Water Conservation Function and Sustainability Assessment of the Yellow River Source Region in China

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Abstract: *The Yellow River Source Region (YRSR) is located in the northeastern part of the Qinghai-Tibet Plateau in China, covering the area above the Tangnaigai hydrological station. It is an important water-producing area and water conservation area in the Yellow River Basin, as well as an important ecological barrier for China's ecological security and regional sustainable development. Based on data from ecosystem runoff, precipitation, and evapotranspiration, this study assesses the water conservation in the YRSR from 2015 to 2022 via the water balance equation, and quantitatively analyzes its spatial distribution and change from multiple perspectives. The results indicate that the water conservation capacity in the YRSR exhibited a spatial distribution characterized by higher values in the south and lower values in the north in both 2015 and 2022. The water conservation capacity is relatively high along the Yellow River in the southern part of the source area, with the grassland ecosystem contributing the most to water conservation. Over the 7-years period, both the area and capacity of water conservation in the YRSR increased. Wetland and grassland ecosystems contributed the highest water conservation capacity, while the increase in artificial ecosystems had a negative impact on water conservation capacity. Based on the "Pressure-State-Response" model and the analytic hierarchy process, a comprehensive assessment of the impacts of human activities, natural conditions, and ecosystem functions on the ecosystem health was conducted. The ecosystem health exhibited a pattern of lower values in the north and higher values in the south in both 2015 and 2022. Compared to 2015, the overall average health score increased by 0.0035 in 2022, indicating an improvement in the overall ecosystem health of the source region.*

Keywords: Yellow River Source Region, water conservation, water balance equation, sustainability, ecosystem health assessment

Introduction

Water conservation regulates the hydrological cycle path through the interception, absorption and storage of precipitation by the ecosystem, thus affecting the ecosystem water resources services (Lv et al. 2015), effectively ensuring the health and stability of the ecosystem, promoting ecological balance, and laying a key foundation for the sustainable development of human society and the natural environment (Daily et al., 2009). Under the dual influence of natural factors and human activities, the objective assessment and monitoring of water conservation has become the core premise of protecting the ecological environment and maintaining the sustainable use of water resources.

The Yellow River Source Region (YRSR) is located in the northeastern part of the Qinghai-Tibet Plateau in China, covering the area above the Tangnaigai hydrological station. It is an important water-producing area and water conservation area in the Yellow River Basin, as well as an important ecological barrier for China's ecological security and regional sustainable development (Wang et al., 2002). As a vital component of the Qinghai-Tibet Plateau, known as the "Water Tower of China," the source region of the Yellow River has consistently played an essential role in water conservation and ecological regulation (Wu et al., 2020). An objective, scientific, and quantitative evaluation of the water conservation function and sustainability at the YRSR provides a robust scientific foundation for regional ecosystem planning, development, and ecological management decisions.

In this study, the 16 m spatial resolution multispectral images of GF-1 and GF-6 in 2015 and 2022 were used as the basis of ecosystem classification in the YRSR. Combined with precipitation data and evapotranspiration data, based on the principle of water balance, the spatial distribution and changes of water conservation in the YRSR were quantitatively analyzed and evaluated, providing a scientific basis for sustainable management countermeasures for the quality of ecosystem services and ecosystem integrity in the upper Yellow River.

Study Area

The YRSR is located in the northeast of the Qinghai Tibet Plateau. It is the source of the Yellow River and an important part of the Three Rivers Source Area, the largest water conservation functional area in China (Guo et al., 2022). This region includes 7 ecosystems including grassland, wetland, artificial, forest, shrub, desert, and others, with a range of 32 ° 09 '~36 ° 06'N and 95 ° 54'~103 ° 22'E （fig.1）. The total area is 131667.58 square kilometers, accounting for about 17.0% of the entire Yellow River Basin, mainly including Gansu Province, Sichuan Province, Qinghai Province, and other regions. The overall terrain is high in the west and low in the east, characterized by cold winters and cool summers, strong radiation, and high evaporation, belonging to a typical inland plateau climate (Wang et al., 2002). The altitude range of the YRSR is between 2394m and 6286m. Due to its high altitude and complex terrain, the ecosystem is highly sensitive to environmental changes (Wu et al., 2020).

