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Assessment and Influencing Factors of Water Supply Capacity and Water Resource Utilization Efficiency in Southwest China

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Abstract: China has been facing serious water scarcity, and improving the supply and utilization of water resources from the perspective of resource endowment, economic development and water infrastructure is of great significance toward sustainable water development. In this work, two index systems for evaluating the water supply capacity (WSC) and the water infrastructure construction level (WICL) were constructed; the water resource utilization efficiency (WRUE) was measured by applying a super slack-based measure model; the ordinary least squares and geographically weighted regression models were used to explore the heterogeneity of spatial relationships. The results showed that both WSC (0.15~0.67) and WRUE (0.25~1.18) had spatial heterogeneity. WSC was positively correlated with water resource accessibility and GDP per capita (R^2 = 0.406, p < 0.01), which represented water resource endowment and economic development, respectively. WRUE was positively correlated with GDP per capita but was negatively correlated with accessibility (R^2 = 0.654, p < 0.01). The relationship of WICL with accessibility and GDP per capita varied over the study's area. We found that the WSC in the southeast, WRUE in the north and WICL in the south were mainly associated with water resource endowments. The WSC in the north, WRUE in the southwest and WICL in the north were mainly associated with the economic development level. Noteworthily, strengthening the construction of water conservancy is one of the effective ways to improve water supply. Suggestions on improving WSC and WRUE were provided based on different accessibility and economic conditions, to promote the sustainable development of water resources.

Keywords: sustainable water resources; water infrastructure construction; super-SBM model; geographical weighted regression; Southwest China

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1. Introduction

1.1. The Importance of Improving Water Supply Capacity and Water Resource Utilization Efficiency

Water plays an important role in sustainable development as a strategic resource. Against the background of more people and less water and the uneven spatial and temporal distribution of water resources, China's per capita available water resource amounted to only one-fourth of the world's average [1–3]; water resources are severely deficient. Restricted by the traditional extensive economic growth mode, the problems of water resource shortage, water environment pollution and water ecological degradation have become increasingly prominent [4]. In some regions, especially in Southwest China, due to uneven distribution of water resources and the insufficient construction of water supply projects, challenges in engineering water shortage exist [5,6]. Currently, the sustainable utilization of water resources in China faces a very serious situation, which has become the main bottleneck restricting the sustainable development of the regional economy and society [7]. China has been paying close attention to water resource management, and published a strategic water resources management plan in 2011, which focused on the three stringent controlling "redlines" concerning national water use, water use efficiency and water pollution [8]. In 2022, the Ministry of Water Resources takes improving the capacity and level of the intensive, economical and safe utilization of water resources as an important task [9]. Therefore, improving water supply capacity (WSC) and water resource utilization efficiency (WRUE) is not only a positive response to China's strictest water resources management system but also a key point for fundamentally alleviating the water resource crisis and solving the uncoordinated water supply and demand.

Southwest China is the source and upstream area of many rivers, and is one of the regions with the richest water resources in China [10]. However, the distribution of water resources in Southwest China is uneven with respect to time and space. Moreover, affected by the complex geological environment, the challenge in engineering water shortage is more prominent [11]. Therefore, the study of water supply, water utilization and water conservancy in Southwest China is of great significance for the sustainable development and comprehensive utilization of water resources in Southwest China.

1.2. Literature Review

In recent years, research on the sustainable utilization of water resources has attracted substantial attention, and it has mainly involved WRUE, water resource carrying capacity, water environment vulnerability [12], etc. Cao et al. [13] calculated the amount of water resources by combining water quantity and water quality, and they proposed that improving WRUE is one of the effective measures for preventing the adverse effects of climate change. Sun et al. [14] evaluated the vulnerability of urban water resources based on development pressure and management capacity, and they found that human factors (e.g., municipalities) were the reason for the vulnerability of water resources in metropolitan cities. Geng [15], Cao [16] and Vicente [17] discussed the sustainability of water resources from the aspects of agricultural water resources carrying capacity and industrial water resources sustainable management. WRUE was originally used to express the relationship between water resources input and output by using a single water input and specific product economic output [18,19], and it was gradually replaced by total factor productivity (TFP) models such as stochastic frontier analysis (SFA) [20,21] and data envelope analysis (DEA) [22]. In 2001, Tone [23] followed the basic idea of DEA and proposed a non-radial and non-angular method called slack-based measure (SBM). Based on the "super efficiency" method proposed by Andersen and Petersen [24], Tone proposed a super slack-based measure (Super-SBM) model by taking into account the undesirable outputs into the efficiency evaluation [25]. Li et al. [26] examined the impact of urbanization on agricultural water efficiency (AWE) and demonstrated that planting structure and irrigation facilities could mediate the urbanization-AWE relationship. Shi et al. [27] used the SBM-DEA model to evaluate the WRUE of 316 cities in China, and they found that technical efficiency was the main determinant of overall efficiency. Yang et al. [28] analyzed WRUE and its influencing factors by the DEA Tobit two-stage model, and they suggested that industrial and water use structures had significant impacts on WRUE. Huang [29] and Zhang [30] used the SBM model based on undesirable output to evaluate China's agricultural WRUE and provincial WRUE. Song et al. [31] constructed an epsilon-based measure super-efficiency model to measure the WRUE of 286 Chinese cities, and they found that economic development, foreign investment and government environmental control intensity had significant influences on WRUE.

