

Article

Research on the Evaluation of Sustainable Use of Water Resources in Gansu Province Based on Water Ecological Footprint

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Abstract

To address the lack of spatiotemporal integrative analysis in studies on sustainable water resource utilization in Gansu Province and to provide scientific guidance for local water management and efficient use, this study employs the water resource ecological footprint and ecological carrying capacity models. Taking the period from 2014 to 2023 as the study interval, we conduct a quantitative assessment of sustainable water use in Gansu Province at both temporal sequences and spatial scales across prefecture-level cities, incorporating indicators such as ecological surplus/deficit and ecological pressure index. The results indicate that, temporally, the water ecological footprint of Gansu shows a decreasing-then-increasing trend, with an average ecological carrying capacity of 6.594 million ha, consistently remaining in ecological deficit and experiencing substantial ecological pressure, with agricultural water use identified as the primary pressure source. The water ecological footprint per 10,000 Yuan of GDP initially decreased and then increased, suggesting that the effectiveness of water-saving measures has lacked sustainability. Spatially, significant regional differentiation is observed: the water quantity ecological footprint is “high in Hexi, low in southeastern Gansu,” with expansion in high-value areas; although the water quality ecological footprint has generally declined, southeastern Gansu remains a core pressure zone. The Hexi water resource pressure belt continues to expand, indicating that while water use efficiency is improving across the province, ecological pressure is intensifying. The study highlights issues such as limited water endowment and highly water-intensive industries in Gansu, and proposes differentiated management and industrial optimization strategies to address challenges in sustainable water use, thereby providing a theoretical basis for scientific water resource management in the region.



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Keywords: ecological footprint; ecological carrying capacity; evaluation indicators; Gansu Province

1. Introduction

Water is the source of life and an indispensable resource for human survival, social progress, and economic development. It plays a crucial role in ensuring resource security, maintaining stable energy supply, promoting food production, and protecting the ecological environment [1]. China has abundant total water resources, but the per capita availability is severely insufficient. Water resources are unevenly distributed in space and time, with

more in the south than in the north and more in summer and autumn than in winter and spring. In addition, interannual variations are significant, with alternating years of plenty and scarcity, leading to frequent droughts and floods, which pose great challenges to water resource allocation and utilization. However, driven by global climate change, intensified human activities, and the acceleration of industrialization and agricultural expansion, freshwater systems worldwide are increasingly under pressure [2]. According to global assessments, water scarcity affects more than two-thirds of the global population for at least one month each year, while climate change further exacerbates the spatial and temporal imbalance of water resource availability. In addition to quantitative shortages, water quality degradation caused by agricultural runoff, industrial discharges, and urban wastewater has become a key constraint on sustainable water resource utilization. These challenges highlight the urgent need for integrated approaches that simultaneously consider both water consumption and environmental impacts [3].

Research on the sustainable use of water resources has become a hot topic, with a variety of methodologies applied, including fuzzy comprehensive evaluation, system dynamics, artificial neural network models, analytic hierarchy process (AHP), and the water ecological footprint method, among others [4]. For example, Gao Hui et al. [5] studied the sustainable use of water resources in Jiangmen City, Guangdong Province, using a multi-level fuzzy comprehensive evaluation model. Li Junxiao et al. [6] investigated Quanzhou City using an AHP–fuzzy comprehensive evaluation method combined with relevant data, and their results indicated that the sustainable use of water resources in Quanzhou was satisfactory. Zhang Jie et al. [7] combined the entropy weight method with fuzzy comprehensive evaluation to assess the sustainable use of water resources in Guangxi Province, verifying the reliability of fuzzy comprehensive evaluation for this purpose. Huang Lixiang et al. [8] applied a system dynamics model combined with the ecological footprint method to study the sustainable use of water resources in Shandong Province, providing a basis for local water resource management and sustainability. Zhang Liang [9] used an improved analytic hierarchy process to evaluate water resource sustainability in Dingxi City, Gansu Province, concluding that sustainable use was challenging and offering several recommendations. Song Songbai et al. [10] employed an artificial neural network model to evaluate regional water resource sustainability, demonstrating the model’s practicality and strong operability.

To address the limitations of traditional water resource evaluation methods, the ecological footprint concept proposed by Wackernagel and Rees [11] has been extended to water systems, forming the water ecological footprint (EF_w) framework [12]. This method quantifies human water resource appropriation by converting water consumption and pollutant discharge into biologically productive water area equivalents, thereby providing a unified indicator for assessing water resource pressure [13]. Compared with conventional indicators such as per capita water use or water stress index, the EF_w model has the advantage of integrating both water quantity and water quality dimensions within a single analytical framework [14]. Since its development, the model has been widely applied in sustainability assessments at global, national, and regional scales, particularly in arid and semi-arid regions where water constraints are most severe [15].

At the global level, water ecological footprint analysis has been applied to evaluate water sustainability in countries with contrasting hydro-climatic conditions, revealing significant disparities in water use efficiency and ecological pressure [16]. Empirical studies indicate that regions characterized by intensive agricultural production and industrial concentration generally exhibit higher water ecological footprints and lower ecological sustainability [17]. At the basin and regional scales, researchers have increasingly focused on integrating socio-economic drivers into water footprint analysis, such as industrial structure, urbanization level, technological efficiency, and consumption patterns [18]. These

studies demonstrate that water resource pressure is not solely determined by natural endowments but is also strongly influenced by human activities and economic structures [19]. In China, water ecological footprint research has expanded rapidly in recent years, covering major river basins and economically developed regions. However, most studies still focus on either water quantity or water quality separately, and relatively few have systematically integrated long-term temporal dynamics with spatial heterogeneity in arid inland regions [20].

Although existing studies have made substantial progress in water ecological footprint assessment, several limitations remain. First, many studies emphasize either temporal trends or spatial patterns, while integrated spatiotemporal analyses remain insufficient, particularly in complex inland arid regions. Second, the driving mechanisms linking socio-economic development and water ecological pressure are not yet fully understood, especially in regions with strong spatial heterogeneity in water resource endowment. Third, as one of the most water-scarce provinces in China, Gansu Province exhibits pronounced contrasts between water-rich southeastern regions and water-deficient northwestern areas [21]. However, systematic assessments that integrate water quantity, water quality, ecological carrying capacity, and efficiency indicators over long time series remain limited. Therefore, a comprehensive understanding of the spatiotemporal evolution characteristics and driving mechanisms of water ecological sustainability in arid inland regions remains limited.

To address these knowledge gaps, this study proposes the following research questions:

- (1) How do water ecological footprint and water ecological carrying capacity evolve spatially and temporally in Gansu Province? Considering the substantial differences in water resource endowment and development patterns between the Hexi Corridor and southeastern Gansu, we hypothesize that water ecological footprint and carrying capacity exhibit significant spatial heterogeneity, characterized by higher water pressure in the Hexi Corridor and stronger ecological carrying capacity in southeastern regions.
 - (2) What are the dominant factors driving regional water ecological pressure? Given the strong dependence of regional development on agricultural and industrial water consumption, we hypothesize that agricultural water use, industrial development, and socioeconomic growth are the primary drivers of water ecological pressure, with agricultural water consumption representing the dominant contributor.
 - (3) Can water-saving practices and industrial restructuring effectively improve water resource utilization efficiency and promote sustainable development? Considering the implementation of water-saving policies and economic transformation in recent years, we hypothesize that technological improvements and industrial optimization can reduce water consumption intensity and enhance water-use efficiency, although natural water scarcity constraints may limit the effectiveness of these improvements.
- Based on these research questions and hypotheses, this study applies the water ecological footprint and ecological carrying capacity models to evaluate water sustainability in Gansu Province during 2014–2023. Specifically, this study aims to quantify temporal variations in water ecological footprint and ecological deficit, identify spatial heterogeneity among cities, evaluate water-use efficiency, and reveal the key drivers of regional water resource pressure.

The findings aim to provide a scientific basis for optimizing water resource management, improving ecological security, and supporting sustainable development strategies in arid inland regions.

2. Overview of the Study Area and Data Sources

2.1. Overview of the Study Area

Gansu Province is located in northwestern China, positioned along the upper reaches of the Yellow River and inland river basins, with geographical coordinates ranging from 32°31' N to 42°57' N and 92°13' E to 108°46' E. The province extends over 1600 km from east to west and serves as a critical ecological transition zone between northern China, northwestern China, and the Qinghai–Tibet Plateau. It also represents a key corridor of the ancient Silk Road, characterized by complex topography and pronounced spatial heterogeneity. The geomorphology of Gansu Province is highly diverse, generally forming a zonal pattern from southeast to northwest, including the Longdong Loess Plateau, central Loess Hilly Region, Gannan Plateau, and the Hexi Corridor. The region is dominated by a temperate continental climate, with highly uneven spatial and temporal distribution of precipitation, decreasing markedly from southeast to northwest. The long-term average annual precipitation is approximately 262.2 mm, indicating a typical arid to semi-arid climate regime.

Water resources in Gansu Province are extremely limited and unevenly distributed, making water scarcity a primary constraint on regional ecological security and socioeconomic development. Hydrologically, the province exhibits a typical “externally supplied–internally consumed” water system structure. In particular, runoff in the Hexi Corridor strongly depends on upstream recharge from high-altitude mountainous regions. The Qilian Mountains and its surrounding cryospheric systems (glaciers and seasonal snow cover) constitute a key and relatively stable water source for the region.

Under global climate warming, significant glacier retreat and snowpack variation in the Qilian Mountains have altered the temporal distribution of meltwater runoff. Rising temperatures have enhanced short-term snow and glacier melt, leading to temporarily increased runoff in some years. However, long-term glacier mass loss has weakened dry-season baseflow supply, thereby increasing interannual variability of runoff in inland river systems such as the Shiyang River, Heihe River, and Shule River basins.

Therefore, water availability in the study area is jointly controlled by precipitation inputs and cryosphere-derived meltwater regulation. This dual dependence results in strong spatiotemporal heterogeneity of water resources and provides a representative case for studying water resource sustainability in arid inland regions.

