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Article

Ecological–Economic Assessment and Managerial Significance of Water Conservation in the Headwaters of the Yellow River

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Abstract: The water conservation function plays a vital role in the land–water cycle. As the "Chinese water tower", the headwaters of the Yellow River are of great significance to the safety of the Yellow River basin and even the global ecosystem. Taking the grassland ecosystem in the Yellow River source area as the research object, the InVEST water yield model with modified parameters and the ecological value evaluation of the modified equivalent factor method were used to explore the simulated spatio-temporal changes and the value of grassland water conservation from 2001 to 2020. The results show that: (1) the average total amount of water conservation in the source area is 549×10^8 m^3, which is 16% of the runoff in the Yellow River basin, with a growth rate of 7.5 mm/year 1 and a contribution rate of 30%; (2) the total ecological value of grassland water conservation in 2020 is USD 340.03×10^8. The proportion of improved grassland in ecological restoration and management is only 0.51%, while the proportion of original alpine meadow reaches 67% and its ecological function and value are irreplaceable; (3) based on the comprehensive indicators of water conservation capacity, value and importance, Qumalai, Chengduo and Maduo counties are ranked as priority areas for the ecological protection of water resources.

Keywords: water conservation function; ecological service value; grassland type; InVEST model; headwater of the Yellow River; water yield

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1. Introduction

Over the past decades, a substantial contradiction concerning the development of human society and the protection of the ecological environment has become increasingly exacerbated and 60% of global ecosystems have been degraded to varying degrees [1]. The headwater of the Yellow River (HYR) is a major ecological and functional area for water conservation in China. The safety of the ecosystem is related to the ecological, environmental and economic development of the Yellow River basin and even East Asia, focusing the interest of scientists from all walks of life [2]. However, the vegetation type of the ecosystem in the headwater is mainly grassland, which is complex, diverse and highly fragile. Due to the stress of global climate change and the influence of anthropological factors, the ecological environment has been damaged and the grasslands' degradation is serious; this leads to a reduction in the water conservation capacity, deterioration of the soil and production loss, all of which impact the lifestyle of local herdsmen in the region [3–5]

For the regional rotational grazing and grass stand management, a comprehensive grazing ban was implemented on moderately degraded grassland in the HYR, under the Qinghai Sanjiangyuan Nature Reserve Construction Phase I and Phase II. The project achieved remarkable results and the ecological situation has improved significantly [6–8].

The existing ecological protection projects and policies are often based on the overall regional planning and the grasslands are not managed in a classified way. Therefore, a water conservation function should be evaluated based on the grassland type, the ecological function and the ecological value, while the priority conservation areas should be determined.

The assessment is based in the northeast of the Qinghai-Tibet Plateau location. Due to the high altitude and complex terrain, it is difficult to obtain scientific research data. With the continuous development of geographic information systems (GIS), hydrological model simulation becomes the preferred method for estimating water yield [9–11]. Common hydrologic models include: SWAT (Soil and Water Assessment Tool) [12,13], ARIES (the artistic intelligence for ecosystem services) [14] and InVEST (Integrated Value of Ecosystem Services and Tradeoffs). The InVEST model is a widely used and mature open-source ecosystem modeling tool. It is superior to other hydrological models in terms of spatial analysis function and valuation accuracy [15–17]. The climate season factor Z of the InVEST model, which enters the model, is an empirical constant. The value of Z is uncertain and ranges from 1 to 30 [18]. For example, when assessing the water yield of 22 catchments in Scotland and Wales, the value of Z is 30 [19]. For calculating the water retention of Ghana and Côte d'Ivoire in West Africa, the value of Z is 17 [20], whereas for the assessment of water production in Kentucky, the value of Z is 30 [21]. For the assessment of water yield in the Danjiang River basin, China, the value of Z is 12.6 [22]. The InVEST model simulates the water conservation quantity in the HYR, and the spatial and temporal dynamic analysis of the water storage quantity index in the source area still needs more rigorous and scientific methods. The Mann–Kendall (MK) trend analysis test method has been mostly reported to analyze hydrological–meteorological element changes [23–25]. It is a nonparametric statistical test that handles the environmental time series, judges the significance of the trends and estimates the mutation point time at which the simulated values appear. Lepeska et al., recognized that urbanization has a potential impact on water resources' loss. From 1990 to 2018, water resources decreased year by year with the development of urbanization [26]. Irannezhad et al., used the Mann–Kendall test climate change effects on the hydrological process of snow cover in Finland over the past 100 years, and it is believed that the temperature change had the most significant effect on the snow water equivalent in Finland ($p < 0.05$) [27].

The ecological assessment of water yield is an important reference for investment in ecological conservation projects. Currently, the ecosystem service value (ESV) is mainly calculated by the functional value method and the equivalence factor method [28–30]. The equivalent factor method can be used to estimate the ecological value of different ecosystems and it is more reasonable to apply this method to the study of the ecosystem value of grassland [31–35]). The equivalence factor method is based on the IGBP classification method [36–42], making the evaluation results more accurate and conducive to the formulation and implementation of policy suggestions. At present, some scholars have adopted this method to evaluate the ecological value and to achieve reliable results. Xie et al., calculated that the ecological service value of the Qinghai-Tibet Plateau ecosystem is USD $596.48 \times 10^{10}/\text{year}^{-1}$, accounting for 17.68% of the annual service value of the national ecosystem, 0.61% of the global ecosystem and 16.5% of the water conservation value [29]. The water conservation value of grassland in the HYR is USD 15.15×10^{8}, grassland with medium cover (12.53%) and grassland with high cover (11.93%) [43]. Based on the improved equivalence factor method of the net primary productivity (NPP) of vegetation, the total value of different types of ecosystem services in China in 2010 was calculated as USD 242×10^{12}, and the national equivalence factor value is USD $21{,}699.41/\text{hm}^2$ [44]. However, for the regional averaging of the national equivalence factor in the HYR, it is necessary to take into account the vegetation cover in the study area, to improve the equivalence factor value based on the NPP data and to develop the reliability of the equivalence factor method at the regional scale [45].

Using the alpine meadow in the HYR, three key problems will be solved using the modified parameter investment water yield model and the modified equivalent factor method: (1) the spatio-temporal pattern of water yield distribution; (2) the evaluation of the ecological function value of water conservation; (3) the comprehensive evaluation of the water conservation function based on grassland type, ecological function and ecological value, and the determination of an ecological priority conservation area to theoretically support the ecological conservation and management of the headwater area.