Water supply security is also very important for the sustainable development of water resources. Suryanarayana et al. [32] improved the sustainability of groundwater supplies by using a coupled simulation-optimization approach. Nivesh et al. [33] analyzed trends in future water demand and supply in the Dhasan River Basin, and they found that improving irrigation technologies and constructing water conservation could significantly reduce unmet demands and shortfalls. Speer et al. [34] explored the precipitation pattern in the northern Murray–Darling Basin and found that global warming had a negative effect on water supplies by influencing the climate drivers. Carmona-Paredes et al. [35] developed a genetic algorithm to optimize the operating policies of a reservoir system, which supplied drinking water to Mexico City's metropolitan area. However, existing WRUE research mostly focuses more on the evaluation method [36,37], spatial distribution [31] and influencing factors [31,38]. Research on water supplies mainly focuses on using different models to simulate or optimize water supply system security [39–41], predicting contradictions between water supply and demand [42,43], and the potential threat of climate change [34,44]. However, less attention has been paid to explore the relationship of water supply and water utilization with the difficulties in accessing water, which is related to relative elevation differences, slopes and land use. Moreover, studies involving influencing factors mostly pay more attention to the numerical relationship between various indicators, lacking discussions on impact differences between local regions and entire regions, making it difficult to achieve a differentiated and accurate management of regional water supply securities and efficient water utilizations.

1.3. Study Objectives and Approach

To understand the spatially varying relationships of water supply and utilization with water resources endowment and economic development, we constructed an evaluation index system for evaluating the WSC of cities in Southwest China, and we calculated the WRUE by using the Super-SBM model. Water resource accessibility (WRA) and GDP per capita (GDPpc) were considered as the natural and economic influencing factors of water supply and utilization, respectively. The WRA assessment refers to the results of Li [45], reflecting the difficulty of obtaining water resources in different regions, which is a comprehensive index involving five elements (relative height difference, slope, land use type, water intake distance and runoff). The impact of WRA and GDPpc on WSC and WRUE was analyzed using the ordinary least squares (OLS) and geographically weighted regression (GWR) models. In particular, considering the engineering water shortage of Southwest China, an evaluation index system of water infrastructure construction level (WICL) was constructed to further discuss the relationship between WICL and the factors and indexes mentioned above. Our study aimed to provide a theoretical basis and decision-making reference for management decision makers in order to strengthen differentiated and efficient management of water supply security and water utilization and further promote regional sustainable development.

2. Materials and Methods

Section 2.1 introduces the basic information of location elevation in our study area. Section 2.2 explains the data source of each indication involved in this paper. The method adopted in this study was illustrated in terms of the evaluation of indexes and spatial relationship analyses. Section 2.3.1 provides two evaluation index systems to estimate WSC and WICL. In Section 2.3.2, the Super-SBM model is applied to estimate WRUE. The model for spatial relationships described in Section 2.3.3 adopted the OLS and GWR model to investigate spatially varying relationships.

2.1. Study Area

Southwest China with diverse and complex geographical landforms is mainly located in the transitional zone of the Qinghai–Tibet Plateau, Sichuan Basin, Yunnan-Guizhou Plateau and Guangxi hills. It is the gathering area of China's major rivers, as well as the source and upstream areas of the Yangtze River, the Pearl River and the southwest rivers, and it plays a role in China's ecological protection. A subtropical climate and numerous mountains lead to abundant but uneven precipitation. It belongs to the western region of China's economic division, where ethnic minorities and financially disadvantaged individuals are centrally distributed, and the level of economic development is relatively low [10]. In this study, 47 cities at the prefecture level and above (98°25–112°04 E, 20°54–33°03 N) in 5 provinces of southwest China were selected as the research objects

(Figure 1), and the other 14 autonomous prefectures (no data area in Figure 1) were excluded from the research objects due to incomplete statistical data. Combined with the endowment of water resources, the level of economic development, WICL and WSC, the development and management of water resources in these cities are analyzed and discussed.

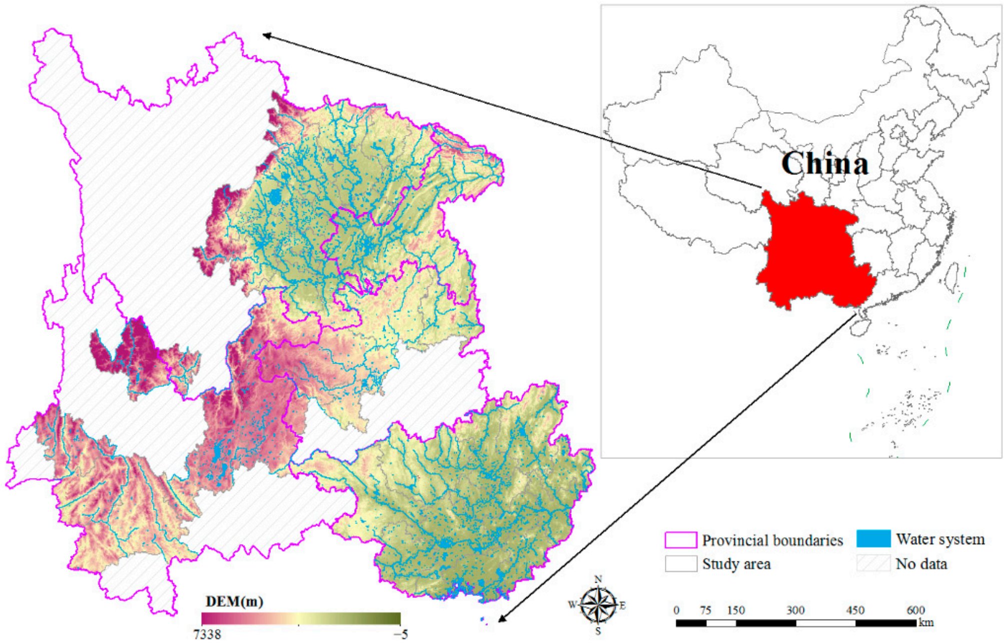


Figure 1. Location of the study area.

