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Spatial-Temporal Distribution and the Influencing Factors of Water Conservation Function in Yunnan, China

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Abstract: Assessing the spatial and quantitative evaluation of water conservation within regional ecosystems holds vital significance for effective regional water resource management, allocation optimization, and enhanced ecological protection. In this study, we focus on Yunnan Province as our research subject and utilize land use data spanning from 2000 to 2018. The InVEST model serves as a key tool for evaluating Yunnan Province's water conservation capacity over the past two decades. Furthermore, we employ Geographical detectors and ArcGIS 10.2 to delve into the spatial distribution patterns and the impact of both natural environmental and socio-economic factors on changes in water conservation capacity. The research findings reveal a spatial trend in regional water source conservation, characterized by a decreasing gradient from the southwest to the northeast. Over the past two decades, we have observed an initial decline followed by a subsequent increase in regional water source conservation, resulting in an overall upward trajectory. Precipitation displays the strongest correlation among natural environmental factors, indicating a significant influence on water conservation. Additionally, socio-economic data exhibit a noteworthy positive correlation with alterations in water conservation, primarily attributed to urbanization and the expansion of impermeable surfaces like urban construction land, which bolster regional water conservation efforts. This research offers valuable insights that can serve as a foundation for establishing local water source protection measures and ecological compensation mechanisms.

Keywords: water conservation; InVEST model; ecosystem services; Yunnan Province; spatiotemporal pattern

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1. Introduction

Ecosystem functions are increasingly used to assess the social and economic impacts of environmental changes and provide basic principles for resource and environment management [1,2]. Water conservation is an important ecosystem function, which is of great significance for maintaining regional biodiversity and improving human well-being [3,4]. Water conservation plays a key role in improving regional hydrological conditions and regulating the water cycle. It not only directly affects regional water supply, but also has an important impact on the regional ecosystem stability, agriculture, industry, human consumption, hydropower generation and fishery [5,6]. Moreover, the regional natural environment and socio-economic factors also restrict the spatial and temporal distribution of water conservation functions [7,8]. In recent years, researchers have conducted in-depth discussions on the water conservation functions of various ecosystems. The research on the impact of land use or land cover change on ecosystem services has become a research hotspot, especially the trade-off between ecosystem services, which objectively reveals the overall effect of implementing land use policies on the ecological environment [9–12]. The research objects are mainly small and medium-sized regions, typical watersheds and other ecologically fragile areas [13–16]. Regarding the essence of water conservation function, there has been a significant evolution in its interpretation. Initially, the emphasis was on safeguarding water resources through the concept of water conservation function [10]. However, the understanding of water conservation function has since broadened to encompass its wider role and significance within the ecological environment, marking a continuous expansion of its connotation. As an important ecological service function, water conservation has the characteristics of dynamics, complexity, space–time evolution, etc. [17,18]. The discussion on how to scientifically evaluate the water conservation function has never been stopped. The assessment of regional water supply is expanded from the traditional soil water storage capacity method, comprehensive water storage capacity method and underground runoff growth method based on small watershed observation data to using the combination of remote sensing technology and hydrological model to quantitatively and visually analyze and assess the water conservation function of the ecosystem. At present, a large number of methods and tools have emerged to quantify and evaluate the provision of ecosystem services [19]. The main evaluation models such as the MIKE SHE model [20], TOPMODEL model, SWAT model [21–23] and InVEST model [11,24] have been well applied in their respective research fields. Moreover, researchers identify the influencing factors affecting the water conservation function of various ecosystems using regression models. For example, multi factor Logistic regression analysis, structural equation model [25] and geographically weighted regression [22] are mainly aimed at the static impact analysis of single factors such as meteorological factors [26], hydrological factors [27], vegetation factors and soil factors [28]. These studies offer both quantitative and spatial insights that can inform decision-making related to regional land use and the utilization of water resources.

Yunnan Province serves as a crucial ecological barrier in the upper reaches of the Yangtze River and holds a strategic position at the crossroads of the "the Belt and Road" initiative and the development of the Yangtze River Economic Belt. This region boasts abundant hydropower resources and is recognized as a significant area for biodiversity preservation and water conservation in China. However, recent decades have witnessed the exacerbation of regional water resource shortages due to rapid increase in climate change, socio-economic development, and population. In light of these challenges, researchers and relevant government bodies require a comprehensive and objective scientific assessment of the spatiotemporal patterns and dynamic transformations in the spatial structure of regional water conservation. This understanding is vital for accurate evaluations of ecosystem water conservation services and their values within the region and for the establishment of effective ecological compensation mechanisms. While a "one size fits all" compensation policy framework serves as a foundational tool, there remains a shortage of research focusing on the visualization of ecosystem water conservation services across the region. Consequently, this article leverages the InVEST model's water production module and employs spatial autocorrelation methods to simulate the water conservation quantities and spatial distribution characteristics for different times periods in Yunnan Province. It also utilizes geographical detectors to delve into the underlying causes, both dynamic and static, behind the spatiotemporal variations in water conservation function. The analysis encompasses the spatial distribution patterns and the influencing factors driving dynamic changes in the spatial structure of water conservation function within Yunnan Province from 2000 to 2018. Furthermore, it integrates these findings with the existing ecological functional zones. The study emphasizes the crucial importance of safeguarding regional water source conservation functions improving enhancing urban development. This research offers valuable insights that can guide decisions related to key functional zoning, ecological restoration, and ecological compensation for regional water source conservation. These findings are of significant importance for gaining a comprehensive understanding of the current status of water supply services in regional ecosystems and providing guidance for essential zoning strategies, ultimately aiding in the establishment of ecological compensation standards.

2. The Geographic Area to Be Studied

Yunnan Province is located between 21°8′~29°15′ N and 97°31′~106°11′ E, which crosses the Yangtze River, Pearl River, Yuanjiang River, Lancang River, Nujiang River and Daying River. It is an important ecological area in the upper reaches of the Yangtze River. As shown in Figure 1, it has obvious traffic location advantages, unique resources and prominent ecological status. The total population of Yunnan Province is 47.209 million, and the urbanization level is 50.05%, of which the minority population accounts for 33.12%. The terrain is mainly mountainous, with a mountainous area of 331,100 km^2, accounting for 84% of the total area of the province. The terrain is high in the northwest and low in the southeast, and it drops step by step from north to south. The climate is mainly subtropical and tropical monsoon climate, and Northwest Yunnan belongs to plateau mountain climate. The lake water area is about 110 $\times$ 10^3 ha, accounting for 0.28% of the total area of the province. The forest area is 2392.65 $\times$ 10^3 ha, with a forest coverage rate of 65.0%. Moreover, 85% of the annual precipitation is concentrated in May to October. In terms of ecological and economic status, the region plays an important strategic role in maintaining the balance between economic development and ecological protection of the Yangtze River economic belt. However, although Yunnan Province is a region with relatively rich water resources in China, the overall situation is not optimistic due to the uneven spatial and temporal distribution of water resources in the region [29].