2. Materials and Methods

2.1. Study Area

The HYR (32°30′ N–35°0′ N—95°50′ E–103°30′ E) is the largest runoff area and accounts for 16.20% of the total Yellow River basin, with a drainage area of 12.37 × 10^4 km^2 [46]. The study area is between 2680 and 6248 m above sea level (a.s.l.) and increases gradually with an average elevation of 4123 m (a.s.l.) from east to west. The area under study characterizes a typical continental highland climate and the annual average temperature ranges from −12.7 °C to 5.6 °C. Under the influence of the southwest monsoon, the annual average precipitation ranges from 281.8 mm to 1058.6 mm. However, the summer (June to September) generally accounts for 90% of the total annual precipitation. The average annual evaporation ranges from 730 mm to 1700 mm. In the HYR, there are various types of grassland, of which the alpine meadow accounts for 51.55% of the total area of the source area, while improved grassland accounts for only 0.01%. The data of vegetation cover types involved in this study generated the spatial distribution map of vegetation types in the study area based on the IGBP and the Chinese grassland type survey map (CERES land classification from the International Geosphere Biosphere Program IGBP) (Figure 1).

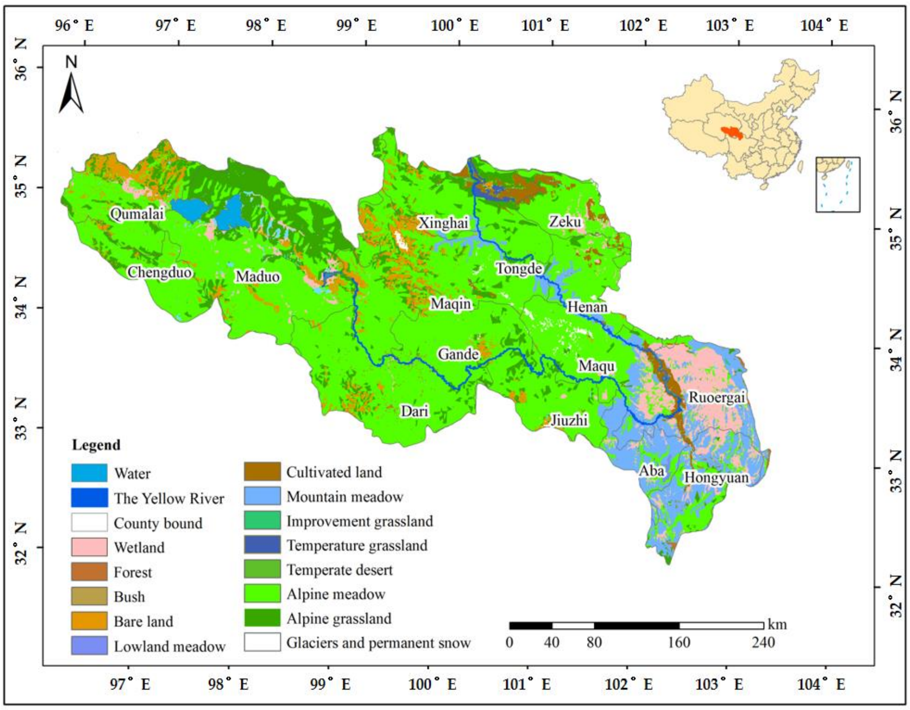

Figure 1. Location of the HRY, grassland types and county locations.

2.2. Data Source and Preprocessing

Environmental variables and socioeconomic data are needed to evaluate water yield and ecological value for the time period 2001–2020 (Table 1). The environmental variables' data are divided into four categories: soil physical and chemical factors (S, 9), terrain factors (T, 5), meteorological factors (A, 4) and vegetation factors (B, 2). The raster images of all variable factors are projected and reclassified according to the geodetic world system 84 (WGS-1984), socioeconomic data (E, 2).

Table 1. The environment variables and data sources.

Category	Abbreviation	Variable Interpretation	Resolution/Unit	Data source
S	CLAY 1	Clay content (0–30 cm)	250 m	HWSD (https://www.fao.org/soils-portal) The accessed date: 11 March 2021
	CLAY 2	Clay content (30–100 cm)	250 m	HWSD (https://www.fao.org/soils-portal) The accessed date: 11 March 2021
	SAND 1	Sand content (0–30 cm)	250 m	HWSD (https://www.fao.org/soils-portal) The accessed date: 11 March 2021
	SAND 2	Sand content (30–100 cm)	250 m	HWSD (https://www.fao.org/soils-portal) The accessed date: 11 March 2021
	SILT	Silt content (0–30 cm)	250 m	HWSD (https://www.fao.org/soils-portal) The accessed date: 11 March 2021
	SOC	Soil organic carbon (0–30 cm)	250 m	HWSD (https://www.fao.org/soils-portal) The accessed date: 11 March 2021
	LUCC	Land use/land cover change	30 m	2005, 2010, 2015, 2020 four years' data of Soil Science Database in China (http://sdb.casnw.net/portal/) The accessed date: 20 March 2021
	IGBP	Land use classification data	250 m	MCD12Q1.V006(https://climatedataguide.ucar.edu/climate-data/ceres-igbp-land-classification) The accessed date: 30 June 2020
	SD	Soil depth	1000 m	Soil Science Database in China (http://sdb.casnw.net/portal/) The accessed date: 2 April 2021
	Velocity	Velocity coefficient	--	USDA-NRCS The accessed date: 5 April 2021
A	PRE	Annual precipitation	1000 m	Meteorological Station The accessed date: 30 June 2020
	TEM	Annual temperature	1000 m	Meteorological Station The accessed date: 30 June 2020
	V	Evapotranspiration	1000 m	Meteorological Station The accessed date: 30 June 2020
	RA	Radiation from the top of solar atmosphere	1000 m	China Meteorological Data Service Centre (http://data.cma.cn/) The accessed date: 30 June 2020
T	LON	Longitude	30 m	ArcGis Calculated
	LAT	Latitude	30 m	ArcGis Calculated
	DEM	Elevation	30 m	Geospatial Data Cloud(http://www.gscloud.cn/) The accessed date: 30 June 2020
	SLP	Slope	30 m	ArcGis Calculated
	TI	Topographic index	30 m	ArcGis Calculated

