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XU Hua¹, REN Heng^{1*}, ZHOU Tao², JIANG Shengji¹, ZHAO Wenzhi¹

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Abstract

The exploration of sustainable water resource development is pivotal for ensuring regional economic and social advancement, as well as maintaining ecological balance. However, scant research has holistically evaluated ecological, living, and production water use through the "community of life" lens. This study developed a sustainable water resource utilization (SWRU) evaluation index system for water resources in the Gansu region of Qilian Mountains from 2000 to 2023. We adopted the "three-life" water use approach within the "community of life" and conducted a complete evaluation of the existing state of SWRU in the study area. We further developed a simulation model using system dynamics (SD) approaches for status quo, economic, and comprehensive multi-scenario forecasting, and employed the obstacle degree model to determine the parameters influencing SWRU. The findings revealed that the SWRU in the Gansu section of Qilian Mountains has advanced from a basic phase (0.438) to a commendable level (0.614), with a spatial distribution of "high in the west and low in the east" . The SD simulation results indicated that the comprehensive scenario achieves the highest SWRU value (0.638), outperforming the economic (0.636) and status quo (0.630) scenarios. In the short term, a comprehensive scenario can support regional sustainable development; however, it has the potential to exacerbate the supply-demand conflict in the long term, necessitating additional refinement of the water resource allocation system. Proportion of ecological water consumption (obstacle degree of 14.388%), gross domestic product (GDP; 12.475%), and total water resources (12.019%) have been highlighted as the primary obstacle factors on SWRU. Future strategies should focus on optimizing resource allocation to provide a high-quality ecological products supply, as well as merging ecological preservation with industrial advancement to support the long-term synergistic development of the living community.

Full Text

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Sustainable water resource management in the Gansu region of Qilian Mountains

XU Hua1, REN Heng1*, ZHOU Tao2, JIANG Shengji1, ZHAO Wenzhi1

1 Chinese Academy of Science, Northwest Institute of Eco-environment & Resources, Lanzhou 730000, China;
2 College of Geography and Environment Science, Northwest Normal University, Lanzhou 730070, China

Abstract: The exploration of sustainable water resource development is pivotal for ensuring regional economic and social advancement, as well as maintaining

ecological balance. However, scant research has holistically evaluated ecological, living, and production water uses through the "community of life" lens. This study developed a sustainable water resource utilization (SWRU) evaluation index system for water resources in the Gansu region of Qilian Mountains from 2000 to 2023. We adopted the "three-life" water use approach within the "community of life" and conducted a complete evaluation of the existing state of SWRU in the study area. We further developed a simulation model using system dynamics (SD) approaches for status quo, economic, and comprehensive multi-scenario forecasting, and employed the obstacle degree model to determine the parameters influencing SWRU. The findings revealed that the SWRU in the Gansu section of Qilian Mountains has advanced from a basic phase (0.438) to a commendable level (0.614), with a spatial distribution of "high in the west and low in the east" . The SD simulation results indicated that the comprehensive scenario achieves the highest SWRU value (0.638), outperforming the economic (0.636) and status quo (0.630) scenarios. In the short term, a comprehensive scenario can support regional sustainable development; however, it has the potential to exacerbate the supply-demand conflict in the long term, necessitating additional refinement of the water resource allocation system. Proportion of ecological water consumption (obstacle degree of 14.388%), gross domestic product (GDP; 12.475%), and total water resources (12.019%) have been highlighted as the primary obstacle factors on SWRU. Future strategies should focus on optimizing resource allocation to provide a high-quality ecological product supply, as well as merging ecological preservation with industrial advancement to support the long-term synergistic development of the living community.

Keywords: sustainable water resource utilization (SWRU); community of life; system dynamics (SD) model; obstacle degree model; Qilian Mountains

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1 Introduction

Water resources are fundamental and strategic for sustaining regional economic, social, and ecological civilization construction (Jing et al., 2022, Yang et al., 2025). Sustainable development is vital for achieving regional economic and social progress and maintaining ecological equilibrium (Qi et al., 2023). However, the increasing frequency of extreme global climate events,

*Corresponding author: REN Heng (E-mail: renheng@llas.ac.cn)
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as well as the rapid acceleration of economic and urbanization processes, have exacerbated the tension between regional water supply and demand. This issue is particularly acute in arid and semi-arid areas with limited water resources and fragile ecological environments (Wang et al., 2025). The loss of glacial meltwater, increased fluctuations in river runoff, and seasonal discontinuities in some basins directly threaten vegetation cover and biodiversity (Ai et al., 2024). Concurrently, ecological degradation phenomena such as soil erosion and land desertification further destabilize the mountain-water-forest-farmland-lake-grassland-desert community of life (Xiong and Leng, 2024). To address these challenges, China has proposed strategic initiatives such as "Beautiful China", "Ecological Civilization Construction", and "Mountain-Water-Forest-Farmland-Lake-Grassland-Desert Community of Life". These initiatives entail studying water resources from the perspective of complex systems in which human activities and natural processes are linked (Yuan et al., 2021). The Qilian Mountains act as a critical ecological barrier in western China, with the Gansu region exemplifying the "community of life". The combination of glaciers, rivers, wetlands, forests, grasslands, and deserts in this region has resulted in distinct water conservation and supply roles. The water resources here not only support agricultural irrigation, industrial production, and urban water needs but also meet the base flow requirements of downstream ecosystems. These resources are vital for the local oasis economy and ecological stability, providing key ecological services to the Hexi Corridor and the wider northwestern region of China. Consequently, accurately assessing and incrementally improving the sustainable use of water resources is critical for optimizing regional water use and addressing related ecological concerns (Zhang et al., 2022).