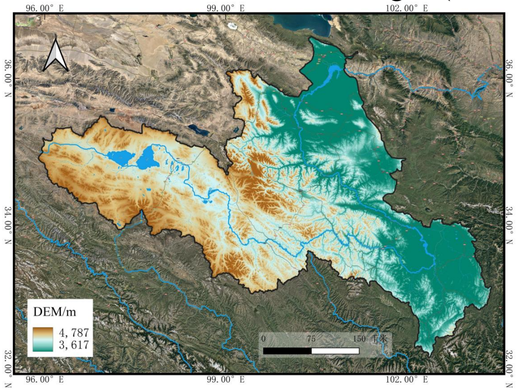
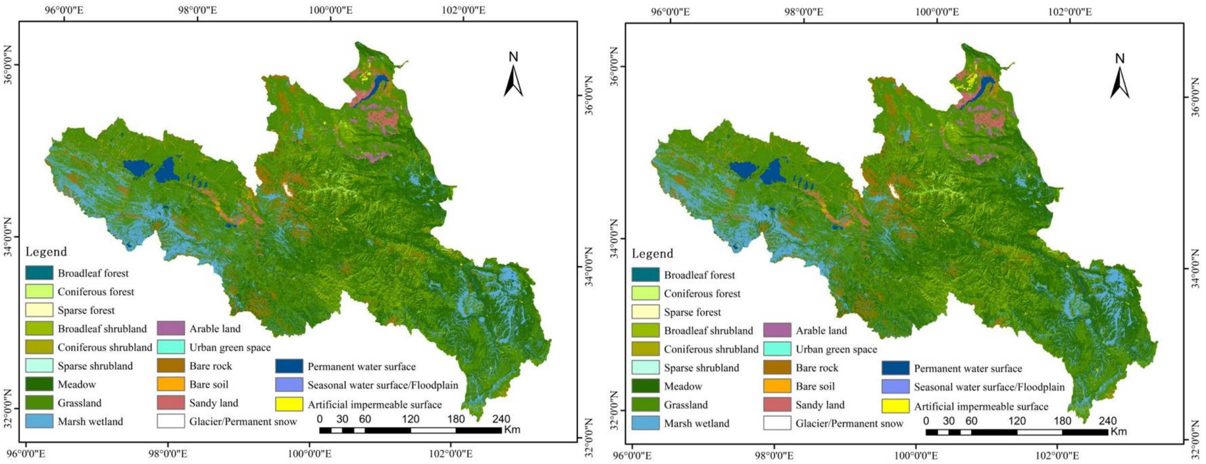


Figure 1: The Yellow River Source Water Conservation Area

Methodology

a. Classification of Ecosystem Types

The calculation of water conservation capacity is closely related to the type of surface ecosystem. The type of ecosystem is interpreted from remote sensing images. The 16 m spatial resolution multispectral images of GF-1 and GF-6 in 2015 and 2022, total 26 scenes, were selected as the data source. The difference image binarization method (Du et al., 2024) was used to extract the change objects, and the machine learning method (Du, 2024) was used to obtain the ecosystem types in 2015 and 2022, including 7 first-level classes and 18 second-level classes (as shown in Figure 2).



(a) **(b)**

Figure 2: Ecosystem classification results: (a) 2015; (b) 2022

b. Calculation of Water Conservation

Water conservation refers to the capacity of surface and groundwater systems to retain, permeate and store rainwater through ecological processes and land use types. It plays a crucial role in the sustainable utilization of water resources, drought resistance, flood relief, maintenance of ecological balance, protection of groundwater, and response to climate change. The Yellow River source water conservation area, as the most important runoff area, water source area, and ecological conservation site in the Yellow River Basin, is a critical region for water security, ecological environment construction, and livelihood production in the Yellow River Basin and northern China.