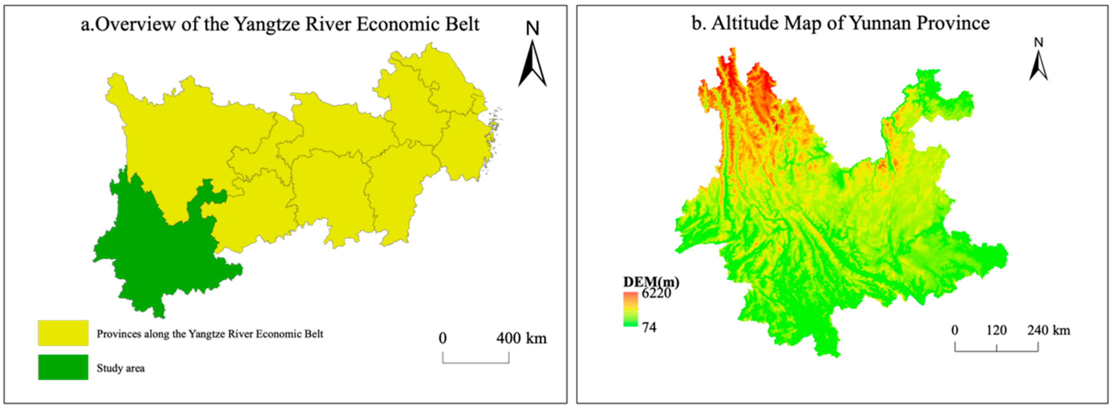


Figure 1. Overview of the study area.

3. Research Methods and Data

3.1. Assessment of Water Conservation Function Based on InVEST Model

The water production module of the InVEST model can be used to evaluate the depth of water conservation by integrating topographic factors, surface runoff differences and other factors. The model has the advantages of flexible parameter adjustment, spatial expression of evaluation results with multi-time, multi-scale, multi-scenario and multi-objective tradeoffs [30]. The specific formula is as follows:

$$Water\ Retention = \min(1, \frac{249}{velocity}) \times \min\left(1, \frac{0.9 \times TI}{3}\right) \times \left(1, \frac{Ks}{300}\right) \times Y_x \tag{1}$$

$$TI = \lg\left(\frac{Drainage\_Area}{Soil\_Depth \times Percent\_Slope}\right) \tag{2}$$

In Equation (1), *Water Retention* is the water conservation depth (mm), *Ks* is the saturated hydraulic conductivity of soil (mm/d), *velocity* is the velocity coefficient, *TI* is the topographic index, which is a dimensionless parameter, and Y_x is the water production depth (mm). In Equation (2), *Drainage_Area* is the number of grids in the catchment area, *Soil_Depth* is soil depth (mm), *Percent_Slope* is the percentage of the slope.

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x \tag{3}$$

$$\frac{AET_x}{P_x} = \frac{(1 + \omega_x + R_x)}{1 + \omega_x \times R_x + 1/R_x} \tag{4}$$

$$\omega_x = Z \times \frac{AWC_x}{P_x} \tag{5}$$

$$R_x = \frac{k_x \times ET_0}{P_x} \tag{6}$$

$$AWC_x = \min(MaxSoilDepth_x, RootDepth_x) \times PAWC_x \tag{7}$$

In Equation (3), AET_x is the grid's annual average actual evapotranspiration (mm), P_x is the grid's precipitation (mm). In Equation (4), R_x is the dryness index, which is a non-physical parameter of climatic soil attributes, ω_x is the non-physical parameters of soil properties, Z is the seasonal constant, and its value range is between 1 and 10. According to the existing research, Yunnan belongs to the monsoon climate region, and the result is relatively scientific when Z is taken as 1 [31]. In Equation (5), AWC_x is the available water content of plants (mm). In Equation (6), k_x is the evapotranspiration coefficient of a vegetation type ET_0 is the reference evapotranspiration (mm). In Equation (7), $MaxSoilDepth_x$ is the maximum soil depth (mm), $RootDepth_x$ is the root depth (mm), and $PAWC_x$ is the available water for plants.

3.2. Spatial Autocorrelation Analysis Based on Moran'I Index

A global spatial autocorrelation analysis measures the overall distribution of water conservation in Yunnan Province by calculating indicators to analyze the overall spatial correlation and spatial differences, and to evaluate whether it has spatial agglomeration [32]. The formula is as follows:

$$K = \frac{\sum_{i=1}^{n}\sum_{j\neq 1}^{n} W_{ij}\left(X_i - \overline{X}\right)\left(X_j - \overline{X}\right)}{s^2 \sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}} \tag{8}$$

In Equation (8), W_{ij} is the spatial weight matrix (1 for spatial adjacency and 0 for non-adjacency). n is the number of space units. X_i and X_j are the attribute value of the spatial unit i and j, respectively. s^2 is the variance of attribute value. $\overline{X}$ is the average of the observed attribute values of each unit.

The local spatial autocorrelation analysis is further used to reveal the heterogeneity characteristics of spatial differences in order to comprehensively reflect the change trend of the spatial differences in regional water conservation. The formula is as follows:

$$K_i = Z_i \sum_i W_{ij} z_j \tag{9}$$

In Equation (9), Z_i and z_j are the standardized values of regional observations, and K_i is the local spatial autocorrelation index, according to which the research units can be divided into four spatial correlation patterns: "high-high" value area, "low-low" value area, "high-low" value area and "low-high" value area.

3.3. Analysis of Influencing Factors Based on Geographic Detector

Compared with the previous regression analysis, the advantage of using geographical detectors to detect spatial differentiation and the driving force behind it is that it can achieve a certain statistical accuracy with a sample size of less than 30. Additionally, for collinearity immunity among multiple independent variables, space continuity is not required in the geographical detectors-based analysis [33,34]. Based on this, the factor detection function is used to calculate the interpretation degree of the influencing factors of water conservation in Yunnan Province, and judge whether the interaction of the two factors is stronger or weaker than that of a single factor based on the interactive detection. Among them, the equation for calculating the detection force value q of influence factors on regional differences is as follows:

$$q = 1 - \frac{1}{n\sigma} \sum_{i=1}^{M} n_i \sigma_i^2 (i = 1, 2, 3 \ldots) \tag{10}$$

In Equation (10), the value of q is between 0 and 1. The greater the value of q, the greater the impact of this factor on regional water conservation. M is the stratification of influence factor x. n and n_i are the number of samples in the study area and layer i, respectively. σ^2 and σ_i^2 are the variances of the study area and layer i, respectively.

3.4. Data Source and Parameter Processing

The data used in this paper mainly include the land use data, precipitation, potential evapotranspiration, soil depth data, root depth, evapotranspiration coefficient, soil saturated hydraulic conductivity, watershed data and elevation. The natural environment and socio-economic factors explored for the influencing factors of water conservation include vegetation coverage (NDVI), net primary productivity of vegetation (NPP), population density, distance from cities and towns, regional GDP. Table 1 summarizes the data source and the data localization processing used in this study.

Table 1. Data source and parameter localization.

