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Spatio-temporal Changes in Water Conservation Ecosystem Service During 1990–2019 in the Tumen River Basin, Northeast China

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Abstract: The water conservation (WC) function of ecosystems is related to regional ecological security and the sustainable development of water resources, and the assessment of WC and its influencing factors is crucial for ecological and water resource management. The Tumen River Basin (TRB) is located in the core of the Northeast Asian ecological network and has been experiencing severe ecological crises and water shortages in recent years due to climate change and human activities. However, these crises have not been fully revealed to the extent that corresponding scientific measures are lacking. This study analyzed the spatial and temporal evolution characteristics and drivers of WC in the TRB from 1990 to 2019 based on the water yield module of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. The results showed that: 1) under the combined effect of nature and socioeconomics, the WC depth of the TRB has slowly increased at a rate of 0.11 mm/yr in the past 30 years, with an average WC depth of 36.14 mm. 2) The main driving factor of the spatial variation in WC is precipitation, there is a significant interaction between precipitation and velocity, the interaction between each factor is higher than the contribution of a single factor, and the interactions between factors all have nonlinear enhancement and two-factor enhancement. 3) Among the seven counties and municipalities in the study area, the southern part of Helong City and the southeastern part of Longjing City are extremely important areas for WC (> 75 mm), and they should be regarded as regional water resources and ecological priority protection areas. It is foreseen that under extreme climate conditions in the future, the WC of the watershed is under great potential threat, and protection measures such as afforestation and forestation should begin immediately. Furthermore, the great interannual fluctuations in WC depth may place more stringent requirements on the choice of time scales in the ecosystem service assessment process.

Keywords: water conservation; Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model; Geodetector; driving factors; Tumen River Basin

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1 Introduction

Water conservation (WC) is an important ecosystem service (Brockerhoff et al., 2017; Reis et al., 2017), in which ecosystems retain precipitation within the ecosystem through the forest canopy layer, dead leaf layer and

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soil layer, which not only meet the water demand of the components within the system but also provide water resources to the outside (Yu et al., 2003). In addition, WC plays an important role in supporting and maintaining regional biodiversity conservation, climate regulation, soil retention and water conservation, and improving regional hydrology (Hu et al., 2021). The study of the regional WC is important for clarifying the interception of precipitation and soil moisture and preventing natural disasters such as regional droughts and floods and soil erosion (Leh et al., 2013).

With the continuous development of remote sensing, Geographic Information System (GIS) technology and hydrological models, water-related ecosystem service assessment models have realized the simulation and assessment of regional hydrological processes, such as the MIKE System Hydrological European (MIKE SHE) model (Thompson et al., 2004; Golmohammadi et al., 2014), Soil and Water Assessment Tool (SWAT) model (Arnold and Fohrer, 2005; Baker and Miller, 2013) and Integrate Valuation of Ecosystem Services and Tradeoffs tool (InVEST) model (Lang et al., 2017; Yang et al., 2019). Among them, the water yield submodule of the InVEST model is able to perform large-scale spatial and temporal modeling based on the principle of water balance (Liang et al., 2021). Compared with other hydrological models, the InVEST model has the advantages of easy access to parameters, high confidence in evaluation accuracy and visual representation (Vigerstol and Aukema, 2011) and has been widely used in ecosystem service assessment (Sharp et al., 2016). At present, extensive and reliable research results have been achieved in applying the InVEST model to the spatial and temporal evolution of the regional water yield and water conservation; for example, the model has been successfully applied in the United Kingdom (Redhead et al., 2016), Nepal (Hamel and Guswa, 2015), the United States (Bastola et al., 2019) and the agro-pastoral ecotone of northern China (Pei et al., 2022). Other scholars have conducted research on the improvement and validation of the model parameters and results (Liu et al., 2020) and the comparison between different models (Cong et al., 2020), and these results provide a reference basis and assessment method for the WC of watersheds.

The evolutionary process of WC is the result of a combination of factors such as human activities and climate change (Hu et al., 2021; Pei et al., 2022), and the coupling mechanism of multiple factors and how to quantify the contributions among them is still a challenge, while the Geodetector method provides an effective method to reveal the relative importance of each factor (Wang et al., 2017). The evolution of WC is an extremely complex process (Zhao et al., 2001) related not only to regional vegetation cover, precipitation, evapotranspiration and soil properties but also to anthropogenic-driven changes in the substratum as a result of a combination of factors. Existing studies have shown that changes in climatic conditions affect the water conservation capacity of a region more than land-use changes (Bai et al., 2019). Changes in WC are the result of a combination of climate, soil and land use (Pei et al., 2022). Climate change is the main contributor and direct driver of WC, and the socioeconomics is an indirect driver (Hu et al., 2021). Under stable climate conditions, landscape factors have a slightly higher impact on water content than climate factors (Hu et al., 2021). Under stable climate conditions, the influence of landscape factors on WC is slightly higher than that of climate factors (Hu et al., 2020). The existing quantitative analysis of WC drivers mainly uses methods such as correlation analysis (Wang et al., 2021) and principal component analysis (Hu et al., 2020), which require linear assumptions and are somewhat subjective in nature. Spatial differentiation of WC is a multifactor interaction in a nonlinear relationship, and the Geodetector is a new spatial statistical method (Zhan et al., 2015), independent of any linear assumptions (Wang and Xu, 2017). It uses spatial variance to quantify the contribution of individual factors to the spatial differentiation of WC and the interaction between the two factors (Ding and Hao, 2021), providing a new idea to quantitatively describe the drivers of WC.