Based on the ecological system types of the Yellow River source, combined with precipitation and evapotranspiration, the water balance equation is used to evaluate and calculate the water conservation capacity of the Yellow River source water conservation area. The water balance equation is based on the law of conservation of mass of water in ecosystems, and describes the water conservation capacity of ecosystems by the difference between the input and output of precipitation within a certain temporal and spatial range. The water balance equation involves three parameters: precipitation, evapotranspiration, and surface runoff.

$$Q_{wr} = \sum_{i=1}^{n} A_i \times \left(P_i - R_i - ET_i\right) \times 10^{-3}$$

where， Q_{wr} is the water conservation （m^3/a）； P_i is the production flow （mm/a）； R_i is the surface runoff (mm/a); ET_i is the evapotranspiration (mm/a); A_i is the area of class i ecosystem (m^2); i is the class i ecosystem type; n is the total number of ecosystem types. The production flow refers to the precipitation using the national center for atmospheric science (NCAS) climate data sets by the CRU TS (http://www.cru.uea.ac.uk/data). In order to reduce the interference of climate factors on the calculation of water conservation capacity, the average annual precipitation of the YRSR from 2011 to 2020 was selected to calculate. The evapotranspiration of the YRSR from 2011 to 2020 was calculated using the GLEAM (global land-surface evaporation: the Amsterdam methodology) product. The surface runoff is obtained by multiplying the rainfall by the surface runoff coefficient, which is determined by the ecosystem type of the surface cover. The reference literature for the surface runoff coefficient for each ecosystem in this study is as follows (Zhang et al., 2021, Wu et al., 2020, Gong et al., 2017, Xu et al., 2018, Li et al., 2016).

Analysis of Water Conservation Function

a. Water Conservation Capacity

The quantile classification map of water conservation capacity serves as a valuable reference for regional water resource protection and management. By categorizing the water source conservation capacity into five levels from low to high based on quantiles—weak, relatively weak, average, relatively strong, and strong (as illustrated in Figure 3)—we can assess the contribution of water source conservation capacity in various regions from the standpoint of coverage distribution. In both 2015 and 2022, the distribution trend of these levels remained consistent. The water source conservation capacity exhibits a gradual decrease from south to north. Specifically, the southern and central regions boast strong water source conservation capacity, whereas the northern region demonstrates weaker capacity.