Table 1. *Cont.*

Category	Abbreviation	Variable Interpretation	Resolution/Unit	Data source
B	PAWC	Plant available water content	30 m	ArcGis Calculated
	K_{sat}	Vegetation evapotranspiration coefficient	--	FAO56
	NPP	Net Primary Productivity	1000 m	MOD16A3
E	Crop	Wheat growing areas; the per unit yield; unit-price	hm^2; kg/hm^2; USD/kg	*China Statistical Yearbook 2002–2021, China Grain and Material Reserve Yearbook 2002–2021* The accessed date: 16 February 2022
	GDP	County GDP	USD	*Qinghai Statistical Yearbook 2021; Gansu Statistical Yearbook 2021; Aba Prefecture Statistical Yearbook 2021* The accessed date: 17 February 2022

2.3. Methods

2.3.1. Spatial and Temporal Pattern and Trend Analysis of Water Yield

Water Yield Calculation

Using the water yield module of the InVEST model, the total annual water yield (mm) was calculated by formula (Equation (1)), where AET (x) is the annual actual evapotranspiration of grid unit X, and P (x) is the annual precipitation of grid unit X. The formula is as follows. AET (x)/P (x) is the approximate Budyko curve (Equation (2)) in terms of annual precipitation and actual evapotranspiration [47]. ω (x) is a nonphysical empirical adjustment parameter that describes the natural climate and soil properties of the watershed (Equation (3)) [48]. The Zhang coefficient is a climatic seasonal factor that represents local hydrogeological properties and is an empirical constant. The standard value ranges from 1 to 30 [18,19]. PAWC effective water retention capacity (Equation (4)), where sand, silt, clay and soil organic matter (om) are described in percent (%).

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

$$\frac{AET(x)}{P(X)} = \frac{1 + \omega_x R_{xj}}{1 + \omega_x R_{xj} + \frac{1}{R_{xj}}} \tag{2}$$

$$\omega_x = z \times \left(\frac{AWC_x}{P_x}\right) \tag{3}$$

$$\begin{aligned} AWC = {} & 54.509 - 0.132 \times sand - 0.003 \times sand^2 - 0.055 \times silt \\ & - 0.006 \times silt^2 - 0.738 \times clay - 0.007 \times clay^2 - 2.688 \times om + 0.501 \times om^2 \end{aligned} \tag{4}$$

Calculation formula for water retention (mm) (Equation (5)), topographic index (TI), soil saturated hydraulic conductivity (Ksat) and velocity coefficient of total annual water storage [49]. The calculation formula is as follows:

$$Retention = \min\left(1, \frac{249}{Velocity}\right) \times \min\left(1, \frac{0.93 \times TI}{3}\right) \times \min\left(1, \frac{K_{sat}}{300}\right) \times Y(x) \tag{5}$$

Water Retention Spatio-Temporal Dynamics and Trend Analysis

The InVEST model is based on ArcGIS and MATLAB 2017 software for analyzing the annual water retention and the spatio-temporal dynamic pattern of the HYR from 2001 to 2020 and for conducting geographic mapping. The trend analysis uses Theil Sen (SEN) median trend analysis and nonparametric (Mann–Kendall, MK) to test each pixel to determine water retention trend and mutation point detection. When the Sen slope > 0, it shows an upward trend, whereas in the opposite situation it shows a downward trend (SEN slope < 0). With a confidence level α = test the significance of the change trend of water retention at 0.05 and confidence level α = 0.05 to test the significance of the change trend of the water yield. If z > 1.96, the results increase significantly; if z < −1.96, the results decrease significantly; if $-1.96 \leq z \leq 1.96$, the results do not change significantly (Table 2).

The Mann–Kendall method (MK) estimates the point of annual change in the simulation value of the annual water production from 2000 to 2020. UF_k is a standard normal distribution (Equation (6)), calculating the statistical sequence by $x_1, x_2, \ldots, x_n$; $UB_k = -UF_k$ generates the inverse order $x_n, x_{n-1}, \ldots, x_1$ (Equation (7)).

$$UF_k = \frac{S_k - E(S_k)]}{\sqrt{VAR(S_k)}} \quad (6)$$

$$UB_k = -UF_k,\ k = n,\ n-1,\ \ldots,\ 1,\ UB_1 = 0 \quad (7)$$

Confidence level α = 0.05 to check the change trend of time series of water retention. When UF or UB > 0, it indicates that the series shows an upward trend, and when UF or UB < 0, it shows a downward trend. The time point corresponding to the intersection of UF and UB curves is the time point at which mutation starts.

Table 2. Water retention change trend assessment table.

SEN_{slope}	Z	Trend
>0.001	>1.96	Significantly increasing
>0.001	−1.96–1.96	Increasing
−0.001–0.001	−1.96–1.96	Stable
<0.001	−1.96–1.96	Decreasing
<0.001	<−1.96	Significantly decreasing

2.3.2. Ecological Value Evaluation of Regional Water Yield

Based on the Chinese terrestrial ecological service value equivalent table [30], the ecological service value equivalent factor in the HYR is calculated using the national average grain and unit price data from 2001 to 2020, according to the principle that the economic value of a standard ecosystem service equivalence factor is 1/7 of the economic value of food production per unit area of farmland [35,42,50]. Based on the NPP data of grassland in the source area of the Yellow River, an ESV equivalent factor of USD 14,461.68/($hm^2 \cdot year^{-1}$) was calculated for the study area and the total value of aquatic ecological services of grassland in the HYR was calculated in combination with the distribution area of grassland species in the headwaters.

2.3.3. Division of Ecological Priority Protection Areas

For the delineation method of the water conservation area, we followed the guidelines for the delineation of the ecological red line of protection [51–54]. Since the delineation of ecological red line certainty, only the water protection amount and importance level in 2020 were extracted and superimposed to delineate the ecological red line and the protection area.

According to the evaluation and classification steps of the guidelines, the grid values corresponding to 30%, 50%, 80% and 90% of the total water conservation capacity are classified as evaluation and classification nodes of water conservation capacity. The analytical hierarchy process (AHP) is used to build the hierarchical structure of importance rating. At the same time, the significance of the data is standardized using the correlation test between the variable environmental factors and the water production. The AHP is used to build the evaluation matrix. After the consistency test, the weighting of the influencing factors is determined. Combined with the comprehensive index algorithm, the water retention importance index (WRI) is obtained. The value range of the WRI ranges from 0–1 and the closer it is to 1, the higher the importance. Finally, the overlay analysis in ArcGIS is used and the natural segment points method is employed for classification.