As of 2023, total water resources in Gansu Province were approximately $2.226 \times 10^9 \text{ m}^3$, including $2.137 \times 10^9 \text{ m}^3$ of surface water and $1.079 \times 10^9 \text{ m}^3$ of groundwater. Overall, the region exhibits high water resource exploitation pressure but limited ecological carrying capacity, highlighting a pronounced constraint on sustainable water use. The location overview map of Gansu Province is shown in Figure 1.

2.2. Data Sources

This study integrates hydrological, socioeconomic, and environmental datasets as follows:

- (1) Water resource data: Data on water availability and water use structure (including agricultural, industrial, domestic, and ecological water consumption) for all prefecture-level cities were obtained from the Water Resources Bulletins of Gansu Province (2014–2023) published by the Gansu Provincial Department of Water Resources.
- (2) Socioeconomic data: Gross Domestic Product (GDP), population statistics, and industrial structure data were derived from the Gansu Statistical Yearbooks (2014–2023) published by the Gansu Provincial Bureau of Statistics and related official statistical reports. These data were used for calculating water ecological footprint per unit GDP and per capita indicators.

- (3) Water quality and pollutant data: Chemical Oxygen Demand (COD) and ammonia nitrogen ($\text{NH}_3\text{-N}$) emission data were obtained from provincial environmental statistical reports and water resource bulletins. These indicators were used to estimate the water quality ecological footprint.

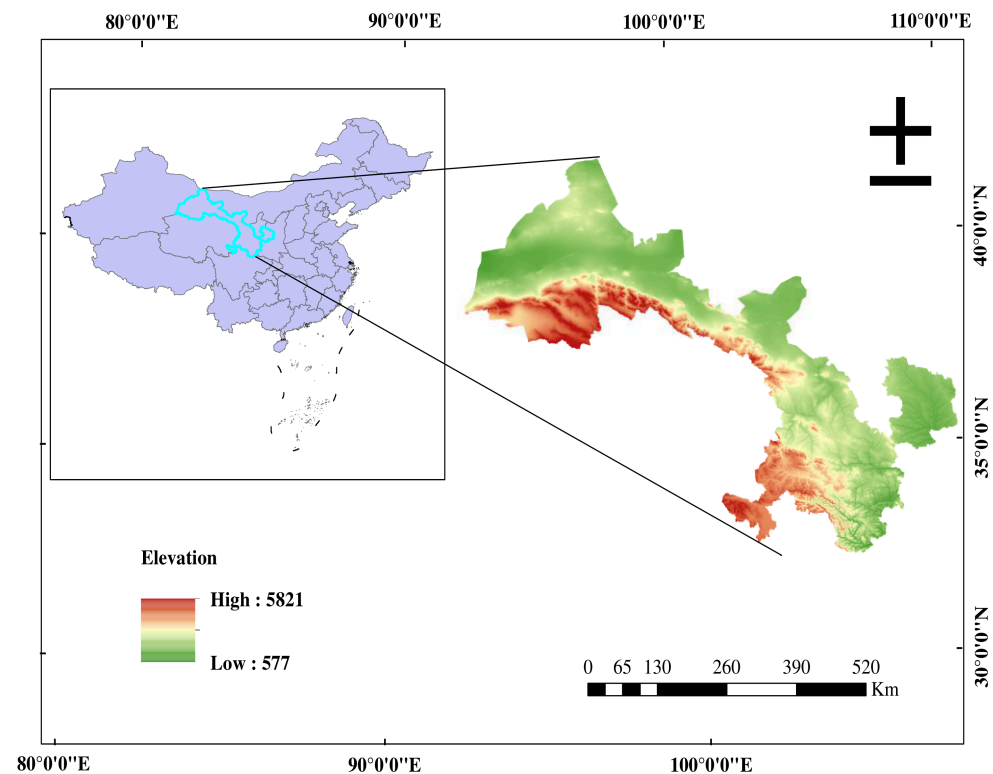


Figure 1. Overview map of the study area.

3. Research Methods

3.1. Water Resource Ecological Footprint Mode

The water resource ecological footprint is an indicator that measures human consumption of and impact on water resources. It translates the demands of human activities on water resource ecosystems into the area of biologically productive land or water required to generate these resources and assimilate the associated pollution. Based on the ecological footprint framework, the model enables the comparability of different types of water use by standardizing them into a unified spatial unit, such as global hectares or standardized ecological productive areas.

The core idea of the model is that higher water consumption corresponds to a larger ecological footprint. When the ecological footprint exceeds the ecological carrying capacity, the region is considered to be in a state of ecological deficit; otherwise, it is in ecological surplus. The water ecological footprint model provides a quantitative approach to assess regional water resource pressure from an ecological appropriation perspective. It effectively reveals the consumption structure of different economic sectors and helps identify spatial-temporal variations in water sustainability. Particularly in arid and semi-arid regions, the model is highly effective in identifying areas under high water stress and ecological risk. Gansu Province is located in an arid and semi-arid region. The water resource ecological footprint of Gansu Province is divided into two components: the water quantity ecological footprint and the water quality ecological footprint. The water quantity ecological footprint is established through four water-use accounts: agricultural water use, industrial water use, domestic water use, and ecological water use. The water quality ecological footprint

considers the emissions of chemical oxygen demand (COD) and ammonia nitrogen (NH₃-N). The model is presented as follows [22]:

$$EF_w = EF_{wr} + EF_{wq} \quad (1)$$

In the formula: EF_w represents the water ecological footprint (million ha); EF_{wr} represents the water quantity ecological footprint (million ha); EF_{wq} represents the water quality ecological footprint (million ha). The calculation formula for the water quantity ecological footprint is as follows.

$$EF_{wr} = \gamma \times U_{wi} / P_w \quad (2)$$

$$ef_w = EF_{wr} / N \quad (3)$$

In the formula: γ denotes the global equilibrium factor for water resources; P_w denotes the global average productivity of water resources (m³/ha). Based on previous studies [23], and are assigned values of 5.19 and 3140 m³/ha, respectively [24]. The water equivalence factor (5.19) and global average water productivity (3140) adopted in this study are standardized parameters widely used in ecological footprint research. Although Gansu Province, as an arid and semi-arid region, differs from the global average in terms of water resource endowment, these parameters are mainly intended to establish a unified conversion benchmark rather than represent local hydrological characteristics. Therefore, internationally accepted parameters were adopted to ensure methodological consistency and facilitate comparisons with previous studies and other regions [25]. U_{wi} represents water resource consumption (million m³), where i takes values from 1 to 4, corresponding to the four water-use accounts; ef_w denotes the per capita water ecological footprint (ha/person); and N represents the regional population (10,000 persons). The calculation formula for the water quality ecological footprint is as follows.

$$EF_{wq} = EF_{COD} + EF_{NH_3} = \gamma \times (U_{COD} / P_{COD} + U_{NH_3} / P_{NH_3}) \quad (4)$$

In the formula: EF_{COD} denotes the water quality ecological footprint of chemical oxygen demand (COD) (million ha); EF_{NH_3} denotes the water quality ecological footprint of ammonia nitrogen (NH₃-N) (million ha); U_{COD} and U_{NH_3} represent the corresponding pollutant discharge amounts (m³), respectively; P_{COD} and P_{NH_3} denote the assimilative capacities of the water body (m³/ha), respectively. According to the study by Zhang Qian et al. [26] P_{COD} is assigned a value of 0.0629 m³/ha, and P_{NH_3} is assigned a value of 0.0031 m³/ha.

3.2. Water Resources Ecological Carrying Capacity Model

Water resource ecological carrying capacity refers to the maximum population size, economic scale, and intensity of social activities that a local water resource system can continue to support within a specific region and period, under particular socio-economic and technological conditions, without compromising the health and stability of the regional ecosystem. The calculation model is as follows [27].

$$EC_w = 0.4 \times \gamma \times \varphi \times Q / P_w \quad (5)$$

In the formula: EC_w denotes the water resource ecological carrying capacity (million ha); φ denotes the regional water resource yield factor. According to the study by Huang Linnan et al. [28], the water resource yield factor for Gansu Province is taken as 0.22; Q represents the total regional water resources (million m³). Based on the calculation method for regional water resource yield factors proposed by Zhu Guanglei et al. [29], the

water resource yield factors for each prefecture-level city in Gansu Province are calculated, and the results are shown in Table 1.

Table 1. Water Resource Yield Factors of Prefecture-Level Cities in Gansu Province.

City	Dingxi	Baiyin	Jiuquan	Jiayuguan	Zhangye	Jinchang	Wuwei	Lanzhou	Pingliang	Qingyang	Gannan	Linxia	Tianshui	Longnan
Yield Factor	0.20	0.03	0.03	0.02	0.23	0.04	0.12	0.07	0.20	0.08	0.76	0.34	0.26	0.76

The significant differences in the water resource production factors among regions (e.g., 0.02 in Jiayuguan and 0.67 in Gannan) essentially reflect the strong spatial heterogeneity of regional water resource endowments controlled by the combined effects of natural climate and topographic conditions. First, the precipitation gradient is the most direct controlling factor. Gansu Province exhibits a clear southeast-to-northwest decreasing precipitation pattern. Regions such as Longnan and Gannan are more strongly influenced by the East Asian monsoon, receiving relatively higher precipitation, which provides more favorable runoff generation conditions and thus higher water resource production capacity, resulting in higher production factors. In contrast, the Hexi Corridor (e.g., Jiayuguan, Jiuquan) is located deep inland, where moisture is blocked by surrounding high mountains, leading to scarce precipitation and strong evaporation. Consequently, surface runoff formation is extremely limited, and the production factors are significantly lower. Second, topography and hydrological processes play a key regulatory role. Gannan and Longnan lie at the eastern edge of the Qinghai–Tibet Plateau and the transitional zone of the Qinba Mountains, characterized by large elevation differences, dense river networks, and relatively strong water conservation capacity of vegetation, all of which enhance runoff generation. In contrast, the Hexi region is dominated by an arid oasis–desert system with a closed terrain structure and heavy reliance on external inflow. Its local water generation capacity is extremely weak, leading to very low water output per unit area. Third, snow and glacier meltwater from high mountain areas provides an important localized water supply. In regions adjacent to the Qilian Mountains (such as Zhangye and Wuwei upstream areas), glacial and seasonal snowmelt contributes to relatively stable runoff even under arid climatic conditions. However, downstream or typical industrial cities such as Jiayuguan have very weak local runoff formation and rely mainly on transboundary or diverted water resources, further reducing their production factor values.