The Tumen River Basin (TRB) is located at the junction of China, D. P. R. Korea and Russia and is an important national ecological function area of China and a distribution area of globally endangered wildlife, such as *Grus japonensis*, *G. leucogeramus*, and the intermediate resting place of world endangered birds such as *Pamhera igris alaica* and *P. pardus orientalis*. With the opening policy in recent years, the TRB has entered the stage of joint development by many countries, and the ecological function of the watershed has declined due to the human activities. Specifically, the capacity of WC has degraded significantly with the deteriorated water ecological environment and decreased water resources. Therefore, there is an urgent need to develop an analysis of the spatial and temporal evolution characteristics and drivers of the WC of the TRB to ensure the water security of the watershed and improve the ecological conditions in Northeast Asia. In this study, based on the InVEST model with localized parameters, we simulated and estimated the WC of the TRB (Chinese side) from 1990 to 2019 and quantitatively evaluated the spatial and temporal evolution characteristics of the WC of the watershed to: 1) reveal the spatial and temporal evolution characteristics of the WC from 1990 to 2019; 2) analyze the factors of spatial and temporal variation in WC; and 3) in conjunction with the ecological protection red line, assess the relative importance of WC in different areas of the watershed. The results of the study can provide valuable references for the formulation of water resource protection policies and sustainable development in the TRB.

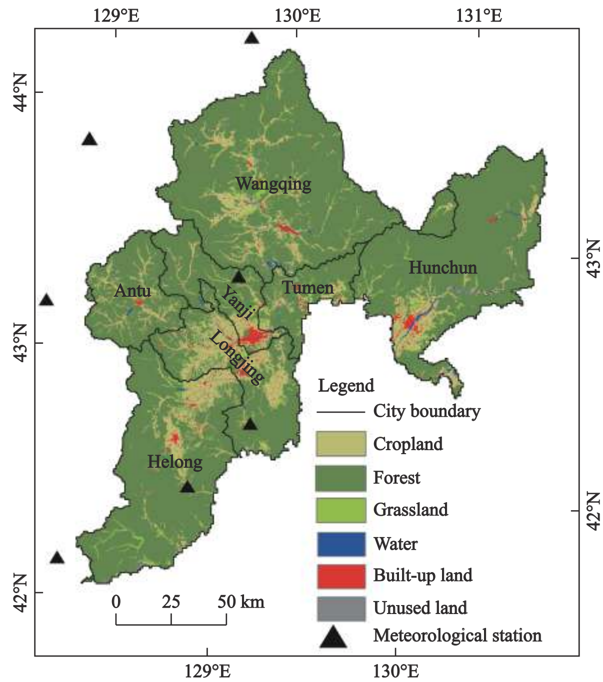

Fig. 1 The location of the Tumen River Basin, Northeast China and land use distribution in 2018

2 Materials and Methods

2.1 Study area

The Tumen River Basin (TRB) is an international river at the junction of China, D. P. R. Korea, and Russia, the only waterway from China's interior to the Sea of Japan, and the intersection of economic, demographic, and geographic centers in Northeast Asia. The TRB covers an area of approximately 22 000 km^2 in China, and the watershed is a distribution area of world-endangered wildlife, such as *G. japonensis* and *G. leucogeramus*, and world-endangered migratory birds, such as *P. igrisalaica* and *P. pardus orientalis*, and has a variety of ecosystem types, such as wetlands and forest. The TRB plays an important role in water conservation, soil retention, biodiversity protection and ecosystem function maintenance in Northeast Asia, and the zonal vegetation in the watershed has a unique evolutionary history and rich community composition of temperate mixed coniferous forest, which is the only remaining vegetation zone with a relatively complete distribution of natural community segments in China. The watershed mainly includes all areas of Longjing, Yanji, Tumen, and Hunchun cities and seven counties and cities, including the southern Wangqing, eastern Helong, and northeastern Antu (Fig. 1).

2.2 Data sources and processing methods

Data and preprocessing required for the evaluation of the WC: 1) land use and land cover data are from the Data Center for Resource and Environmental Sciences of the Chinese Academy of Sciences (http://www.resdc.cn), with a time scale of 1990–2018 and a spatial resolution of 30 m. 2) DEM data are from the Geospatial Data Cloud (http://www.gscloud.cn) with a spatial resolution of 30 m. 3) Yearly precipitation data in seven meteorological stations were from the National Meteorological Science Data Center (http://data.cma.cn), with a time scale of 1990–2019 and a resolution of 1 km after interpolation by ANUSPLIN software. 4) Yearly crop reference evapotranspiration (ET_0) was calculated by the Penman-Monteith formula based on seven meteorological stations, and was interpolated into the 1-km grid data in ANUSPLINE software, in which elevation was chosen as a covariate to take into account underlying surface factor. 5) Plant-available water content (PAWC) was obtained by calculating soil texture (proportion of soil sand, powder and clay particles) and soil organic matter content for soil types. 6) Soil property data were obtained from the Western China Environmental and Ecological Science Data Center (http://westdc.westgis.ac.cn). 7) Sub-watershed, extracted in the Arc-SWAT platform based on DEM data, to form sub-watershed zoning maps. 8) Velocity coefficient with reference to the model parameter table and related studies. 9) Topographic index (TI): calculated based on the DEM and soil depth using the ArcGIS spatial analysis tool. 10) Soil saturation hydraulic conductivity: calculated based on soil property data using SPAW software. 11) GDP and population data came from the Resource and Environment Science Data Center, Chinese Academy of Sciences (http://www.resdc.cn).

In this study, we used two types of resolution data (30 m and 1 km), and to ensure the accuracy of the results, we upgraded all 1 km resolution data to 30 m. We resampled all 1 km data to 30 m by using the adjacent pixel method in GIS. This method decomposes a large grid into many small grids and does not change the original grid value, thus ensuring the accurate calculation for each grid. In addition, we ensured the accuracy of the results of this study by verifying the seasonality coefficient Z value in the water yield module. The basis of water yield is the Budyko framework (Zhang et al., 2004; Donohue et al., 2012), whose principle is the water balance equation (Water yield = Precipitation – Evapotranspiration – ΔS), which must be in a closed basin and at least at a year-scale. The Budyko framework assumes that the surface water change (ΔS) on the multi-year scale is 0 (Bai et al., 2019; Pei et al., 2022). In the InVEST water yield module, we used the annual average precipitation and reference evapotranspiration as input data to simulate the annual average runoff. When adjusting Z = 3.95, the simulated water yield was close to published runoff data. The Z value determines the watershed characteristics (ω) in Eq. (4), so it is a constant (however, many studies have set the individual Z value for each year). Therefore, the process of adjusting the Z value has been verified for water yield (Li Mingyue, 2021; Yang et al., 2021). Furthermore, we conducted sensitivity analysis on the Z value, and water yield was very sensitive to the Z value. Therefore, the verification of the Z value must be carefully selected according to the model principle.