Data Required	Data Source
Land Use	Downloaded from the Data Center for Resource and Environmental Sciences, Chinese Academy of Sciences [35,36] (https://www.resdc.cn/ (accessed on 4 December 2021)), including 4 periods of data in 2000, 2005, 2010 and 2018, with a spatial resolution of 100 m × 100 m.
Precipitation	Source from China Meteorological Data Network (https://data.cma.cn/ (accessed on 4 December 2021)) Monthly precipitation data from 2000 to 2018 were obtained by spatial interpolation using the meteorological software ANUSPLIN 4.1.
Potential evapotranspiration	Solar radiation data from the World Climate website (https://www.worldclim.org/ (accessed on 4 December 2021)), Temperature data from China Weather Data Network (https://data.cma.cn/ (accessed on 4 December 2021)), Calculated using Modified-Hargreaves formula.
Maximum soil depth	Soil depth data of Yunnan Province was extracted from the 1:1 million soil database of the Cold and Arid Zone Scientific Data Center, with a spatial resolution of 1 km.
Root depth	Referring to existing studies, the CSV table of root depth was constructed by land use/cover type as a unit [25,37].
Plant available water content (PAWC)	The sand, powder, clay and organic carbon contents of the study area were extracted from the 1:1 million soil database of the Cold and Arid Zone Scientific Data Center, and PAWC was the difference between the field water holding capacity and the permanent wilting coefficient, both of which were calculated by the empirical equation [38].
Soil saturation hydraulic conductivity	Soil data sets in the study area were extracted based on the Chinese soil data set mask, and the saturated hydraulic conductivity of the soil was calculated using the field calculator in the attribute table.

Table 1. *Cont.*

Data Required	Data Source
Basin Data	Extraction based on DEM data using the ArcGIS hydrological analysis tool.
DEM	Source from Geospatial Data Cloud (http://www.gscloud.cn (accessed on 4 December 2021)).
Flow rate coefficient	Reference model parameter table data [24].
Terrain Index	Calculated from soil depth, percentage of slope and catchment area.
Percentage slope	Based on the ArcGIS spatial analysis and DEM calculation.
NDVI	MOD13Q1 satellite data, spatial resolution 1 km (http://www.ntsg.umt.edu (accessed on 4 December 2021)).
NPP	MOD17A3 dataset (http://www.ntsg.umt.edu (accessed on 4 December 2021)).
Population density, GDP	Yunnan Provincial Statistical Yearbook and Yunnan County and municipal government portals.
Distance from town	Euclidean distance calculation using ArcGIS.
Zhang factor	Z represents the seasonal characteristic value of precipitation, the study area belongs to the monsoon climate zone, precipitation is concentrated in summer, Z value is taken as 1 [31].

4. Results and Discussions

4.1. Spatial and Temporal Distribution Characteristics of Water Conservation Function in Yunnan Province

The water conservation function fully reflects the process and capacity of the ecosystem to maintain water [39]. As shown in Figure 2, from 2000 to 2018, the water conservation depth in the study area decreased first and then increased, and generally maintained an upward trend. The average conservation depth over the years was 65.58 mm. The average depth of conservation in 2005 was 59.95 mm, a decrease of 12.7% compared with 2000. The average conservation depth in 2010 was 59.74 mm, slightly lower than that in 2005, and then recovered to 73.79 mm in 2018. During the study period, the average water conservation depth in the study area increased by 3.5%. Its spatial distribution pattern is basically stable, showing a distribution pattern of high in the southwest and low in the northeast. High value areas are concentrated in the north of Dehong, Pu'er, Xishuangbanna and the south of Wenshan mountain, with an average value of 166–349 mm. Low value areas are distributed in densely populated areas in the north of the study area, with an average value of 0–40 mm. Their distribution pattern is directly related to the average annual precipitation and the actual evapotranspiration of the region.

4.2. Spatial and Temporal Changes in Water Conservation Function at Different Spatial Scales

As the main body of eco-environmental policy implementation, the administrative units' response to the policy will directly affect the regional eco-environmental quality. The natural environment and other factors will have an impact on human activities and especially affect land use primarily. At the same time, the heterogeneity of environmental factors such as climate and altitude will also affect the ecosystem functions. Therefore, this paper uses ArcGIS 10.2 spatial analysis to make zoning statistics on water conservation functions of cities, prefectures, elevations and land types in Yunnan Province, and further explore the spatial-temporal distribution characteristics of water conservation functions in Yunnan Province from different spatial scales.

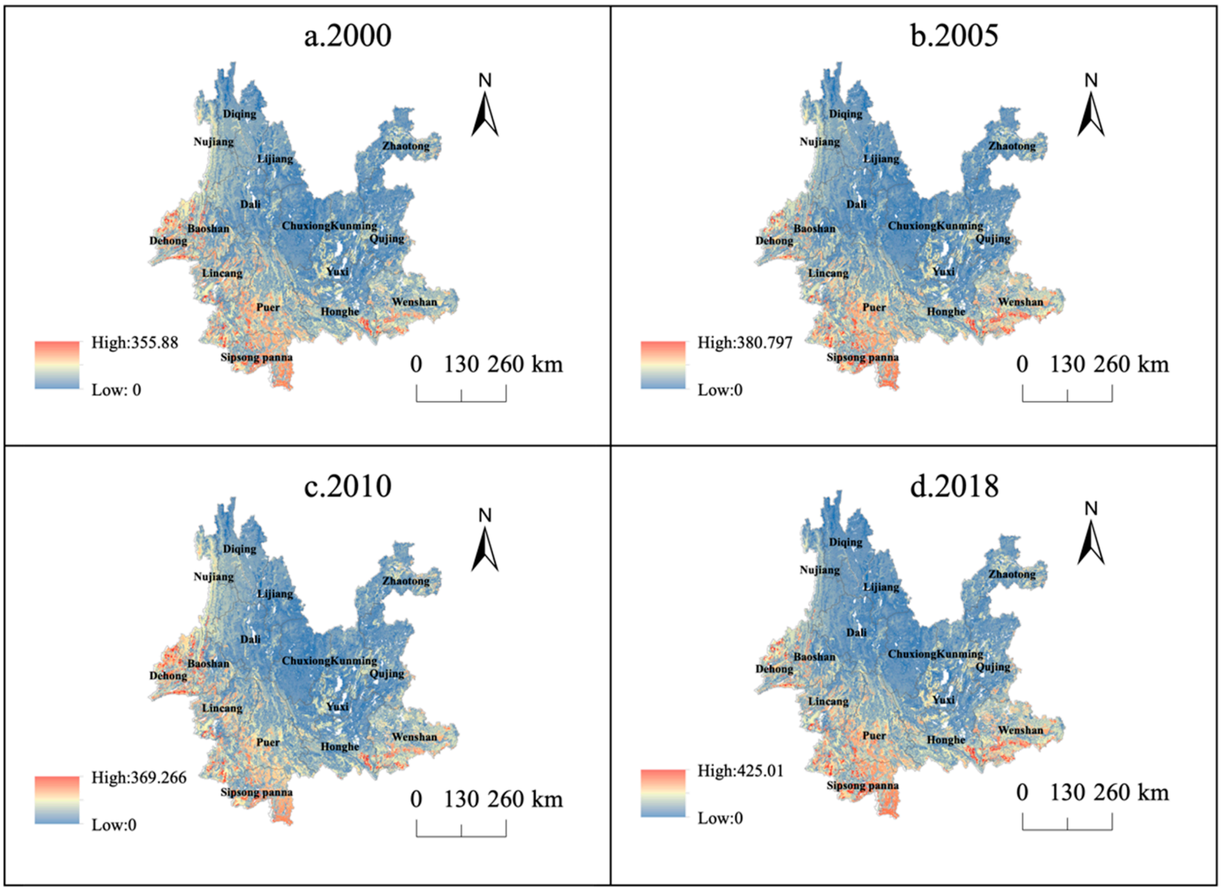
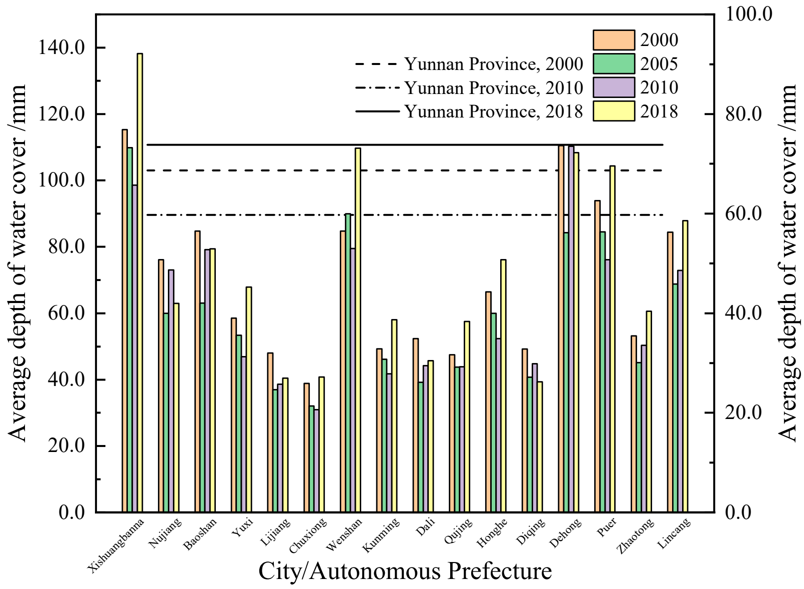


