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Analysis of the Water Resource Carrying Capacity in Guyuan City

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Abstract: To assess the water resource carrying capacity of Guyuan City, an analysis was conducted using the load index method, principal component analysis, and ecological water footprint method. A comprehensive analysis was carried out using these three methods to evaluate the current state of water resource carrying capacity in Guyuan City. The results indicate that the water resource carrying capacity in Guyuan City is mainly influenced by economic development factors, water supply–demand balance factors, and natural factors. During the period from 2002 to 2016, the water resource carrying capacity fluctuated in response to changes in the total water resources. However, from 2016 to 2021, it exhibited an increasing trend due to improvements in water resource utilization efficiency and effective water conservation measures. However, the water resource carrying capacity remains at a relatively low level, and it has consistently been in an overloaded state, with the development and utilization of water resources approaching their limits. Water scarcity in Guyuan City is a pressing concern, characterized by severe limitations on its potential for development and utilization. The persistent supply–demand imbalance is anticipated to impede the region's pursuit of high-quality economic development in the foreseeable future.

Keywords: water resource; ecological carrying capacity; load index; principal component analysis; ecological water footprint; Guyuan City

Citation: Peng, W.; Li, C.; Yu, H.; Zhang, Y.; Li, M. Analysis of the Water Resource Carrying Capacity in Guyuan City. *Sustainability* **2023**, *15*, 16159. https://doi.org/10.3390/su152316159

Academic Editor: Francesco Granata

Received: 21 September 2023
Revised: 31 October 2023
Accepted: 16 November 2023
Published: 21 November 2023

1. Introduction

As the economy continues its growth, the disparity between water supply and demand, along with the deterioration of aquatic ecosystems and water environments, have become a pivotal factor hindering urban development. Water resource carrying capacity, serving as a cornerstone for urban water resource security, constitutes a pivotal indicator in gauging a region's development capacity. The extent of water resource carrying capacity directly or indirectly influences the permanent population, the surrounding environment, interrelated ecosystems, and the socio-economic development of a region [1].

The concept of water resource carrying capacity was explained in the published literature by both Peng et al. [2] and Yang et al. [3] as the maximum scale at which a water resource system can sustain socio-economic development in a sustainable manner, while Wang et al. [4] explained it as the state of integration and coupling between water resources, society, economy, ecology, and environmental system. Despite differences in interpretation, both viewpoints concur that water resource carrying capacity is determined by the collective influence of water resources, society, the economy, ecology, and environmental system. They aim to resolve conflicts between socio-economic development and the water resource environmental system [5].

As the comprehension of water resource carrying capacity advances, the array of research methods employed to explore it has grown more diverse. These various methods can be primarily categorized into three groups. The first category comprises the empirical formula method, in which researchers estimate the regional water resource carrying capacity based on their expertise and analyses, including analog analysis, trend analysis, and quota analysis [6]. The second category involves the index system evaluation method, utilizing techniques like principal component analysis, the entropy weight method, fuzzy comprehensive evaluation [7], projective tracking, and other techniques to establish a representative indicator system for the comprehensive evaluation of water resources carrying capacity. Various indicators for estimating water resource carrying capacity currently lack unified standards. However, some commonly utilized standards encompass economic, social, and ecological aspects of water resources [8], as well as criteria related to driving forces, pressures, states, impacts, and responses [9]. The third category is the systems analysis method [10], which comprehensively considers numerous potential factors that influence water resources and establishes a complex integrated system.

Leeuw et al. [11] introduced a method to calculate water resource carrying capacity by analyzing factors such as population and climate conditions in sub-Saharan Africa. Engelman et al. [12] expanded on this approach by incorporating a supply–demand analysis of freshwater resources required for urban industrialization, taking into account both the population growth rate and the overall population size. Rijsberman et al. [13], in their exploration of water resource utilization and conservation, incorporated the concept of water resource carrying capacity into the assessment framework to ensure regional water resource security. Alice [14] applied a functional quantitative approach to refine the vague and general notion of water resource carrying capacity when researching the water resource carrying capacity of the Florida Islands. Menem et al. [15] designed software to calculate water resource carrying capacity, utilizing residential water consumption in the Algerian region as an evaluation criterion. They also made projections regarding the trends in water resource carrying capacity for the foreseeable future. Djuwansyah [16] advocated for the utilization of water resource carrying capacity in the context of ecological sustainability, with Indonesia as a case study. His work emphasized the importance of regular calculations of water resource carrying capacity for evaluating urban sustainability. In 1992, Shi et al. [17] were pioneers in introducing the specific concept of water resource carrying capacity in China and developed corresponding assessment models. In 2015, You et al. [18] conducted a quantitative study using Qiannan Prefecture as a case study, investigating the relationship between water resources, varying welfare living standards, and their capacity to support the population in the Qiannan region by comparing different methods. Their conclusion is that focusing solely on water resources is insufficient to study water resource carrying capacity, and they emphasize the importance of determining carrying capacity control factors based on regional resource factors. Yu [19] calculated water ecological deficits and surpluses using the ecological footprint method. They introduced balance and output factors to analyze the water resource carrying capacity of the Ninglang River in Yunnan. Zheng [20] conducted a comprehensive evaluation of water resource carrying capacity in Guangdong Province. This assessment was grounded in the rational allocation of regional water resources and ecological circulation. It took into account the development of water resources, the ecological environment, and socio-economic conditions, employing a multi-level fuzzy comprehensive evaluation method. Liu et al. [21] scrutinized water resources in the Yellow River Basin, underscoring the intricate interplay between water resource challenges, population dynamics, economic development, societal factors, and environmental aspects. They emphasized that analyzing water resource carrying capacity serves as an effective approach to illustrate these intricate connections. Zhang et al. [22] integrated the examination of water resource carrying capacity within industrialized urban zones into a broader regional complex system encompassing "economy-water resources-ecology and environment." This approach unveiled the fundamental nature of water resource carrying capacity. Wang et al. [23] conducted a principal component analysis in

Hubei Province, employing a set of 17 indicators to identify the key influencing factors that impact Hubei Province's water resource carrying capacity.