A dynamic feedback mechanism exists between sustainable use of water resources and regional development. Sensible development and use of these resources are vital for quality regional development in sectors such as agriculture, industry, and ecological protection, all of which require a consistent water supply (Yang et al., 2025). In contrast, improving regional economic strength can support water resource management, where technological innovation leads to new productivity, supporting efficient management and reform of water resources (Ma et al., 2025). These interactions form a dynamic balance and sustainable synergy between water resources and regional development through a "demand-supply-innovation" feedback cycle. When researching water resource management, scholars typically use different sources to investigate ecologically sustainable development. Araza et al. (2020) investigated likely streamflow changes and associated risks to water resources in the Abuan watershed of the Philippines, focusing on the effects of climate and land use changes. Wang et al. (2019)

examined the spatial and temporal distribution of the degree of coordination between regional water resources, social economy, and ecological environment systems. By assessing the sustainability of water resource use, understanding spatial variations, and investigating the underlying causes of these differences, it is possible to address regional water scarcity and imbalance issues while balancing economic development and water resource conservation (Zhang and Duan, 2024). Domestic and international studies have explored more accurate and reliable methods for achieving sustainable water resource management and governance, including approaches such as coupled coordination assessment (Li et al., 2021a), system dynamics (Zhang et al., 2019a; Tao et al., 2025), and water ecological footprint analysis (Irandoost et al., 2025). Water resource management is a highly interconnected system that includes not only resource usage and environmental capacity but also broader goals such as economic growth, social equity, and environmental protection (Ding et al., 2023). Consequently, sustainable water resource utilization (SWRU) should be evaluated holistically, taking all factors into account. Many scholars use integrated indicator modelling and complex systems analysis to detect and evaluate SWRU (Zeng et al., 2022; Zhang and Duan, 2024). Integrated indicator modelling entails creating a comprehensive evaluation system, determining indicator weights, and selecting appropriate and accurate evaluation methods. The natural-economic-social-environmental index system is a mature environmental assessment framework that has been frequently used by researchers to evaluate system interactions (e.g., Jiang and He, 2023). System dynamics (SD) model employs mathematical modelling to simulate

complex behaviours and feedback mechanisms in real-world systems. It functions as an additional tool for predicting future system trends by adjusting parameters and generating different development scenarios (Tao et al., 2025). Recent challenges, such as increased glacier melting and vegetation degradation in the Qilian Mountains, have become more apparent (Ma et al., 2019), resulting in a decline in the water supply capacity and a threat to ecosystem integrity and stability. A comprehensive approach is required to conduct a coupled examination of social, economic, and ecological systems as a whole. Examining SWRU within a "socio-economic-ecological" composite system is more in line with the practical requirements of complex watershed management.

This study used the macroecological concept of the mountain-water-forest-farmland-lake-grassland-desert community of life as its core guiding ideology to innovatively construct a SWRU model that covers ecological, living, and production water uses from the holistic perspective of "community of life". Methodologically, we accomplished a successful integration of three models—the SWRU model, the SD model, and the obstacle degree model—to improve the research's systematicity and predictability. The SD model was used to simulate the dynamic evolution rules of water resources under various development scenarios, and the barrier degree model was used to identify the primary obstacle factors of SWRU. The study systematically revealed the current state of SWRU in the Gansu region of Qilian Mountains, providing a scientific foundation for land and water resource management in the region, as well as a replicable demonstration model for SWRU in arid and semi-arid areas.

2 Study area

The Qilian Mountains (36°-40°N, 93°-104°E) are located at the intersection of the Qinghai-Xizang Plateau, Inner Mongolia Plateau, and Loess Plateau, spanning Qinghai Province and Gansu Province of China. They have a topography that descends from west to east, with elevations ranging from approximately 1100 to 5800 m (Ren et al., 2024). The Gansu region of Qilian Mountains (study area) is a critical water source replenishment zone for the Shiyang, Heihe, and Shule rivers and Suigan Lake. Every year, it adds 7.468×10^9 m^3 of runoff volume to the Hexi Corridor Oasis (Guo et al., 2023). The study area includes the urban agglomeration of Lanzhou City, Baiyin City, Wuwei City, Jinchang City, Zhangye City, Jiayuguan City, and Jiuquan City in Gansu Province (Fig. 1). It is characterized by a continental subarctic semi-humid mountainous climate and receives 30-600 mm of annual precipitation (Ma et al., 2019). This part of the Qilian Mountains supports varied terrestrial ecosystems, resulting in an intricate natural mosaic that includes mountains, waters, forests, farmlands, lakes, grasslands, deserts, and ice. This mosaic has a substantial impact on the ecological health and water resource security of the Hexi Corridor Oasis and the surrounding northwestern region of China (Guo et al., 2023; Ren et al., 2024). Since the start of ecological restoration operations in 2016, there have been local improvements to ecological health. However, the lack of systematic governance has exacerbated the tension between conservation and development, emphasising the critical need for an integrated "socio-economic-ecological" governance structure.

3 Methods and data sources

3.1 SWRU evaluation

3.1.1 Evaluation index system This study used panel data from the seven municipal administrative regions in the study area, covering the years 2000-2023. Adopting a "three-life" water use perspective, we integrated the mountain-water-forest-farmland-lake-grassland-desert community of life within a socio-economic-ecological-resource framework and selected 17 indices to represent the ecological, production, and living function subsystem levels (Table 1). The average terrain relief influences the

Fig. 1 Overview of the Gansu region of Qilian Mountains based on the digital elevation model (DEM). The boundary is based on the standard map (GS(2024)0650) of the Map Service System (https://bzdt.ch.mnr.gov.cn/), and the boundary has not been modified.

Table 1 Evaluation index system of the sustainable water resource utilization (SWRU)

Target layer	System layer	Index layer	Index attribute	W_{j1}	W_{j2}	W_j	W_j^*
Level of SWRU	Ecological function	Average terrain relief (m)	−	0.060	0.024	0.042	0.459
Level of SWRU	Ecological function	Forestland area (hm^2)	+	0.040	0.082	0.061	0.459
Level of SWRU	Ecological function	Water consumption in forestland (10^9 m^3)	−	0.065	0.063	0.064	0.459
Level of SWRU	Ecological function	Total water resources (10^9 m^3)	+	0.033	0.102	0.068	0.459
Level of SWRU	Ecological function	Proportion of ecological water consumption (%)	+	0.044	0.087	0.066	0.459
Level of SWRU	Ecological function	Water supply-demand ratio	+	0.068	0.002	0.035	0.459
Level of SWRU	Ecological function	Grassland area (hm^2)	+	0.059	0.042	0.051	0.459

Target layer	System layer	Index layer	Index attribute	W_{j1}	W_{j2}	W_j	W_j^*
Level of SWRU	Ecological function	Water consumption in grassland (10^9 m^3)	−	0.066	0.084	0.075	0.459
Level of SWRU	Production function	Water consumption per ten thousand CNY of GDP ($m^3/10^4$ CNY)	−	0.067	0.078	0.072	0.369
Level of SWRU	Production function	Per capita farmland area (hm^2)	+	0.056	0.046	0.051	0.369
Level of SWRU	Production function	GDP (10^4 CNY)	+	0.048	0.088	0.068	0.369
Level of SWRU	Production function	Water consumption in farmland irrigation (10^9 m^3)	−	0.064	0.047	0.056	0.369