These extreme differences are not caused by a single factor but result from the combined influence of a southeast–northwest climatic gradient, a high mountain–desert geomorphic pattern, and varying levels of human water use intensity.

3.3. Evaluation Indicators for Sustainable Use of Water Resources

3.3.1. Water Resources Ecological Profit and Loss

Ecological water surplus refers to a situation in which the water supply in a region exceeds the demand from human activities. In this case, the natural ecosystem can obtain sufficient water to maintain its health and functioning, while simultaneously meeting the requirements of socio-economic development, thus ensuring sustainability. Conversely, if the water supply is less than the demand, a water ecological deficit occurs. To satisfy human needs under such conditions, it becomes necessary to over-extract groundwater, appropriate ecological water, or transfer water from other regions [30]. The calculation formula is as follows.

$$ED_w = EC_w - EF_w \quad (6)$$

If $ED_w > 0$, it indicates that water resources are sufficient, and the region is in a state of ecological surplus. Conversely; If $ED_w < 0$, it indicates a water shortage, and the region is in a state of ecological deficit.

3.3.2. Water Ecological Pressure Index

The water ecological pressure index is a comprehensive indicator used to measure the degree of pressure and stress exerted by human activities on the natural water resource system within a specific region (e.g., country, river basin, or province). It reflects the balance between water supply and demand. The calculation formula is as follows [31].

$$WEPI = EF_w / EC_w \quad (7)$$

In the formula: When $WEPI < 1$, it indicates that the pressure on water resources is low and the aquatic environment is in a safe state; When $WEPI > 1$, it indicates that the pressure on water resources is high and the aquatic environment is in a critical state. In general, a smaller value of the water ecological pressure index corresponds to a safer water ecological environment.

3.3.3. Water Ecological Footprint per 10,000 Yuan of GDP

The efficiency of water resource utilization can be expressed by the water ecological footprint per unit of regional GDP. The calculation formula is as follows [32]:

$$WFG = EF_w / GDP \quad (8)$$

Its value is inversely proportional to the efficiency of water resource utilization; a higher value indicates lower water use efficiency.

3.4. Sensitivity Analysis

To examine the stability of the water resource ecological footprint model and the influence of uncertainty in key parameters, a sensitivity analysis was conducted on the main parameters of the model. Sensitivity analysis effectively evaluates the extent to which variations in input parameters affect model outputs, thereby verifying the reliability and applicability of the model.

3.4.1. Parameter Selection and Perturbation Design

In this study, three key parameters in the water resource ecological footprint model were selected for sensitivity analysis: the water resource equilibrium factor (5.19), the average water resource productivity (3140), and the water resource yield factor (0.22). These parameters were derived from previous studies and regional statistical adjustments and serve as critical conversion coefficients in model construction. Based on these parameters, perturbations of $\pm 10\%$ and $\pm 20\%$ were applied to each variable. A one-at-a-time (OAT) approach was adopted, in which only one parameter was varied at a time while the others were held constant, in order to isolate and quantify the effect of individual parameter changes on model outputs.

3.4.2. Sensitivity Calculation Method

The sensitivity coefficient is calculated as follows:

$$S = \frac{\Delta Y / Y}{\Delta X / X} \quad (9)$$

where S denotes the sensitivity coefficient; X represents the input parameters (including the water resource equilibrium factor, average water resource productivity, and water resource yield factor); and Y represents the model outputs (in this study, the 2023 water resource ecological footprint, ecological carrying capacity, and ecological surplus/deficit are used as examples). ΔX and ΔY denote the changes in the input parameters and model outputs before and after perturbation, respectively.

When $S > 1$, the model is considered highly sensitive to the corresponding parameter; when $S < 1$, the model is insensitive to parameter variations, indicating strong stability of the results.

By comparing model outputs under different scenarios, the influence of key parameter perturbations on the results can be evaluated, thereby verifying the applicability and robustness of the uncertainty parameters at the scale of Gansu Province.

To improve the readability of the research methodology, a flowchart is presented in Figure 2, illustrating the overall methodological framework. It includes the calculation of each component of the water ecological footprint, the construction of a water resource sustainability evaluation indicator system, and the parameter sensitivity analysis used to assess model robustness and uncertainty.

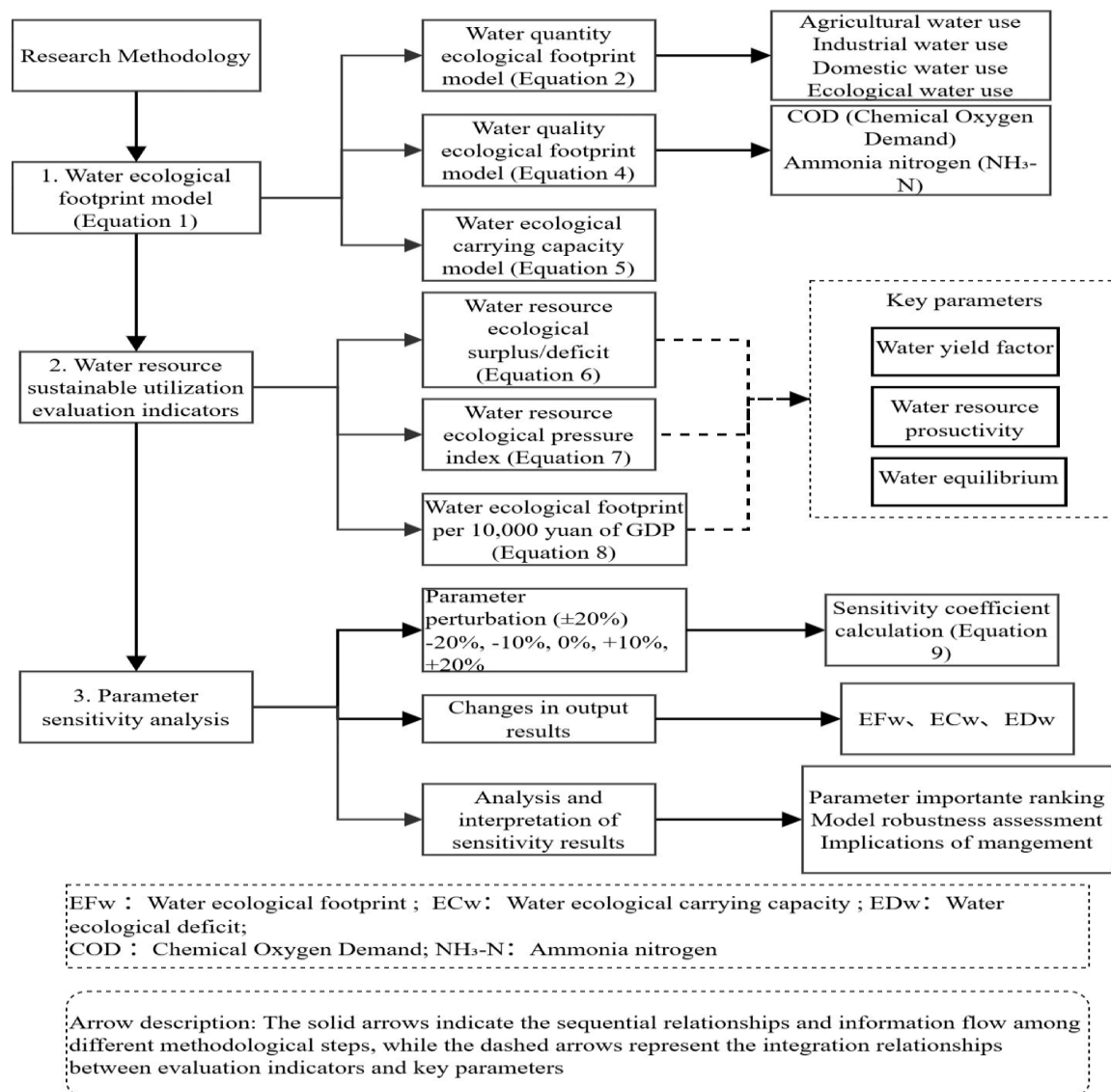


Figure 2. Flowchart of the research methodology.

4. Results and Analysis

4.1. Trend Analysis of the Time Series

4.1.1. Changes in the Water Ecological Footprint

The water quantity ecological footprint of Gansu Province was calculated using Equations (2) and (3), and its variation trend is shown in Figure 3. Overall, it exhibits a pattern of gradual decline followed by an increase, with a mean value of 23.244 million ha, reaching its minimum of 22.057 million ha in 2020.