3. Results

3.1. Spatial and Temporal Distribution of Water Yield

3.1.1. Spatio-Temporal Variation Characteristics

The annual average water retention from 2001 to 2020 in the study area was 443.86 mm, and the overall interannual variation trend of water conservation showed a slight increase, with a rate of 7.5 mm/year $^{-1}$. The total annual average water retention was 5.49×10^{10} m^3.

The estimated water retention was mainly between 300 and 700 mm, which accounted for 93.65% of HYR, and the areas with less than 300 mm and more than 700 mm accounted for 3.21% and 3.15%, respectively. The high value areas were located in Maduo, Toronto and Qumai counties, with heavy rainfall and narrow alpine grassland areas. After rainfall, it is easy to form surface runoff and the regional water retention capacity is high. The median water conservation was observed in Ruoergai, Aba and Hongyuan counties, with water retention of more than 600 mm/year $^{-1}$, whereas Maqu and Jiuzhi counties also showed high water retention, at 540 mm and 587.79 mm/year $^{-1}$, respectively. The median area has a high forest cover and the forest canopy, litter and surface soil effectively intercept the rainfall, thus reducing the water conservation capacity. The least water retention of Qumalai county was 229.69 mm/year^{-1}, with less rainfall, flat terrain and dense forest vegetation coverage intercepting rainfall and surface runoff, resulting in less water retention (Figure 2).

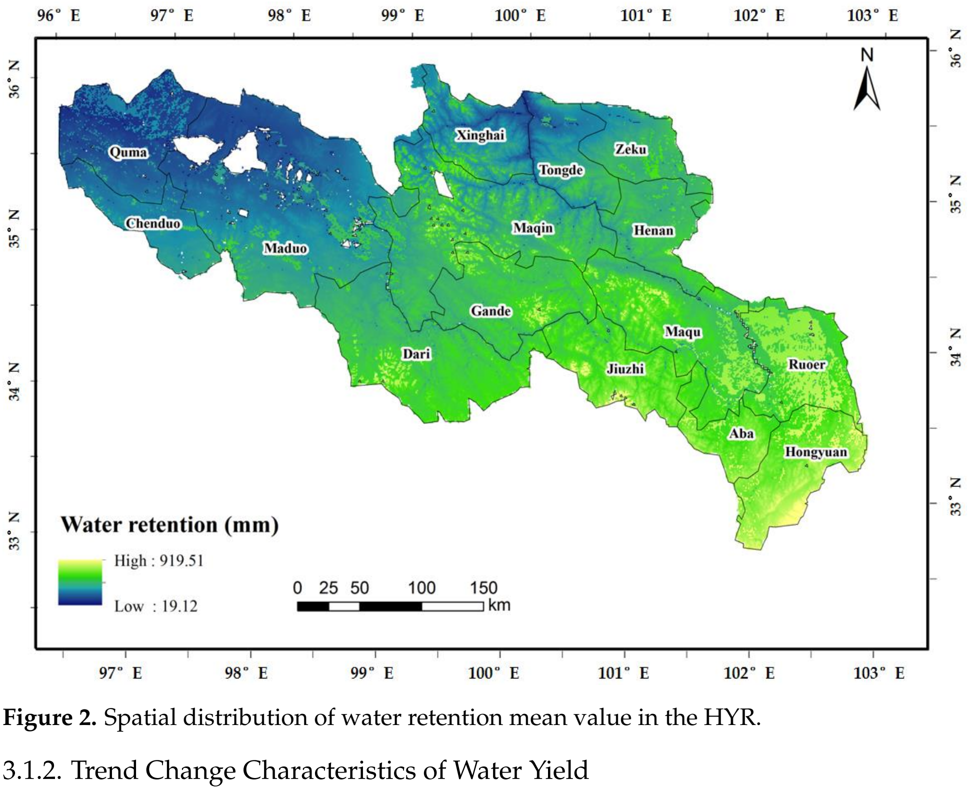

Figure 2. Spatial distribution of water retention mean value in the HYR.

3.1.2. Trend Change Characteristics of Water Yield

The water conservation capacity of most regions in the HYR showed an upward trend from 2001 to 2020 (Figure 3). The area with significant growth accounted for 9.44%, mainly in the southeast of Zeku and Henan counties, the middle of Maqin and the north of Qumalai, with 90.56% of regional water conservation, which showed a slight upward trend.

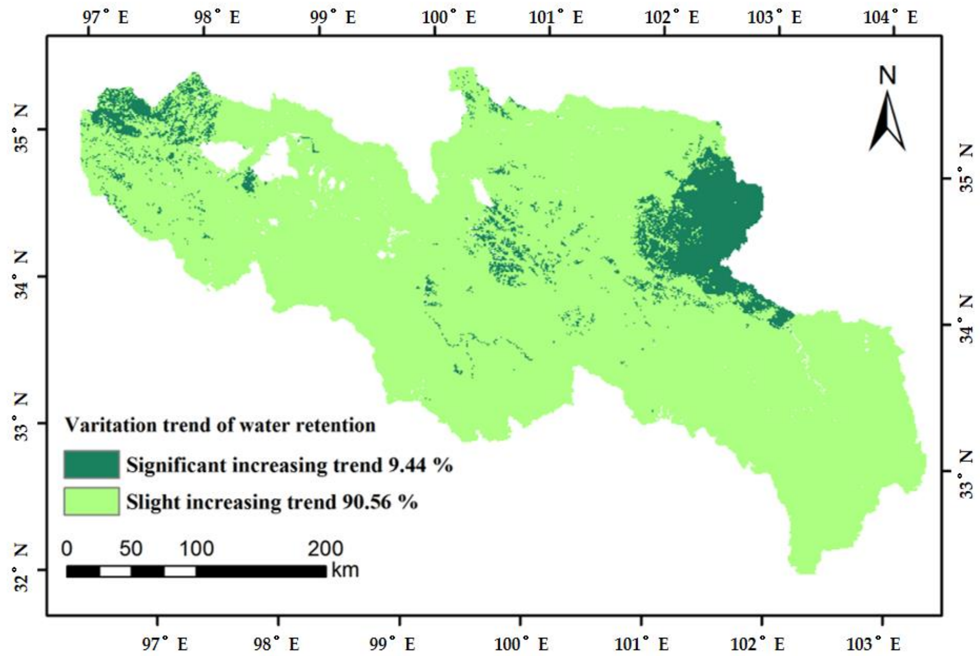

Figure 3. The trend of water retention Change in the HYR from 2001 to 2020.