2.3 WC evaluation and analysis methods

2.3.1 InVEST water yield module

The water yield module of the InVEST model is an estimation method based on a Budyko hypothesis of coupled hydrothermal equilibrium (Zhang et al., 2004; Donohue et al., 2012), where the precipitation (P) over a raster cell is subtracted from the actual evapotranspiration (AET) to obtain the water yield (Y) over the raster cell (Redhead et al., 2016). The core parameters are the average annual precipitation, actual evapotranspiration, potential evapotranspiration, and land use (Redhead et al., 2016; Hu et al., 2020).

$$Y_{x,j} = \left(1 - \frac{AET(x,j)}{P(x)}\right) \times P(x) \tag{1}$$

where $Y_{x,j}$ is the annual water yield (mm) of raster cell x on landscape j landscape, $AET_{x,j}$ is the annual actual evapotranspiration (mm) of raster cell x on landscape j landscape, and P_x is the annual precipitation (mm) of raster cell x.

$AET_{x,j} / P_x$ is the approximate Budyko curve derived by Zhang et al. (2001) on the basis of Budyko:

$$\frac{AET_{x,j}}{P_x} = \frac{1+\omega_x R_{x,j}}{1+\omega_x R_{x,j} + 1/R_{x,j}} \tag{2}$$

$$R_{x,j} = \frac{k_{x,j} \times ET_0}{P_x} \tag{3}$$

$$\omega(x) = Z\frac{AWC(x)}{P(x)} + 1.25 \tag{4}$$

where $R_{x,j}$ is the dryness index at raster x on a class j landscape; $k_{x,j}$ is the vegetation evapotranspiration coefficient; $\omega(x)$ is a nonphysical parameter of natural climate-soil properties of raster x, which defines the shape of the curve related to potential evapotranspiration; and $\omega(x)$ is calculated using the equation proposed by Donohue et al. (2012). Z is the seasonal constant (Zhang et al., 2001), which captures local precipitation patterns and hydrogeological characteristics, and the characteristics take values ranging between 1 and 30 (Sharp et al., 2016). In this study, the optimal Z value was obtained by repeatedly verifying the simulated and measured water yield. AWC_x is the effective soil water content (mm) of grid x and is the product of plant-available water content ($PAWC$) and the maximum soil root burial depth and the minimum plant root depth (Sharp et al., 2016).

$$AWC_x = \min(\max S_x, R_x) \times PAWC \tag{5}$$

where $\max S_x$ is the maximum soil depth, and R_x is the maximum root restriction depth.

2.3.2 WC evaluation method

The evaluation of WC is based on the water yield, and in this study, the water yield was corrected by using the soil saturation hydraulic conductivity (Ksat), velocity coefficient (Velocity) and topographic index (TI) (Li Mingyue, 2021) to obtain the raster-scale WC depth. This evaluation method comprehensively considers the influence of topographic differences in the watershed and soil permeability under different land-use types on runoff, and can better express the spatial distribution characteristics of WC in the watershed.

$$WC = \min\left(1, \frac{249}{V}\right) \times \min\left(1, \frac{0.9 \times TI}{3}\right) \times \min\left(1, \frac{Ksat}{300}\right) \times Yield \quad (6)$$

where WC is the water conservation depth (mm); V is the velocity coefficient; $Ksat$ is the soil saturation hydraulic conductivity (cm/d); $Yield$ is the water yield calculated in the InVEST model, and TI is the topographic index which is calculated according to Eq. (7).

$$TI = \lg\left(\frac{D\_Area}{S\_Depth \times P\_Slope}\right) \quad (7)$$

where D_Area is the number of raster in the catchment area; S_Depth is the soil depth (mm), and P_Slope is the percentage slope.

The widely used linear regression method was used for revealing spatial trend of the WC change in the TRB in the last 30 years.

2.3.3 Classification of the WC importance degree

In this study, the WC importance evaluation in the technical guidelines for ecological protection red line delineation was used and combined with the quantile classification method in ArcGIS software to classify the importance of WC in the study area, which was divided into five grades: generally important (grade I; < 20 mm), secondarily important (grade II; 20–35 mm), moderately important (grade III; 35–50 mm), highly important (grade IV; 50–75 mm), and extremely important (grade V; > 75 mm).

2.3.4 Geodetector

Geodetector is a set of statistical methods used to reveal the driving forces of spatial differentiation of elements, which are usually used to detect and reveal the spatial differences and influencing factors of geographical units (Wang et al., 2010). It connotes that if an independent variable (X) has a significant influence on a dependent variable (Y), the spatial distribution of the two should have similarity (Wang and Xu, 2017). In this study, WC was used as the dependent variable, and Geodetector was used to determine the main factors influencing the spatial differentiation of WC. Based on existing studies (Fang et al., 2021; Li Zhihui, 2021), natural drivers were selected including P (precipitation), AET (actual evapotranspiration), NDVI (normalized difference vegetation index), PET (potential evapotranspiration), PAWC (plant-available water content), DEM (digital elevation model), Velocity (velocity coefficient) and Ksat (soil saturated hydraulic conductivity), which are related to climate, vegetation, soil and topography and directly influence the WC supply and distribution (Fang et al., 2021). Other factors included GDP (gross domestic product), POP (population), SHDI (Shannon's diversity index), CONTAG (contagion index), and MESH (effective mesh size), and PLAND (proportion of the landscape area) of cropland and forest. These indicators were proved to be related to WC and have been widely utilized in the studies of ecosystem services (Dai and Wang, 2020; Hu et al., 2020; Li Junhua, 2021).

$$q = 1 - \frac{SSW}{SST} = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2} \quad (8)$$

where q value is the independent variable that reveals $(100 \times q)$% of spatial heterogeneity of WC, $q \in [0, 1]$. A larger q value in the interval indicates a stronger explanatory power of the influencing factors on WC; SSW represents the sum of variance within different strata, and SST represents the total variance of the whole region. h represents the stratification status of the influencing factors such as WC or climate, and there are L strata. N_h and N are the number of sampling units in the layer h and within the whole region. σ^2 and σ_h^2 represent the variance in WC in layer h and the whole region, respectively.