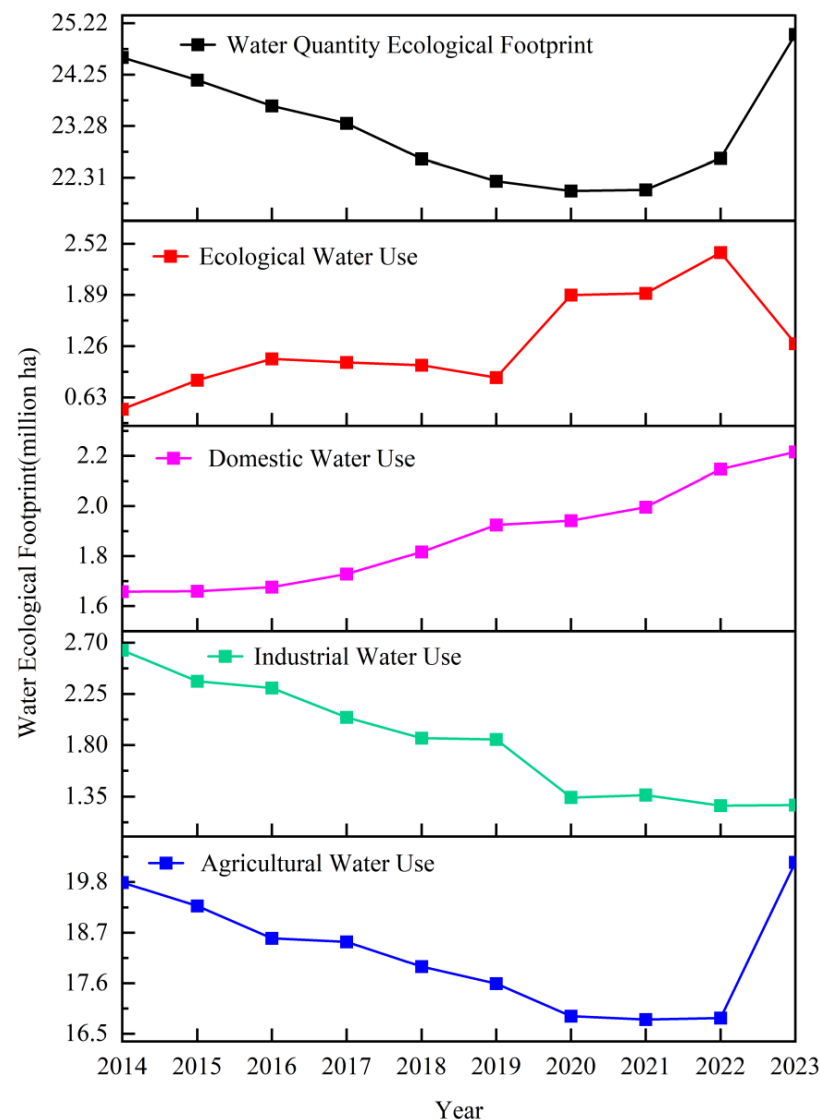


Figure 3. Temporal variation in the water quantity ecological footprint in Gansu Province (2014–2023).

Agricultural water use dominated the water footprint structure throughout the study period and served as the primary source of water resource consumption in Gansu Province. From 2014 to 2023, the average agricultural water footprint was 18.248 million ha, accounting for approximately 78.5% of the total water footprint (23.244 million ha), which was substantially higher than that of industrial water use (~5%), domestic water use (~10%), and ecological water use (~6%).

In terms of temporal variation, the agricultural water footprint exhibited a pattern highly consistent with that of the total water footprint, indicating that fluctuations in total water demand were primarily driven by agricultural water consumption. Moreover, the agricultural water footprint remained significantly higher than other water-use sectors

in all years, with its minimum value (16.8120 million ha) still exceeding the combined footprint of industrial and domestic water use. These results confirm that agricultural water use is the dominant component of the water ecological footprint and the primary driving force behind the sustained water resource pressure in Gansu Province.

The domestic water footprint has been steadily increasing, reflecting growing water demand associated with improvements in living standards. The ecological water footprint has fluctuated over the study period but shows an overall upward trend compared to 2014, peaking at 2.410 million ha in 2022, suggesting that, in line with new development concepts, increasing attention is being given to the development and protection of the ecological environment.

The water quality ecological footprint of Gansu Province was calculated using Equation (4), and its variation trend is shown in Figure 4. Chemical oxygen demand (COD) and ammonia nitrogen ($\text{NH}_3\text{-N}$) are considered the primary pollutant indicators, and their emissions largely determine the changes in the water quality ecological footprint. Overall, the water quality ecological footprint first declined and then increased, with a mean value of 62.020 million ha, reaching a minimum of 32.998 million ha in 2020 and a maximum of 95.195 million ha in 2023.

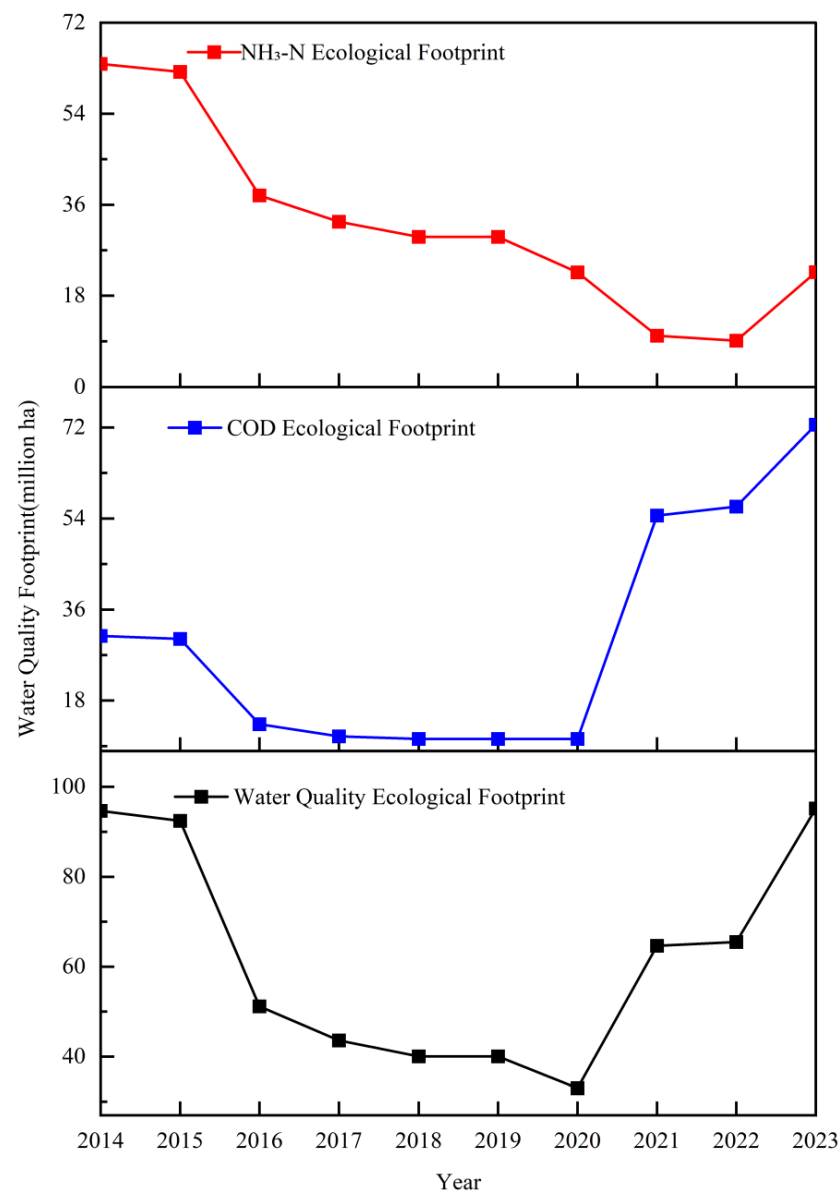


Figure 4. Temporal variation in the water quality ecological footprint in Gansu Province (2014–2023).

The COD ecological footprint exhibited a similar pattern of decline followed by an increase, with a mean of 29.989 million ha, reaching its minimum in 2020 and its maximum in 2023, accounting for 67% of the total water quality ecological footprint. The ammonia nitrogen ecological footprint followed the same trend as the overall water quality ecological footprint before 2020; however, after 2020, it displayed an opposite trend, decreasing until 2022 before rising again. Its mean value was 32.032 million ha, with a maximum of 63.850 million ha in 2014, representing 33% of the total water quality ecological footprint. A clear turning point was observed in 2020 in the variation in the water quality ecological footprint, which is closely associated with the outbreak of the COVID-19 pandemic and its impacts on socio-economic activities. From a mechanistic perspective, the pandemic affected pollutant discharge and water use structure through multiple pathways. First, at the industrial level, lockdown measures and temporary production suspension led to a short-term reduction in industrial wastewater discharge, thereby suppressing COD and $\text{NH}_3\text{-N}$ emissions and contributing to the minimum value observed in 2020. Second, although agricultural production was less directly affected, disruptions in logistics and labor mobility reduced operational efficiency in some areas, resulting in fluctuations in agricultural non-point source pollution.

In addition, changes in household consumption behavior further reshaped water use patterns. Domestic water demand increased due to enhanced hygiene and disinfection requirements, while reductions in catering, tourism, and service activities indirectly reduced certain types of commercial water consumption and wastewater generation. This structural substitution between industrial decline and increased domestic demand led to an internal reconfiguration of the water footprint structure.

After 2020, with the gradual recovery of economic activities, industrial production rebounded rapidly, and agricultural water demand remained rigid, resulting in increased pollutant emissions and a subsequent rise in the water quality ecological footprint. This indicates that the impact of the pandemic was temporary, characterized by a “short-term suppression followed by rebound” dynamic process.

Therefore, 2020 represents not only a statistical turning point but also a key transition node where socio-economic disruptions were transmitted to the water environment system through changes in industrial output and household consumption behavior.

4.1.2. Changes in the Ecological Carrying Capacity of Water Resources

The water ecological footprint and ecological carrying capacity of Gansu Province from 2014 to 2023 were calculated using Equations (1) and (5), and their variation trends are shown in Figure 5. From 2014 to 2016, the water ecological carrying capacity exhibited an inverted “V” pattern, after which it tended to stabilize. The maximum value was observed in 2015, reaching 28.918 million ha, with values ranging from 3.048 to 28.918 million ha and a mean of 6.594 million ha. The per capita water ecological carrying capacity averaged 0.256 ha per person. A comparison between the trends of the water ecological footprint and the water ecological carrying capacity indicates an imbalance between water supply and demand in Gansu Province.

4.1.3. Water Resources Ecological Surplus–Deficit Dynamics

The water resource ecological surplus/deficit was calculated using Equation (6), and the results are shown in Figure 6. From 2014 to 2023, the ecological profit and loss of water resources in various regions of Gansu Province was predominantly negative, indicating that the regional ecological water resources were generally in a deficit state during the study period. However, significant spatiotemporal differences were observed among regions.