The water retention in the source area in the last 20 years is statistically described in four time periods (Table 3) and the water production in each period shows an increasing trend. Among them, the annual water production from 2015 to 2020 is the largest. It should be noted that the water production of Chengduo, Gande, Maqu, Dari, Ruoergai, Jiuzhi, Aba and Hongyuan counties increased consistently from 2001 to 2020, while that of the other counties increased from 2001 to 2010, decreased from 2011 to 2015 and increased from 2016 to 2020.

Table 3. Statistical description of water yield of counties in the HYR (unit: mm).

Country	2001–2005	2005–2010	2011–2015	2016–2020
	Mean	Mean	Mean	Mean
Xinghai	290.24	339.6	299.4	424.32
Qumalai	195.27	240.17	220.2	263.12
Maduo	262.43	303.63	303	365.73
Tongde	300.93	349.41	315.91	447.75
Zeku	362.96	414.2	381.63	509.36
Maqin	395.5	432.09	419.02	516.88
Chengduo	277.36	327.05	331.08	356.71
Henan	412.14	446.51	422.37	540.13
Gande	458.34	483.5	490.15	569.31
Maqu	505.19	496.08	529.65	632.68
Dari	451.44	473.6	509.8	558.69
Ruoergai	565.87	530.2	607.6	710.77
Jiuzhi	545.21	548.92	593.75	663.29
Aba	554.83	538.09	623.99	710
Hongyuan	603.22	587.23	686.87	785.74

Analysis of the water retention data by the MK test shows that 2005 is a mutation year. Therefore, we take 2005 as the cut-off point to analyze the change in water retention (Figure 3). The annual water retention increased from 347.14 mm in 2001 to 510.17 mm in 2005 and the lowest annual water retention was recorded in 2002 with 306.06 mm. From 2005 to 2015, the annual water production was 435.77 mm, with a growth rate of 2.71 mm/year $^{-1}$. Another abrupt change occurred in 2015, which shows the water production increased significantly from 435.77 mm to 518.75 mm. In 2018, the water yield in the HYR was the highest since 2001. Overall, the simulation results show that the water yield in the HYR continues to increase (Figure 4).

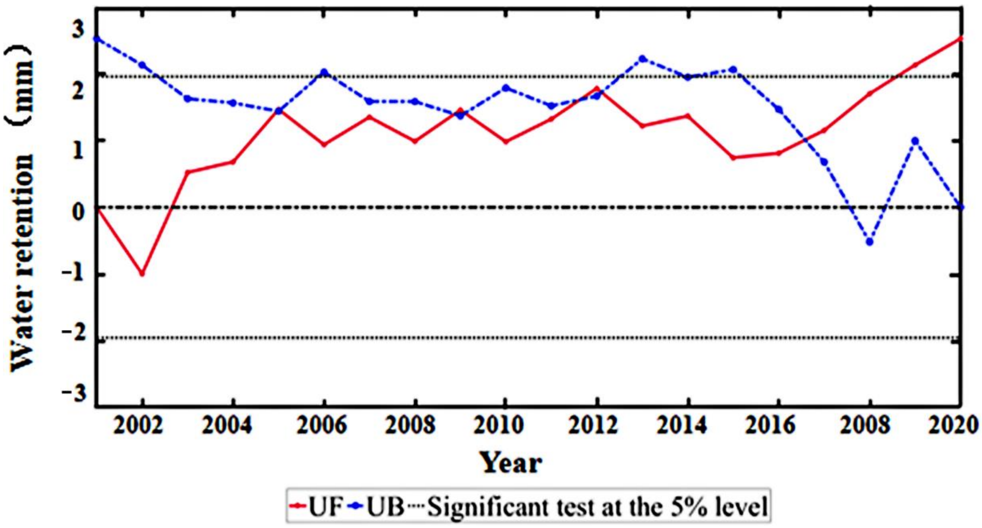

Figure 4. The trend of water retention mean value change in the HYR from 2001 to 2020. The Y axis represents the statistical sequence of water yield calculated at time X, which includes time series UF and inverse time series UB, and x refers to the years 2001–2020.

In general, the spatial and temporal changes of water storage in grassland ecosystems are related to rainfall, vegetation cover, surface runoff and local ecological governance policies, and have seen high values in 2005 and 2015 [55–58]. The ecological protection project of the HYR is an important part of the Sanjiangyuan ecological protection program. The "Sanjiangyuan ecological protection project of China" is divided into two phases, every eight years; 2005 and 2014 are the two phases of the project, respectively. Affected by the policy, the ecological environment in the source area has been significantly improved, the vegetation coverage has increased, the overall production and water storage capacity has shown a steady growth trend, the ecological service function of water conservation in the source area has been improved and the ecological management has achieved remarkable results.

3.2. Ecological Service Value of Water Conservation in Grassland Ecosystem

The service value of grassland water conservation in the HYR is divided into five intervals: 2001, 2005, 2010, 2015 and 2020. The total ecological value was USD 173.06 $\times$ 10^8, USD 247.20 $\times$ 10^8, USD 296.17 $\times$ 10^8, USD 296.26 $\times$ 10^8 and USD 340.03 $\times$ 10^8 during 2001, 2005, 2010, 2015 and 2020, respectively, with the value of water conservation services increasing steadily over the past 20 years. The ecological value of water conservation apparently differs between different grassland types. The low-value area improves grassland, but the value of ecological service also shows a weak growth trend from USD 3.3 $\times$ 10^8 in 2001 to USD 5.74 $\times$ 10^8 in 2020, with an annual contribution rate of 5%, distributed in the north of Zeku County. Alpine grassland in the high-value area was from USD 146.15 $\times$ 10^8 in 2001 to USD 227.59 $\times$ 10^8 in 2020, with an annual contribution rate of 80%. From high to low, the average ecological values and contribution rates over the years are: alpine meadow (66.93%) > temperate grassland (11.30%) > mountain meadow (7.85%) > lowland meadow (7.19%) > temperate desert (5.17%) > alpine grassland (1.03%) > improved grassland (0.51%) (Figure 5).

