annual average precipitation in the southeastern part of the YRSA exceeds 600 mm, and the WY exceeds 270 mm, with relatively flat terrain and high vegetation cover. In precipitation events, the flat terrain slows down the formation of runoff and increases water infiltration. The high-water conservation in the area is due to the climatic conditions and underlying surface conditions, resulting in spatial heterogeneity in water yield and water conservation services (Li et al., 2021b).

In this study, the land use types were reclassified by combining the dominant position of grassland in the YRSA. WC is positively proportional to grassland coverage. The distribution patterns of high-water yield and low water conservation in unused land and artificial construction, as well as low water yield and low water conservation in water bodies, are consistent with previous research results (Wang et al., 2019; Yang et al., 2021; Li et al., 2021b). The average water conservation capacity in the YRSA accounts for about 18% of the precipitation, which is close to the study by Wang et al. (2022d) on the Tibetan Plateau where the average water conservation capacity accounts for 22% of precipitation. This indicates that the reliability of the WC calculation results and the water conservation services in the YRSA need to be further improved.

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Analysis of main influencing factors of water yield and water conservation services

As a result of climate and landscape pattern changes (Wei et al., 2021), both water yield and water conservation services have been affected to varying degrees. On the one hand, with the implementation of environmental protection measures, the woodland area in the YRSA has increased by 522.5 km^2, and the area of high, medium, and low coverage grassland has increased by 3953.7 km^2 from 2000 to 2020. This is mainly manifested in the transformation of unused land to low-coverage grassland, low-coverage grassland to medium-coverage grassland, and medium-coverage grassland to high-coverage grassland (*Fig. 7*). Different land types can affect hydrological processes such as infiltration and evapotranspiration (Lian et al., 2020). The increase in grassland coverage and forest area can have a positive impact on water yield and water conservation services. The increase of land types with high water-saving performance will lead to the increase of water conservation capacity.