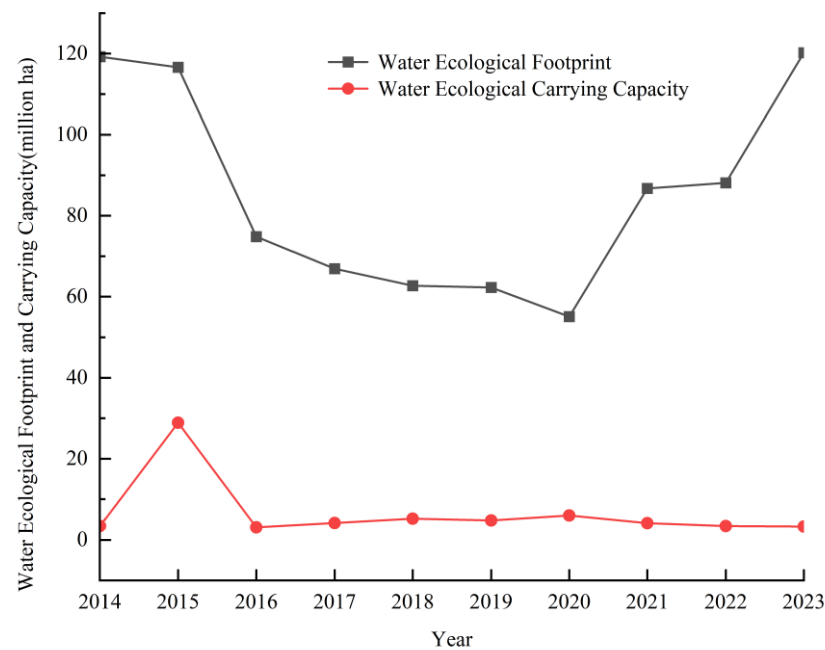


Figure 5. Temporal variation in the water ecological carrying capacity in Gansu Province (2014–2023).

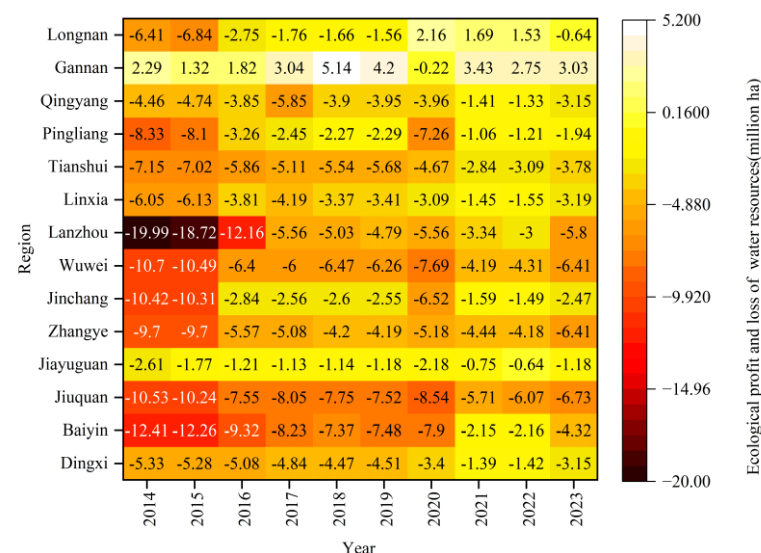


Figure 6. Temporal Variation in Water Resources Ecological Deficit in Gansu Province (2014–2023).

From the perspective of temporal variation, the most severe ecological water resource deficits occurred during 2014–2016, when most regions exhibited relatively large negative values. Among them, Lanzhou showed the highest deficit, reaching -19.99 million ha in 2014. In addition, Baiyin, Wuwei, Jiuquan, and Jinchang all recorded values below -10 million ha, indicating substantial ecological water-use pressure and pronounced contradictions between water supply and demand during this period. After 2017, the ecological water resource deficits in most regions gradually decreased. For example, the deficit in Lanzhou declined from -12.16 million ha in 2016 to -4.79 million ha in 2019, while that in Zhangye decreased from -5.57 to -4.19 million ha, suggesting that the implementation of water-saving measures, strengthened ecological management, and improved water-use efficiency contributed to the improvement of regional ecological water resource conditions. In 2020, some regions experienced fluctuations, with deficits increasing again in Pingliang, Jiuquan, and Wuwei, indicating that ecological water resource conditions remain sensitive to climate change and human activities. During 2021–2023,

deficits in most regions were further alleviated, and the overall ecological water resource conditions exhibited a recovery trend.

With the continuous advancement of ecological protection and water-saving policies, regional ecological water resource conditions have shown a gradual improvement trend. However, ecological water resource pressure remains relatively high in some arid regions. Therefore, further optimization of water resource allocation and enhancement of ecological water-use security are still required in the future.

4.1.4. Changes in the Water Ecological Pressure Index

The water ecological pressure index was calculated based on the water ecological footprint and the water ecological carrying capacity, as shown in Equation (7), and the results are presented in Figure 7. From 2014 to 2023, the water ecological pressure index in Gansu Province remained consistently greater than 1, fluctuating within a range of 4 to 38. This indicates that the region is under significant water resource pressure and that the aquatic environment is in a critical state. The highest value was recorded in 2023, reaching 37.119, while the lowest value occurred in 2015, at 4.032.

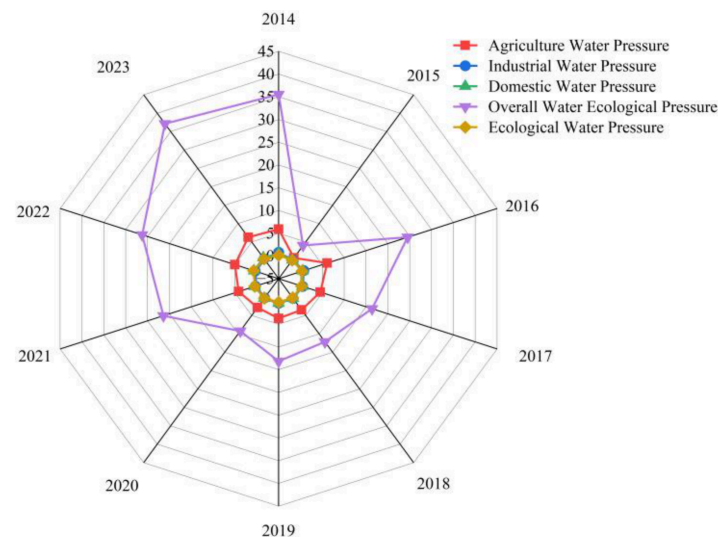


Figure 7. Temporal variation in the water ecological pressure index in Gansu Province (2014–2023).

The agricultural water pressure index varied between 0 and 7. In 2015, it reached its minimum value of 0.667, which is less than 1, indicating low pressure; however, in all other years, it exceeded 1, reflecting relatively high water use pressure. In contrast, the pressure indices for industrial, domestic, and ecological water use were all less than 1, suggesting that the water ecological conditions for these sectors remained within a safe range.

The pressure indices reached their lowest levels in 2015, which can be attributed to the relatively abundant total water resources and higher ecological carrying capacity in that year.

4.1.5. Changes in the Water Ecological Footprint per 10,000 Yuan of GDP

The water resource ecological footprint per 10,000 yuan of GDP was calculated using Equation (8), and its variation trend is shown in Figure 8. The water ecological footprint per 10,000 Yuan of GDP in Gansu Province from 2014 to 2023 exhibits a trend of initial decline followed by an increase. The highest value was recorded in 2014, reaching 1.744 ha per 10,000 yuan of GDP. It then decreased steadily, reaching a minimum of 0.611 ha per 10,000 yuan in 2020. This indicates that, from 2014 to 2023, the efficiency of water resource utilization improved progressively, with reductions in water consumption and waste. However, after 2020, the utilization efficiency showed a slight decline.

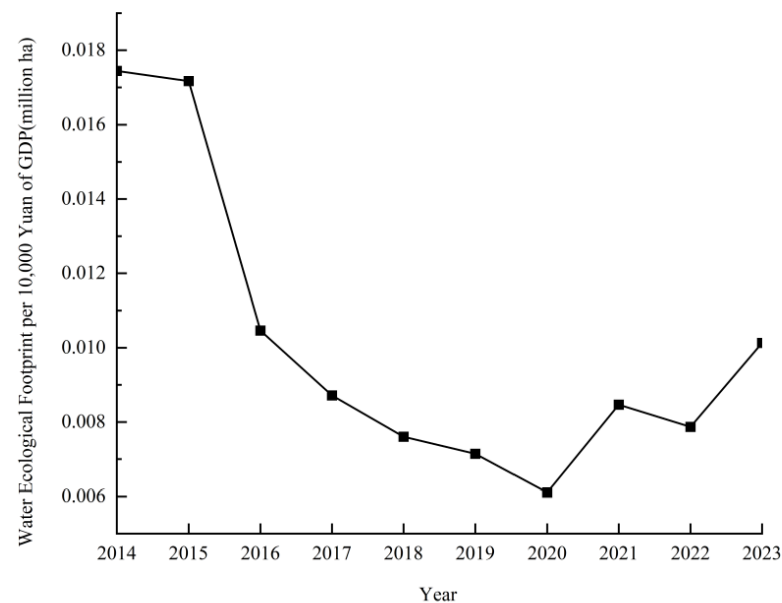


Figure 8. Temporal variation in the water ecological footprint per 10,000 Yuan of GDP in Gansu Province (2014–2023).

4.2. Comparative Analysis of Spatial Differences

4.2.1. Analysis of Spatial Differences in the Water Ecological Footprint

The changes in the water quantity and water quality ecological footprints in Gansu Province were calculated, and the results are shown in Figure 9.