The value of water conservation in grassland ecosystems is increasing year after year, which further illustrates the importance of ecological protection. Monetary value cannot only make people intuitively feel the ecological value and improve the awareness of ecological protection but can also provide a reference for the formulation of local ecological protection and management policies and planning and design according to ecological values and land uses. The first phase of the ecological protection project invested RMB 7.5 billion, reaching one third of the assessed value in 2005; the second phase investment reached RMB 16 billion, reaching one half of the assessed value in 2015. Ecological restoration planning was classified and managed according to different ecosystems and land use types with remarkable achievements.

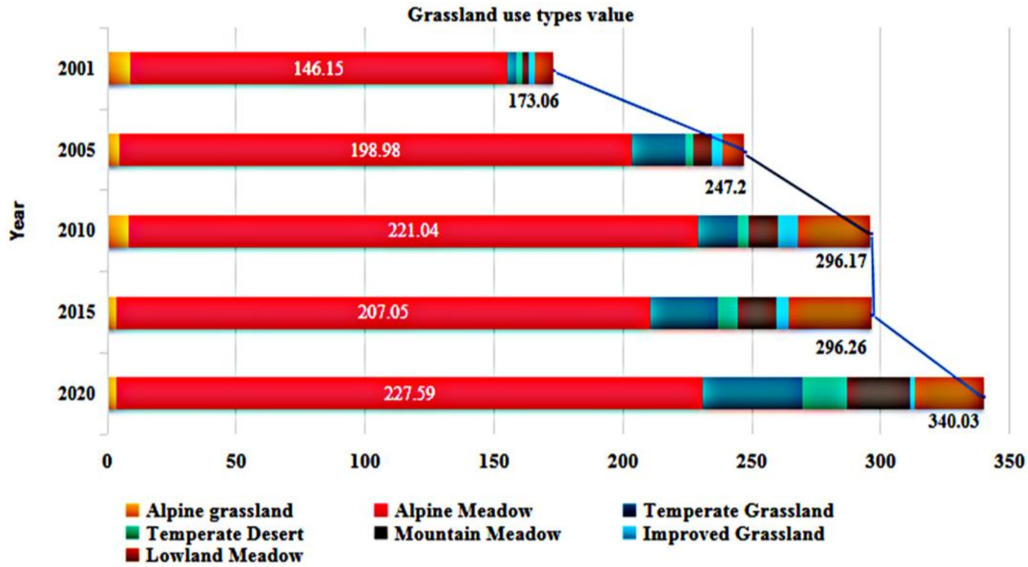

Figure 5. Water conservation function values of different grassland types (USD $\times$ 10^8).

3.3. Spatial Division of Water Conservation Capacity and Its Importance

Five levels of water conservation capacity were identified. The lowest value area (grade I) is concentrated in the northwest of Qumalai, Maduo and Chengduo counties; the low-value area (grade II) is in the southeast of Maduo and Chengduo counties and the northwest of Xinghai and Maqu counties. The medium-grade area (grade III) is in the northeast of Gande, Maqin, Dari and Xinghai counties; the high-grade area (grade IV) is in the northwest of Zeku, Henan, Maqu and Jiuzhi counties. The highest areas (grade V) are in Ruoergai, Aba and Hongyuan counties and account for 14.30%, 13.40%, 21.40%, 34.20% and 16.70% of the HYR, respectively. In general, the spatial distribution of water yield in the source area of the Yellow River is imbalanced and decreases from the southeast to the northwest, showing a step-like distribution (Figure 6).

Five levels of importance were identified: general important area (grade I; <127.5 mm), slightly important area (grade II; 127.5–202.5 mm), moderately important area (grade III; 202.5–340.0 mm), highly important area (grade IV; 340.0–382.5 mm) and extremely important area (grade V; >382.5 mm).

The patterns of the water conservation importance are: the northwest of Qumalai, Maduo and Chengduo counties (mainly grade I); the northwest of Qumalai, Maduo and Chengduo districts (mainly grade II); the southeast of Maduo and Chengduo counties and the northwest of Xinghai and Maqu counties (mainly grade III); the higher-grade area (grade IV) is located in the northwest of Zeku, Henan, Maqu and Jiuzhi counties. The highest areas (grade V) are concentrated in Ruoergai, Aba and Hongyuan counties (mainly grade V) and account for 14.30%, 13.40%, 21.40%, 34.20% and 16.70% of the HYR, respectively. In general, the spatial division of water conservation importance in the HYR is uneven and decreases from the southeast to the northwest, showing a step-like distribution (Figure 7).

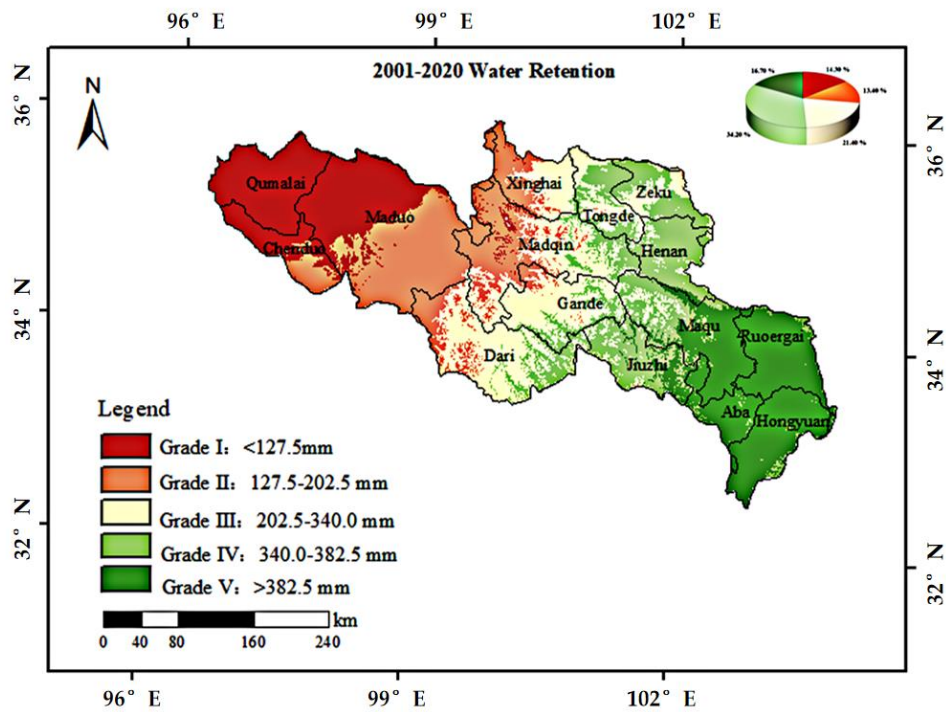

Figure 6. Spatial division of water retention in the HYR (the pie chart shows the proportion of water retention distribution ranges).