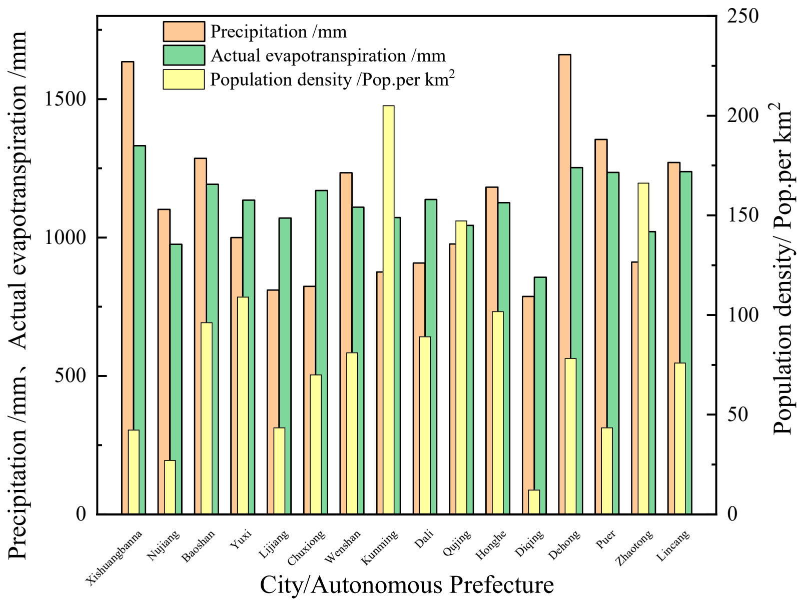
Figure 2. Spatial change in water conservation function in Yunnan Province from 2000 to 2018.

4.2.1. Average Water Conservation Depth of Different Cities and States

From 2000 to 2018, seven cities and prefectures demonstrated an average water conservation depth exceeding the regional average, as depicted in Figure 3a. The ranking from highest to lowest water conservation depth is as follows: Xishuangbanna (115.50 mm) > Dehong (103.32 mm) > Wenshan (90.95 mm) > Pu'er (89.69 mm) > Lincang (78.48 mm) > Baoshan (79.45 mm) > Nujiang (73.09 mm). Conversely, the remaining nine cities and prefectures exhibited water conservation depth below the regional average, with Honghe (63.71 mm) > Yuxi (56.66 mm) > Zhaotong (52.32 mm) > Kunming (48.79 mm) > Qujing (48.16 mm) > Dali (45.37 mm) > Diqing (43.53 mm) > Lijiang (41.02 mm) > Chuxiong (35.65 mm). As shown in Figure 3b, the water conservation services in all cities and prefectures exhibited a similar trend in response to precipitation and actual evapotranspiration, reflecting the characteristics of a monsoon climate with concurrent rainy and warm seasons in the region. Regional statistics did not reveal a conspicuous change trend in low-value areas and population density. However, high-value areas and population density displayed an opposite change pattern. Concerning inter-annual variations, Xishuangbanna, Yuxi, Chuxiong, Wenshan, Kunming, Qujing, Honghe, Pu'er, Zhaotong, and Lincang consistently followed the regional change trend.



(**a**)

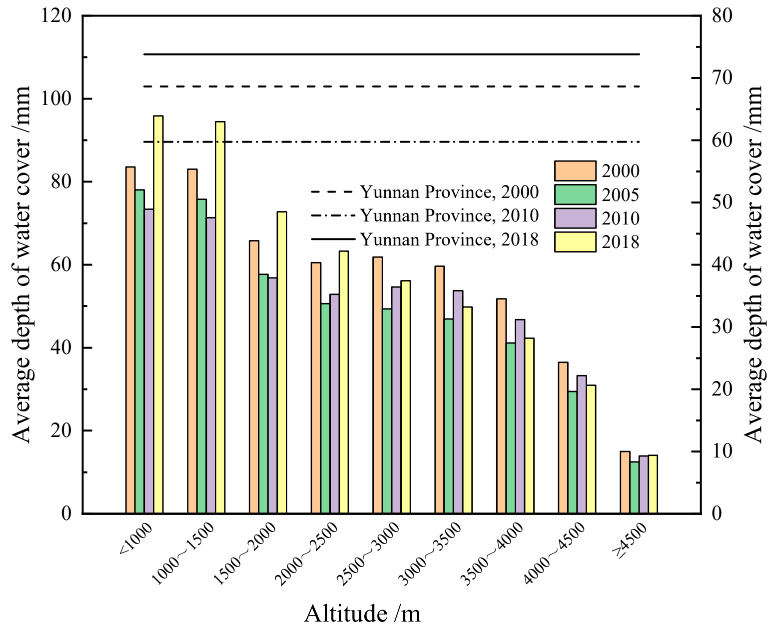


(**b**)

Figure 3. Water conservation function and its influencing factors of cities and prefectures in Yunnan Province. (**a**) Water Conservation Capacity and Annual Average of 16 Cities and Prefectures in Yunnan Province in 2000, 2005, 2010, and 2018. (**b**) Water precipitation, actual evapotranspiration, and population density of 16 cities and states in Yunnan Province in 2018.