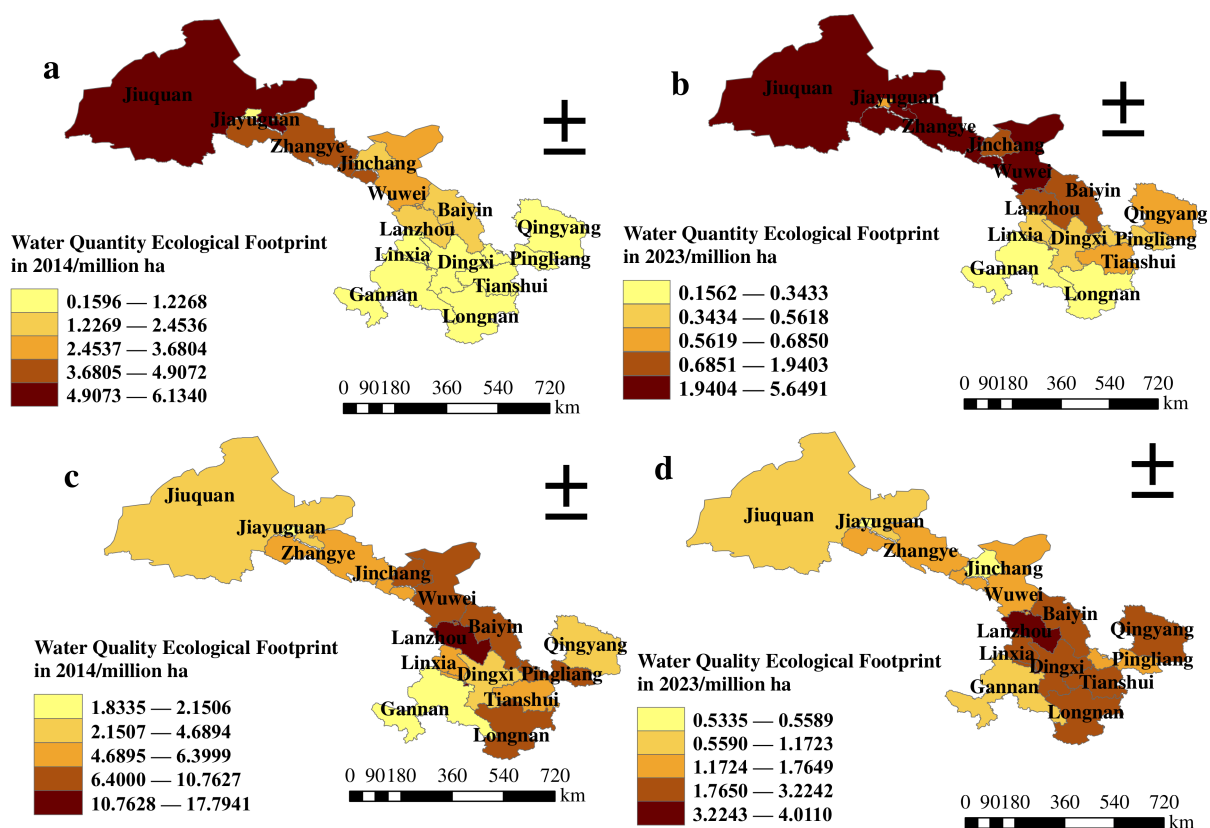


Figure 9. Spatial patterns of water ecological footprints in Gansu Province in 2014 and 2023: (a) spatial distribution of water quantity ecological footprint in 2014; (b) spatial distribution of water quantity ecological footprint in 2023; (c) spatial distribution of water quality ecological footprint in 2014; and (d) spatial distribution of water quality ecological footprint in 2023.

Panels a (2014) and b (2023) clearly illustrate the spatial patterns and temporal evolution of the water quantity ecological footprint in Gansu Province. In 2014, the water quantity ecological footprint exhibited a distinct single-center high-value pattern, with Jiuquan City serving as the core area at 6.134 million ha. Other cities in the Hexi Corridor, such as Zhangye and Wuwei, followed with values of 4.814 million ha and 3.524 million ha, respectively. In contrast, the southeastern regions of Gansu (e.g., Longnan, Tianshui, and Qingyang) generally displayed lower values, ranging from 0.1596 to 1.2268 million ha, resulting in a clear spatial disparity characterized by “high in Hexi, low in southeastern Gansu.”

By 2023, this pattern had undergone substantial changes. The high-value areas expanded significantly, with Hexi cities including Jiuquan, Zhangye, Jinchang, and Wuwei entering the 1.940–5.649 million ha range, forming a contiguous high-value belt. At the same time, cities such as Lanzhou, Baiyin, and Qingyang experienced noticeable increases in their water quantity ecological footprint, with some areas reaching 0.685–1.940 million ha. These results indicate that over the past decade, the overall pressure on water consumption in Gansu Province has intensified, particularly in the Hexi Corridor, where water-intensive industries such as agriculture and manufacturing have increasingly relied on water resources, making this region the core area of water quantity ecological pressure in the province.

Panels c (2014) and d (2023) illustrate the evolution of the water quality ecological footprint in Gansu Province. In 2014, the water quality ecological footprint displayed a spatial pattern of “high in southeastern Gansu, low in Hexi.” Cities in central and southeastern Gansu, such as Lanzhou, Baiyin, Tianshui, and Longnan, fell within the high-value range of 10.763–17.794 million ha, indicating significant water pollution pressure. In contrast, Hexi cities such as Jiuquan, Jiayuguan, and Zhangye exhibited relatively low values, ranging from 1.834 to 2.151 million ha.

By 2023, the overall water quality ecological footprint across the province showed a notable decline, and regional disparities were significantly reduced. High-value areas (3.224–4.011 million ha) remained concentrated in core cities such as Lanzhou, Baiyin, Tianshui, and Longnan, but their values had decreased substantially compared to 2014. Although the water quality ecological footprint in the Hexi region experienced a slight increase, it remained generally at a low level. These changes reflect the significant achievements Gansu Province has made in water pollution control, particularly in the reduction and management of pollution in southeastern Gansu. Nevertheless, this region remains the core area of water quality pressure in the province, necessitating continued and strengthened regulatory measures.

4.2.2. Comparative Analysis of Spatial Differences in the Ecological Carrying Capacity of Water Resources

The water ecological carrying capacity in Gansu Province is shown in Figure 10. Left panel (2014) and right panel (2023) clearly illustrate the spatial pattern and evolution of the water ecological carrying capacity in Gansu Province. In 2014, the water ecological carrying capacity exhibited significant spatial heterogeneity. Gannan Tibetan Autonomous Prefecture and Longnan City were identified as the core advantageous regions in terms of water resource endowment, with carrying capacities of 4.276 million ha and 1.793 million ha, respectively. In contrast, the Hexi regions, such as Jiuquan and Jiayuguan, generally exhibited extremely low values, ranging from 0.0001 to 0.0408 million ha. This resulted in a spatial pattern characterized by “high in southeastern Gansu and low in Hexi,” which is closely associated with natural background conditions such as precipitation and river network density.

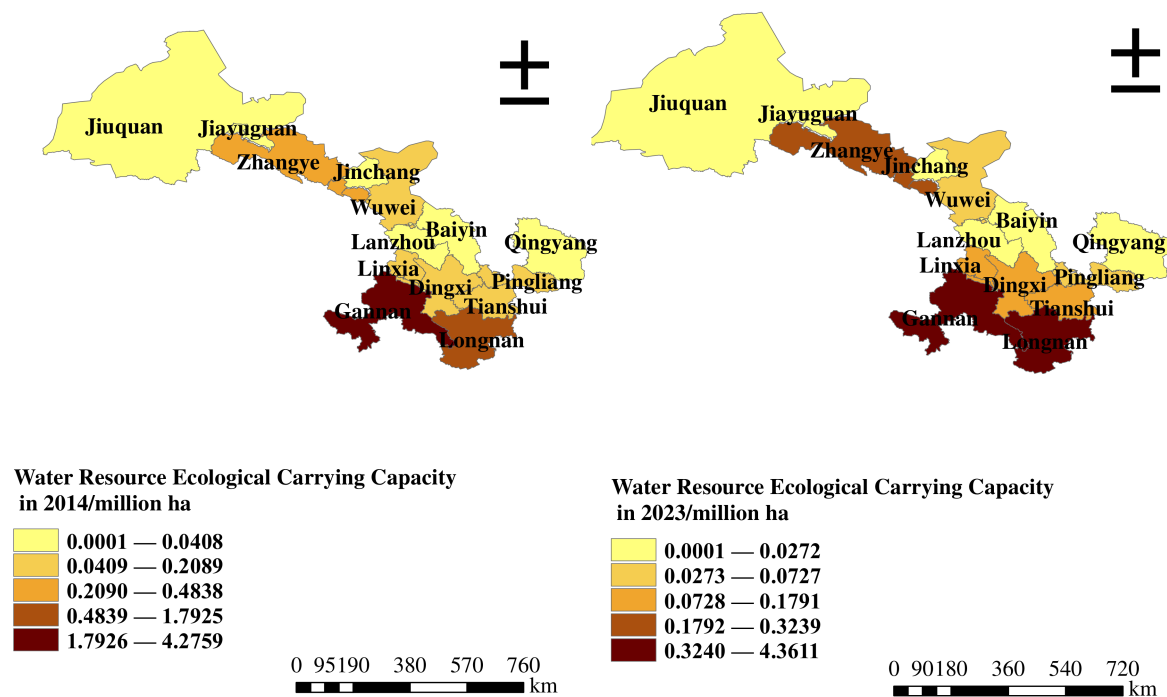


Figure 10. Spatial distribution of water ecological carrying capacity in Gansu Province (2014 and 2023).

By 2023, although this spatial pattern did not change fundamentally, the overall level of carrying capacity increased significantly. Core advantageous regions, including Longnan, Tianshui, and Dingxi, experienced further enhancement in carrying capacity, entering the high-value range of 0.324–4.361 million ha. At the same time, the carrying capacity in Hexi cities such as Zhangye, Jinchang, and Wuwei has also increased significantly, with some areas entering the range of 0.0728–0.1791 million ha. Overall, from 2014 to 2023, the water ecological carrying capacity in Gansu Province has shown a general upward trend, reflecting the positive effects of regional water resource management and ecological protection measures.

However, pronounced regional disparities still persist. The Hexi region continues to face severe constraints in terms of water resource endowment, whereas southeastern Gansu possesses greater potential for water resource carrying capacity. Based on these findings, regional water resource management should emphasize spatial coordination. The Hexi Corridor should focus on developing water-saving industries and optimizing water resource allocation in accordance with its limited carrying capacity. In contrast, southeastern Gansu can, under the premise of protecting its water resource endowment, moderately undertake industrial transfer and leverage its carrying capacity advantages, thereby promoting the efficient and coordinated utilization of water resources across the province.

Spatial Analysis of the Ecological Pressure Index and the Water Ecological Footprint per 10,000 Yuan of GDP.