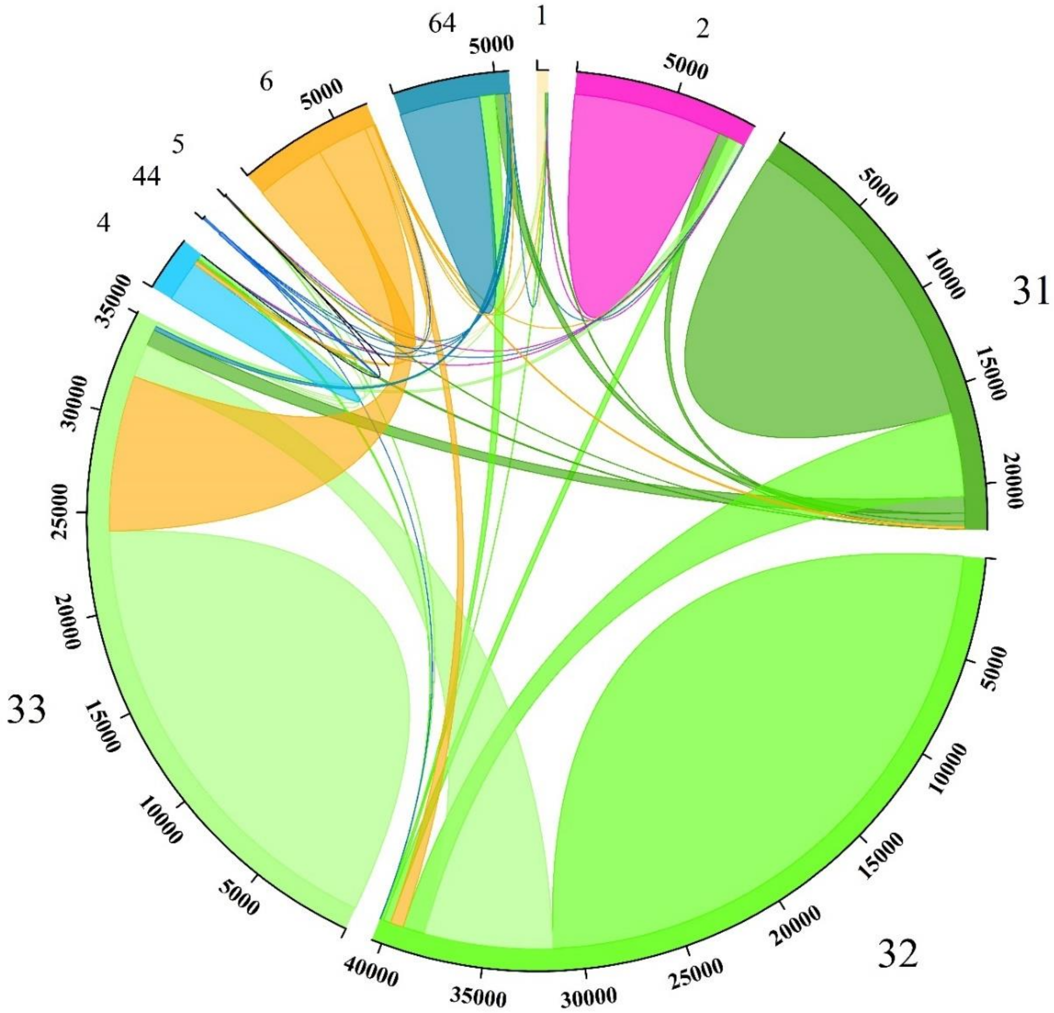

Figure 7. *Land use type transition matrix chord diagram for 2000-2020, with numbers indicating the area of each patch type in km^2; 1 = Dry land; 2 = Forest land; 4 = Water body; 5 = Artificial surface; 6 = Unused land; 31 = High coverage grassland; 32 = Medium coverage grassland; 33 = Low coverage grassland; 44 = Permanent snow and glacier; 64 = Wetland*

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According to correlation statistics, we found that the contagion index CONTAG in the YRSA is conducive to increasing WY and WC, which is consistent with previous research (Wang et al., 2022b; Tran et al., 2022). The dominant patch types have formed good physical connectivity. The increase in landscape connectivity promotes material transformation and ecological processes (Lyu et al., 2022), thereby improving water yield and water conservation services. Through spatial analysis, WC shows a significant positive spatial correlation with SHDI ($p < 0.05$), indicating that WC is more spatially driven by landscape heterogeneity than WY. Therefore, it is necessary to ensure a certain level of patch connectivity and landscape heterogeneity in landscape planning (Qin and Chen, 2023), which provides a reference for the rational formulation of land use and allocation in the YRSA. In addition to being affected by WY, water conservation service is also influenced by factors such as topography and soil properties (Wang et al., 2022d), indicating that water conservation service may be more driven by landscape patterns than water yield service, as suggested by correlation analysis. In addition, some studies have shown that there has been a decrease in perennial frozen soil and an increase in seasonal frozen soil in the YRSA in recent years (Li et al., 2023; Yang et al., 2023). Generally speaking, the degradation of frozen soil will expand the soil water storage capacity (Yang et al., 2023), and the water migration caused by the freezing-thawing process and glacier snow melting will make the regional water cycle process more complex (Xiang et al., 2013), which will affect the quantification of water yield and water conservation services.

On the other hand, through Pearson correlation analysis and bivariate Moran's index calculation, significant positive correlations ($p<0.01$) were found between WY, WC, and climate factors at both temporal and spatial scales. Both water yield and water conservation services are greatly influenced by climate change. The average precipitation and temperature increased at rates of 7.355 mm/a and 0.039°C/a, respectively, from 2000 to 2020. Due to the increase in precipitation and temperature, both actual evapotranspiration and potential evapotranspiration showed an upward trend (Qin et al., 2017; Xu et al., 2018), which affected the water yield. Climate, especially precipitation, is the main driving factor affecting WY and WC, which is consistent with relevant studies (Yang et al., 2021; Che et al., 2022; Ma et al., 2022). Landscape patterns have a certain impact on water production and conservation services, but not as much as climate. Precipitation is the main condition affecting water yield and water conservation services, and the impact of land use and land cover changes on water ecosystems services should not be ignored. Therefore, studying changes in water yield and conservation services by combining land use and land cover changes with climate data is more convincing (Che et al., 2022).

Conclusion

In this study, we used the InVEST water yield model to calculate WY and a correction equation to calculate WC. The correlation between influencing factors and water yield and water conservation services was analyzed at both temporal and spatial scales. The results showed that:

From 2000 to 2020, the WY and WC in the YRSA increased at rates of 14.72 mm/5a and 10.03 mm/5a, respectively. On one hand, the increase in precipitation over the past 20 years led to a general increase in WY and WC. On the other hand, the increase in grassland coverage and forest area further enhanced water conservation service. The response of water yield and water conservation services to different land use types varied.

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Overall, grasslands had relatively high WY and WC, particularly high-coverage grasslands played a significant role in water yield and water conservation services.

From 2000 to 2020, the average annual WY and WC in the YRSA were 22.27 billion m^3 and 11 billion m^3, respectively, with a distribution pattern of higher values in the east and south, and lower values in the west and north. It is recommended to focus on the southeast of the study area, where the WY and WC are high, and the value of water ecosystem services is high. The Chinese government has implemented a series of ecological protection projects in the Qinghai-Tibet Plateau and the Three Rivers Source. The implementation of these projects has achieved significant results, with alleviation of grassland degradation and a noticeable improvement in soil and water conservation functions.

Climate change and landscape pattern synergistically contribute to the enhancement of water ecosystem services in the YRSA. Increasing patch connectivity is beneficial for increasing water yield and water conservation services. The increase in grassland, forest, and wetland areas has a positive effect on water yield and water conservation services, and it is recommended to focus on improving grassland coverage and increasing forest area to enhance the water ecosystem service function of the YRSA, leading to higher quality development. Additionally, although the InVEST model can simulate water yield service, it does not fully consider the hydrological processes of permafrost degradation and glacier melting, and we will improve the model in the future.

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