Target layer	System layer	Index layer	Index attribute	W_{j1}	W_{j2}	W_j	W_j^*
Level of SWRU	Production function	Water consumption per ten thousand CNY of secondary industry output value (10^9 m^3)	–	0.066	0.070	0.068	0.369
Level of SWRU	Production function	Water consumption per ten thousand CNY of tertiary industry output value (10^9 m^3)	–	0.066	0.034	0.050	0.369

Target layer	System layer	Index layer	Index attribute	W_{j1}	W_{j2}	W_j	W_j^*
Level of SWRU	Living function	Proportion of domestic water consumption (%)	−	0.067	0.055	0.061	0.173
Level of SWRU	Living function	Urbanization rate (%)	+	0.063	0.027	0.045	0.173
Level of SWRU	Living function	Population density (persons/km^2)	−	0.066	0.068	0.067	0.173

Note: W_{j1} and W_{j2} are the weights of the j^{th} index calculated by the entropy weight method and the coefficient of variation method, respectively; W_j is the comprehensive weight of the j^{th} index; W_j^* is the stratification weight of the ecological function, production function, and living function subsystems. GDP, gross domestic product.

distribution and utilization of mountain-related natural resources. The extent of forestland area, grassland area, and total water resources reflects the scale of their respective ecosystems. The per capita farmland area indicates the ability of the entire farmland to support the regional population. Water consumption in forestland, grassland, farmland irrigation, and the secondary and tertiary industries measured in ten thousand CNY demonstrates these sectors' reliance on water. The proportion of domestic water consumption and proportion of ecological water consumption provide insight into the intensity with which water resources are used in these two areas. Water supply–demand ratio is a key indicator for determining water resource sufficiency. Water consumption per ten thousand CNY of gross domestic product (GDP) sheds light on the efficiency with which water is used in economic activities, whereas GDP is used to measure regional economic health. The urbanization rate evaluates local social development, whereas population density indicates the demand for land resources to support the population. The data for this study are primarily derived from the Gansu Water Resources Bulletin (Gansu Provincial Department of Water Resources, 2000–2023), with land use data obtained from the Resource and Environmental Science Data Platform (http://www.resdc.cn).

3.1.2 Entropy weight method

The entropy weight method, which assigns weights based on the utility of the information provided by the data, effectively eliminates the subjectivity inherent in manual weight assignment (Ding et al., 2023). Consequently, this study first standardized the indicators, then used the entropy weight method to calculate their weights.

The formula for data standardization processing is as follows:

$$Y_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}, \tag{1}$$

where Y_{ij} is the standardized value for the i^{th} sample and j^{th} index; x_{ij} is the original value for the i^{th} sample and j^{th} index; and $\min(x_j)$ and $\max(x_j)$ are the minimum and maximum values of the j^{th} index, respectively.

The index weight calculation formulas are as follows:

$$W_{j1} = \frac{g_j}{\sum_{j=1}^{n} g_j}, \tag{2}$$

$$g_j = 1 - E_j, \tag{3}$$

$$E_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} P_{ij} \ln(P_{ij}), \tag{4}$$

where W_{j1} is the weight of the j^{th} index calculated by the entropy weight method; g_j is the information entropy redundancy of the j^{th} index; n is the number of indices; E_j is the information entropy value of the j^{th} index, reflecting the information purity and difference of each index; m is the number of samples; and P_{ij} is the proportion of the i^{th} sample under the j^{th} index.

3.1.3 Coefficient of variation method

We further used the coefficient of variation method to determine the weight of each index. When applied to a dataset, this coefficient is defined as the absolute value of the standard deviation relative to the mean. The calculation process is summarized as follows:

$$\bar{x}_j = \frac{1}{m} \sum_{i=1}^{m} x_{ij}, \tag{5}$$

$$S_j = \sqrt{\frac{1}{m-1}\sum_{i=1}^{m}(x_{ij}-\bar{x}_j)^2}, \tag{6}$$

$$V_j = \frac{S_j}{|\bar{x}_j|}, \tag{7}$$

$$W_{j2} = \frac{V_j}{\sum_{j=1}^{n} V_j}, \tag{8}$$

where $\bar{x}_j$ represents the mean value of the j^{th} index; S_j is the standard deviation of the j^{th} index; V_j is the coefficient of variation of the j^{th} index; and W_{j2} is the weight of the j^{th} index calculated by the coefficient of variation method.

3.1.4 Comprehensive weight calculation

$$W_j = \alpha W_{j1} + (1-\alpha)W_{j2}, \tag{9}$$

where W_j is the comprehensive weight of the j^{th} index; and α is the proportion occupied by the coefficient of variation method, which typically takes a value of 0.5. The comprehensive weights of each index are listed in Table 1.

3.1.5 Quantification of SWRU

This study quantified the SWRU in the study area on the basis of the weighted summation of each index' s weight and standardized value (Song et al., 2024). The formula is as follows:

$$\text{SWRU} = \sum_{j=1}^{n} W_j Y_{ij}. \tag{10}$$

Based on a synthesis of prior research findings, we categorized the SWRU of the study area into five distinct levels: very bad (0.000–0.200), poor (0.200–0.400), general (0.400–0.600), good (0.600–0.800), and excellent (0.800–1.000).

3.2 SD model construction

3.2.1 Model structure

The SD model begins by studying the system' s internal composition, using first-order differential equations to determine the causal relationships among various system variables (Song et al., 2024). This study used VensimPLE 10.2.1 software (Ventana Systems, Inc., Cambridge, USA), with the spatial research boundary including the administrative boundaries of Jiuquan City, Jiayuguan City, Zhangye City, Jinchang City, Wuwei City, Lanzhou City, and Baiyin City in Gansu Province, and the temporal boundary ranging from 2000 to 2035. The data collection period of model's historical statistics was 2000–2023, and the simulation period, which advances at 1-a time intervals, was 2024–2035. The model was divided into three modules: population, economy, and water resources (Fig. 2). The data of three module indicators of population, economy and water resources used in this study were sourced from the Gansu Water Resources Bulletin (Gansu Provincial Department of Water Resources, 2000–2023), and the Gansu Statistical Yearbook (Gansu Provincial Bureau of Statistics, 2000–2023).