3 Results

3.1 Spatial and temporal evolution of WC

3.1.1 Characteristics of interannual variation in WC

The coefficients of variation of the TRB precipitation and WC depth from 1990 to 2019 were 14.57% and 36.42%, respectively, with moderate variability, both of which showed cyclical fluctuations with increasing trends and strong consistency in temporal changes (Fig. 2). During the study period, the precipitation in the study area fluctuated between 455.41 and 793.46 mm, and the

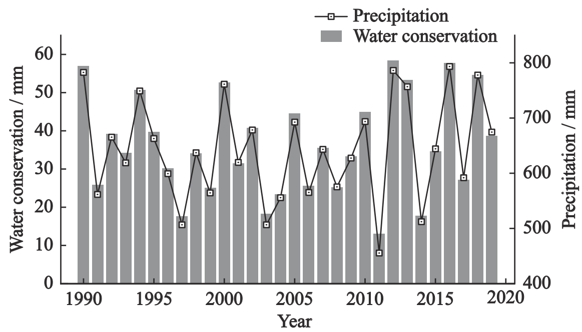

Fig. 2 Interannual variation characteristics of precipitation and water conservation depth from 1990 to 2019 in the Tumen River Basin, Northeast China

overall precipitation in the TRB increased at a rate of 0.97 mm/yr in the past 30 years, with the maximum value of precipitation occurring in 2015 (793.46 mm) and the minimum value occurring in 2011 (455.41 mm). The average annual precipitation was 642.04 mm. The WC depth of the TRB fluctuated between 12.99 and 58.35 mm (Fig. 2b), and the overall WC depth of the TRB has increased at a rate of 0.11 mm/yr over the past 30 yr, with the maximum value of water content depth occurring in 2012 (58.35 mm) and the minimum value occurring in 2011 (12.98 mm). The average WC depth was 36.14 mm.

3.1.2 Spatial distribution of WC

As the main water input of WC, the precipitation showed a spatially high consistency with WC with high in the south and low in the north. The abundant precipitation mainly spread in the south and northeast of the TRB (Fig. 3a), where the mountainous areas were covered by forest and were additionally influenced by the topography causing frequent precipitation events. Similarly, medium and high WC were both located in the same regions (Fig. 3b), respectively, and low WC were primarily observed in the central and southeastern parts of the TRB, where the TRB cropland and built-up land were quite concentrated (Fig. 1). Notably, high precipitation and low WC were distributed in the northeast TRB, implying that WC in this region is highly correlated to watershed characteristics including soil, topography and land use, compared to the climatic factor.

3.1.3 Spatial trend changes in WC depth in different periods

The spatial variation in the WC depth of the TRB showed obvious heterogeneity in different time periods; specifically, the WC depth showed a decreasing trend before 2000 (Fig. 4a) and an increasing trend after 2000 (Fig. 4b), and the overall spatial variation in the WC depth was small in the past 30 years (Fig. 4c). Before 2000, the WC depth in the study area showed an overall decreasing trend, with an overall decreasing rate of –1.14 mm/yr, and the most obvious decreasing WC depths were concentrated in the northeast and the southernmost parts of the study area, with decreasing rates ranging from –2 to –4 mm/yr, while the decreasing rates in other areas were mainly in the range of –2–0 mm/yr. After 2000, the WC depth showed an overall increasing trend, with an overall increasing rate of 0.41 mm/yr, and only a small part of the central region showed a decreasing trend. Overall, the WC depth in the northern part of the TRB showed an increasing trend, while the WC depth in the central and southern parts showed a decreasing

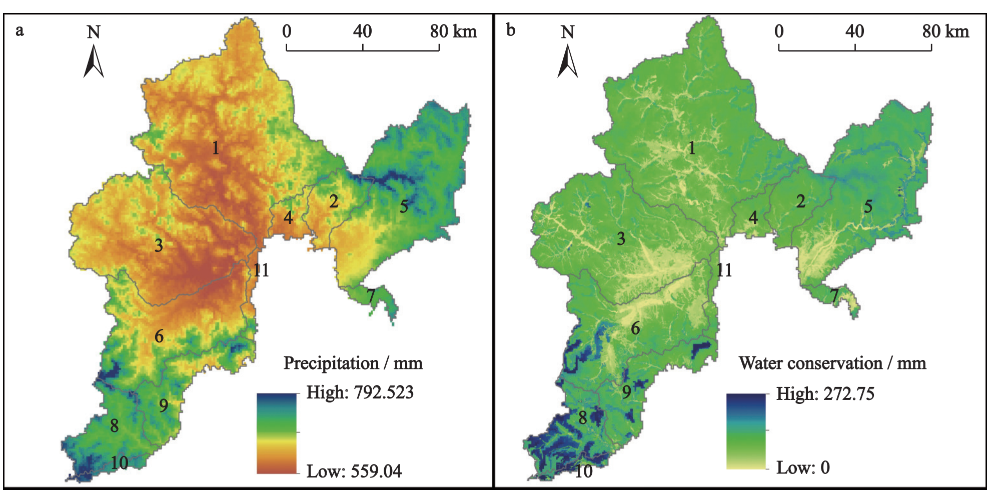

Fig. 3 Spatial distribution of precipitation (a) and water conservation (b) from 1990 to 2019 in the Tumen River Basin, Northeast China