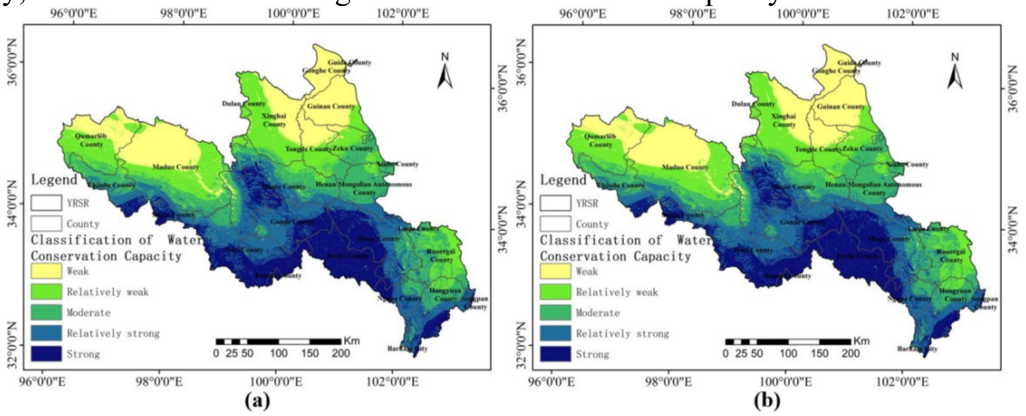
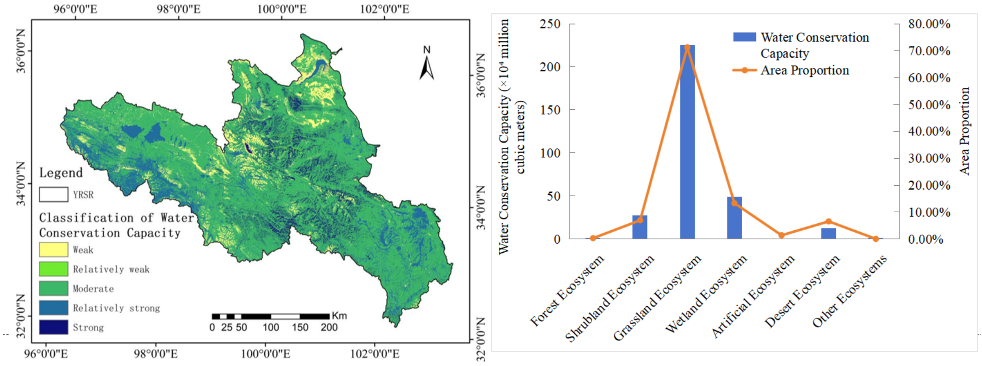


Figure 3: Yellow River Source Region Water Conservation Capacity Grading Map: (a) 2015, (b) 2022

According to the primary categories of ecosystems, the water conservation capacity of the ecosystems in the Yellow River Source Water Conservation Area is statistically analyzed by zone. Through the analysis of the differences in water conservation capacity among different ecosystems, we can better identify the average contribution of different ecosystems to water conservation capacity. Figure 4(a) shows the grading of water conservation capacity of each ecosystem in the Yellow River Source Water Conservation Area. Artificial ecosystems have weaker water conservation capacity, while other ecosystems dominated by glaciers and permafrost have stronger water conservation capacity. Wetland ecosystems, shrub ecosystems, and grassland ecosystems follow in that order. Figure 4(b) presents a bar chart illustrating the water conservation capacity of each ecosystem. Grassland ecosystems, which cover 71.25% of the study area, make the largest contribution to the total water conservation capacity in the Yellow River Source Water Conservation Area, reaching 22.5 billion m^3. Wetland ecosystems, accounting for 13.35% of the area, rank second in terms of total water conservation capacity among all ecosystems. Grassland ecosystems contribute the most to water conservation capacity; although shrub ecosystems only account for 6.99% of the area, they contribute the third-largest total water conservation capacity, highlighting the outstanding water conservation potential of this ecosystem.

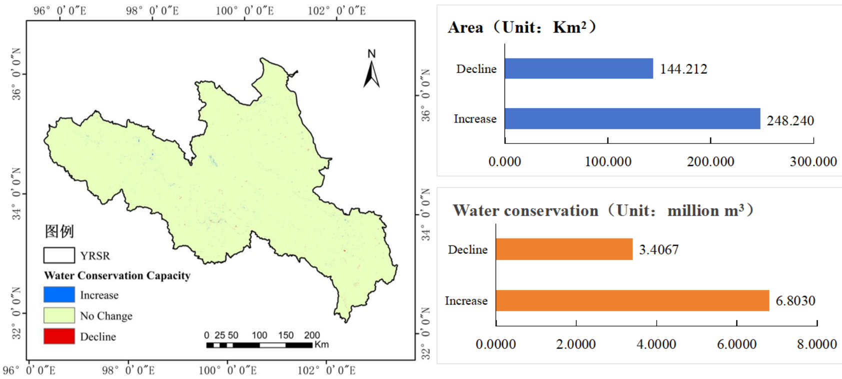


(a) **(b)**

Figure 4: Ecosystem Type Analysis of the Yellow River Source Region: (a) water conservation capacity grading Map; (b) water conservation capacity in 2022