The variation in the water ecological pressure index and the water ecological footprint per unit of GDP in Gansu Province is shown in Figure 11. Panels a (2014) and b (2023) illustrate the spatial pattern and evolution of the water ecological pressure index in Gansu Province. In 2014, the cities with the highest pressure indices were Jiayuguan, Jinchang, Baiyin, and Lanzhou, with values of 35,905.3, 4341.78, 2779.92, and 2105.91, respectively, indicating extremely severe contradictions between water supply and demand. Cities such as Jiuquan, Wuwei, Qingyang, and Pingliang followed, with pressure indices of 259.366,

110.99, 147.15, and 94.78, respectively. In contrast, regions including Linxia, Gannan, Dingxi, Tianshui, and Longnan exhibited relatively low pressure indices, ranging from 0.47 to 53.20, suggesting comparatively abundant water resource endowments and a more balanced relationship between supply and demand.

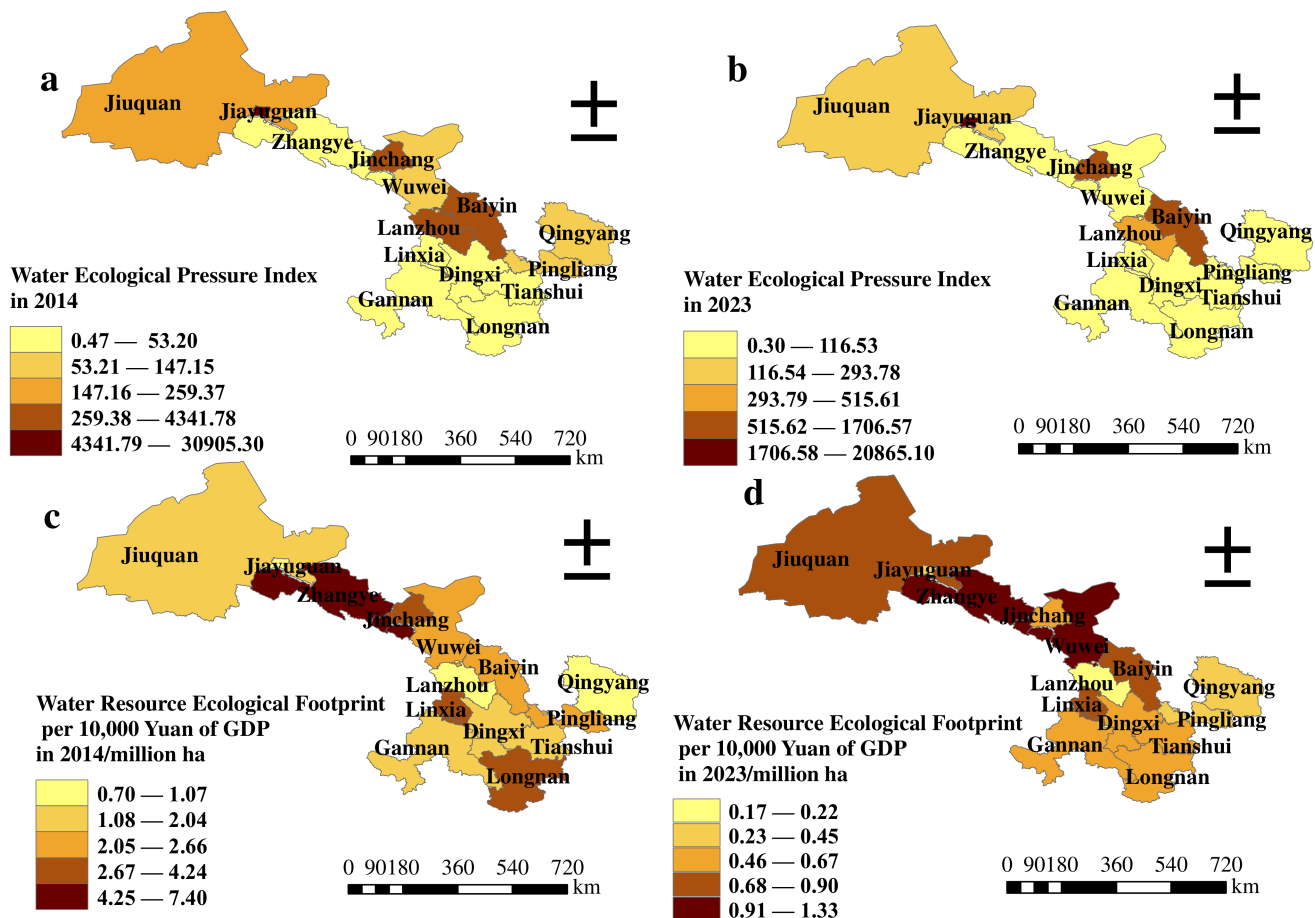


Figure 11. Spatial patterns of water ecological pressure index and water ecological footprint intensity in Gansu Province during 2014 and 2023: (a) spatial distribution of water ecological pressure index in 2014; (b) spatial distribution of water ecological pressure index in 2023; (c) spatial distribution of water ecological footprint per 10,000 yuan of GDP in 2014; and (d) spatial distribution of water ecological footprint per 10,000 yuan of GDP in 2023.

By 2023, this spatial differentiation pattern had further intensified. The high-pressure zones in the Hexi Corridor expanded significantly, with cities such as Jiuquan, Zhangye, Jinchang, and Wuwei entering the extremely high-pressure range of 1706.58–20,865.10, forming a contiguous core pressure belt. Meanwhile, the pressure indices in cities such as Lanzhou, Baiyin, and Qingyang also increased markedly, with some areas reaching the range of 515.62–1706.57. These findings indicate that over the past decade, the overall water resource pressure in Gansu Province has intensified, particularly in the Hexi region, where the contradiction between water supply and demand has continued to worsen, making it the core risk area for water resource security in the province.

Panels c (2014) and d (2023) illustrate the spatiotemporal evolution of the water ecological footprint per unit of GDP in Gansu Province, reflecting changes in water resource utilization efficiency. In 2014, the spatial pattern exhibited a clear differentiation of “high in Hexi and low in southeastern Gansu.” Cities in the Hexi Corridor, such as Jiuquan, Zhangye, Jinchang, and Wuwei, fell within the high-value range of 4.25–7.40 ha per 10,000 yuan, indicating relatively low water use efficiency. In contrast, southeastern regions including

Longnan, Gannan, and Linxia generally showed lower values, ranging from 0.70 to 1.07 ha per 10,000 yuan, suggesting comparatively higher efficiency.

By 2023, the water ecological footprint per unit of GDP across the province exhibited a significant overall decline, and regional disparities were notably reduced. The high-value range in the Hexi Corridor decreased substantially to 0.91–1.33 ha per 10,000 yuan, indicating marked improvements in water use efficiency in cities such as Jiuquan, Zhangye, Jinchang, and Wuwei. Meanwhile, cities such as Lanzhou, Baiyin, and Qingyang also experienced notable reductions, with values falling to 0.46–0.67 ha per 10,000 yuan. These changes reflect the significant achievements made by Gansu Province in optimizing industrial structure and promoting water-saving technologies. In particular, the improvement in water use efficiency in the Hexi region has been most pronounced. However, compared with southeastern Gansu (0.17–0.22 ha per 10,000 yuan), a certain gap still remains.

In summary, from a spatial perspective, both the water ecological pressure index and the water ecological footprint per unit of GDP consistently exhibit a pattern of “high in the Hexi region and low in southeastern Gansu,” reflecting the dual challenges in the Hexi region of pronounced water supply–demand conflicts and relatively low utilization efficiency. From a temporal perspective, water resource pressure has generally intensified, with the imbalance between supply and demand continuing to worsen. In contrast, the water ecological footprint per unit of GDP has shown an overall declining trend, indicating a significant improvement in water use efficiency. This suggests that water-saving measures have achieved positive outcomes; however, these improvements remain insufficient to effectively alleviate the overall pressure on water resources.

Based on these findings, differentiated strategies should be adopted for regional water resource management. The Hexi Corridor should prioritize water conservation, promote the transformation of water-intensive industries, and enhance water use efficiency to mitigate supply–demand conflicts. In contrast, southeastern Gansu can, under the premise of protecting its water resource endowment, moderately undertake industrial transfer and leverage its comparative advantages in water resources, while continuously improving utilization efficiency, thereby achieving efficient coordination and sustainable use of water resources across the province.

5. Discussion

This section is organized into three main parts. First, the temporal variation in the water resource ecological footprint in Gansu Province from 2014 to 2023 is analyzed and discussed. Second, a sensitivity analysis is conducted to assess the uncertainty associated with the key parameters. Third, the limitations of this study and potential directions for future research are discussed.

5.1. Analysis of the Water Resource Ecological Footprint

The integrated results indicate that the water resource system in Gansu Province has long remained in a state of significant ecological deficit, with persistent and pronounced conflicts between water supply and demand. This phenomenon is fundamentally driven by the combined effects of natural endowment constraints, industrial structure, and regional development imbalance. From a temporal perspective, although the water ecological footprint shows a declining trend in certain years, it remains consistently higher than the ecological carrying capacity, resulting in sustained high ecological pressure. This finding is consistent with previous studies conducted in arid and semi-arid regions, which have shown that water scarcity depends not only on the total amount of available water resources but also on intensive human water use and inefficient allocation patterns [33]. The results suggest that existing water-saving technologies and management measures have improved

water-use efficiency to some extent, but they have not fundamentally altered the highly constrained water resource regime.

From the perspective of driving mechanisms, agricultural water use is identified as the dominant factor influencing the provincial water quantity ecological footprint, which is consistent with the findings of Li Xiaopeng et al. [34] and other studies emphasizing the critical role of agricultural irrigation in shaping water resource pressure in inland arid regions. However, compared with previous studies that mainly focused on water quantity consumption, this study further incorporates the water quality ecological footprint, providing a more comprehensive assessment of regional water resource sustainability. The inclusion of water quality factors reveals additional spatial differences that may be overlooked in traditional water consumption-based assessments. Specifically, the Hexi Corridor exhibits particularly prominent water ecological footprint characteristics [35]. This region is highly dependent on irrigation agriculture with large water consumption, making it the primary source of water resource depletion and leading to a pronounced spatial concentration of high water quantity ecological footprint values. Similar patterns have also been reported in other arid agricultural regions, where excessive irrigation and limited water regeneration capacity have become key constraints on sustainable development [36]. Meanwhile, although industrial and domestic water use account for relatively smaller proportions at the provincial scale, they still exert additional pressure in urbanized areas, further intensifying local water supply–demand imbalances.