Assessing whether regional water resources can effectively support socio-economic development and ecological environment construction is a pivotal consideration for achieving regional sustainability. In light of the research background discussed earlier, to overcome the limitations of relying on a single research method, this paper adopts a tripartite approach, including the load coefficient method, principal component analysis method, and ecological water footprint method, to evaluate Guyuan City's water resource carrying capacity from 2002 to 2021. The objective is to establish a foundation for the future rational allocation of water resources in Guyuan City.

2. Materials and Methods

2.1. Study Area

Guyuan City is positioned between longitudes 105°19′ to 106°57′ east and latitudes 35°14′ to 36°31′ north, situated on the northwestern periphery of the Chinese Loess Plateau. It covers a total area of 10,500 km^2. In 2021, Guyuan City experienced an annual average precipitation of 472 mm, with surface evaporation reaching 1364 mm. It also registered an annual average runoff of 6.822×10^9 m^3, accompanied by an average runoff depth of 64.1 mm. It belongs to the warm-temperate semi-arid climate zone of the Loess Plateau. The per capita water resources in the region have consistently remained at a mere 378 m^3 per year, representing a mere 16.7% of the national average surface runoff depth. The widely distributed saline and brackish water resources cover nearly one-third of the total natural surface water resources, and the overall municipal area has a relatively weak inter-basin water transfer network. This, coupled with a low level of water supply security, severely affects the sustainability of water resources development. As supply–demand imbalances continue to grow due to economic development, gaining a comprehensive understanding of the actual water resource carrying capacity of this region is essential for devising innovative strategies to "enhance water sources and promote water conservation". The geographical location of Guyuan City is shown in Figure 1.

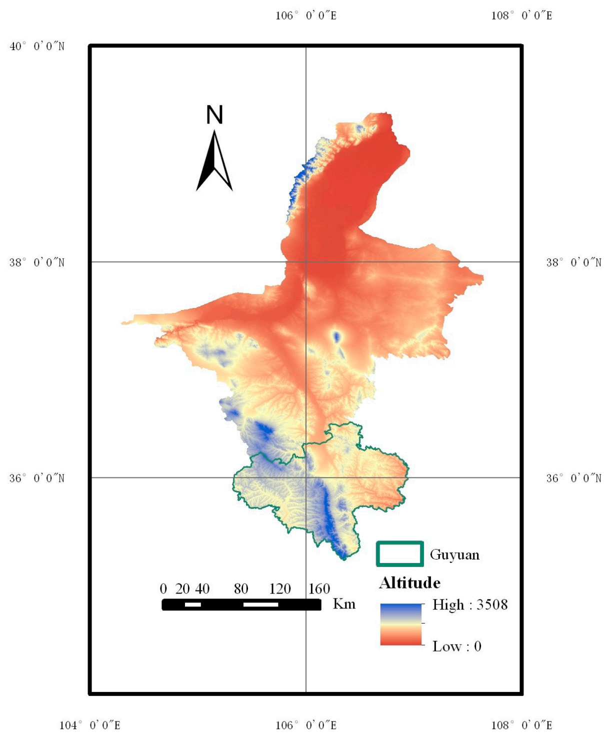

Figure 1. Geographical location of the study area.

2.2. Source of Data

The data used in this study are derived from various sources, including Guyuan City Statistical Yearbooks, Water Resources Bulletins, Environmental Reports, Government Work Reports, etc. The data cover the period from 2002 to 2021, with the latest available data up to 2021, considering limitations related to data updates.

2.3. Research Methods

2.3.1. Load Index Method

The water resource load index holds a significant physical interpretation, serving as a framework that considers precipitation within a specific region, the total population, and irrigated agricultural land to gauge the demand for water resources. This index effectively portrays the present utilization status of water resources, offering insights into the feasibility and challenges of water resource development [24]. The formula for computing the water resource load index is provided below:

$$C = \frac{K \cdot \sqrt{P \cdot G}}{W} \tag{1}$$

In the formula: C represents the water resource load coefficient; P represents the population (10^4 person); G represents the gross domestic product (10^8 Yuan); W represents the total water resources (10^8 m^3).

K is a coefficient related to precipitation, and the specific algorithm is as follows:

$$K = \begin{cases} 1.0 & R \le 200 \\ 1.0 - 0.1(R-200)/200 & 200 < R \le 400 \\ 0.9 - 0.2(R-400)/400 & 400 < R \le 800 \\ 0.7 - 0.2(R-800)/800 & 800 < R \le 1600 \\ 0.5 & R > 1600 \end{cases} \tag{2}$$

In the equation: R represents precipitation (mm).

2.3.2. Principal Component Analysis

Principal component analysis is a widely employed multivariate statistical analysis technique. Its primary objective is to convert multiple correlated variables into a reduced set of uncorrelated principal components. By utilizing principal component analysis, it becomes feasible to streamline the dataset and diminish inter-variable correlations, consequently augmenting the efficiency and reliability of data analysis [25].

The specific steps for conducting a principal component analysis are as follows:

(1) Data Preprocessing: In the initial step, raw data are preprocessed and standardized to mitigate issues associated with scale and unit disparities, which can introduce errors.
(2) Correlation Coefficient Matrix: The preprocessed data are then used to compute a correlation coefficient matrix.
(3) Eigenvalues and Eigenvectors: Based on the calculations from the previous step, eigenvalues and eigenvectors are derived.
(4) Component Contribution: The eigenvalues and eigenvectors are analyzed to ascertain the contribution of each component. It is widely accepted in academia to consider components with a cumulative contribution rate exceeding 85% as principal components.
(5) Principal Component Loadings: Principal component loadings are calculated.
(6) Impact Analysis: The impact of each component is assessed by examining the major components and their respective contribution rates.