3.2.2 Model checking

To ensure the specificity of the simulation, the model was debugged, and its reliability was tested using historical data (2000–2023). This was accomplished using the VensimPLE software' s "Units Check" and "Check Model" functions, which ensure that variables, parameters, dimensions, and system boundaries are appropriate across all model equations. The verification results withstood the scrutiny.

To ensure the precision and adaptability of the model, it was calibrated, and the reliability was confirmed using historical data from 2017 to 2022. Taking Zhangye City' s population, GDP, and production water consumption as examples, a comparison of the simulation findings with the actual values revealed an average error of only 0.019%, substantially less than 10.000%, indicating that the model is very reliable (Table 2).

Table 2 Tests of historical errors

Index	Year	Historical value	Simulated value	Error (%)
Population ($\times 10^4$ persons)	2017	122.930	122.930	0.000
Population ($\times 10^4$ persons)	2018	123.380	123.380	0.000
Population ($\times 10^4$ persons)	2019	123.760	123.760	0.000
Population ($\times 10^4$ persons)	2020	113.100	113.100	0.000
Population ($\times 10^4$ persons)	2021	112.250	112.250	0.000
Population ($\times 10^4$ persons)	2022	112.010	112.010	0.000

Index	Year	Historical value	Simulated value	Error (%)
GDP ($\times 10^9$ CNY)	2017	404.100	404.100	0.000
GDP ($\times 10^9$ CNY)	2018	407.707	407.707	0.000
GDP ($\times 10^9$ CNY)	2019	448.730	448.730	0.000
GDP ($\times 10^9$ CNY)	2020	467.050	467.060	−0.002
GDP ($\times 10^9$ CNY)	2021	526.230	526.220	0.002
GDP ($\times 10^9$ CNY)	2022	581.500	581.500	0.000
Production water consumption ($\times 10^9$ m^3)	2017	21.061	21.061	0.000
Production water consumption ($\times 10^9$ m^3)	2018	19.614	19.614	0.000
Production water consumption ($\times 10^9$ m^3)	2019	19.938	19.938	0.000
Production water consumption ($\times 10^9$ m^3)	2020	19.409	19.363	0.237
Production water consumption ($\times 10^9$ m^3)	2021	19.219	19.239	−0.104
Production water consumption ($\times 10^9$ m^3)	2022	18.558	18.558	0.000

Index	Year	Historical value	Simulated value	Error (%)
The average value of the absolute error	The average value of the absolute error	The average value of the absolute error	The average value of the absolute error	0.019

3.2.3 Scheme design

This study aimed to elucidate the dynamic relationship between socio-economic development and water resources, as well as to design a plan for their sustainable use and regulation. To this end, we integrated the concept of ecological civilization into the socio-economic planning policies and water conservation strategies of the Gansu Province. The "Gansu Province Water Security Guarantee Plan" establishes water supply index parameters such as surface water (including water diversion), groundwater, and other water supply volumes for each city in 2035. In 2016, the "Qilian Mountain Area in Gansu Province" was designated as the first pilot project for the ecological protection and restoration of mountains, rivers, forests, farmlands, lakes, and grasslands. The relevant indicators and criteria for the industrial economy were established in accordance with the "Notice on the Outline of the 14th Five-Year Plan and the Long-Range Objectives through the Year 2035 for the National Economic and Social Development of Gansu Province" . Moreover, Policies such as the "Gansu Province' s '14th Five-Year Plan' for the Construction of a Water-Saving Society" , "Gansu Province' s Implementation Plan for the Conservation and Intensive Utilization of Water Resources in the Yellow River Basin" , and "Gansu Province' s Industry Water Quota (2023 Edition)" have been used to establish production water and related decision-making variables. The SD model simulation included three distinct development scenarios: status quo, economic, and comprehensive. These scenarios were used to estimate the potential SWRU between 2024 and 2035. Population growth rate was adjusted based on current development and planning. Table 3 is a collection of specific scenario settings.

3.2.4 Obstacle degree model

This study employed an obstacle degree model to scrutinise the key elements influencing the development of SWRU. The methodology included the introduction of factor contribution (F_j), index deviation (I_j), and obstacle degree (Q_j; %) for diagnostic analysis. The F_j indicates the overall impact of a single factor and is calculated as follows:

Table 3 Parameters for each scenario used in the study

Parameter	Status quo scenario	Economic scenario	Comprehensive scenario
Urbanization rate (%)	Data in 2023	1.2 times the status quo scenario	1.1 times the status quo scenario
Population growth rate (‰)	Data in 2023	Same as the status quo scenario	Same as the status quo scenario
Per capita domestic water consumption quota in urban areas (m^3/person)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario
Rural per capita domestic water quota (m^3/person)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario
Growth rate of farmland area (%)	Average from 2017 to 2023	1.6 times the status quo scenario	1.6 times the status quo scenario
Farmland irrigation quota (m^3/hm^2)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario
Growth rate of forestland area (%)	Average from 2017 to 2023	1.6 times the status quo scenario	1.6 times the status quo scenario
Forestland irrigation quota (m^3/hm^2)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario
Growth rate of grassland area (%)	Average from 2017 to 2023	1.6 times the status quo scenario	1.6 times the status quo scenario
Grassland irrigation quota (m^3/hm^2)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario
Growth rate of water supplement area of fishpond (%)	Average from 2017 to 2023	1.6 times the status quo scenario	1.6 times the status quo scenario
Water supplement quota for fishpond (m^3/hm^2)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario

Parameter	Status quo scenario	Economic scenario	Comprehensive scenario
Livestock growth rate (%)	Average from 2017 to 2023	1.6 times the status quo scenario	1.6 times the status quo scenario
Livestock water use quota (m^3/head)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario
Water supplement of river course (10^9 m^3)	Data in 2023	Same as the status quo scenario	Same as the status quo scenario
Urban environmental water consumption (10^9 m^3)	Data in 2023	Same as the status quo scenario	Same as the status quo scenario
Rural ecological water consumption (10^9 m^3)	Data in 2023	Same as the status quo scenario	Same as the status quo scenario
Surface water supply (10^9 m^3)	Gansu Province Water Security Guarantee Plan	Same as the status quo scenario	Same as the status quo scenario
Underground water supply (10^9 m^3)	Gansu Province Water Security Guarantee Plan	Same as the status quo scenario	Same as the status quo scenario
Other water consumption (10^9 m^3)	Gansu Province Water Security Guarantee Plan	Same as the status quo scenario	Same as the status quo scenario
Growth rate of primary industry (%)	Average from 2017 to 2023	2.0 times the status quo scenario	1.8 times the status quo scenario
Growth rate of the secondary industry (%)	Average from 2017 to 2023	2.0 times the status quo scenario	1.8 times the status quo scenario
Growth rate of the tertiary industry (%)	Average from 2017 to 2023	2.0 times the status quo scenario	1.8 times the status quo scenario

Parameter	Status quo scenario	Economic scenario	Comprehensive scenario
Water consumption per ten thousand CNY of secondary industry output value (10^9 m^3)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario
Water consumption per ten thousand CNY of tertiary industry output value (10^9 m^3)	Data in 2023	Same as the status quo scenario	0.9 times the status quo scenario

$$F_j = W_j W_j^*, \tag{11}$$

$$W_j^* = W_a + \cdots + W_b, \tag{12}$$

where W_j indicates the impact of a single factor; W_j^* is the stratification weight of the ecological function, production function, and living function subsystems; W_a is the comprehensive weight of the first indicator at the system level; and W_b is the comprehensive weight of the final indicator at the subsystem level.

The I_j represents the gap between a single factor and the sustainable utilization development goal, and the calculation formula is as follows:

$$I_j = 1 - Y_j. \tag{13}$$

The obstacle degree (Q_j; %) indicates the overall impact of a single factor and is calculated as follows:

$$Q_j = \frac{F_j I_j}{\sum_{j=1}^{n} F_j I_j} \times 100\%. \tag{14}$$

Fig. 2 System dynamics (SD) model flowchart. GDP, gross domestic product. <Time> denotes the temporal attributes defined by the SD model for simulation, which is used to establish the simulation timeframe and assist in setting the time step. Black arrows represent flow, directly causing changes in stock levels. Blue arrows indicate information flow within the SD model, transmitting signals only.

4 Results

4.1 Temporal and spatial variation of SWRU

This study quantified the SWRU for the seven cities in the Gansu region of Qilian Mountains from 2000 to 2023 (Fig. 3). From a time-series perspective, an overall upward trend was noted in the SWRU of the study area between 2000 and 2023. SWRU increased from 0.438 to 0.614, indicating a substantial improvement from general to good utilization. Between 2000 and 2004, there was a modest increase in SWRU, maintaining a general level between 0.438 and 0.496. SWRU gradually increased from 0.523 to 0.599 between 2005 and 2019, suggesting a high level of consumption. From 2020 to 2023, the SWRU exceeded 0.600, indicating a good but not excellent level of utilization and suggesting room for further improvement.

From a regional perspective (Fig. 4), there was tremendous opportunity to improve SWRU in all the seven cities in the Gansu region of Qilian Mountains. Furthermore, the level of SWRU varied substantially among these cities. Based on a review of improvements in each city, by 2023, the SWRU ranking was as follows: Jinchang City>Wuwei City>Jiayuguan City>Jiuquan City>

Fig. 3 Temporal variation in sustainable water resource utilization (SWRU) in the study area from 2000 to 2023

Figure annotations: SWRU; Trend line; Year.

(a) 2000

(b) 2005

(c) 2010

(d) 2015

(e) 2020

(f) 2023

Legend: City boundary; Qilian Mountains; SWRU: 0.400–0.500, 0.500–0.550, 0.550–0.600, 0.600–0.800.

Fig. 4 Spatial variations of SWRU in the study area in 2000 (a), 2005 (b), 2010 (c), 2015 (d), 2020 (e), and 2023 (f)

Zhangye City>Baiyin City>Lanzhou City. Jiuquan City, Jiayuguan City, Zhangye City, Jinchang City, and Wuwei City had reached a good level of SWRU, whereas Baiyin City and Lanzhou City remained at a general level. Although certain cities reached a good level of SWRU in 2023, the temporal development features differed among them. Jiayuguan City was the earliest (2008) to reach a good level of SWRU but exhibited a fluctuating growth trend.

Jiuquan City, Zhangye City, and Wuwei City reached a good level of SWRU in 2016, 2017, and 2018, respectively, demonstrating a stable growth trend. Lanzhou City and Jinchang City reached a good level of SWRU in 2020, but Lanzhou City regressed to a general level from 2022. Baiyin City remained in the general development phase from 2000 to 2023, with the overall SWRU showing an upward trend, continuously approaching a good level.

4.2 SD simulation of SWRU

This study estimated the trajectory of SWRU within the study area for the period 2024–2035 under three distinct scenarios by combining the SWRU with SD simulation results. According to the simulation, the SWRU in the study area is expected to remain satisfactory under all three scenarios from 2024 to 2035 (Fig. 5a). The change thresholds are 0.630–0.636 under the status quo scenario, 0.636–0.640 under the economic scenario, and 0.637-0.640 under the comprehensive scenario. By 2035, the SWRU under the comprehensive scenario ranks highest (0.638), followed by the economic (0.636) and status quo (0.630) scenarios. SWRU under both the status quo and economic scenarios show a general downward tendency. Compared with those

in 2023, both the economic and status quo scenarios exhibit a lower SWRU in 2035, indicating issues for SWRU under either status quo or economic development conditions. Particularly in the economic context, demand is rapidly increasing and outpacing supply, exacerbating the mismatch between water supply and demand. On the contrary, the SWRU under the comprehensive scenario experiences an upward trend during the initial phase (2024–2032), rising from 0.637 to 0.640, before gradually declining to 0.638 in the later phase, but it remains higher than the current value in 2023, indicating overall growth. This pattern suggests that the comprehensive scenario is the best option for the sustainable use of water resources in the Gansu region of Qilian Mountains. Although the SWRU under the comprehensive scenario has improved over time, it remains in a good state and is far from being excellent. Adopting measures to safeguard and conserve water resources can help to balance supply and demand. However, after 2033, the demand for a fast-growing economy and society will increase. This serves as a reminder that the sensible use and protection of water resources should be prioritized to preserve their long-term sustainability in the pursuit of economic and social development.