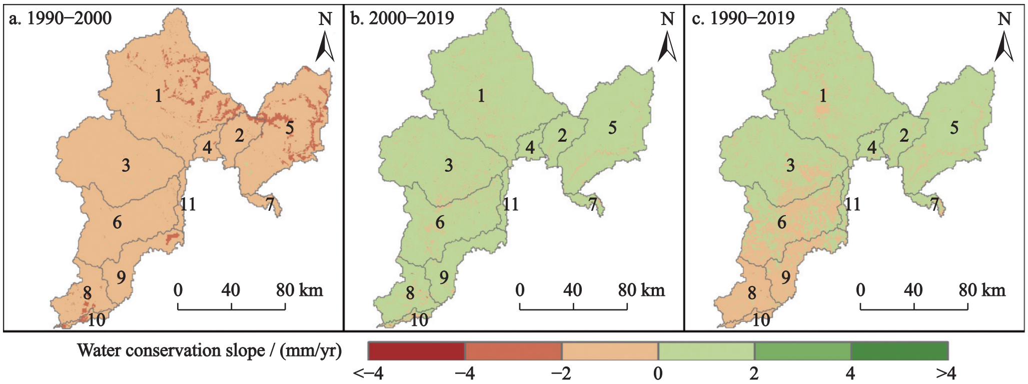

Fig. 4 Spatial distribution of water conservation slope in 1990–2019 in the Tumen River Basin, Northeast China. The numbers in the figure represented the unique small sub-watersheds

trend, and the overall linear WC trend in the TRB was 0.04 mm/yr.

From the sub-watershed perspective (Fig. 5), all sub-watersheds showed a decreasing trend in WC depth before 2000, with sub-watersheds 2 and 5 showing the most significant rate of decrease, reaching 1.49 mm/yr, and sub-watershed 6 showing the lowest rate of decrease, reaching 0.66 mm/yr. After 2000, only sub-watershed 10 showed a decreasing trend, but the rate of decrease was only 0.05 mm/yr, while the rest of the sub-watersheds showed an increasing trend, and sub-watershed 1 showed the most significant increase, reaching 0.62 mm/yr. Overall (1990–2019), the variation in WC depth in each sub-watershed of the TRB was concentrated between [–0.5, 0.5], and the spatial variation in the WC depth was small.

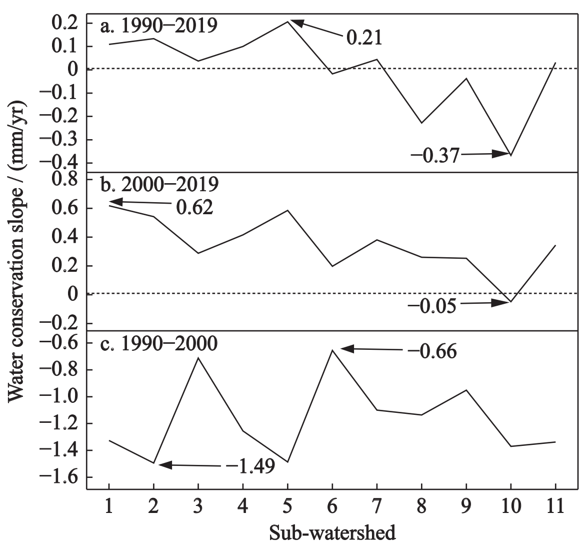

Fig. 5 Trends in water conservation by sub-watershed in 1990–2019 in the Tumen River Basin, Northeast China. Location of sub-watersheds 1–11 see Fig. 4

3.2 Driver analysis

3.2.1 Drivers of spatial divergence in WC

The results of the TRB spatial differentiation of the WC factor detector showed that the spatial differentiation of WC within the watershed was driven by both natural and socioeconomic factors, but the natural factors had more determining power than the socioeconomic factors. P (precipitation) had the highest explanatory power for the spatial heterogeneity of WC, with a q value of 0.475, followed by the DEM and Velocity, with q values of 0.468 and 0.449, respectively, mainly because the WC in the study area was estimated as the corrected values of the DEM and Velocity. Thus, the distribution of WC within the watershed had a strong consistency with the DEM and Velocity. The q value of forest in the land-use pattern was 0.392, and cropland was 0.186, which was related to the area in the study area. The landscape level indices SHDI (q = 0.029), MESH (q = 0.021), and CONTAG (q = 0.027) had the lowest contributions to the watershed WC differentiation, and the socioeconomic factors POP and GDP had q values of 0.237 and 0.267, respectively, indicating that the TRB socioeconomic factors influenced the spatial divergence of WC to some extent (Fig. 6).

The above content analyzed the extent to which a single factor explained the spatial variance of WC, but the spatial variance of WC was determined by the combined effect of multiple factors. The interaction detector also proved that the contribution of the two-factor interaction was greater than that of a single factor within the watershed, and there was nonlinear enhancement and two-factor enhancement in all interactions between factors. Among the interaction factors, there are three groups of factors greater than 0.70, namely, Velocity ∩