2.3.3. Ecological Footprint Method

The ecological footprint method for water resources is a comprehensive approach that bridges various interdisciplinary fields, including environmental science and ecology. This method systematically evaluates water resource carrying capacity in a quantitative manner, enabling a better understanding of the level of sustainable water resource utilization [26]. The calculation model for the water resource ecological footprint is derived from the model originally introduced and subsequently refined by Huang et al. [27] to assess sustainability and utilization. In the ecological footprint model, it is crucial to account for variations in the unit area production capacity across different land types. To render the results comparable on a global scale, enabling international comparisons, a standardization process is employed. This involves applying an equivalence factor to the land area of various bioproductive types, thereby transforming them into standardized values for intercomparison. This equivalence factor, denoted as γ_W, is referred to as the global balance factor for water resources.

(1) Water Resource Carrying Capacity Calculation Model: Following the ecological footprint model introduced by Mathis et al. [28], the ecological carrying capacity of water resources is defined as the extent of bioproductive land required to sustain water resources. In this study, recognizing the importance of reserving a minimum of 60% of a country or region's water resource carrying capacity to ensure the well being of the natural ecological environment and the conservation of biodiversity, we introduce a water resource development constant of 0.4. The global average water resource production capacity is established at 314.0 m^3/km^2, and γ_W is set to 5.19, a value previously validated by the World Wide Fund for Nature (WWF) in 2002 [29]. The calculation model for water resource carrying capacity is outlined as follows:

$$EC_W = 0.4 \cdot \gamma_W \cdot \phi_W \cdot \left[\frac{Q}{P_W} \right] \tag{3}$$

In the equation: EC_W represents water resource carrying capacity (km^2); γ_W is the global water resource balance factor; φ_W is the regional water resource yield factor; Q represents the regional total water resources (m^3); P_w is the global average water resource production capacity (m^3/km^2).

Determination of the Yield Factor: The use of a yield factor becomes necessary due to variations in the productivity of similar ecological productive land across different regions, making it unsuitable to directly compare the actual areas of similar ecological productive land in these regions. Essentially, the yield factor serves as a parameter that standardizes the areas of similar ecological productive land in different regions for comparative purposes. In hydrology, the concept of the average water yield modulus is employed to calculate the quantity of surface water resources, subtracting the duplicated calculation amount of groundwater resources and dividing by the area of the calculation region during the specified calculation period. The calculation formula is expressed as follows:

$$P = \frac{Q}{S} \tag{4}$$

In the equation: P represents the average water yield during the calculation period (m^3/km^2); Q represents the total water resources in the calculation region during the calculation period (m^3), which includes the sum of surface water resources and groundwater resources, minus the duplicated calculation amount; S is the area of the calculation region (m^2).

The formula for the Chinese water resource production factor is:

$$\psi_1 = \frac{P_C}{P_0} \tag{5}$$

In the equation: ψ_1 represents the Chinese water resource yield factor; P_c is the Chinese water production per unit area (m^3/km^2); P_0 is the world water yield per unit area (m^3/km^2).

$$\psi_W = \frac{P}{P_C} \cdot \psi_1 \tag{6}$$

In the equation: ψ_W represents the regional water resource yield factor on a global scale; P represents the water yield per unit area within the region (m^3/km^2); P_C represents the water yield per unit area on a national scale (m^3/km^2).

(2) Water Resource Ecological Deficit Calculation Model: The difference between water footprint and water resource ecological carrying capacity is the water resource ecological deficit. When the ecological carrying capacity of water resources EC_W exceeds the water footprint C_W, it indicates an ecological surplus of water resources in the study area. This signifies that the region's human living conditions are within the reasonable ecological carrying capacity of the water resource environment. Consequently, the ecosystem is secure and can support various human activities, and social and economic human development remains within a sustainable range. Conversely, if the ecological carrying capacity EC_W is smaller than the water footprint C_W, it indicates an ecological deficit of water resources in the area. This means that the region's water resource ecosystem has exceeded its capacity and can no longer support various human activities for living and production. In such a situation, the region's social, economic, and human development is unsustainable. To assess ecological deficits, the ecological deficit model proposed by Hu et al. [30] in 2006 is utilized. This model identifies ecological deficit issues when the total water resources available in a region cannot meet the region's water resource needs. Ecological deficits and surpluses serve as the primary theoretical basis for assessing regional water resource sustainability using the ecological footprint method.

3. Results and Analysis

3.1. Analysis of Water Resource Carrying Capacity in Guyuan City Based on the Load Index Method

By inputting the data for total water resources, gross domestic product (GDP), year-end population, and annual precipitation into Equation (1), we can derive the water resource load coefficients for Guyuan City spanning from 2003 to 2021. Referring to the classification of water resource load index in the analysis of water resource potential development in Xuzhou City by Wang [24], the graded evaluation of the water resource load index is provided in Table 1. Agriculture has consistently served as the foundational industry in both Xuzhou City and Guyuan City, playing a pivotal role in supporting local economic development. Therefore, the water resource carrying capacity in Guyuan City was also classified into five levels, and the results of this water resource load classification can be found in Table 2.

Table 1. Assessment of water resource load index levels.

Level	C	Water Resource Utilization Level	Water Resource Development Evaluation
I	>10	Very high, limited potential	When conditions permit, water transfer from external basins is required
II	5~10	High, limited potential	Development conditions are challenging
III	2~5	Medium, moderate potential	Development conditions are moderate
IV	1~2	Low, significant potential	Development conditions are relatively favorable
V	<1	Low, very high potential	Undertaking small- to medium-sized projects, development is relatively straightforward

Table 2. Load grade classification table for Guyuan City, 2002–2021.