2.2. Data Source

Administrative boundary vector data, water system vector data and the digital elevation model (90 m × 90 m) were downloaded from the Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences at http://www.eds.ceode.ac.cn/sjglb/dataservice.htm (accessed on 10 August 2021). The spatial raster data, including land-use types (30 × 30 m), were obtained from the Resource and Environment and Data Center, Chinese Academy of Sciences at http://www.resdc.cn (accessed on 15 August 2021). Socio-economic data (GDP, investment in fixed assets, employed population, effective irrigation area of farmland, number of large reservoirs, urban production capacity of tap water supply, tap water access rate, density of water supply pipelines in built-up areas, waste and sewage discharge) were obtained from the statistical yearbooks of provinces (municipality and autonomous region). The water supply per capita and the water sources amount were obtained from the water resource bulletins of provinces (municipality and autonomous region). The density of ditches and the area of land for hydraulic construction were obtained from National Catalogue Service for Geographic Information at http://www.webmap.cn (accessed on 28 September 2021). The spatial coordinate system had a unified projection of WGS_1984_Albers, with a spatial resolution of 250 × 250 m.

2.3. Methods

Our study aimed to assess WSC and WRUE, and to explain their relationship with water resource endowment and economic development. Considering the engineering water shortage in Southwest China, we further analyzed the impact of WICL on WSC and WRUE. Figure 2 summarized the overall research process and framework, including preparation, assessing indexes and analyzing the relationship between different indexes and factors.

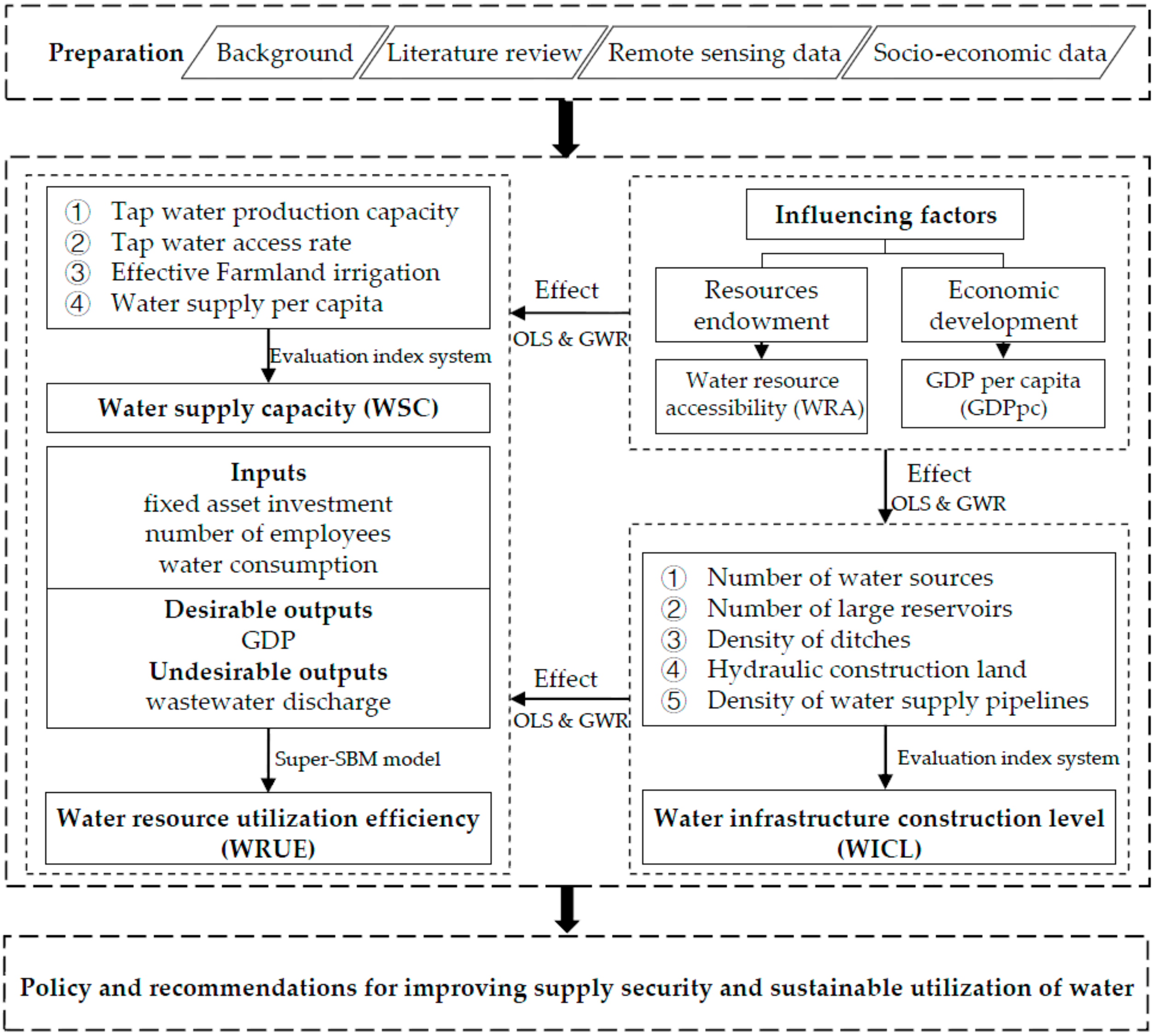


Figure 2. Overall research process and framework.