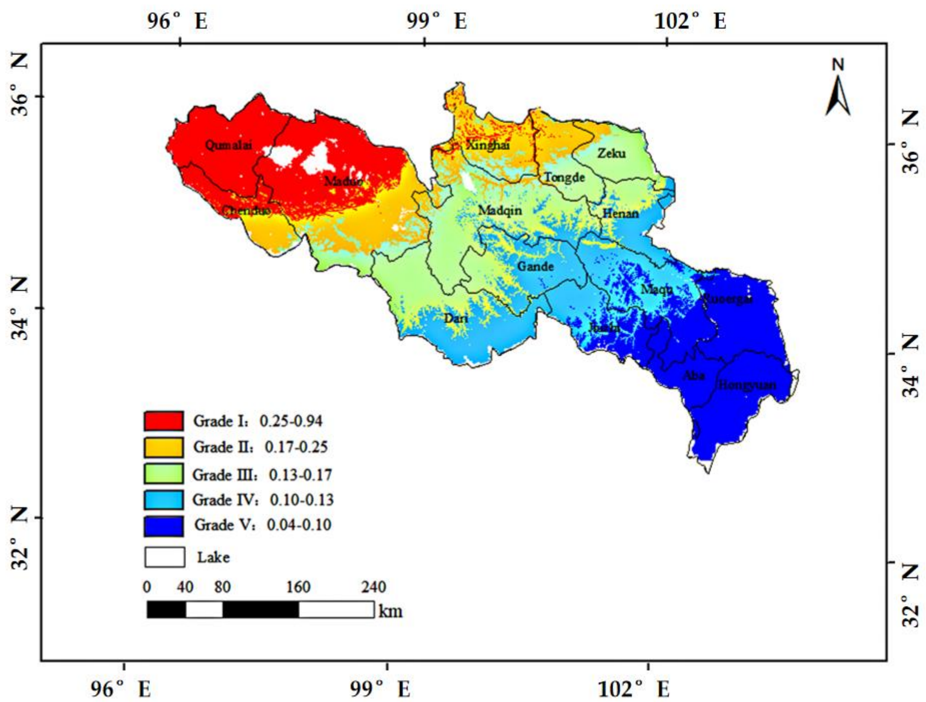

Figure 7. The importance of water conservation evaluation.

Overall, the spatial division of water conservation capacity and its importance is an indicator of the ecosystem assessment of water conservation capacity. In this study, by dividing the importance level of the water conservation capacity, the spatial mapping of the water conservation function facilitates the division and management of the regional ecological reserves.

4. Discussion

4.1. Regionalization of Model Parameters

Regionalization of Z-Value Parameters in the Model

At present, only a few researchers have used the water production module of the InVEST model to analyze the ecological service function of water conservation in the HYR. Yang et al., used the InVEST model to obtain the total water production and to trend change dynamics of the grassland in the Yellow River basin from 1990 to 2018. Our results demonstrated that, when Z is taken as 3.6, the average annual water production is simulated as (534×10^8 m^3) and the actual average water production in 1995, 2005 and 2018 was (596×10^8 m^3), which is relatively close to their study results [59]. A recent study conducted by Zhao et al., calculated the water volume of grassland in the source area of the Yellow River, and the value of Z is 3.5. It is obtained that the average water production for many years from 2001 to 2020 is 509×10^8 m^3, which is similar to the results of the present study (549×10^8 m^3) [60]. Kang et al., analyzed the annual water production and its change trend in the source area of the Yellow River from 1990 to 2010. They calculated the value of Z as 5, and the simulated total water production in 2010 was 0.27×10^8 m^3, lower than the actual total water production in 2010 (497.27×10^8 m^3). The reason for this unreasonable value is that the simulated and measured values are not verified [61]; therefore, Z = 5 is not applicable to the source area of the Yellow River. In this study, based on the annual average water resources of the Tangnaihai hydrological station in the Yellow River Water Resources Bulletin [62], the water yield results of the InVEST model were repeatedly verified (Figure 8). The InVEST model is based on ArcGIS software for data processing and mapping of the environmental variable grid. We take Z = 3.5 as the starting value [60], design the difference (every 0.5 is an interval and gradually increase the difference to run the model. When Z = 5, the average annual water production in 2001, 2005, 2010 and 2020 is close to the value of the actual water production in the bulletin (Figure 8).