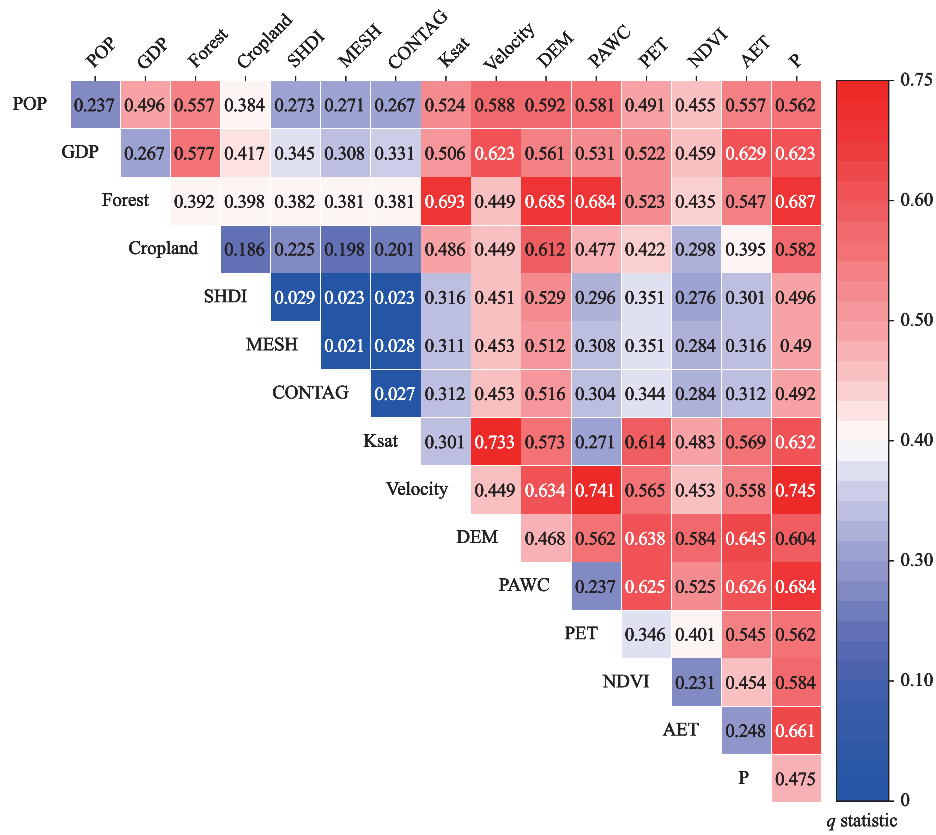

Fig. 6 Water conservation factor detector and interaction detector matrix. P represents the precipitation, AET represents the actual evapotranspiration, NDVI represents the normalized difference vegetation index, PET represents the annual potential evapotranspiration, PAWC represents the plant-available water content, DEM represents the digital elevation model, Velocity represents the velocity coefficient, Ksat represents the hydraulic conductivity, CONTAG represents the contagion index, MESH represents the effective mesh size, SHDI represents the Shannon's diversity index, GDP represents the gross domestic product, POP represents the population. The q-value as an independent variable reveals $(100 \times q)$% of the spatial heterogeneity of water conservation in the range of 0–1. The larger the q-value in this interval, the stronger the explanatory power of the influencing factors on water conservation

Ksat (q = 0.733), Velocity ∩ PAWC (q = 0.741), and Velocity ∩ P (q = 0.745), and all factors greater than 0.70 were related to Velocity, which was widespread in the study area and had a well-developed root system. The study area has extensive forest and well-developed root systems, which have different degrees of precipitation retention, absorption and infiltration, and the forest Velocity is low, weakly disturbed by human activities and has a strong WC capacity; thus, the interaction of Velocity with other factors within the watershed was significantly higher than the interaction of other factors. The q-value of the interaction between precipitation and any other factors in the TRB was greater than 0.50, which was significantly higher than the interaction between other factors. The interactions between POP, DEM and Velocity were the most significant among the socioeconomic factors (q = 0.592), and the interactions between POP and both of them could well explain the spatial variation in WC due to the influence of topographic factors, fewer human activities at high altitudes, and extensive forest (Fig. 6).

3.2.2 WC response to land use

In this study, the average WC depths were statistically calculated under the three main land-use practices (cropland, forest and grassland) of the TRB from 1990 to 2000, 2000 to 2010, 2010 to 2019 and 1990 to 2019. All three land-use practices in the four time periods showed the following: forest (40.73 mm) > grassland (24.50 mm) > cropland (14.12 mm) (Table 1). The average WC depth was similar to the total WC results, and the total WC size ranking under different land-use practices was forest > cropland > grassland > built-up land > unused land > water. Overall, WC was stronger in forest and grassland, with forest WC depth being the largest with

Table 1 Total water conservation under different land use practices

Year	Water conservation of each land use type						
	Cropland / 10^7 m^3	Forest / 10^8 m^3	Grassland / 10^7 m^3	Water / 10^5 m^3	Built-up land / 10^6 m^3	Unused land / 10^5 m^3	Total amount of water conservation / 10^8 m^3
1990–2000	3.67	7.45	0.79	2.97	1.51	5.74	7.91
2000–2010	2.61	7.09	1.37	4.27	2.43	2.45	7.52
2010–2019	3.93	8.29	1.39	2.21	3.72	8.63	8.87
1990–2019	4.19	7.26	1.28	5.01	3.05	9.55	7.84

the strongest WC, while water and built-up land had the weakest WC. The total WC showed different results with WC depth, and the total WC under different land-use practices in 2018 was related to the area of each land use in the TRB. The combined area of forest, cropland and grassland in the study area accounted for 97.3%, and the total WC of the three accounted for more than 99.5% of the total WC in the study area, with forest accounting for more than 68.9% of the total WC in the study area.

3.3 Assessment of the importance of the WC

The spatial distribution pattern of WC importance in the TRB was expressed in Fig. 7: Grade I areas were mainly located in the central part of Wangqing County, the southeastern part of Hunchun City and Yanji City, the central and western part of Longjing City and the southern part of Helong City; grade II areas were mainly located in the Antu County, Tumen City, Wangqing County and the northwestern part of Yanji City; grade III areas were mainly located in the southeastern part of Wangqing County, the central and northern part of Hunchun City, the southeastern part of Longjing City; grade IV areas were mainly located in the southeastern part of Helong City and the southeastern part of Hunchun City; and grade V areas were mainly located in the southeastern part of Longjing City and the southern part of Helong City. WC depth > 75 mm was considered an extremely important WC area in the study area, i.e., the area with the highest WC value in the watershed and the key water ecological function area for protection within the watershed. The extremely important protected areas in the study area were mainly concentrated in the southern part of Helong City and the southeastern part of Longjing City, which were also the areas with high values of precipitation in the watershed and relatively low actual and potential evapotranspiration. The very important WC protection area in the study area was mainly located in the upstream area of the watershed, which has the freshwater supply area of the whole watershed. The water resource condition in the upstream area is related to the water resource condition of the whole watershed, which provides strong support for the socioeconomic development and sustainable management of water resources in the watershed and deserves social attention and priority protection.