2.3.1. Assessment of WSC and WICL

In this study, the four indicators, including the urban production capacity of tap water supply, tap water access rate, and effective irrigation rate of farmland and water supply per capita, were selected to reflect the WSC in Southwest China, and the weight of each indicator was 0.25. Among them, the urban production capacity of tap water supply corresponds to the water supply level of the design capacity of the water conservancy project. The effective irrigation rate of farmlands accounts for more than half of the total water consumption, which is the main water resource consumption. The effective irrigation rate of farmlands and tap water access rates can reflect the level of agricultural irrigation and people's drinking water security, respectively, corresponding to the water distribution of users. The water supply per capita corresponds to the maximum water supply that can meet the demand. Based upon this, the evaluation index system of water supply capacity in Southwest China was constructed (Table 1).

Table 1. Evaluation index system of WSC in Southwest China.

Indicators	Description	Weight
Urban production capacity of tap water supply (10^4 m^3/day)	Calculation based on the design capacity of water supply facilities	0.25
Tap water access rate (%)	Proportion of population with access to tap water to total population	0.25
Effective irrigation rate of farmlands (%)	Proportion of effective irrigation area in total farmland area	0.25
Water supply per capita (m^3)	Annual water supply per capita	0.25

WICL mainly refers to the engineering facilities related to water supply, including the storage, diversion, lifting and transfer of water and other projects related to water conservancy. Five indicators, including the number of water sources, the number of large reservoirs, the density of ditches, the density of land for hydraulic construction, and the density of water supply pipelines in built-up areas, were selected to reflect the water infrastructure construction levels in southwest China, with a weight of 0.2. Among them, the number of water sources and large reservoirs corresponded to the water source project related to the water intake; the density of ditches and water supply pipelines in the built-up area corresponded to the pipe network's layout in water transmission and distribution; the density of land for hydraulic constructions corresponded to water plant construction in water purification processes. Based upon this, the evaluation index system for WICL was established (Table 2).

Table 2. Evaluation index system of WICL in Southwest China.

Indicators	Description	Weight
Number of water sources	Number of drinking water sources	0.2
Number of large reservoirs	Number of reservoirs with a storage capacity greater than 100 million m^3	0.2
Density of ditches (%)	Proportion of area of canals, main channels branch channels, aqueducts and tunnels	0.2
Density of land for hydraulic constructions (%)	Proportion of land area of hydraulic structures above the ordinary water level shoreline (e.g., sluices, dams and hydropower stations)	0.2
Density of water supply pipelines in built-up areas (km/km^2)	Distribution density of water supply pipelines in built-up areas	0.2

2.3.2. Assessment of WRUE

The Super-SBM model with undesirable outputs was based on the input and output, and it took into account the undesirable output. Each decision-making unit (DMU) comprised three input–output vectors: input, desirable output and undesirable output. On the basis of the traditional DEA model, the deviation and influence caused by the difference in radial and angle selection were eliminated, and the decision-making units with efficiency values that are greater than 1 can be further evaluated to obtain more accurate efficiency results. At the same time, the undesirable output in the production process is considered, which is more consistent with the actual situation. It is widely used in the research of carbon emission performance [46,47], ecological efficiency [48,49] and energy efficiency [50,51].

We assumed a production system with n DMUs which were composed of m inputs, s_1 desirable outputs and s_2 undesirable outputs. Capital, labor and water resources are generally the most important inputs in water use efficiency calculations [30,38]. In this study, we took fixed asset investments, the number of employees and water consumption as input indicators. Taking GDP as the desirable output, it reflected the economic benefits generated by the effective use of water resources in economic activities. Taking wastewater discharge as the undesired output, it reflected the environmental pollution problems that might be introduces during the process of water resource utilization. The input/output indicators mentioned above are shown in Table 3.

Table 3. The Input/output indicators of WRUE.

Category	Variable	Units	Description
Inputs	Fixed asset investments	10^8 yuan	Capital input
	Number of employees	10^4 person	Labor input
	Water consumption	10^8 m^3	Water resources input
Desirable outputs	GDP	10^8 yuan	Economic benefits generated
Undesirable outputs	Wastewater discharge	10^8 m^3	Environmental problems caused

The vector form can be, respectively, expressed as $x \in R^m$, $y^d \in R^m$, $y^u \in R^m$, among which x, y^d and y^u are inputs, desirable and undesirable outputs. The matrices of $X > 0$, $Y^d > 0$ and $Y^u > 0$ are defined as $X = [x_1, \ldots, x_n] \in R^{m \times n}$, $Y^d = \left[y_1^d, \ldots, y_n^d\right] \in R^{s_1 \times n}$ and $Y^u = [y_1^u, \ldots, y_n^u] \in R^{s_2 \times n}$. Then, the Production Possibility Set (PPS) can be stated in Equation (1):

$$P = \left\{ \left(x, y^d, y^u\right) \middle| x \geq X\theta, y^d \leq Y^d\theta, y^u \geq Y^u\theta, \theta \geq 0 \right\} \tag{1}$$

where θ is the intensity vector. The three inequalities in the P function stand for the situation when the actual input level is greater than the frontier investment level, the actual desirable output level is lower than the frontier desirable output level, and the actual undesirable output is greater than the leading edge of the undesirable output level, respectively [52].