Year	Annual Precipitation R (mm)	Population P (10^4 Person)	Gross Domestic Product G (10^9 Yuan)	Total Water Resources W (10^9 m^3)	K	Load Coefficient	Load Grade
2002	412	188.19	25.79	6.186	0.894	10.068	I
2003	523	187.83	31.45	7.691	0.839	8.379	II
2004	410	151.27	35.75	4.918	0.895	13.383	I
2005	428	150.62	44.88	5.334	0.886	13.657	I
2006	411	152.24	51.94	5.090	0.895	15.627	I
2007	391	142.58	63.52	4.338	0.905	19.843	I
2008	370	134.42	75.79	3.452	0.915	26.754	I
2009	348	135.14	89.77	3.078	0.926	33.136	I
2010	496	123.32	105.80	3.892	0.852	25.005	I
2011	447	124.71	134.18	4.398	0.877	25.780	I
2012	475	126.43	158.45	4.281	0.863	28.516	I
2013	656	124.41	184.58	6.990	0.772	16.736	I
2014	560	122.74	201.03	4.960	0.820	25.969	I
2015	452	121.18	217.31	4.171	0.874	34.004	I
2016	403	122.03	239.80	3.734	0.899	41.162	I
2017	491	122.82	270.09	5.110	0.855	30.456	I
2018	638	124.23	303.19	7.153	0.781	21.190	I
2019	628	125.05	322.66	7.402	0.786	21.33	I
2020	538	114.3	352.46	5.971	0.831	28.818	I
2021	236	114.8	375.13	4.905	0.864	36.554	I

From Table 2, it is evident that in Guyuan City between 2002 and 2021, the load grade for the year 2003 is the only instance classified as Level II. This classification signifies high water resource utilization with constrained potential and formidable development circumstances. In all other years, the load grade remains at Level I, signifying exceptionally high water resource utilization, limited availability of regional water resources, and constrained development potential. As the local economy continues to expand, Guyuan City is inevitably poised to confront water scarcity challenges in the future. To ensure the sustainable utilization of water resources, Guyuan City needs to take proactive and scientifically informed measures. Additionally, reforming current water resource utilization practices to enhance reclaimed water efficiency is equally crucial.

Between 2002 and 2021, Guyuan City's population experienced a decrease of 7.339×10^5 people, translating to an average annual decline rate of 3.67%. In contrast, the local economy exhibited robust growth, registering an impressive average annual expansion rate of 17.47% over these two decades. During this time frame, water resources within the region remained relatively stable in terms of total volume, albeit with some fluctuations. Over the course of these 20 years, the peak total water resources reached 7.69×10^9 m^3, while the lowest recorded figure stood at 3.08×10^9 m^3. Combining the data from Table 2 and Figure 2, it becomes evident that Guyuan City experienced its highest water resource load factor in 2016, within the timeframe spanning from 2002 to 2021. This increase in the water resource load index can be attributed to a concurrent decline in water resources and a significant rise in GDP during that period. After 2016, the implementation of water-saving irrigation technology and efficient management systems initiated a decline in the water resource load index within the region. Nevertheless, the years 2020 and 2021 witnessed a noteworthy reduction in precipitation, resulting in a sharp decline in total water resources, and subsequently causing an increase in the load index. Moreover, despite the growth in GDP and a slight decrease in the permanent population, Guyuan City's load index remained consistently high. This persistence can be attributed not only to the inherent water resource scarcity, but also to its intricate connection with economic development and urbanization.

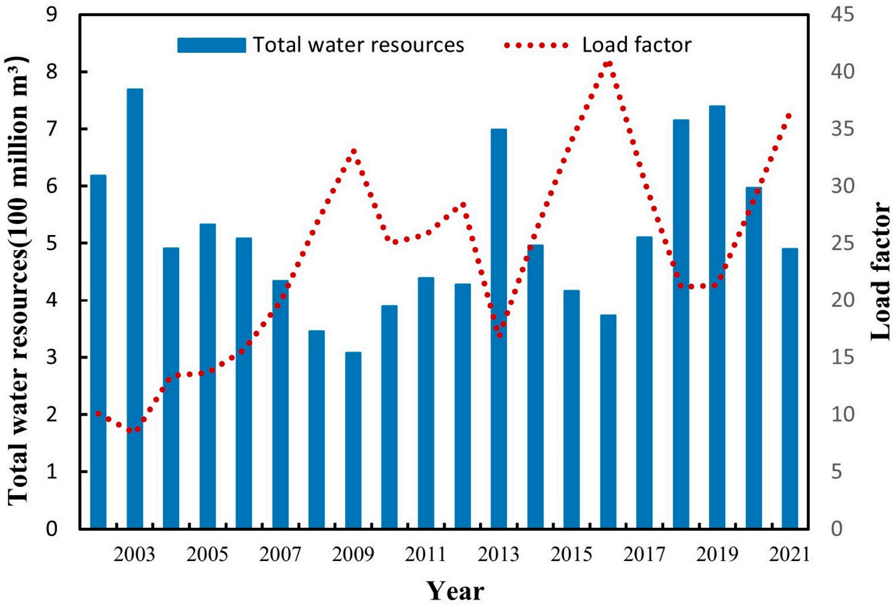

Figure 2. Load factor and variations in total water resources in Guyuan City.

3.2. Analysis of Guyuan City's Water Resource Carrying Capacity Based on Principal Component Analysis

3.2.1. Construction of Evaluation Indicator System

Principal component analysis is a multivariate statistical technique designed to condense multiple variables into a more manageable set of comprehensive factors. Mathematically, it serves as a method for reducing the dimensionality of a high-dimensional variable space. When assessing water resource carrying capacity, numerous factors come into play, including economic, industrial, agricultural, and various other considerations. Following the principles of rationality, systematicity, comprehensiveness, and feasibility, and drawing insights from the work of Hong et al. on water resources carrying capacity calculation in Xinjiang using principal component analysis [31], we developed a water resources carrying capacity indicator model tailored for Guyuan City. This model comprises 13 key indicators, namely, year-end total population X_1 (10^4 people); urban gross domestic product (GDP) X_2 (10^9 CNY); fixed asset investment X_3 (10^9 CNY); per capita disposable income of urban residents X_4 (CNY); per capita net income of rural residents X_5 (CNY); total water resources X_6 (10^9 m^3); total water supply X_7 (10^9 m^3); per capita water consumption X_8 (10^3 m/person); residential water consumption X_9 (10^9 m^3); agricultural water consumption X_{10} (10^9 m^3); industrial water consumption X_{11} (10^9 m^3); water use per 10,000 CNY of GDP X_{12} (m^3); annual precipitation X_{13} (mm). These indicators collectively provide a comprehensive framework for assessing Guyuan City's water resources carrying capacity.