4.2.2. Average Water Conservation Depth at Different Altitudes

Considering the distinctive features of the Digital Elevation Model (DEM) and the study area, characterized by significant changes in altitude, steep mountainous terrain, and high elevations, as depicted in Figure 4a, altitude is categorized into nine levels. The findings reveal a consistent trend in the depth of regional water conservation relative to elevation. Specifically, for the years 2000, 2005, 2010 and 2018, elevations exceeding the regional average were primarily concentrated at altitudes below 1000 m and between 1000 m to 1500 m, aligning closely with the variations in precipitation and actual evapotranspiration, as illustrated in Figure 4b. Conversely, at altitudes ranging from 1500 m to 2000 m and 2000 m to 2500 m, a substantial decline in water conservation depth was observed, indicating a contrary pattern to population density., This suggests that human activities at these elevations had a notable impact on water conservation, whereas the influence of population density at other altitudes was less pronounced.



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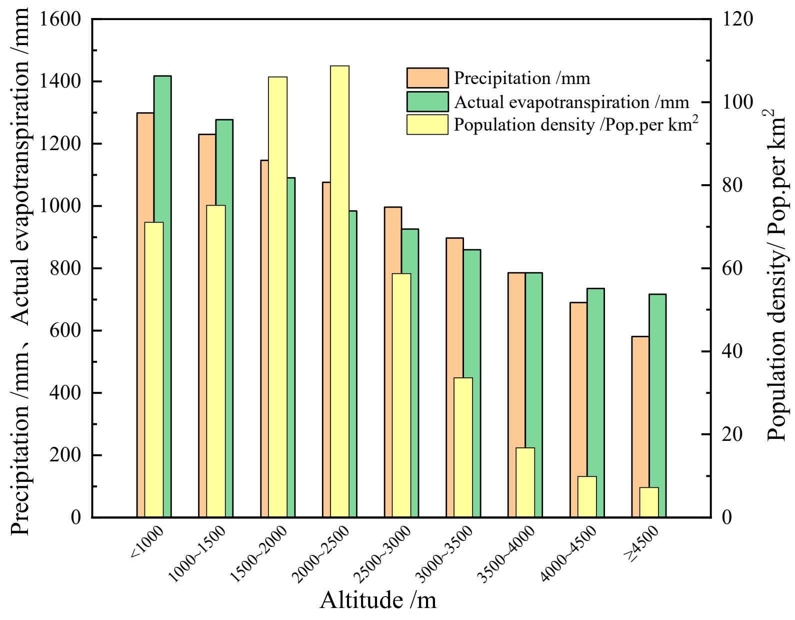

(**b**)

Figure 4. Water conservation function and its influencing factors at different elevations in Yunnan Province. (**a**) The relationship between altitude and water conservation capacity. (**b**) The relationship between altitude and precipitation, actual evapotranspiration, and population density.

In terms of interannual fluctuations, the analysis revealed the following trends: at elevations of 3000 m to 3500 m, 3500 m to 4000 m, 4000 m to 4500 m, and above 4500 m, the water conservation depth was higher in 2000 than in 2010 and 2018. In the altitude range of 2500 m to 3000 m, the water conservation depth was greater in 2000 than in 2018 and 2010.

For all other elevations, the water conservation depth in 2018 exceeded that of 2000 and 2010, mirroring the ranking seen in the change in regional average conservation depth.

4.2.3. Average Water Conservation Capacity of Different Land Types

The water source conservation function in the study area was assessed and statistically analyzed based on the initial classification from China's multi-period land use database, enabling the calculation of the average water source conservation depth for each year. As depicted in Figure 5, the water source conservation depth exhibited the following order: forest land > arable land > grassland > urban construction land > water area > unused land. Notably, the water source conservation depth of forest land consistently exceeded the regional average over multiple years.

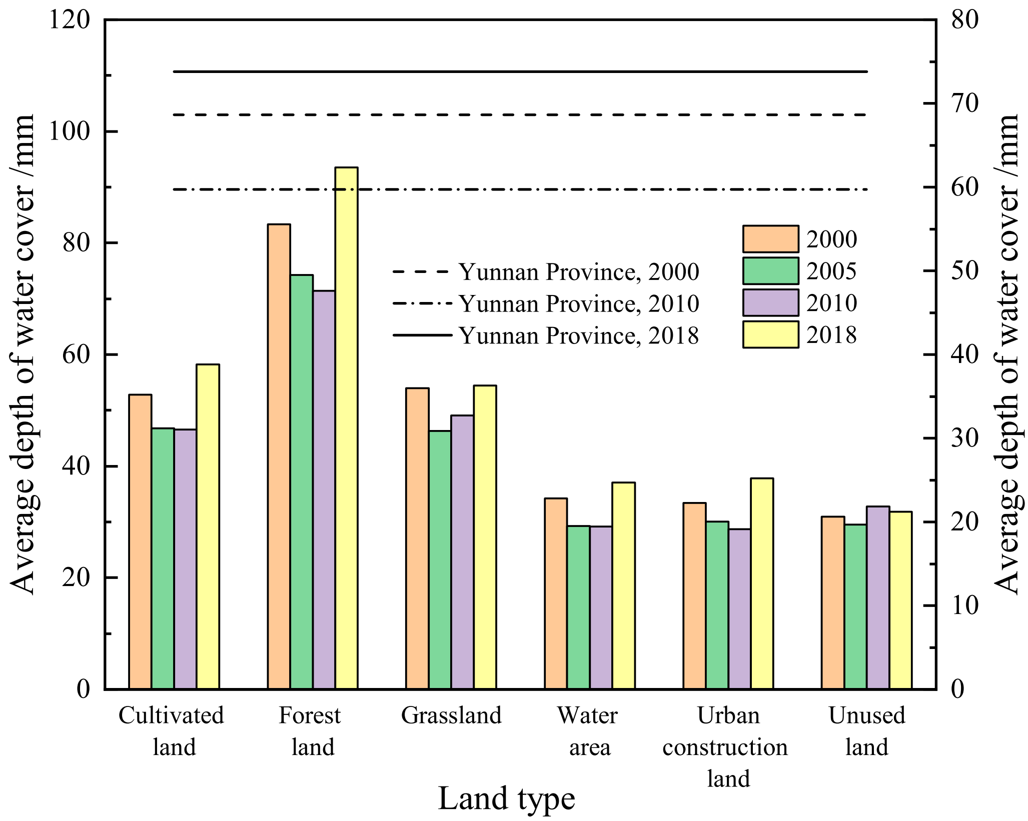

Figure 5. Conservation function and influencing factors of different water resources in Yunnan Province.