The Super-SBM with undesirable outputs is stated in Equation (2) [23,25,38]:

$$\rho^* = min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\overline{x_i}}{x_{i0}}}{\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{\overline{y_r^d}}{y_{r0}^d} + \sum_{r=1}^{s_2}\frac{\overline{y_r^u}}{y_{r0}^u}\right)}; s.t. \begin{cases} \overline{x} \geq \sum\limits_{j=1,\neq 0}^{n} \theta_j x_j \\ \overline{y}^d \leq \sum\limits_{j=1,\neq 0}^{n} \theta_j y_j^d \\ \overline{y}^u \geq \sum\limits_{j=1,\neq 0}^{n} \theta_j y_j^u \\ \sum\limits_{j=1,\neq 0}^{n} \theta_j = 1 \\ \overline{x} \geq x_0, \overline{y}^d \leq y_0^d, \overline{y}^u \leq y_0^u, \overline{y}^d \geq 0, \theta \geq 0 \\ x_0 = X\theta + S^-, y_0^d = Y^d\theta - S^d, y_0^u = Y^u\theta + S^u \\ S^- \geq 0, S^d \geq 0, S^u \geq 0 \end{cases} \tag{2}$$

where S $= \left(S^-, S^d, S^u\right)$ denotes the slack in inputs, desirable outputs and undesirable outputs. The target function value of ρ^* is the WRUE value of the DMU. It is worth noting that the above improved SBM model and the Super-SBM model dealing with undesirable outputs are under the assumption of constant returns-to-scale (CRS). If $\rho^* \geq 1$, the DMU is SBM-efficient. Otherwise, the DMU is inefficient, and inputs and outputs need to be improved.

2.3.3. Analysis of Spatial Correlation

This study first used the OLS model to preliminarily analyze the relationship between the parameters of the global scale, and then, the study further explored the spatial relationship differences between the parameters of different cities using the GWR model. As a common function reflecting the decreasing relationship between weight and distance, the Gaussian distance attenuation function ensures that each regression feature will have many neighbors and thus increases the chance that there will be variation in the values of those neighbors. It is applicable to experiments with concentrated sample distributions, and it is widely used in evaluating spatially varying relationships in cities and regions [53,54]. As the distribution of cities in our study was relatively compact and had no obvious dispersions, the Gaussian distance attenuation function was used to determine the spatial weight in this paper. The optimal bandwidth was determined based on the minimum correction Akaike information standard. The formula of GWR model is stated in Equation (3) [53].

$$y_i = \beta_0(\mu_i, v_i) + \sum_{k=1}^{m} \beta_k(\mu_i, v_i)x_{ik} + \varepsilon_i \quad (3)$$

where i is the unique identification number of sampling points ($i = 1, 2, 3 \ldots n$). y_i represents the dependent variable (WSC, WRUE, WICL). μ_i and v_i are the longitude and latitude coordinates of the sample i, respectively. β_0 indicates the intercept of the sample i. x_{ik} is the kth independent variable (different influencing factors). k is the number of independent variables (k = 1, 2, 3 … m). ε_i is the random error term of the sampling point i. β_k is the local estimated coefficient of the kth independent variable. The regression coefficient represents the contribution of each influencing factor to WSC, WRUE and WICL.

3. Results

In this section, the spatial and numerical results were organized as follows: (1) the calculation and spatial characteristics of WSC and WRUE; (2) the spatially varying impacts of WRA and GDPpc on WSC and WRUE; (3) the assessment results of WICL considering the engineering water shortage; (4) the analysis of the relationships of WICL with WRA, GDPpc, WSC and WRUE.