The differences between this study and previous research highlight the importance of considering both water quantity and water quality dimensions when assessing regional water sustainability. Traditional water resource evaluation methods often focus primarily on water withdrawal or consumption, thereby underestimating ecological pressure; by contrast, the integrated ecological footprint approach adopted in this study provides a more comprehensive understanding of the interactions between human activities and aquatic ecosystems. Therefore, the results contribute to the broader scientific discussion on sustainable water management by demonstrating that regional water security in arid areas requires not only reducing water consumption but also improving water-use efficiency, controlling pollution loads, and optimizing the spatial allocation of water resources.

Under these circumstances, reliance solely on traditional experience-based regulation is no longer sufficient to meet the requirements of refined water resource management. Local water resource management authorities should further adopt advanced numerical simulation tools, such as hydrological and water resource simulation models, system dynamics models, and multi-scenario optimal allocation models. These tools can help establish multi-scale and multi-scenario forecasting and allocation systems, thereby improving the ability to respond to variations in agricultural water demand, climate fluctuations, and industrial restructuring. Ultimately, integrating scientific modeling approaches with adaptive management strategies can support the dynamic optimization and precise regulation of water supply–demand relationships, providing practical guidance for sustainable water management and ecological civilization development in arid regions.

5.2. Sensitivity Analysis of Parameters

Sensitivity analysis was calculated using Equation (9), and the variations in output results under a $\pm 20\%$ perturbation range, together with the corresponding sensitivity coefficients, are shown in Figure 12. The results indicate that the water resource ecological footprint model exhibits strong stability and consistency under $\pm 20\%$ parameter perturbations. As the scenario changes from -20% to $+20\%$, the water ecological footprint (EF_w), ecological carrying capacity (EC_w), and ecological deficit (ED_w) all show an almost perfectly linear and synchronous increasing trend. The relationships among the three indicators

remain stable, with no structural discontinuities or directional reversals, indicating that the model outputs respond smoothly to parameter perturbations.

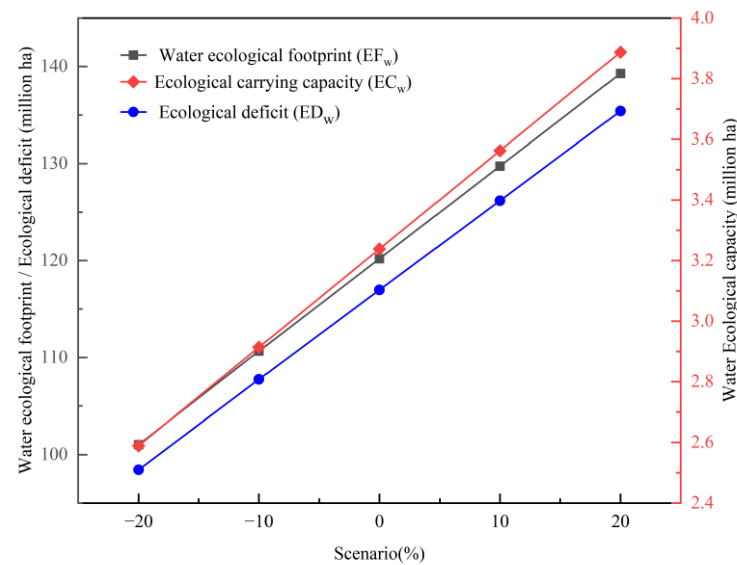


Figure 12. Impact of Parameter Perturbations on Output Results.

The sensitivity analysis shows that all three key parameters have sensitivity coefficients below 1. As shown in Figure 13. Among them, the water yield factor (0.83) has the greatest influence, followed by water productivity (0.80), while the water equilibrium factor (0.79) has the weakest influence. This indicates that the model exhibits low-to-moderate sensitivity to parameter variations, and that parameter uncertainty does not significantly affect the overall conclusions of the study.

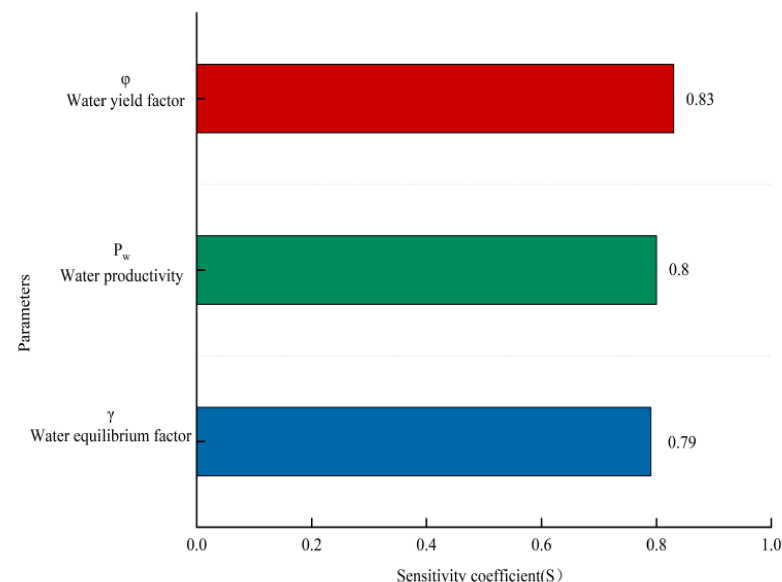


Figure 13. Sensitivity coefficients of key parameters in the water ecological footprint model.

Furthermore, although the key parameters were derived from previous studies and were not recalibrated specifically for Gansu Province, the sensitivity results demonstrate that the model conclusions remain consistent within a reasonable perturbation range. This suggests that the parameter system has good applicability and robustness at the regional scale of Gansu Province.

5.3. Limitations and Future Directions

5.3.1. Limitations

This study conducted a spatiotemporal assessment of the sustainable utilization of water resources in Gansu Province based on the water ecological footprint model; however, several limitations remain.

First, the water quality ecological footprint only considers two major pollutants, namely chemical oxygen demand (COD) and ammonia nitrogen ($\text{NH}_3\text{-N}$). Due to limited data availability, other pollutants such as total phosphorus (TP) and total nitrogen (TN) were not included, which may introduce certain deviations in the evaluation results.

Second, the current spatial analysis is mainly conducted at the municipal scale using discrete administrative units. Although this approach can reveal the macroscopic spatial pattern of water resource utilization, it still has limitations in capturing internal spatial heterogeneity. On the one hand, substantial variations in water resource exploitation intensity exist within administrative units, and analyses based on municipal averages may obscure the actual distribution of water stress in localized areas, such as intensive agricultural irrigation zones or highly water-intensive industrial clusters. On the other hand, this approach cannot adequately represent the continuous spatial gradients of water resource elements, thereby limiting the in-depth interpretation of spatial process mechanisms. Moreover, analyses at the prefecture-level scale involve relatively large spatial units, which may mask significant differences among counties within the same administrative region, leading to an averaging effect that weakens the representation of localized high-pressure or high-capacity areas. In addition, at the municipal scale, spatial heterogeneity in industrial structure, water use patterns, and ecological conditions cannot be fully captured, resulting in reduced accuracy in identifying key driving factors.

5.3.2. Future Directions

Future research could be further deepened in two aspects.

First, more representative water pollutant data should be collected to enrich the evaluation indicator system of the water quality ecological footprint, thereby improving the comprehensiveness of water quality assessment. Second, a fine-scale assessment of water resource sustainability at the county level should be conducted to more accurately reveal the spatial clustering characteristics of water resource pressure and to identify representative high-risk areas.

Furthermore, by integrating GIS spatial analysis techniques or remote sensing big data platforms such as Google Earth Engine (GEE), a raster-based continuous spatiotemporal analytical framework can be developed to achieve spatially explicit representation of the water ecological footprint and related indicators. By incorporating high-resolution remote sensing data and surface environmental information, it is expected that the spatial distribution patterns of agricultural water stress can be more precisely characterized, and potential water stress hotspots and ecologically sensitive areas can be identified. This approach will significantly enhance the accuracy and interpretability of spatial analysis and provide more robust scientific support for refined regional water resource management and differentiated policy regulation.

6. Conclusions

Based on the integrated assessment of water resource ecological footprint and ecological carrying capacity in Gansu Province from 2014 to 2023, the results indicate that the region has remained in a long-term ecological deficit with consistently high water resource ecological pressure ($\text{WEPI} > 1$). Both water quantity and water quality ecological footprints show a general “decrease first and then increase” trend, while ecological carrying

capacity remains relatively limited, leading to a persistent imbalance between water supply and demand. Agricultural water use is identified as the dominant stressor, imposing a strong and sustained constraint on the regional water system. Spatially, a pronounced heterogeneity is observed, with the Hexi Corridor representing a high water consumption and high ecological pressure zone, while southeastern Gansu exhibits relatively higher carrying capacity but still faces localized water quality stress. Although the decline in GDP-based water ecological footprint indicates an improvement in water use efficiency, the sustainability of water-saving effects remains insufficient, and overall water resource pressure continues to intensify.

In alignment with the principle of “water conservation priority, spatial balance, and systematic governance,” Gansu Province—representative of arid inland regions—should further strengthen the strictest water resource management system and enhance binding constraints on water consumption. Within the framework of the Yellow River Basin ecological protection and high-quality development strategy, it is necessary to strictly control the expansion of water-intensive industries in the Hexi Corridor and promote agricultural water-saving practices, industrial restructuring, and optimized spatial allocation of water resources.

Furthermore, under the dual-carbon goals, water constraints have become a key limiting factor in energy-based development. It is therefore essential to coordinate water resources with energy and ecological systems, optimize the layout of hydropower and renewable energy development, and avoid the compounded ecological pressure caused by simultaneous expansion of energy exploitation and water-intensive industries. By building a water–energy–ecology coordinated governance system, strong support can be provided for achieving both high-quality development and ecological security in arid regions.

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