3.2.2. Principal Component Analysis

Conducting a principal component analysis on the 13 influencing factors affecting water resource carrying capacity in Guyuan City, we derive the correlation matrix of these driving factors, as illustrated in Table 3. Furthermore, Table 4 provides an overview of the principal component eigenvalues and their respective contributions.

It is evident that there exists a strong correlation among the 13 factors that influence Guyuan City's water resource carrying capacity. The cumulative contribution rates of X_1, X_2, and X_3 have already exceeded 90.150%, surpassing the widely recognized academic threshold of 85%. Consequently, this study opts to analyze the influence of the first, second, and third principal components on Guyuan City's water resource carrying capacity. This approach allows for a comprehensive reflection of the driving factors affecting changes in water resource carrying capacity and facilitates a thorough analysis of the associated trends.

Table 3. Correlation coefficient matrix of influential factors.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}
X_1	1.000												
X_2	−0.745	1.000											
X_3	−0.466	0.820	1.000										
X_4	−0.803	0.979	0.818	1.000									
X_5	−0.712	0.994	0.809	0.953	1.000								
X_6	0.313	0.211	0.314	0.122	0.216	1.000							
X_7	−0.112	0.288	0.496	0.297	0.308	−0.128	1.000						
X_8	−0.781	0.803	0.784	0.889	0.751	−0.074	0.342	1.000					
X_9	−0.473	0.845	0.739	0.763	0.888	0.195	0.485	0.520	1.000				
X_{10}	0.369	0.040	0.190	−0.081	0.116	0.198	0.523	−0.197	0.494	1.000			
X_{11}	−0.536	0.883	0.773	0.872	0.876	0.317	0.398	0.732	0.823	0.196	1.000		
X_{12}	0.832	−0.920	−0.634	−0.951	−0.882	−0.088	−0.114	−0.830	−0.616	0.236	−0.791	1.000	
X_{13}	−0.296	0.561	0.445	0.546	0.526	0.757	−0.172	0.384	0.304	−0.190	0.556	−0.594	1.000

Table 4. Eigenvalues and contribution rates.

	Eigenvalue	**Contribution Rate (%)**	**Cumulative Contribution Rate (%)**
The first principal component	7.322	56.326	56.326
The second principal component	2.300	17.689	74.016
The third principal component	2.097	16.135	90.150

According to the results presented in Table 5, the first principal component exhibits positive correlations with urban GDP (X_2), fixed asset investment (X_3), per capita disposable income of urban residents (X_4), per capita net income of farmers (X_5), per capita water consumption (X_8), household water consumption (X_9), and industrial water consumption (X_{11}). Conversely, it displays a negative correlation with year-end total population (X_1) and water consumption per 10,000 Yuan of GDP (X_{12}). These relationships primarily illustrate the influence of population dynamics and the level of socio-economic development on water resource development, utilization, and quality. The second principal component demonstrates positive correlations with water supply (X_7) and agricultural water consumption (X_{10}), highlighting its connection to water resource utilization and supply–demand balance factors. The third principal component exhibits positive correlations with water resource quantity (X_6) and annual average precipitation (X_{13}), primarily reflecting the natural endowment factors related to water resources. These three major principal components encompass various factors, including population dynamics, economic development, water resource utilization, and the natural endowment of water resources. Together, they offer a comprehensive understanding of the driving forces behind changes in water resource carrying capacity. Consequently, these three principal components are employed to analyze the temporal trends in water resource carrying capacity in Guyuan City. Table 6 illustrates the comprehensive scores of water resource carrying capacity in Guyuan City spanning from 2002 to 2021. $F1$, $F2$, and $F3$ signify the scores of principal components, and the overarching score of principal components is denoted as F.

It is essential to emphasize that the positive or negative values of principal component scores do not directly reflect the actual water resource carrying capacity level; instead, they indicate the relative position in relation to the average level. When F holds a negative value, it implies that the water resource carrying capacity for that year, within the analyzed timeframe, falls below the average level. Conversely, a positive F value suggests that the water resource carrying capacity for that year, within the analyzed timeframe, surpasses the average level. The comprehensive score F can be calculated by multiplying the scores of each principal component by its respective contribution rate. A higher F value signifies a more extensive water resource carrying capacity, while a lower F value indicates a more limited water resource carrying capacity. The annual fluctuations in the comprehensive score F of water resource carrying capacity are visually presented in Figure 3.

Table 5. Factor loading matrix.

	The First Principal Component	The Second Principal Component	The Third Principal Component
X_1	−0.745	0.486	0.353
X_2	0.987	−0.018	0.016
X_3	0.859	0.243	0.023
X_4	0.987	−0.128	−0.056
X_5	0.972	0.054	0.008
X_6	0.213	0.283	0.922
X_7	0.360	0.632	−0.471
X_8	0.859	−0.230	−0.235
X_9	0.827	0.437	−0.077
X_{10}	0.042	0.942	−0.046
X_{11}	0.916	0.180	0.092
X_{12}	−0.914	0.327	−0.001
X_{13}	0.579	−0.191	0.744

Table 6. Comprehensive evaluation of water resource carrying capacity from 2002 to 2021.