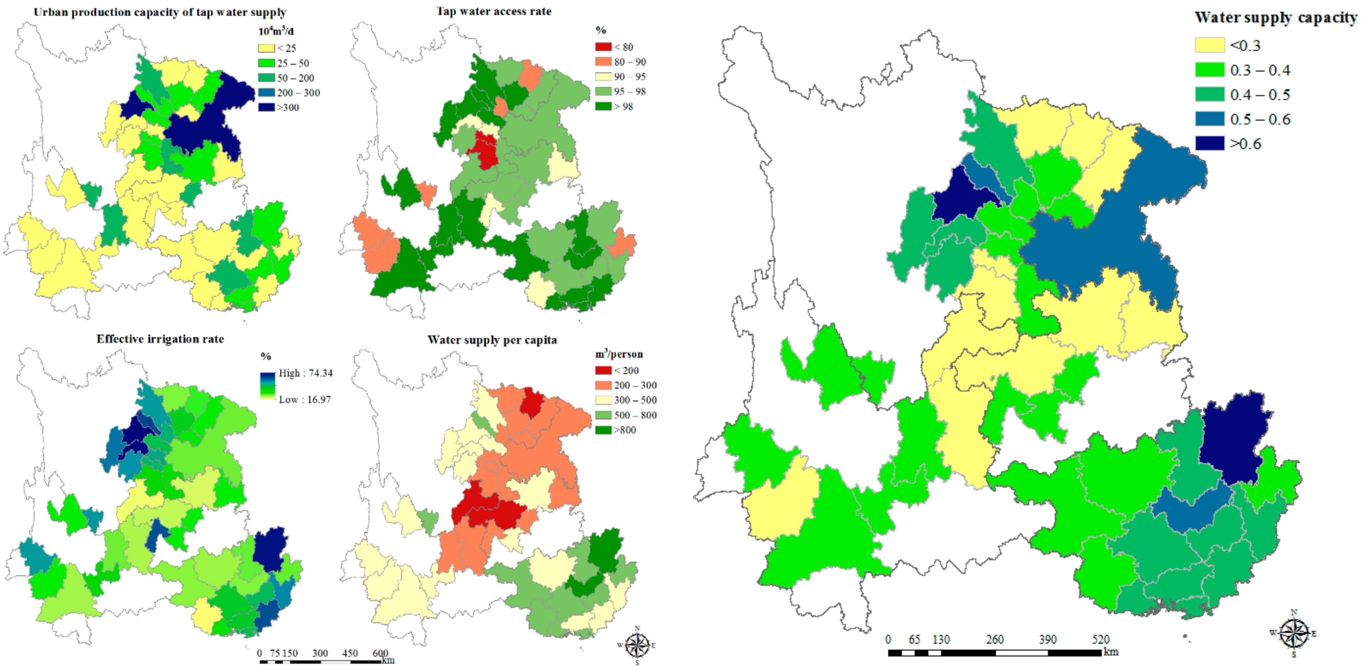
3.1. Spatial Distribution of WSC and WRUE

3.1.1. Spatial Distribution of WSC

There were significant differences in WSC among different areas in the study area (Figure 3), with a maximum of 0.67 and a minimum of 0.15. The WSCs of 11 cities were less than 0.3, only 5 cities were higher than 0.5, and the water supply capacity of the entire area was low. Spatially, the high-value areas were mainly distributed in Chongqing, Guangxi and central Sichuan, and they had characteristics of a high construction level of water supply infrastructure, wide coverage of water supply, large amount of water supply per capita and a high degree of water conservancy in agricultural production. The low-value areas were mainly distributed at the junction of Yunnan, Guizhou and Sichuan. These areas were deficient in the production, transportation and scheduling of available water resources, as well as in the modern management of farmland, and the guaranteed water supply capacity requires improvements.

3.1.2. Spatial Distribution of WRUE

The WRUE in Southwest China had obvious spatial differences, while the WRUE was mainly low in the southern areas and high in the northern areas (Figure 4). The distribution of high-value areas was relatively scattered, and they are mainly located in Chongqing, central and eastern Sichuan and northeastern Yunnan; the maximum value (1.18) was observed in Ziyang City, Sichuan Province. The WRUE of eight cities in the study area were greater than 1; among them, five cities were located east of Sichuan, indicating that these cities performed very well in efficiently using water resources. The WRUE of 12 cities was less than 0.4, and they were mainly located in Guangxi and western Yunnan, and the lower WRUE might be related to redundant investments in water resources corresponding to the easy access to water resources or the relatively backward water-saving technology due to low levels of economic development.



(**a**) (**b**)

Figure 3. Spatial distribution of WSC: (**a**) indicators in the evaluation index system; (**b**) WSC.

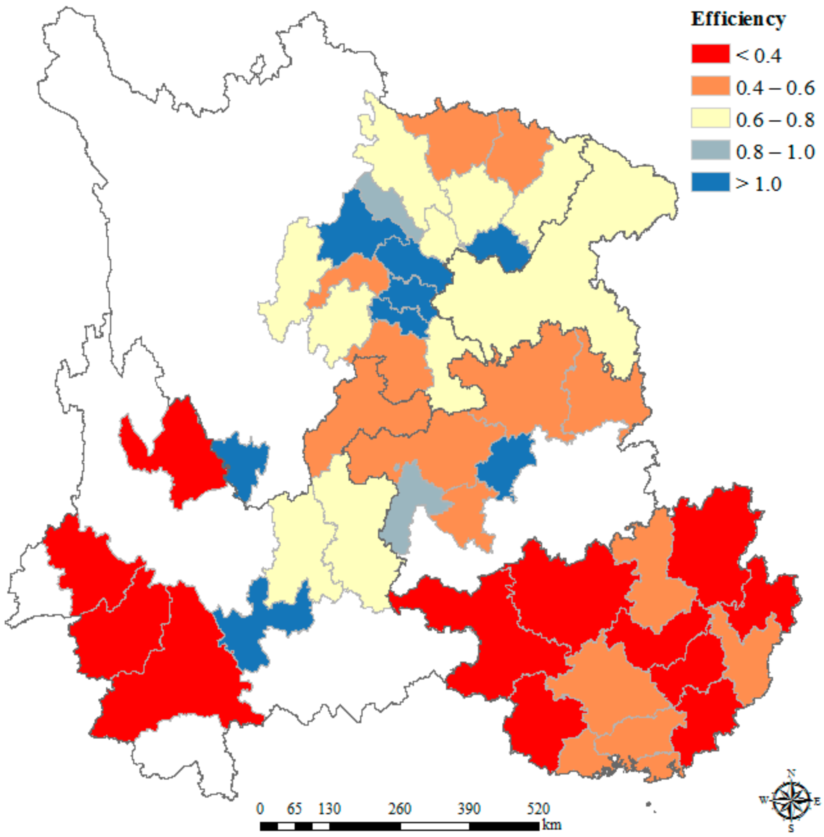


Figure 4. Spatial distribution of WRUE.