Examining the supply and demand dynamics of water resources in the study area (Fig. 5b) reveals that the supply–demand ratio constantly decreases under all three scenarios. Notably, the economic supply–demand ratio falls below the status quo situation and the comprehensive scenario. Furthermore, the comprehensive scenario first exceeds the status quo situation; nevertheless, from 2033, it falls below the status quo situation. The supply–demand ratio gradually falls from 2024 to 2035, with all values being less than 1. This suggests that the entire water supply in the study area is insufficient to meet overall demand, resulting in a growing deficit in the water resource balance. Between 2024 and 2035, the water consumption per ten thousand CNY of GDP decrease gradually under the three scenarios (Fig. 5c), in the order of comprehensive<economical<status quo. By 2035, the water consumption per ten thousand CNY of GDP will drop to 138.638 $m^3/10^4$ CNY under the status quo scenario, with values of 101.239 $m^3/10^4$ CNY under the economic scenario and 100.292 $m^3/10^4$ CNY under the comprehensive scenario. These results show

Fig. 5 Temporal variations in SWRU (a), water supply-demand ratio (b), and water consumption per ten thousand CNY of GDP under different scenarios from 2023 to 2035. Note that 2023 is the base year, and the SD simulation period is 2024–2035.

decreases of 25.213%, 45.388%, and 45.901%, respectively, from the current value in 2023, indicating an improvement in water use efficiency in the region. This transition suggests a shift away from extensive and inefficient water use toward more intensive and efficient use.

4.3 SWRU obstacle degree analysis

This study used an obstacle degree model to identify the key variables affecting SWRU, thereby providing a framework for understanding how to achieve sustainable use of water resources under various future scenarios. Natural resource distribution and economic growth had a substantial impact on SWRU in the Gansu region of Qilian Mountains. Critical factors were the proportion of ecological water consumption, GDP, total water resources, forestland area, per capita farmland area, and grassland area, with obstacle degrees of 14.388%, 12.475%, 12.019%, 11.206%, 7.058%, and 6.378%, respectively. This revealed that the main obstacle factors to improving SWRU in this region are ecological and production function systems. In contrast, living functional systems had minimal impact. An examination of the interannual variation in these obstacle factors (Fig. 6) showed that the proportion of ecological water consumption and GDP consistently have a high impact, suggesting that the use of ecological water and the level of economic development are crucial for improving SWRU in the region. Furthermore, the obstacle degrees of total water resources and forestland area are constantly increasing, with total water resources increasingly becoming the primary obstacle to SWRU.

Fig. 6 Temporal variations in the obstacle degree of various obstacle factors. *X1*, average terrain relief; *X2*, forestland area; *X3*, water consumption in forestland; *X4*, total water resources; *X5*, proportion of ecological water consumption; *X6*, water supply-demand ratio; *X7*, grassland area; *X8*, water consumption in grassland; *X9*, water consumption per ten thousand CNY of GDP; *X10*, per capita farmland area; *X11*, GDP; *X12*, water consumption in farmland irrigation; *X13*, Water consumption per ten thousand CNY of secondary industry output value; *X14*, Water consumption per ten thousand CNY of tertiary industry output value; *X15*, proportion of domestic water consumption; *X16*, urbanization rate; *X17*, population density.

From the perspective of different cities, primary obstacle factors (with obstacle degrees exceeding 10.000%) varied among these cities (Fig. 7). The primary obstacle factors of SWRU in Jiuquan City were forestland area (obstacle degree of 15.400%), proportion of ecological water consumption (13.040%), water consumption of grassland (12.816%), and GDP (11.992%). The primary obstacle factors of SWRU in Jiayuguan City were forestland area (17.214%), total water resources (17.192%), GDP (14.580%), grassland area (14.152%), per capita farmland area (11.095%), and proportion of ecological water consumption (9.544%). The primary obstacle factors of SWRU in Zhangye City included proportion of ecological water consumption (16.784%), water consumption in forestland (13.429%), GDP (13.519%), and average terrain relief (11.351%). The primary obstacle factors affecting the SWRU in Jinchang City were proportion of ecological water consumption (15.594%), total water resources (15.470%),

forestland area (15.358%), GDP (13.192%), and grassland area (11.003%). The primary obstacle factors of SWRU in Wuwei City were proportion of ecological water consumption (16.638%), GDP (14.154%), and total water resources (11.878%). The primary obstacle factors of SWRU in Lanzhou City were total water resources (15.408%), proportion of ecological water consumption (13.014%), per capita farmland area (10.614%), and forestland area (10.577%). The primary obstacle factors of SWRU in Baiyin City were proportion of ecological water consumption (16.100%), forestland area (15.307%), total water resources (14.834%), and GDP (12.579%). The proportion of ecological water consumption was the most common obstacle factor in these cities, and, except for Lanzhou City, GDP was the second most common obstacle factor in these cities.

Visible labels in Fig. 7: Water consumption in grassland; Water consumption in forestland; Average terrain-relief; Forestland area; Proportion of ecological water consumption; GDP; Total water resources; Per capita farmland area; Grassland area; Jiuquan City; Zhangye City; Baiyin City; Wuwei City; Jiayuguan City; Lanzhou City; Jinchang City.

Fig. 7 Primary obstacle factors (with obstacle degrees exceeding 10.000%) for each city in the study area

5 Discussion

5.1 SWRU dynamics and scenario analysis

SWRU represents a dynamic equilibrium between socio-economic development and water resource systems. It is influenced by several factors, including resource endowment characteristics, intensive use efficiency, and the efficacy of management and regulatory policies (Du et al., 2023). Within the Gansu section of Qilian Mountains, SWRU showed a spatial pattern of "an overall steady rise, with local fluctuations" . To promote regional or basin sustainable development in the 21st century, the study area has gradually implemented measures such as

"Water-saving Society Construction"in 2002, "Water Ecological Civilization Construction" in 2012, "National Water Network Construction and Intelligent Water Conservancy Construction" in 2021. These high-quality development initiatives are intended to increase the carrying capacity of resource systems (Zuo, 2023). Notably, SWRU in the study area decreased by 3.69% in 2013 compared to 2012. The Qilian Mountains community is a multifaceted composite system made up of mountains, water, forests, farmlands, lakes, grasslands, deserts, and human activities. This system is limited by water and land resources and is influenced by the water consumption in forestland, farmland, and grassland. Furthermore, population and industrial changes have exacerbated conflicts between regional ecological protection and the water used for production and living. This leads to a phenomenon wherein one system' s function increases at the expense of other system functions,

impeding the coordinated development of the social, economic, and resource systems (Swallow et al., 2009; Liu, 2022). In 2020, the Chinese government implemented the "Mountain-Water Project" at the national and local levels. This initiative contributed to the improvement of SWRU in the study area to a commendable level and the integrated protection and restoration of mountains, waters, forests, farmlands, lakes, and grasslands.