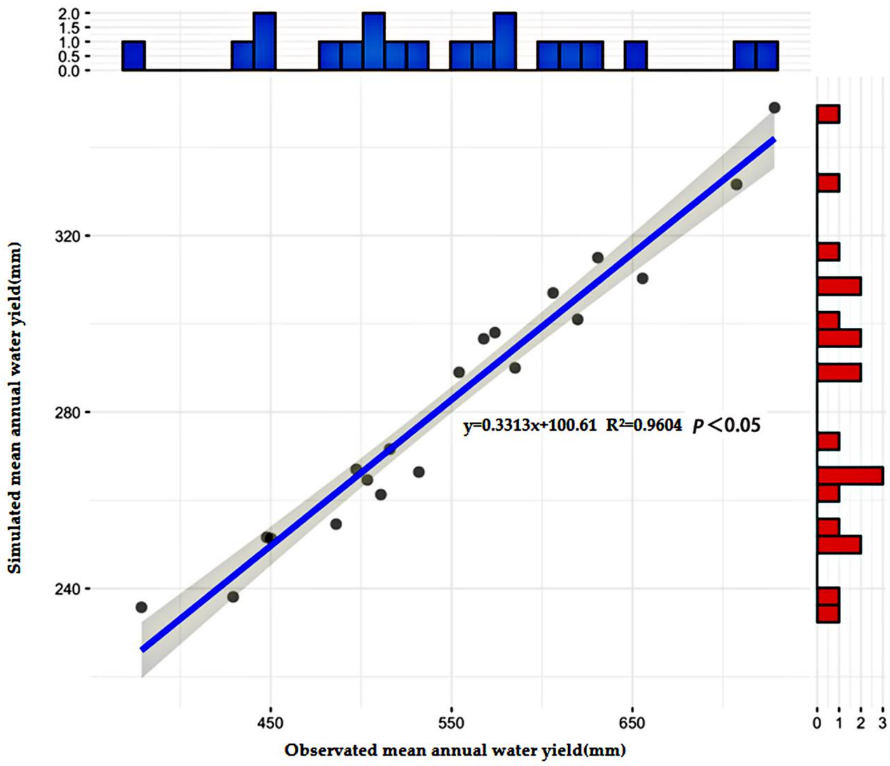

Figure 8. InVEST modeled mean annual water yield against observed mean annual water yield. Blue line indicates a relationship with intercept = zero and slope = one.

4.2. Improvement Measures of Water Conservation Function

The contribution rate of improved grassland to the value of water conservation function in the source area is only 0.51%, which plays a greater role in maintaining biodiversity and productivity, while the restoration ability of water conservation and ecological function is lower [63]. On the other hand, the original alpine grassland plays a significant role, ensuring 60% of the water conservation and ecological value of the source area. Ecological protection projects and policies play a positive role in the restoration of regional ecological functions [59]. The previous "one size fits all" management model is no longer applicable. Due to the change of management ideas, the goal of restoring grassland productivity is changed to the goal of restoring ecological functions. According to the classification standard of ecological service value, ecological management is being carried out on the grassland in the study area and the high-value area is fenced. Generally, the vegetation coverage has increased by 10% and the biomass has increased by 50g/m^2 in the past three years, which can effectively enhance the water conservation function [64]. The median area is divided into rotational grazing and grassland livestock balance and the appropriate livestock carrying capacity of herdsman. The grasslands in the warm season (livestock carrying capacity = their own grassland area/10.62) and the cold season (livestock carrying capacity = their own grassland area/25.21) are checked and verified, respectively, in order to curb the phenomenon of overgrazing and to reduce the ecological pressure of the grasslands [65,66]. In low-value areas, grassland fertilization can increase the content of soil organic carbon and phosphorus, change the structure of soil particle size, increase soil water content, reduce soil erosion and improve the water conservation function of grassland [66].

4.3. Ecological Priority and Regional Management

From 2005 to 2010, the implementation of China's "phase I project of ecological protection and construction in the HYR" effectively curbed the trend of ecological degradation in the HYR and the ecological situation in the source area showed a stable improvement. In 2018, the water production of the source area was 498.79 mm, reaching the highest value in the recent 20 years. In January 2018, Sanjiangyuan National Park, the source of the Yellow River Park, carried out key ecological restoration projects. According to the remote sensing monitoring results of 2020, the vegetation coverage of sandy land in the source area increased from 33.36% to nearly 40%. The wetland vegetation coverage increased by more than 4%, the grassland vegetation coverage reached 74%, the grass yield reached 3082 kg/hm^2, the water yield reached 587.5 mm and the water conservation function was significantly improved [67]. However, the ecological environment in the source area of the Yellow River has a stage of overall improvement and local degradation. Based on the grassland type, ecological function and ecological value, evaluating the water conservation function determines the priority protection areas and determines that Qumalai, Chengduo and Maduo counties are in extremely sensitive areas. The National Nature Reserve of the Yellow River source park is established in Maqu County to expand the ecological reserve to Qumalai and Chengduo counties, with Maqu County as the center. These three counties and districts are set as the priority protection areas for the ecological functions of water conservation.

5. Conclusions

The stability of the water conservation function and the evaluation of the ecological value in the HYR are related to the protection and management of water resources in the Yellow River basin. The quantitative analysis of water retention and the management of ecological spatial planning are the focus of the research. Based on the calculation of water retention using improved parameters of the InVEST model, this study analyzes the spatio-temporal dynamic characteristics of water conservation in the headwaters of the Yellow River from 2001 to 2020; the modified NPP equivalent factor method is used to evaluate the ecological value of the water production services and to classify the ecological conservation areas. Finally, the following three conclusions are drawn:

From 2001 to 2020, the average annual water yield of the study area was 443.86 mm and the average annual total water yield was 4.29×10^{10} m^3, with an increase in water retention in most areas. The area with significant growth accounted for 9.44% and is mainly located in the southeast of Zeku County, Henan, the middle of Maqin and the north of Qumalai; 90.56% of the regional water retention showed a slight upward trend, with an average annual growth rate of 7.5 mm/year^{-1}. The water production capacity of the study area is divided into five levels. Low-value areas are in the northwest of Qumalai County, Maduo County and Chengduo County, while high value areas are in Ruoergai, Aba and Hongyuan counties.

The total value of water conservation ecological services in the grassland ecosystem increased from USD 146.15×10^8 in 2001 to USD 227.59×10^8 in 2020, showing a steady growth trend. The areas with low value are in the improved grasslands, while the areas with high value are distributed in the alpine grassland. The ecological value of alpine grassland increased from USD 146.15×10^8 in 2001 to USD 227.59×10^8 in 2020, with an average annual growth rate of 80%.

The Chinese government has carried out ecological protection projects in the HYR. The implementation of the projects has achieved remarkable results, the grassland degradation has been alleviated and the water conservation function has been significantly improved. Qumalai, Chengduo and Maduo counties are in extremely important areas. It is proposed to classify them into priority areas for the ecological protection of water resources. In areas with high ecological values such as alpine meadows, temperate grasslands and mountain meadows in the headwaters, regional rotational grazing and grass balance should be introduced, and a comprehensive grazing ban should be implemented for lowland meadows, temperate deserts and alpine grasslands. Our suggestions are based on the policies and measures implemented in previous ecological projects, which are reasonable for the restoration and management of the water conservation function in the HYR.

This study evaluates the ecological function and value of water conservation in the HYR, provides reference data and policy suggestions for the formulation of ecological conservation measures and technical project investments and is of great significance for the sustainable development of water resources in the headwaters and watershed of the Yellow River.

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