3.2. Impact of Water Resource Accessibility and Economic Development Level

Water resource accessibility and GDP per capita were selected as the main influencing factors in this study, and their spatial distributions are shown in Figure 5. The WRA represents the natural endowment of water resources, and it is the comprehensive embodiment of relative height differences, slope, land-use type, water intake distance and runoff [45]. Southwest China, as a typical minority nationality region in China, was relatively backward in economic development, and there was a significant difference in the GDP per capita between different cities.

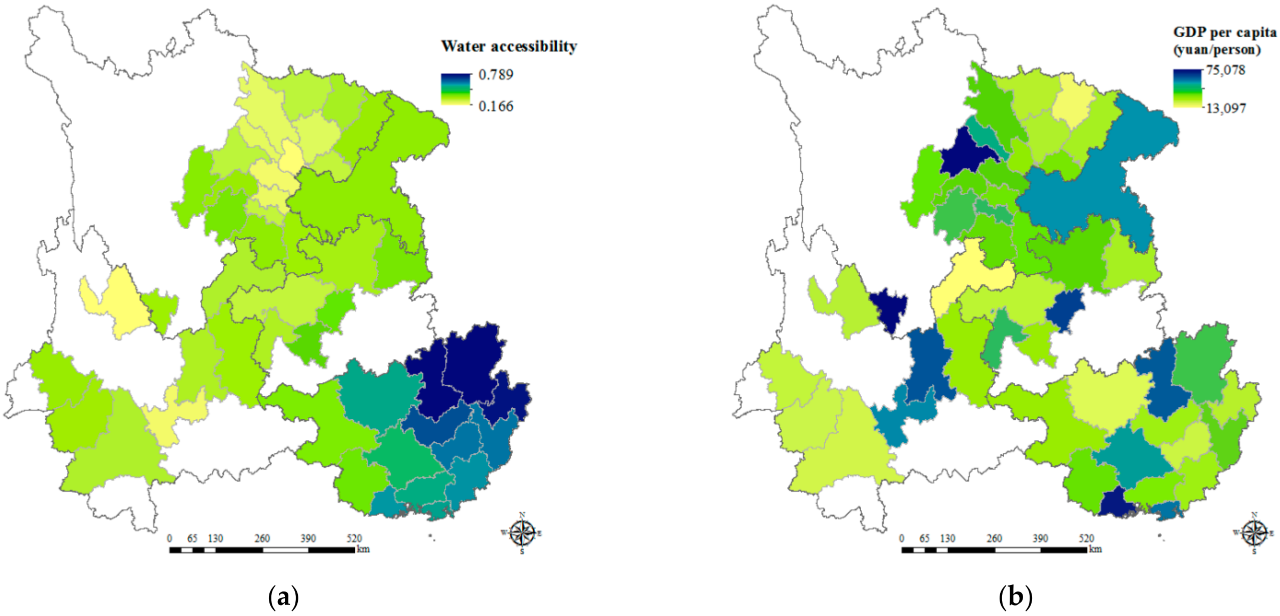


Figure 5. Spatial distribution of influencing factors: (**a**) water resource accessibility; (**b**) GDP per capita.

3.2.1. Impact on WSC

The OLS model was used to study the relationship between WSC and the influencing factors (WRA and GDPpc) in Southwest China (Table 4). Both influencing factors passed the significance test. By comparing the coefficients of each variable, GDPpc and WRA were significantly positively correlated with WSC, and the impact of economic was slightly greater than WRA.

Table 4. Parameter and estimation results of OLS model.

	WSC
WRA	0.314 **
GDPpc	0.369 **
Intercept	0.201 **
AICc	−24.93
Adjusted R^2	0.314

Note: ** Significance at 1% level.

The adjusted R^2 of the GWR model was 0.406, and the AICc was −29.08, and these are better than the OLS model. The GWR regression coefficient of WRA and WSC in different cities varied from 0.001 to 0.443, which is basically consistent with the OLS model's results (Figure 6). From the perspective of spatial distributions, the correlation gradually decreased from the southeast to the northwest. In 27 cities in the southeast areas, the WRA had a significant positive impact on WSC. In 20 cities in the northwest areas, the impact of the WRA on the WSC was not significant. With an overall low WRA, the WSC was affected more by other factors.