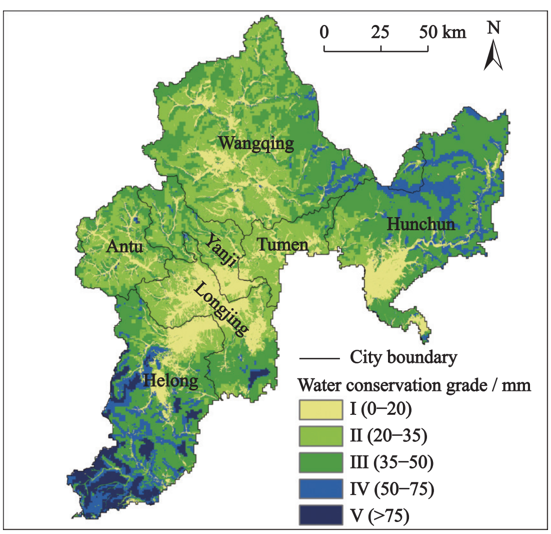

Fig. 7 Spatial distribution of the water conservation grade during 1990–2019 in the Tumen River Basin, Northeast China

4 Discussion

4.1 Spatial distribution pattern of WC under precipitation and land-use change in the TRB

This study shows that the evolution of ecosystem WC is a complex ecohydrological process driven by the coupling of climate factors and multiple land use factors, which is consistent with previous findings (Jia et al., 2014; Berghuijs et al., 2017). At the temporal scale, WC can regulate the water unevenness within the ecosystem due to seasonal differences in precipitation, cut flood peaks during the flood season, and recharge rivers through groundwater during the dry season, thus effectively protecting water resources and reducing the occurrence of floods within the watershed (Vose et al., 2011; Wang et al., 2013). At the spatial scale, the interchange between surface runoff, mid-loam flow, and subsurface runoff within the ecosystem can be achieved, i.e., the regulation of the terrestrial ecosystem water cycle at the vertical level (Núñez et al., 2006). However, the evolution of WC within watersheds may be influenced by climate and human activities (Gao et al., 2017).

The WC in the study area showed a spatial pattern of high values in the south and low values in the central part under the combined effect of precipitation and land use. In this study, we demonstrated that precipitation is an important driver of WC spatial divergence (Fig. 6), which is consistent with the findings that WC is mainly influenced by climate change factors such as precipitation (Su and Fu, 2013; Xiao and Ouyang, 2019) and that the spatial divergence of WC is largely the result of regional precipitation. The southern part of the TRB was the area with high values of WC depth and precipitation (Fig. 3), while the southern part was higher in elevation and had less human activities, and forest was the main land use type (Fig. 1). The retention of precipitation by the forest canopy layer, irrigation and grass layer and deadfall layer reduces the precipitation reaching the ground and prolongs the time of precipitation to runoff conversion. Precipitation to runoff conversion time and precipitation reaching the ground are retained and absorbed by the deadfall layer and soil layer, thus reducing surface runoff and making the WC depth of forest higher than that of other land-use types (Table 1) (Sun et al., 2006), so the spatial distribution of forest had a strong consistency with that of WC. Cropland and built-up land were mainly distributed in the central and southeastern parts of the study area (Fig. 1), both of which have a single community level, and precipitation is not easily retained when it reaches the ground (Chen et al., 2020); thus, the WC depth was low in the central and southeastern areas (Fig. 3b). The TRB forest accounted for up to 80% of the total, coupled with the establishment of the Northeast Tiger and Leopard National Park in the study area, the natural environment is less variable and the ecosystem is more intact (Wang et al., 2020), making the WC depth trend less variable.

4.2 Drivers of WC changes

In this study, both the factor detector and the interaction detector results indicated that precipitation was the main driver of the spatial variation in WC (Fig. 6), and this result was consistent with the results of existing studies (Sun et al., 2011; Delphin et al., 2016). This was because precipitation is the main water input in the study area, and the precipitation amount determined the remaining water volume. The spatial and temporal variation in WC was the result of multiple factors acting together in a nonlinear relationship, and the coupling mechanism of multiple factors and how to quantify the contribution of each factor is still a challenge. Coupling mechanisms and quantifying the contributions among the factors are still challenges, and in this study, the Geodetector tool was used to identify the drivers of WC spatial changes.

This study showed that the overall WC of the TRB depth increased at a rate of 0.11 mm/yr in the last 30 years (Fig. 2), which may be related to the vegetation cover in the study area in addition to precipitation and land-use changes, with significant differences in the WC effects of different forest types (Gong et al., 2017). The conversion of each type within the forest ecosystem may also lead to changes in the WC of the TRB depth, while the hydrological and soil effects of different forest types of deadfall layers may also affect watershed WC to some extent (Biao et al., 2010; Vose et al., 2011). In addition, precipitation in the TRB has increased at a rate of 0.97 mm/yr over the past 30 years (Fig. 2), potential and actual evapotranspiration have increased at 0.45 mm/yr and 0.24 mm/yr, respectively, and the increase in potential evapotranspiration from year to year indicated a gradual increase in WC in the watershed. However, the actual evapotranspiration in the study area increased at a lower rate than the precipitation, which, together with the retention of precipitation by soil and vegetation, increased the depth of WC in the study area (Fig. 4c). This study also found that the spatial variation of the DEM on WC depth was second only to precipitation, and the DEM had a significant effect on the spatial variation of WC of the TRB, and DEM was often an important factor affecting the variation of ecological structure and spatial pattern in mountainous areas (Shi et al., 2022). In higher-altitude areas, where there is relatively little anthropogenic disturbance, the structure of forest vegetation, forest fallout due to the condition of mountain water-heat combination accumulation and soil physicochemical properties, all affect WC variation to some extent (Wang et al., 2013; Gong et al., 2017). Although it has been shown in existing studies that landscape patterns have some facilitating or inhibiting effects on the expression of ecosystem services (Bai et al., 2020), the SHDI, MESH and CONTAG indices selected in this study all had significantly lower effects on the spatial partitioning of WC than did the other drivers (Fig. 6). The reason for the low explanatory power of the landscape pattern index may be related to the scale of the study; the study unit in this study was 2 km × 2 km, and the selection of this scale may mask to some extent the small amount of spatial differences in land-use structure (Dai and Wang, 2020). The evolution of WC is the result of the interaction of multiple factors, and only GDP and POP were selected among the economic factors in this study, which do not fully account for the influence of socioeconomic factors on WC. In addition, the InVEST model has certain requirements for the research object (Hu et al., 2021), and since WC is the water conservation capacity of ground cover, it is easy to ignore the influence of human factors when there is an impervious surface or ground hardening (Peng et al., 2015), and more human factors should be added in subsequent studies to better measure the influence of human and natural factors on WC.