Year	*F*1 (First Principal Component Score)	*F*2 (Second Principal Component Score)	*F*3 (Third Principal Component Score)	*F* (Principal Component Composite Score)
2002	−3.68	2.43	0.86	−1.51
2003	−3.01	1.61	2.79	−0.96
2004	−2.96	1.15	−0.32	−1.52
2005	−2.75	1.29	−0.22	−1.35
2006	−2.74	0.40	0.17	−1.45
2007	−2.31	0.40	−0.90	−1.38
2008	−2.15	−0.82	−1.30	−1.56
2009	−2.44	−1.23	−1.72	−1.87
2010	−1.36	−1.82	−0.36	−1.15
2011	−1.05	−2.00	−0.11	−0.96
2012	−0.21	−1.74	−0.04	−0.44
2013	0.74	−1.54	2.88	0.51
2014	1.03	−1.04	0.16	0.42
2015	2.19	0.32	−1.67	1.02
2016	2.10	−0.06	−1.92	0.86
2017	2.85	−0.12	−0.50	1.50
2018	4.09	0.30	1.36	2.58
2019	3.23	−0.82	2.14	2.02
2020	3.49	−0.06	0.61	2.05
2021	4.95	3.36	−1.30	3.17

Figure 3 illustrates a consistent upward trend in Guyuan City's water resource carrying capacity over the years. The comprehensive score of water resource carrying capacity closely follows the trajectory of the first principal component but exhibits a slower rate of change. This suggests that the comprehensive score is significantly influenced by the first principal component, emphasizing that the level of socio-economic development plays a primary role in determining Guyuan City's water resource carrying capacity. With the ongoing urban development in Guyuan City, the demand for water resources has steadily increased, potentially placing greater pressure on water resource carrying capacity. However, advancements in technology have led to a consistent reduction in water consumption per unit of GDP. Additionally, population size, as an external factor, can influence water resource carrying capacity. In recent years, there has been significant population migration in the Guyuan region, resulting in a gradual decline in population from 2002 to 2021.

This demographic trend has somewhat alleviated the pressure on water resource carrying capacity caused by the increasing water demand. The second principal component exhibits fluctuating scores over time. According to the data, the overall water supply in Guyuan City has remained relatively stable. However, fluctuations in annual rainfall have led to an unstable supply–demand situation for agricultural water use. Water resources are crucial for productivity, and the sustainable use of water for production is vital for industrial development. Agriculture is a major water consumer in Guyuan City, but its water use efficiency is relatively low. To promote modern agricultural development and create new specialized agricultural practices, adopting scientifically effective water-saving irrigation measures and establishing efficient water-saving demonstration zones is imperative. Although the population has gradually decreased over the years, residential water consumption has remained relatively stable but has increased annually, constituting 24.1% of the total water consumption. This rise in residential water consumption inevitably results in an increase in domestic wastewater volume. Consequently, enhancing urban sewage treatment capacity has become a bottleneck in urban development. The third principal component reflects the influence of natural factors on water resource carrying capacity. While the impact of natural resource factors is not as pronounced as socio-economic and supply–demand balance factors, the volume of water resources in the natural endowment serves as the foundation for ensuring water resource carrying capacity. A relatively stable volume of water resources provides solid support for the sustainable development of the economy and society. The combination of socio-economic development level, supply–demand balance of water resources, and natural resource factors encompasses economic, supply–demand, and natural aspects, offering a comprehensive and objective representation of the factors affecting Guyuan City's water resource carrying capacity.

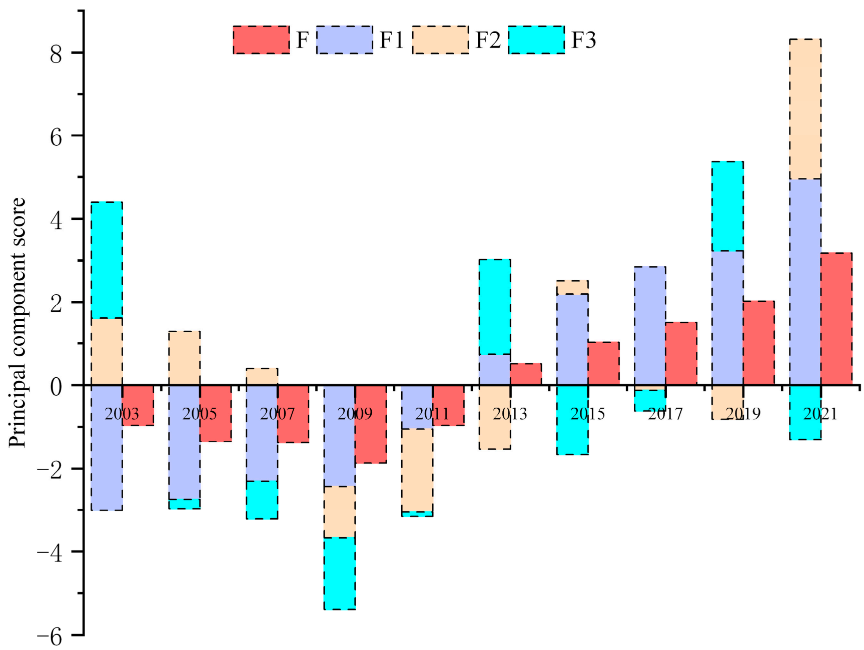

Figure 3. The main component scores and overall scores of Guyuan's water resource carrying capacity.