It is important to highlight that when assessing the multi-year change rates, urban construction land (13.19%) demonstrated the highest increase, primarily attributed to urbanization expansion leading to a rise in impermeable surfaces. This, in turn, disrupted the water balance, reducing precipitation infiltration and elevating flood peak flows [40]. In contrast, forest land and arable land played roles in mitigating surface runoff, alongside promoting soil infiltration, thus delaying the precipitation convergence within the watershed. Consequently, they exhibited relatively low change rates [21].

4.3. Evolution Pattern of Spatial Characteristics of Water Conservation in Yunnan Province

In order to further explore the changes in spatial agglomeration characteristics of water conservation functions in Yunnan Province and eliminate the errors caused by the size differences of administrative units, 129 county-level administrative regions in Yunnan Province were taken as samples to conduct global and local spatial autocorrelation statistics of water conservation functions in the province from 2000 to 2018, as shown in Table 2. The results show that the Moran's *I* of water conservation in 2000, 2010 and 2018 are greater than

0.5. In addition, the p values of the four phases are all 0.00. Through the significance test, it shows that the water conservation function of Yunnan Province has a strong positive spatial agglomeration. This shows that the water conservation is concentrated and connected in clusters, and the average depth of water conservation in the surrounding areas is also higher in the areas with a higher average depth of water conservation. Where the average depth of water conservation is low, the depth of water conservation in the surrounding areas is also low. Its strong positive global spatial autocorrelation also indicates the existence of spatial differences in water conservation functions within Yunnan Province.

Table 2. Spatial autocorrelation statistics of water conservation in Yunnan Province from 2000 to 2018.

Year	2000	2005	2010	2018
Moran's I	0.524	0.239	0.535	0.533
Z-value	876.35	56.36	376.84	1130.18
p-value	0.0000	0.0000	0.0000	0.0000

The global spatial autocorrelation reflects the spatial evolution process of the whole study area, and we further analyze the local spatial agglomeration phenomenon of water conservation in Yunnan Province through local spatial autocorrelation to evaluate its high-value agglomeration area and low-value agglomeration area. As shown in Figure 6, the water conservation function showed similar phenomena in the three phases of research in 2005, 2010 and 2018. The "high-high" concentration areas are in Lincang, Pu'er, Xishuangbanna, Honghe and Wenshan in the southwest and southeast, mainly located in the Irrawaddy River, Nujiang River, Lancang River and Panlong River Basins in the provincial water resources zoning. The "low-low" concentration areas are in Lijiang, Dali, Chuxiong, Zhaotong and Qujing in the north and East, mainly located in the Jinsha River (lower) basin. The change in agglomeration area occurred from 2000 to 2005, among which the "high-high" agglomeration was transferred to Dehong, Lincang, Pu'er and Wenshan, the "low-low" agglomeration was transferred to Dali, Lijiang and Zhaotong, and the "high-low" agglomeration changed to Kunming. There was no "low-high" transfer phenomenon in the study area, and there was no significant transition from low value areas to high value areas. It is worth noting that the "low-low" agglomeration areas in Kunming shrank significantly during this period. There is obvious spatial heterogeneity in the distribution of water conservation functions in Yunnan Province, and there are obvious differences between the north and the south. Specifically, the water conservation functions on the north and south sides of Hengduan Mountain, Wuliang Mountain and Ailao Mountain show different spatial agglomeration with high concentration, while the concentration in the central mountain area is low due to the complex and diverse terrain. In terms of spatial differences, the key improvement areas of water conservation function in Yunnan Province should focus on low value areas, especially Chuxiong and Zhaotong, which have been in low value areas for a long time. Among the key ecological functional areas, Wuliang-Ailao Mountain Biodiversity reserve should focus on strengthening the water conservation function of Yuxi and Honghe regions. The conservation of biodiversity in western Yunnan should pay attention to Baoshan. Except Dehong, other cities and prefectures in the Northwest Yunnan Plateau biodiversity protection and water conservation protection areas have not improved significantly. In addition, it is necessary to strengthen the protection of water conservation function in Qujing and Zhaotong Yunnan Guizhou Plateau karst areas.

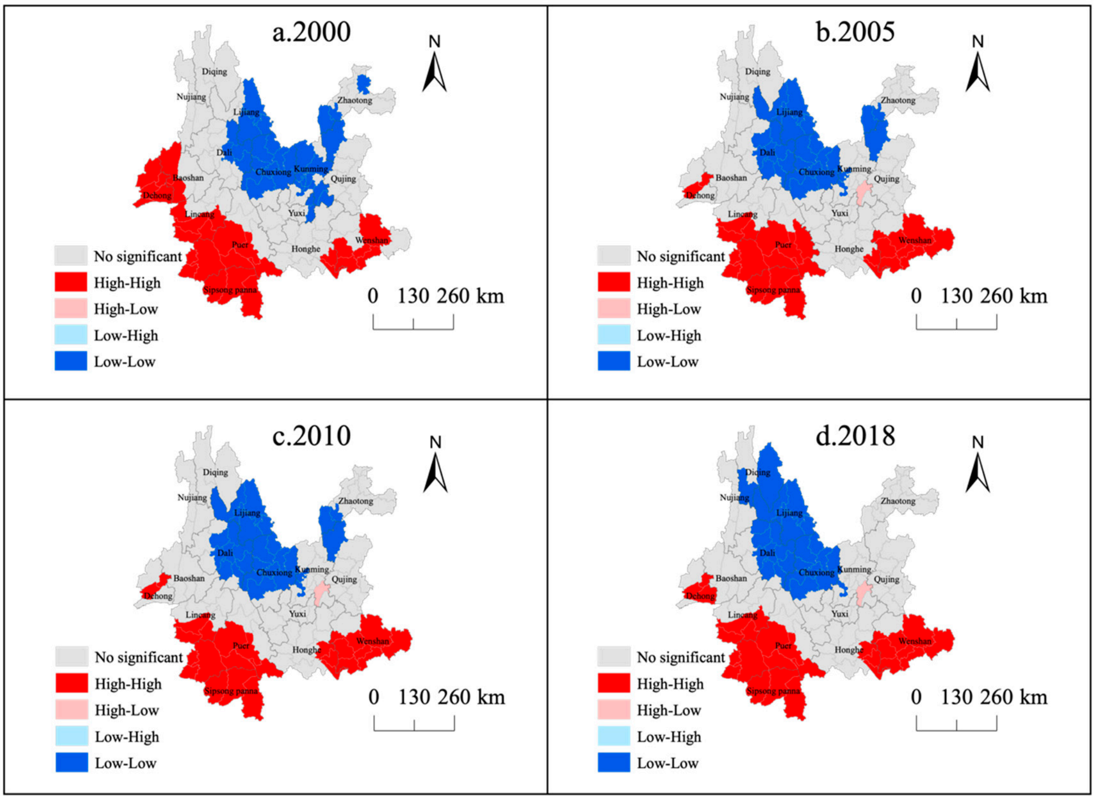

Figure 6. Local spatial autocorrelation of water conservation function in Yunnan Province.