4.3 Implications for local water resource management

Effective forest management is the key to the sustainable development of WC ecological functions in the TRB. The TRB is a predominantly forested watershed (Fig. 1). We found that the forest area had a strong correlation with the DEM and precipitation (Fig. 6). The reason for this is mainly that human activities are usually slight in mountain areas at high elevations and are suitable for forest growth and expansion (Tasser and Tappeiner, 2002; Geri et al., 2010); also, mountain areas are prone to form topographic precipitation due to high air humidity by intensive forest evapotranspiration, thus resulting in the abundant precipitation conditions (Pei et al., 2022). Hence, the forest area, elevation and precipitation showed the mutual positive correlation relationships. The high evapotranspiration of forest and the retention of precipitation by leaves and dead leaves jointly reduced surface runoff but increased subsurface runoff (PONETTE-GONZÁLEZ et al., 2010; Zhang et al., 2022). In the process, the forest's large underground root system holds large amounts of soil water and exerts a role in conserving water (Biao et al., 2010; Jia et al., 2022). During the dry season, the soil water can recharge the river to maintain surface runoff and thus ensure a fundamental water supply for living and agriculture for downstream residents. Therefore, it is crucial to maintain the water conservation function of local ecosystems, in which the key is to effectively manage forest ecosystems. Establishing no-logging zones, promoting reforestation and increasing species diversity are all good measures to guarantee the sustainable use of forest resources. Specifically, the Tumen River is a transnational river, and the international cooperation in water resource management must be strengthened to maintain the long-term development of rivers.

4.4 Limitations and prospects

This study analyzes the spatial and temporal evolution characteristics and drivers of WC in the TRB from 1990 to 2019 based on the water yield module of the InVEST model, but there are still some limitations in this study. First, in the current study, we mainly considered the response of the main drivers to WC and did not fully reveal the influence mechanism of each driver on WC. In future studies, we should further strengthen the influence of the coupling of other factors on WC and quantify the contribution of climate elements of the main drivers to WC. Second, WC is an important regulating service, and the accuracy verification is still a challenge for the related research. In this study, we used the parameter-based correction method for the estimated water yield, and these parameters may introduce uncertainties into the result of WC. The another method defined WC by the water yield minus runoff as the remaining water amount, which, however, was limited within a strictly closed watershed. These are worthy of further study. Hence, we have referred to many studies on WC (Wang et al., 2013; Jia et al., 2022; Xu et al., 2022) and found that there is no effective way to quantify WC. This is mainly because WC is a kind of regulating service, which is different from provisioning services, e.g., water yield service can be verified by runoff data. How to effectively quantify the function of WC is a challenge in the field of ecosystem services and is a key issue for future research.

Current studies on WC have mainly focused on shorter scales, which do not reflect the evolution of WC in the watershed (Pei et al., 2022). In this study, based on the water yield module of the InVEST model, combining TI, Ksat and Velocity, the spatial and temporal evolution characteristics of WC in the TRB from 1990 to 2019 were explored, and compared with the traditional water estimation methods, the model breaks through the single ecosystem service estimation and can better express the effect of spatial heterogeneity under different substrates from the perspective of watersheds, thus realizing WC evaluation under different land uses (Pei et al., 2022). In addition, the long time scale can explain the evolution of WC to a certain extent and provide an effective reference for watershed water resource protection. In this study, we identified the southern part of Helong City and the southeastern part of Longjing City in the study area as WC priority protection zones based on the simulation results of WC depth combined with the technical guidelines for ecological protection red line delineation (Fig. 7), and we identified the WC of the TRB protection zones, which is beneficial to the sustainable management of watershed water resources and ecological protection. The TRB is a core area in the ecological network of Northeast Asia and an important WC functional area in China. Its WC evolution is of strategic importance for watershed ecological protection and water resource management. During the study period, the WC depth of the TRB showed an overall increasing trend, which also reflected the effectiveness of ecological conservation in the TRB in recent years to some extent. Therefore, future plans should continue to implement ecological protection policies and establish ecological compensation mechanisms for ecologically damaged areas in the watershed, in concert with the ecological protection of the entire watershed.

5 Conclusions

In this study, we used the InVEST model to quantitatively evaluate the water conservation (WC) of the Tumen River Basin (TRB) from 1990 to 2019 by parameter localization, and on this basis, we explored the drivers of spatial and temporal WC divergence in the watershed. We found the following:

1) The average WC in the TRB in the past 30 yr was 36.14 mm with an increased rate of 0.11 mm/yr, and the proportion of multiyear average WC depth to specific precipitation was 5.63%. 2) Spatially, the overall trend of WC depth was increasing in the northern part of the TRB, while decreasing in the central and southern regions with an increased trend of 0.04 mm/yr. 3) The analysis of driving factors showed that the spatial divergence of WC in the TRB was driven by both natural and socioeconomic factors, but natural factors were more determinant than socioeconomic factors. Precipitation was identified as the dominant factor influencing the spatial divergence of WC depth in the watershed. 4) The WC in different land-use types showed the obvious heterogeneity, with the highest WC in forest (40.73 mm), followed by grassland (24.50 mm) and cropland (14.12 mm). 5) The southern part of Helong City and the southeastern part of Longjing City are highly important areas for WC (WC > 75 mm), and these region should be protected as key areas for water resources and ecological environments. Overall, the forest protection and management in mountain areas must be vigorously maintained in the TRB to ensure the ecosystem regulating function of WC.

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