3.3. Analysis of Guyuan City's Water Resource Carrying Capacity Based on the Ecological Footprint Method

The water resource carrying capacity of Guyuan City was determined using Equation (4), and the results are presented in Table 7. It is evident that the maximum water resource carrying capacity in Guyuan City was recorded in 2003, at 33.52 km^2, while the minimum was observed in 2009, at 13.49 km^2. During the period spanning from 2002 to 2021, the water resource carrying capacity of Guyuan City exhibited fluctuations, involving both increases and decreases, but it demonstrated an overall declining trend. In the ecological deficit calculation, Guyuan City consistently reported an ecological deficit greater than 0 for all years, indicating a persistent shortfall in water resource carrying capacity within the region. The area has been utilizing water resources excessively, resulting in a severe inadequacy of water supply. However, there is a declining trend in the magnitude of the deficit over the years, suggesting that the region has initiated water conservation measures that have yielded some degree of success. Guyuan City experienced substantial fluctuations in water resource carrying capacity from 2009 to 2013. In 2013, the highest value was recorded at 7.32 km^2/ten thousand people, while the lowest occurred in 2009, plummeting to 1.31 km^2/ten thousand people. Over the period spanning from 2002 to 2021, the water resource carrying capacity displayed a fluctuating pattern. Notably, between 2017 and 2021, the water resource carrying capacity consistently maintained a relatively high level, closely linked to the availability of water resources.

Table 7. Calculation of water resource carrying capacity and ecological deficit.

Year	Total Water Consumption W (10^9 m^3)	Total Water Resources Q (10^9 m^3)	Ecological Water Footprint C_W (km^2)	Yield Factor φ_W	Water Resource Carrying Capacity EC_W (km^2)	Ecological Deficit ED (km^2)
2002	1.974	6.186	32.63	0.174	7.12	25.51
2003	2.028	7.691	33.52	0.217	11.03	22.49
2004	1.553	4.918	25.67	0.139	4.52	21.15
2005	1.144	5.334	18.91	0.150	5.29	13.62
2006	1.097	5.09	18.13	0.144	4.85	13.29
2007	1.233	4.338	20.38	0.122	3.50	16.88
2008	1.121	3.452	18.53	0.097	2.21	16.31
2009	0.816	3.078	13.49	0.087	1.77	11.72
2010	0.875	3.412	14.46	0.096	2.17	12.30
2011	0.901	4.398	14.89	0.124	3.61	11.29
2012	0.944	4.281	15.60	0.121	3.42	12.18
2013	0.957	6.99	15.82	0.197	9.10	6.71
2014	1.052	4.960	17.39	0.140	4.59	12.80
2015	1.214	4.171	20.07	0.118	3.25	16.81
2016	1.128	3.734	18.64	0.105	2.59	16.05
2017	1.097	5.11	18.13	0.144	4.87	13.27
2018	1.128	7.153	18.64	0.202	9.55	9.09
2019	0.973	7.402	17.65	0.156	7.63	10.01
2020	1.023	5.971	16.35	0.136	5.37	10.98
2021	0.986	4.905	16.23	0.195	6.32	9.90

Figure 4 displays a linear regression plot depicting the relationship between water resource carrying capacity per ten thousand people and total water resources. This analysis utilizes the linear fitting method to assess the correlation between water resource carrying capacity per ten thousand people and the total water resources. It is clear that in cases of abundant total water resources, the water resource carrying capacity is high, while conversely, in situations with limited total water resources, the carrying capacity decreases. For instance, in 2003, when total water resources peaked at 7.691×10^9 m^3, the per capita water resource carrying capacity was relatively high, at 5.87 km^2/ten thousand people. Conversely, in 2009, with the lowest total water resources recorded at 3.078×10^9 m^3, the per capita water resource carrying capacity reached its lowest point at 1.31 km^2/ten thousand people.

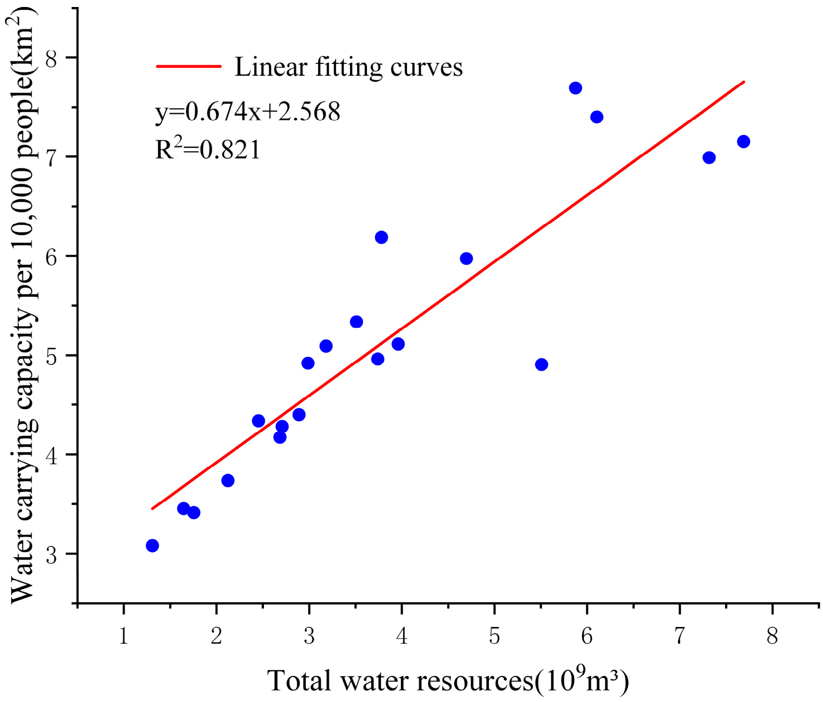

Figure 4. Linear regression plot of water resource carrying capacity and total water resources.