4.4. Geographical Exploration of Spatial Differentiation of Water Conservation in Yunnan Province

4.4.1. Construction of an Impact Factor Index System

Prior research has established a connection between spatial variations in water source conservation and factors stemming from both the natural environment (including climate, terrain, and ecology) and socio-economic elements (encompassing economic conditions, social development, transportation infrastructure, and land use) [14,35,41]. Drawing on these existing studies, we have devised an index system that comprises influencing factors responsible for the spatial differentiation of water conservation function. This system, encompassing dimensions from both the natural environment and social economy, is presented in Table 3 for reference. ArcGIS is used for spatial processing; the grid data of 100 m × 100 m are resampled. In order to explore the difference of influencing factors of water conservation function in different climate years, the representative year 2000 of wetter climate, 2010 of normal climate and 2018 of drier climate are selected here for driving factor analysis.

Table 3. Index system of influencing factors of spatial differentiation of water conservation function in Yunnan Province.

Tier 1 Indicators	Secondary Indicators	Tertiary Indicators	Specific Indicators
Natural Environment	Climate factors	X_1	Average annual precipitation
		X_2	Actual evaporation amount
	Terrain factor	X_3	DEM
	Ecological factors	X_4	NPP
		X_5	NDVI
Socio-economic	Economic level	X_6	GDP
	Social Development	X_7	Population density
	Traffic Location	X_8	Distance from town
	Land Use	X_9	Land Use Change

4.4.2. Detection of Spatial Differentiation Factors of Water Conservation Function in Yunnan Province

As displayed in Table 4, the results of single-factor static year analysis of water conservation function in Yunnan Province highlight that precipitation and Net Primary Productivity (NPP) stand out as the most influential factors in explaining spatial heterogeneity. Specifically, across the years 2000, 2010, and 2018, these two factors exhibited an average correlation exceeding 50%, indicating their central role as core influencing factors [42]. Precipitation, in particular, consistently demonstrated an explanatory power surpassing 75% throughout the years.

Table 4. Static year factor detection for geographic detectors.

Factor		2000		2010		2018	
		q-Value	q-Value Sorting	q-Value	q-Value Sorting	q-Value	q-Value Sorting
Natural Environment	Precipitation	0.766	1	0.822	1	0.784	1
	Evaporation volume	0.279	5	0.233	5	0.192	5
	DEM	0.434	4	0.402	4	0.532	2
	NPP	0.603	2	0.590	2	0.530	3
	NDVI	0.579	3	0.442	3	0.446	4
Socio-economic	GDP	0.143	7	0.114	7	0.028	9
	Population density	0.028	9	0.025	9	0.035	8
	Distance from town	0.103	8	0.054	8	0.071	7
	Land Use	0.152	6	0.120	6	0.112	6

Factors such as Normalized Difference Vegetation Index (NDVI), elevation, and evapotranspiration maintained explanatory powers above 30%, signifying their secondary yet substantial impact. NDVI, closely linked to vegetation types, exerts an influence on soil characteristics, and previous research underscores the vital role of soil properties in water conservation [40,43]. Categorized by factor types, climate and ecological factors emerged as the primary contributors to explanatory power. Among socio-economic factors, land use changes exert a more pronounced influence on the spatial differentiation of water source conservation than other variables. This is primarily attributed to regions characterized by dense urban construction, high population density, and extensive impervious surfaces, all of which are susceptible to surface runoff.

Table 5 shows the influencing factors of spatial differentiation of water conservation in the three dynamic periods of 2000~2010, 2010~2018 and 2000 to 2018 after excluding the factors that have no significant change between years in ArcGIS spatial processing. Except for NPP and GDP, the explanatory power of other factors increased significantly from 2010 to 2018. In the three periods, the changes in precipitation, evapotranspiration and NPP are the most powerful ones, which further explains the strong explanatory power of climate and ecological factors on water conservation. During the study period, the explanatory power of land use change, population density change and precipitation change on the spatial differentiation of water conservation in the study area was enhanced, while the explanatory power of the other four factors was weakened. It can be seen that the q value of the population density change factor increases with the passage of years, indicating that the intervention intensity of human activities on water conservation function is increasing. The single factor explanatory power of static years and dynamic periods reflects that natural environmental factors are the dominant factors affecting the spatial differentiation of water conservation in the study area.

Table 5. Dynamic time factor detection for geographic detectors.

Factor		2000–2010		2010–2018		2000–2018	
		q-Value	q-Value Sorting	q-Value	q-Value Sorting	q-Value	q-Value Sorting
Natural Environmen	Precipitation change	0.827	1	0.857	1	0.893	1
	Evapotranspiration change	0.404	3	0.668	2	0.531	2
	NPP change	0.411	2	0.299	3	0.160	3
Socio-economic	GDP change	0.101	4	0.044	4	0.011	6
	Population density change	0.021	5	0.039	5	0.047	5
	Change in distance from town	0.005	7	0.013	7	0.004	7
	Land use change	0.006	6	0.023	6	0.060	4

4.4.3. Interactive Detection of Spatial Differentiation of Water Conservation in Yunnan Province

The preceding analysis primarily delves into the individual role of each factor in shaping the spatial differentiation of water conservation function within the study area. However, it is essential to recognize that water conservation function is often a product of the interplay between multiple factors. Consequently, it is necessary to further investigate how these factor interactions impact the spatial distribution of water conservation in Yunnan Province through interaction analysis.

As detailed in Table 6, the interactions between various influencing factors are characterized by dual-factor enhancement (BE) and nonlinear enhancement (NE), with no factors operating in complete independence. Among these interaction factors, precipitation exhibits the most pronounced interactivity, as indicated by its interaction q value surpassing 0.7 in relation to other variables. Except for the nonlinear enhancement between precipitation and population density in 2018, all other factor interactions manifest as dual-factor enhancements. This underlines the importance of factor interactions, which collectively exerts a more substantial explanatory power than the isolated influence of individual factors.

Table 6. Static year interactive detection of geodetectors.

2000			2010			2018		
Reciprocal Factor	q-Value	Type	Reciprocal Factor	q-Value	Type	Reciprocal Factor	q-Value	Type
$X_1 \cap X_6$	0.811	BE	$X_1 \cap X_2$	0.871	BE	$X_1 \cap X_7$	0.829	NE
$X_1 \cap X_4$	0.808	BE	$X_1 \cap X_7$	0.851	BE	$X_1 \cap X_9$	0.826	BE
$X_1 \cap X_5$	0.807	BE	$X_1 \cap X_3$	0.848	BE	$X_1 \cap X_4$	0.826	BE
$X_1 \cap X_9$	0.803	BE	$X_1 \cap X_5$	0.845	BE	$X_1 \cap X_8$	0.824	BE
$X_1 \cap X_2$	0.798	BE	$X_1 \cap X_8$	0.843	BE	$X_1 \cap X_5$	0.815	BE
$X_1 \cap X_8$	0.796	BE	$X_1 \cap X_9$	0.843	BE	$X_1 \cap X_6$	0.812	BE
$X_1 \cap X_7$	0.793	BE	$X_1 \cap X_6$	0.840	BE	$X_1 \cap X_2$	0.808	BE
$X_1 \cap X_3$	0.793	BE	$X_1 \cap X_4$	0.836	BE	$X_1 \cap X_3$	0.799	BE
$X_4 \cap X_5$	0.718	BE	$X_3 \cap X_4$	0.711	BE	$X_3 \cap X_4$	0.764	BE
$X_4 \cap X_2$	0.716	BE	$X_4 \cap X_8$	0.687	NE	$X_3 \cap X_8$	0.667	NE

Prior research has highlighted the discernible shifts in water conservation function, with the combined impact of both time and space contributing to the variations in the ecological environment within the study area [42]. By conducting dynamic period interaction analysis, as outlined in Table 7, it becomes evident that the top six interaction factors across the three time periods pertain to the interplay of precipitation variations with other influencing factors.