b. Changes in Water Conservation Pattern

Comparative analysis reveals that from 2015 to 2022, the water conservation capacity in the Yellow River Source Water Conservation Area showed localized increases and decreases, reflecting the fluctuations in water conservation capacity in different regions as the surface ecosystem types changed. The changes in water conservation are distributed in small, scattered patches (as shown in Figure 5(a)). Overall, the area where water conservation capacity increased is larger than the area where it decreased (as shown in Figure 5(b)), and the total water conservation capacity in the study area increased by 3.39634 million m^3 over the seven years. The distribution of water conservation capacity recovery is consistent with natural water systems such as the Yellow River, Zaling Lake, and Eling Lake. The decline in water conservation capacity mainly occurred near the main urban areas of each county-level administrative region.



(a) **(b)**

Figure 5: Water conservation changes in the Yellow River Source Region: (a) spatial distribution of water conservation changes; (b) statistical analysis of water conservation changes

The changes in water conservation capacity for each ecosystem type from 2015 to 2022 vary (Figure 6). Wetland ecosystems experienced the largest increase in water conservation, reaching 10.4912 million m^3, followed by grassland ecosystems and other ecosystems, which increased by 2.8869 million m^3 and 1.7349 million m^3, respectively; the ecosystem with the largest decrease was the artificial ecosystem, which decreased by a total of 10.3667 million m^3, and the desert ecosystem decreased by a total of 1.0965 million m^3. Combining the changes in ecosystems from 2015 to 2022, the increase in wetland ecosystems and grassland ecosystems contributes to the overall increase in water conservation capacity, while the increase in artificial ecosystems has a negative impact on water conservation capacity.

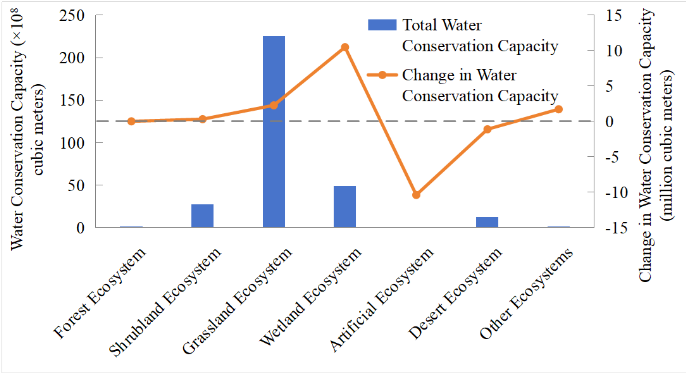


Figure 6: Changes in water conservation capacity in the Yellow River Source Region(ecosystem units)

c. Overall Ecosystem Health Assessment

Based on the observation of ecosystems in the Yellow River Source Water Conservation Area and the inversion of water conservation, a quantitative assessment of the overall ecosystem health in the source area was conducted using the "Pressure-State-Response" model framework (Zhang et al., 2022; Li et al., 2021). Pressure indicators represent the impacts and stresses on ecosystems from human activities and resource utilization. In this study, population size, nighttime light, and gross domestic product (GDP) were used as specific evaluation indicators; state indicators represent the current state of the ecosystem, and biodiversity index, PM2.5 concentration, and NDVI were adopted in this study; response indicators describe the ability of humans to take initiative and provide ecological environmental services, thus land use degree and water conservation capacity were selected as specific indicators.