4. Discussion

Water resource carrying capacity serves as a vital metric for evaluating the harmonization of water resources, human development, and regional sustainability. Assessing the water resource carrying capacity of various regions is imperative for effective water resource planning, conservation, and rational utilization. Traditionally, regional water resource carrying capacity assessments often relied on single-method approaches. However, this study adopts a more comprehensive approach, employing three distinct methods to evaluate Guyuan City's water resource carrying capacity. Utilizing the load index method, the analysis reveals that Guyuan City's water resource carrying capacity has been consistently surpassed, with water resource development approaching its limits. This underscores a significant water scarcity issue in Guyuan City, where existing water resources fall short of supporting the demands of economic development. These findings align with Ma et al.'s [32] conclusions, which identified a similar overloaded state in Ningxia's water resource carrying capacity based on the 2015 situation. The principal component analysis is employed to provide a comprehensive assessment of the key factors influencing Guyuan City's water resource carrying capacity. The outcomes underscore the significance of factors related to economic development, water supply–demand equilibrium, and natural influences in determining the region's water resource carrying capacity. These findings are consistent with the research conducted by Zhao et al. [33], who utilized the principal component analysis and factor analysis to investigate Guyuan City's water resource carrying capacity. Furthermore, the evaluation employing the ecological water footprint method unveils fluctuations in Guyuan City's water resource carrying capacity, with an upward trajectory observed post 2016. From an ecological deficit perspective, Guyuan City consistently operates in an ecological deficit state, signifying that the region's water resource development and utilization have exceeded sustainable levels. Nevertheless, the decreasing ecological deficit indicates that Guyuan City has made strides in improving water conservation practices in recent years, alleviating water resource pressures and enhancing utilization efficiency. Based on the DRSIP model, Fan et al. [34] conducted an evaluation of water and soil resource carrying capacity in the Ningxia region. The findings revealed a consistent trend of increasing water and soil resource carrying capacity in Guyuan City over recent years, positioning it as the leading city in the entire Ningxia region. This aligns with the results of our study.

In conclusion, the analysis of water resource carrying capacity in Guyuan City underscores a critical deficit in water resources and overloading in the region. To tackle these challenges, it is recommended that Guyuan City implements a comprehensive set of strategies within water resource management, primarily focusing on three pivotal factors: economic development, water resource supply and demand balance, and natural considerations. Firstly, there is a need to intensify efforts aimed at conserving and managing water resources, optimizing land use, fostering water efficient and sustainable agriculture, and advocating for responsible water resource utilization and protection. Secondly, strengthening cooperation and coordination with neighboring regions is vital to achieve shared management and utilization of water resources spanning across regions. Furthermore, bolstering public engagement and enhancing societal governance are key to increasing public awareness and involvement in water resource management. Lastly, promoting technological innovation and leveraging advanced water resource management technologies are essential for enhancing water resource utilization efficiency.

It is essential to acknowledge the limitations inherent in this study. Firstly, there may be issues related to data timeliness, as the research relies on existing data and literature. Water resource conditions are subject to change over time, which could impact the accuracy of the analysis. Secondly, data acquisition limitations have led to a relatively narrow selection of evaluation indicators, potentially affecting the representativeness of the study. To address these limitations, future research can adopt a more comprehensive approach by incorporating a broader range of data sources, including field surveys and real-time monitoring data. This would provide a more accurate and holistic view of the region's water resources. Furthermore, the integration of alternative analytical methods and models, such as hydrological cycle simulation models and dynamic water resource system models, can enhance the assessment of Guyuan City's water resource carrying capacity and its future development prospects. It is crucial to emphasize that achieving sustainable water resource utilization and management in Guyuan City requires a comprehensive consideration of various factors and active collaboration among different departments and regions. This multifaceted approach will contribute to the effective and sustainable management of water resources in the city.

5. Conclusions

This article analyzes the water resource carrying capacity of Guyuan City from different perspectives using the water resource load index method, principal component analysis method, and ecological water footprint method. After identifying the main influencing factors affecting the carrying capacity, an evaluation model is applied to assess the water resource carrying capacity of Guyuan City. The main conclusions are as follows:

(1) Employing the water resource load coefficient model, the load index for Guyuan City between 2002 and 2021 reached Level II solely in 2003, with all other years maintaining Level I. This signifies that the city's water resource carrying capacity has been consistently exceeded, and water resource development has reached its limits. The current water resources are inadequate to sustain economic development. Since 2002, Guyuan City has experienced a consistent decrease in precipitation. Coinciding with this trend, GDP growth and a declining population have led to a consistently high load index. Consequently, it is of paramount importance to implement essential measures such as strengthening water resource conservation, fostering intensive utilization, and adopting the "increased supply and reduced consumption" approach to address the issue of water resource scarcity in Guyuan City.

(2) By employing the principal component analysis method to evaluate the water resources of Guyuan City over time, a set of 13 evaluation indicators was chosen. The key determinants of water resource carrying capacity in Guyuan City were identified as factors related to economic development, the equilibrium between water resource supply

and demand, and natural variables. Over the span from 2002 to 2021, there has been a consistent upward trend in Guyuan City's water resource carrying capacity. Looking ahead, the focus should be on enhancing the city's water resource carrying capacity within these three pivotal dimensions.

(3) The assessment of Guyuan City's water resource carrying capacity based on the ecological water footprint method indicates fluctuating changes between 2002 and 2021, with an upward trend observed after 2016. From the perspective of ecological deficit, Guyuan City has consistently been in an ecological deficit state, which aligns with the actual situation. Factors such as uneven precipitation and extensive agricultural irrigation have led the water resource carrying capacity of Guyuan City to exceed its capacity. However, there is a decreasing trend in the deficit, indicating that the region has implemented effective water-saving measures.

Author Contributions: Software, formal analysis, writing—original draft, W.P.; project administration, conceptualization, methodology, C.L.; investigation, supervision, H.Y.; writing—review and editing, Y.Z. and M.L. All authors have read and agreed to the published version of the manuscript.

Funding: The work described in this publication was supported by (1) The National Natural Science Foundation of China (No. 52369005), (2) The National Key Research and Development Program of China (No. 2022YFC3002902), (3) The Natural Science Foundation of Ningxia (No. 2023AAC03034), (4) The National Natural Science Foundation of China Yellow River Water Science Research Joint Fund Project (No. U2243601-02), and (5) The First Class Discipline Construction Project of Ningxia (No. NXYLXK2021A03).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data supporting this study's findings are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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