Table 7. Dynamic time interval interactive detection of geographic detectors.

Reciprocal Factor	2000–2010 *Q*-Value	Type	Reciprocal Factor	2010–2018 *q*-Value	Type	Reciprocal Factor	2000–2018 *q*-Value	Type
$X_1 \cap X_2$	0.875	BE	$X_1 \cap X_2$	0.911	BE	$X_1 \cap X_8$	0.922	NE
$X_1 \cap X_9$	0.860	NE	$X_1 \cap X_8$	0.889	BE	$X_1 \cap X_9$	0.919	NE
$X_1 \cap X_6$	0.858	BE	$X_1 \cap X_6$	0.887	BE	$X_1 \cap X_4$	0.912	BE
$X_1 \cap X_8$	0.844	NE	$X_1 \cap X_9$	0.886	NE	$X_1 \cap X_6$	0.909	BE
$X_1 \cap X_4$	0.839	BE	$X_1 \cap X_4$	0.875	BE	$X_1 \cap X_2$	0.906	BE
$X_1 \cap X_7$	0.837	BE	$X_1 \cap X_7$	0.871	BE	$X_1 \cap X_7$	0.903	BE
$X_2 \cap X_4$	0.668	BE	$X_2 \cap X_4$	0.770	BE	$X_2 \cap X_4$	0.660	BE
$X_2 \cap X_6$	0.546	NE	$X_2 \cap X_8$	0.739	BE	$X_2 \cap X_9$	0.644	NE
$X_2 \cap X_9$	0.530	BE	$X_2 \cap X_7$	0.711	BE	$X_2 \cap X_8$	0.637	NE
$X_4 \cap X_8$	0.507	NE	$X_2 \cap X_6$	0.705	BE	$X_2 \cap X_6$	0.601	NE

Although the socio-economic factors may not exhibit significant individual explanatory power in single-factor analysis, they demonstrate substantial influence when interacting with other natural environmental variables. This observation underscores that changes in socio-economic factors frequently exert their influence on the natural environment first, subsequently affecting the regional water conservation function. Thus, their role in elucidating spatial differentiation becomes apparent primarily through interaction analysis.

In the process of actual ecological environment change in the study area, the interaction and complexity of factors in different regions are important reasons for the spatial differentiation of water conservation. The two-factor synergistic enhancement in the interactive detection of static years and dynamic periods of factors further illustrates this point. Regarding the dominant factors, both single-factor analysis and interaction assessment consistently underscore that natural factors serve as the primary driving force behind the spatial variations in water conservation. This aligns with findings from pertinent studies [44]. However, it is undeniable that other factors also play a role in the spatial differentiation of water conservation functions. Especially in interactive detection, it further explains that the impact of social and economic factors on the regional water conservation function is usually interactive. The existing research also shows that there are two situations of resource-based water shortage and engineering-based water shortage in Yunnan Province [20]. Therefore, in the future process of urban economic development, it is necessary to coordinate the regional ecological functions and minimize the impact on regional water conservation.

5. Discussion

(1) Concerning spatial disparities, the primary efforts to enhance water conservation function in Yunnan Province should be concentrated on low-value areas, with particular emphasis on regions such as Chuxiong and Zhaotong, which have long struggled with lower conservation levels. Within the key ecological functional areas, Wuliangshan Ailaoshan Biodiversity Protection Zone should prioritize bolstering the management of water source conservation functions in the Yuxi and Honghe regions, while the preservation of biodiversity in western Yunnan should place special attention on Baoshan. In the case of the Northwest Yunnan Plateau, with the exception of Dehong, other cities and prefectures exhibit minimal improvements in both biodiversity protection and water conservation. Moreover, it is imperative to intensify the protection of water conservation function in the karst regions of Qujing and Zhaotong on the Yunnan–Guizhou Plateau.

(2) Regarding the primary influencing factors, both single-factor analysis and interactive assessment consistently point to natural factors as the predominant drivers behind the spatial variations in water conservation functions, corroborating with findings from prior research [42]. Nevertheless, it is essential to acknowledge that other

factors have also contributed to some extent to the spatial differentiation of water conservation functions. This is especially evident in interactive detection, highlighting that the impact of socio-economic factors on regional water source conservation function typically occurs within interactive contexts. Previous studies have identified two scenarios in Yunnan Province: resource water shortage and engineering water shortage [20]. As a result, in the ongoing trajectory of urban economic development, it is imperative to strike a balance between regional ecological functions and minimize adverse impacts on regional water source conservation as much as possible.

(3) It is important to highlight that Yunnan Province's climate types and terrain are relatively intricate, and climate data are influenced by factors such as meteorological station selection and interpolation methods. Future research should aim to enhance the precision of results by expanding the dataset and conducting comparisons among various interpolation techniques. In terms of factor analysis, this study does not offer specific explanations for different terrains and climate zones. Subsequent research could employ geographic detectors to identify these zones and delve into the primary influencing factors within each zone, facilitating more accurate water conservation function protection planning. Additionally, considering data availability, this study did not incorporate indicators such as soil type, vegetation type, and landscape fragmentation in the selection of variables. Therefore, the indicator system for assessing the spatial differentiation of water conservation functions in Yunnan Province requires further refinement. Furthermore, the study faces challenges in understanding how land use structure impacts the spatial variations in water source conservation. Although this study assigns values to different water source conservation types based on existing research, these parameters are not localized to a significant extent, which introduces a level of uncertainty into the research results. Subsequent efforts should aim to address this aspect of the research for greater accuracy.

6. Conclusions

In this study, we employed the InVEST model to assess the average annual water conservation quantity in Yunnan Province, which was determined to be 65.58 mm. Over the study duration, a noteworthy trend emerged, characterized by an initial decrease followed by an increase, resulting in an overall upward trajectory. The spatial distribution exhibited a distinct pattern of "higher values in the southwest and lower values in the northeast". Notably, the southeastern and southwestern regions of the research area experienced a shift toward "high-high" value clusters, while several cities in the northern and eastern areas shifted toward "low-low" value clusters.

Key drivers influencing the spatial differentiation of water conservation included natural environmental factors such as precipitation and Net Primary Productivity (NPP). Additionally, socio economic data, encompassing factors like land use changes and GDP, exhibited a significant positive correlation with variations in water conservation. It is important to emphasize that the interaction among various influencing factors welded a far greater impact on the spatial differentiation of water conservation in Yunnan Province than single factors alone. Notably, the interaction of precipitation and evapotranspiration, population density, land use changes, and regional GDP emerged as dominant interactive factors influencing water conservation.

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