This study revealed that the SWRU in the Gansu section of Qilian Mountains has recently reached a favorable level (0.614). The trend reflects the growing alignment of the social, economic, and resource systems in this ecological community, transitioning from excessive use that hampers development to rational use that fosters development. This is consistent with previous studies on mountain-oasis-desert ecosystems supported by glacier meltwater on the Qinghai-Xizang Plateau (Yang et al., 2024) and the Tianshan Mountains (Dong et al., 2025) in China. There is substantial opportunity to improve current water resource utilization in the Qilian Mountains. The status quo scenario assumes that the development policies of each city will remain constant in areas such as economics, society, and resources until 2035. The economic scenario, an extension of the status quo, focuses on regional socio-economic growth by primarily modifying the industrial expansion ratio while ignoring the consumption of water resources for domestic use, production, and ecological sustenance. This comprehensive scenario aims to solve the numerous difficulties raised by swift economic growth and the subsequent use of water resources. This scenario, which builds on the underlying principles of the status quo and economic scenarios, promotes both rapid socio-economic growth and water resource conservation. Our simulation, similar to that of Sun et al. (2024), showed that, to differing degrees, agricultural modernization and industrialization are accelerated by maintaining the status quo and developing economic models. The demand for water resources has significantly increased as a result of these activities, which have resulted in relatively high irrigated area expansion and GDP growth rates (Sun et al., 2024).

Under the comprehensive scenario, SWRU shows an initial increase followed by a slight decline (Fig. 5a). This trajectory is the outcome of a dynamic interplay between two opposing forces: improved water-saving efficiency and increased water demand. Substantial results have been achieved through the early implementation of water conservation and protection measures, such as optimizing industrial structure, promoting water-saving technologies, and implementing water resource management policies (Zhang et al., 2019b; Tian et al., 2022), resulting in a marked decrease in water consumption per ten thousand CNY of GDP (Fig. 5c). However, as the general economic and social scale expands after 2033, the total water consumption for production will continue to grow at a steady pace, particularly in regions such as Jinchang City and Jiuquan City, where secondary industry is the primary source of income. The model projects that by 2033, the proportion of water used for production in Jinchang City and Jiuquan City will rise by 2.317% and 4.957%, respectively, compared to 2023, with an average increase of 3.369% across all cities. Water-intensive industries such as nonferrous metallurgy and petrochemicals have boosted urban GDP while simultaneously increasing water demand. This has resulted in a steady decline in the water supply–demand ratio, making water resources a limiting factor for future coordinated regional development (Zhang et al., 2019b; Li et al., 2021b). Furthermore, growing industrial water use fragments the limited total water resources, reducing the proportion of ecological water consumption (with an obstacle degree reaching 14.388%). This eventually leads to a deceleration in SWRU growth and a slight decline, highlighting the fact that in the Gansu region of Qilian Mountains, where water resources are inherently fragile, pursuing economic and social development should be accompanied by a renewed emphasis on water resource rationalization and conservation. Furthermore, various techniques should be used to overcome obstacle factors, and these should integrate policy tools, technical methods, and management strategies to improve water resource utilization.

5.2 Spatial variations of SWRU and its obstacle factors

The spatial distribution of SWRU within the Gansu region of Qilian Mountains is closely linked

to industrial structure, water use efficiency, and local water resource endowment. From the perspective of water resource utilization structure, the study area exhibits tight interconnections among water use for production, living, and ecological purposes, characterized by mutual interactions and constraints. The study area' s "three-life" water uses are intricately linked, showing mutual interactions and limits. The relationships among these "three-life"water uses necessitate holistic research that includes ecological conservation, industrial development, and societal welfare to ensure balanced development across the "three-life" functional zones. A significant proportion of ecological water consumption can promote harmony between socio-economic and natural systems (Zhang et al., 2023). This study identified the primary obstacle to SWRU in each city as the "proportion of ecological water consumption" , with obstacle degrees ranging from 9.544%

to 16.784%. This highlights the tension between ecological and economic water demands within the study area. The Hexi Corridor region, which acts as the grain reservoir of Gansu, uses water mainly for agricultural purposes in Zhangye City, with only 1.212% going to ecological needs by 2023. This presents a challenge, given the region' s responsibility for transporting ecological base flows in the middle reaches of the Heihe River. The fragmented terrain further reduces water transfer efficiency, revealing inconsistencies in water resource distribution (Wu et al., 2022).

GDP is the second most obstacle factor in the seven cities (obstacle degrees of 11.992%-14.580%), suggesting a palpable conflict between GDP growth and water resource demand. The economic prosperity of cities has increased water resource use, particularly as secondary and tertiary sectors have expanded rapidly, increasing water demand. From a natural endowment perspective, the total water resources appeared as the greatest obstacle to SWRU in the study area, with insufficient total quantity preventing sustainable use of water resources. The rapid urbanization of Jiayuguan City has resulted in a substantial increase in demand for water-to-fuel economic development. This surge in demand has led to over exploitation of water resources, resulting in increased surface water pollution and a steady decline in groundwater level. The strict demand for water produced by urban development eventually limits the amount of water available for ecological use, causing environmental stress (Li et al., 2021a). Furthermore, the presence of forestland areas hampered SWRU in regions such as Jiuquan City and Jiayuguan City. Forestland has a greater capacity to conserve water than farmland. Increasing forestland cover improves the watershed' s soil and water conservation abilities (Jia et al., 2025). Plant transpiration can also increase air humidity, which encourages water recycling and conservation (Cui et al., 2024).