Based on a comprehensive analysis of the three aspects of pressure, state, and response, the ecosystem health assessment results for the Yellow River Source Water Conservation Area are shown in the figure 7. From a spatial distribution perspective, the ecosystem health distribution in the YRSR in 2015 and 2022 is similar. The ecosystem health assessment scores are highest on the south side of the Yellow River and gradually decrease from south to north, with the low values in the north presenting a fragmented distribution. Areas with lower ecosystem health assessment scores, such as the north side of Zaling Lake and Eling Lake and near the Longyangxia Reservoir, are covered with a large amount of bare rock, bare soil, and sandy land, with little surface vegetation cover, making them susceptible to changes due to external disturbances. In 2022, the health index assessment score on the east side of Zaling Lake increased. On an annual average basis, the ecosystem health in the YRSR shows a trend of improvement, with the average ecosystem health score in 2022 being 0.7381, which is 0.0035 higher than in 2015.

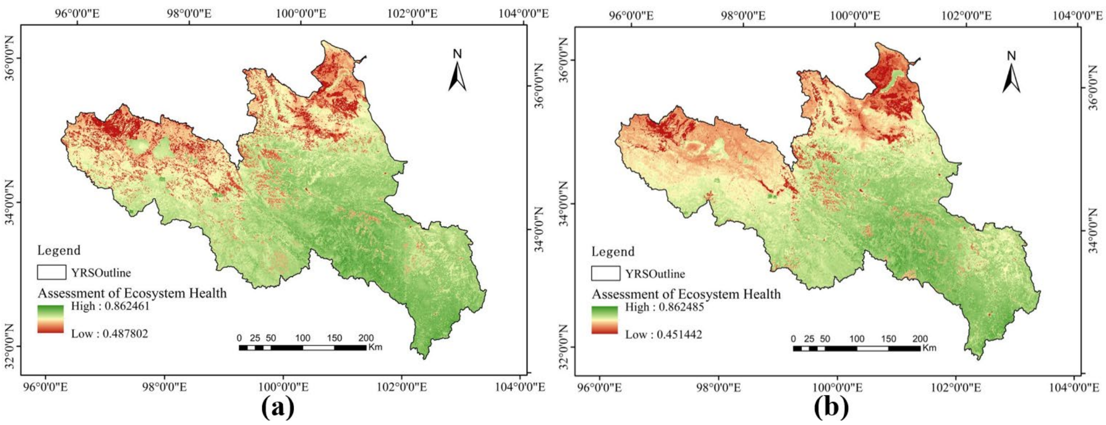


Figure 7: Results of the overall ecosystem health assessment; (a) 2015; (b) 2022

Conclutions

This paper estimates the water conservation capacity of the YRSR through the water balance equation, analyzes the spatial distribution and changes of water conservation, and comprehensively evaluates the overall ecosystem health score and changes in the YRSR by combining multiple types of environmental data. The main conclusions are as follows:

(1) In 2015 and 2022, the water conservation capacity and classification of the YRSR showed a distribution trend of high in the south and low in the north, with grassland and wetland ecosystems making the greatest contribution to the total water conservation.

(2) From 2015 to 2022, the water conservation capacity in the YRSR showed an increasing trend, with both the area and total amount of increased water conservation capacity increasing. The recovery of water conservation capacity was mainly distributed along the Yellow River.

(4) The main reason for the reduction of water conservation capacity is the expansion of artificial ecosystems, which has led to an increase in the density of cities and transportation networks; one of the reasons for the increase in water conservation capacity is the effective implementation of protection measures for wetland and grassland ecosystems, and the surface vegetation helps to store water resources.

(5) The spatial distribution of the overall ecosystem health in the YRSR showed a fragmented low-value distribution in the north and a gradually increasing trend to the south in both 2015 and 2022; the overall average health evaluation in 2022 was improved compared to 2015, indicating that the overall ecosystem health in this region has improved.

This study not only reveal the current ecological situation and its changing trends in the YRSR but also provide important scientific basis for the ecological protection and sustainable development of the region. Through reasonable planning and implementation of targeted protection measures, the ecosystem service functions of the YRSR can be further improved and enhanced, ensuring the water resources security and ecological security of the Yellow River Basin.

Acknowledgements

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