In Jiuquan City, Jiayuguan City, Zhangye City, Jinchang City, and Wuwei City, the SWRU has reached a good level. However, constrained by obstacle factors, all cities still have significant room for improvement. Among them, Jinchang City and Wuwei City exhibited relatively high SWRU not due to superior water resource endowment, but rather as a result of the combined effects of industrial development and water resource management strategies. Jinchang City, dominated by its secondary industry, has extended industrial chains and implemented industrial water conservation and recycling. This approach supports high industrial output value through high water use efficiency, thereby reducing the economy' s dependence on water resources (Zhao et al., 2021). Wuwei City has achieved a significant leap in its SWRU by implementing profound agricultural restructuring. This involved reducing the area of water-intensive crops and promoting water-saving technologies, which markedly improved agricultural water use efficiency. The conserved water resources were then redirected to safeguard ecological and domestic needs (Wang et al., 2022). Conversely, the SWRU in Baiyin City and Lanzhou City, located in the eastern part of the study area, has long remained at a general level, reflecting a mismatch between their industrial structure and local water resource conditions. As the provincial capital of Gansu, Lanzhou City experiences population concentration, rapid growth in tertiary and emerging industries, and rigid increases in domestic and ecological water demand, resulting in structural water scarcity. Baiyin City lags in upgrading its traditional heavy chemical industries that exhibit high industrial water intensity. Limited Yellow River resources struggle to simultaneously meet

the demands of traditional industrial transformation, urban development, and ecological restoration, leading to intense competition among water systems and hindering SWRU improvement (Shan et al., 2023). From the perspective of differences in water resource endowment and development conditions, western cities in the region (such as Zhangye City) are inland with limited surface water resources, while they rely on glacial meltwater replenishment from the Qilian Mountains and possess relatively abundant groundwater resources. In contrast, cities like Lanzhou City and Baiyin City, despite their proximity to the Yellow River, face strict limitations on available water due to nationally allocated Yellow River water quotas, with local water resource development potential nearly exhausted. This unique characteristic of being "water-adjacent yet water-scarce" necessitates that eastern cities upgrade their industries by phasing out outdated, high-water-consuming production capacities and vigorously develop low-water-consuming high-tech industries and modern service sectors (Jiang, 2024).

5.3 Management implications across the Qilian Mountains

The Qilian Mountains, which serve as the source region and water conservation area for numerous inland rivers in the Hexi Corridor and northeastern Qinghai Province, face a common backdrop of uncertainty for the long-term sustainable use of water resources in the Gansu and Qinghai provinces. This uncertainty stems from global climate change-induced glacier retreat, snowline elevation, and changed precipitation patterns. In this study, the SWRU across seven cities in the Gansu region of Qilian Mountains has collectively reached a good level, despite significant challenges. The industrial structure is diverse, including farmland irrigation, energy and chemical industries, and non-ferrous metals, with water-intensive industries accounting for a substantial proportion. Production water consumption accounts for a high proportion of total water consumption in this region (Deng, 2018). The key difficulty in the Gansu region of the Qilian Mountains is balancing water use for production, living, and ecological purposes while maintaining the current high development intensity. This may be achieved by improving industrial structure, increasing water use efficiency, and enforcing the strictest water resource management ("three red lines"). This phase is categorized as "development optimization" and "demand management" (Bai et al., 2021). The Qinghai region of Qilian Mountains is mostly comprised of the Haibei Tibetan Autonomous Prefecture and Haixi Mongolian and Tibetan Autonomous Prefecture, where animal husbandry and ecotourism are the dominant industries. The water resource development intensity is significantly lower than that of Gansu region, with management responsibilities primarily focused on source protection and pollution prevention (Tong et al., 2024). Constraints may focus more on aspects such as changes in total water resources due to climate change and the impact of permafrost degradation on runoff (Wang et al., 2023). The Qilian Mountains in the Gansu and Qinghai provinces serve as an ecological security barrier and essential water source for China' s western region. However, sustainable water resource usage pathways and strategies should be tailored to local conditions: Qinghai Province should prioritize protection and prevention, whereas Gansu Province should concentrate on water conservation and optimization. Both provinces should collaborate to protect water resources and ensure rational allocation, consequently improving water use efficiency and increasing the effective supply of total water resources.

The unpredictable nature and complexity of climatic factors make it difficult to precisely anticipate the large-scale spatial distribution of precipitation over extended periods. The impact of temperature and precipitation on changes in land-use categories was not quantified in the model used in the present study. Additionally, the developed SWRU quantification model met the most stringent water resource management criteria without considering the greywater footprint generated by everyday life and industrial activities. As global warming increases and human activities rise, future research can integrate climate scenario simulations with pollution emission data to obtain more comprehensive and precise results in SWRU research. This approach will simplify the sensible use of the limited water resources in the Qilian Mountains and lay a foundation for the sustainable development of water resources in mountain–oasis–desert

ecosystems that rely on glacier meltwater.

6 Conclusions

This study investigated the spatiotemporal evolution of SWRU and its obstacle factors in the Gansu section of the Qilian Mountains, based on historical data (2000–2023) and scenario simulations (2024–2035). The SWRU level improved from general to good, with social, economic and resource systems showing enhanced coordination. Spatially, western cities such as Jiuquan City and Jinchang City achieved the most significant growth, while eastern areas developed more gradually, forming a distinct "high in the west and low in the east" pattern. The SWRU under the comprehensive scenario outperformed both economic and status quo scenarios, though all remained at a good level. While water-saving measures and industrial development can improve short-term sustainability, they may intensify long-term supply–demand imbalance, requiring optimized allocation. Primary obstacle factors included the proportion of ecological water consumption, GDP, and total water resources. These reflect the fundamental challenges in balancing ecological protection with economic development under limited water availability. The key to sustainable use of water resources in the Gansu section of the Qilian Mountains is balancing ecological conservation with economic growth. Implementing holistic management and developing ecological industries like tourism are essential. Strengthening Gansu–Qinghai basin cooperation to establish ecological compensation and water coordination mechanisms is critical. This will reconcile water use conflicts among living, production, and ecological needs, elevating the SWRU level from good to excellent, thereby supporting the long-term, balanced development of the entire Qilian Mountains ecosystem.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Conceptualization: XU Hua, REN Heng; Methodology: XU Hua, ZHAO Wenzhi; Data curation: XU Hua, JIANG Shengji; Formal analysis: XU Hua; Writing - original draft preparation: XU Hua; Writing - review and editing: XU Hua, ZHOU Tao; Visualization: ZHOU Tao, XU Hua; Funding acquisition: REN Heng. All authors approved the manuscript.

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Note: Figure translations are in progress. See original paper for figures.