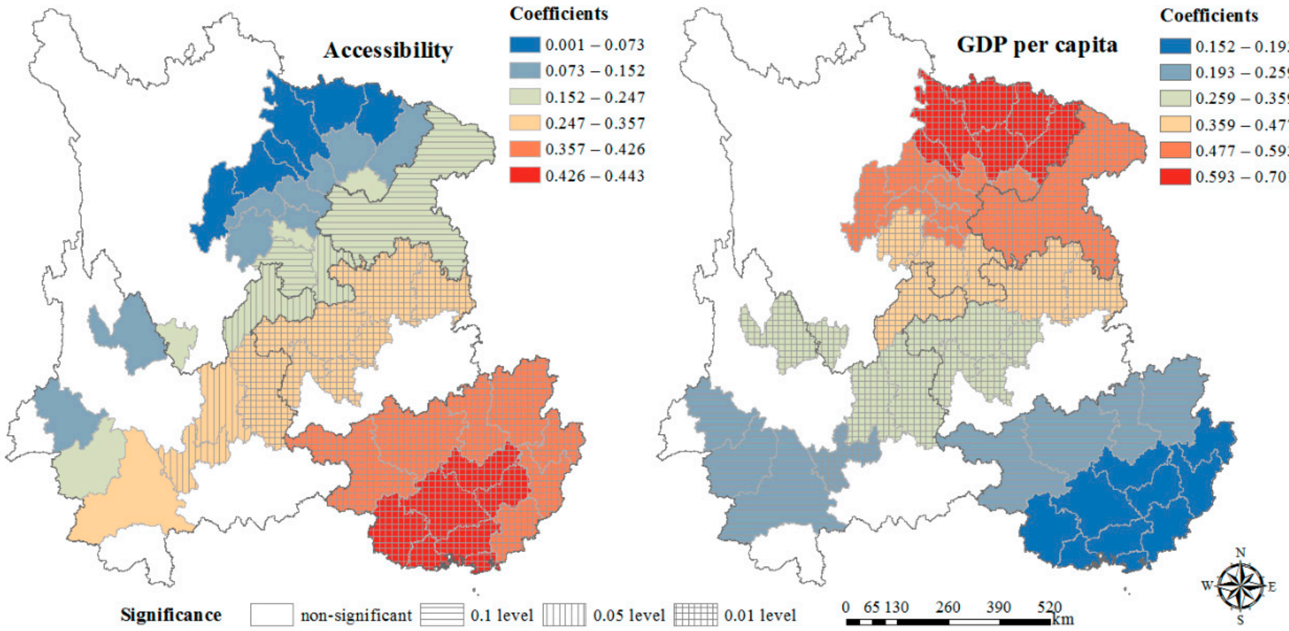


Figure 6. Spatial distribution of regression coefficients between WSC and influencing factors.

The GWR regression coefficient of GDPpc in the study area varied from 0.152 to 0.701, and it showed a decreasing trend from north to south in the spatial distribution. The GDPpc of 37 cities had a significant positive impact on WSC. The high-value areas were mainly concentrated in Sichuan and Chongqing, and the maximum was in Guangyuan City, Sichuan Province, indicating that the GDPpc of these cities had a great impact on WSC. The low-value areas were mainly concentrated in Guangxi and southwestern Yunnan, and the minimum was in Beihai City, Guangxi Province. The GDPpc and WSC of all cities were positively correlated, which is consistent with the results of the OLS model. It showed that an improvement in a city's economic development level could increase investments in water supplies, water diversion projects and agricultural modernization to a certain extent. It helped promote the improvement of the configuration system of a water supply system and thus improve the supply capacity and security of water resources.

The impacts of WRA and GDPpc on WSC had obvious spatial differences. The WRA in Sichuan and Chongqing was relatively low, and obtaining water resources is difficult. However, due to the high GDPpc of these cities, the WSC improved, which made the impact of economic developments on WSC higher than WRA. The WRA in Guangxi was relatively high, and the GDPpc of different cities was quite different and relatively low as a whole. However, due to the high endowment and low access difficulty of water resources, the WSC was generally high; the impact of WRA was higher than the economic level. The WRA in Yunnan was relatively low, and the GDPpc of different cities varied greatly. Among the four cities with GWR coefficients that passed the significance test, the WRA had a greater impact on the WSC of Lijiang, Baoshan and Lincang, while the economic level had a greater impact on WSC of Zhaotong. The low WSC of Guizhou was a result of the difficulty in obtaining water resources and the relative backwardness of economic development.

3.2.2. Impact on WRUE

The OLS model was used to study the relationship between WRUE and the influencing factors (WRA and GDPpc) in Southwest China (Table 5). There was a significant negative correlation between WRA and WRUE, and the correlation coefficient was −0.616. GDPpc was highly significantly positively correlated with WRUE, and the correlation coefficient was 0.663. It can be preliminarily judged that the impact of GDPpc on WRUE was slightly greater than WRA.

Table 5. Parameter and estimation results of OLS model.

	WRUE
WRA	−0.616 **
GDPpc	0.663 **
Intercept	0.326 **
AICc	−23.04
Adjusted R^2	0.586

Note: ** Significance at 1% level.

The adjusted R^2 of the GWR model was 0.654, and the AICc was −28.27, which were better than the OLS model. The GWR regression coefficient of WRA in different cities varied from −0.841 to −0.497, and all cities passed the significance test. From the spatial distribution of regression coefficients (Figure 7), the correlation gradually decreased from the northwest to southeast areas. The areas with high coefficients were mainly concentrated in Sichuan and Chongqing, and the maximum was in Mianyang City, Sichuan Province, indicating that in these areas, WRA had a relatively great impact on WRUE. The areas with low coefficients were mainly concentrated in Guangxi, and areas with minimum values were in Beihai City, Guangxi Province. The WRA in all cities was negatively correlated with WRUE, which was consistent with the results of the OLS model. With the high difficulty in obtaining water resources, it was necessary to strengthen the efficient and repeated utilization of water resources to alleviate the relative shortage of water resources caused by the difference in natural conditions.

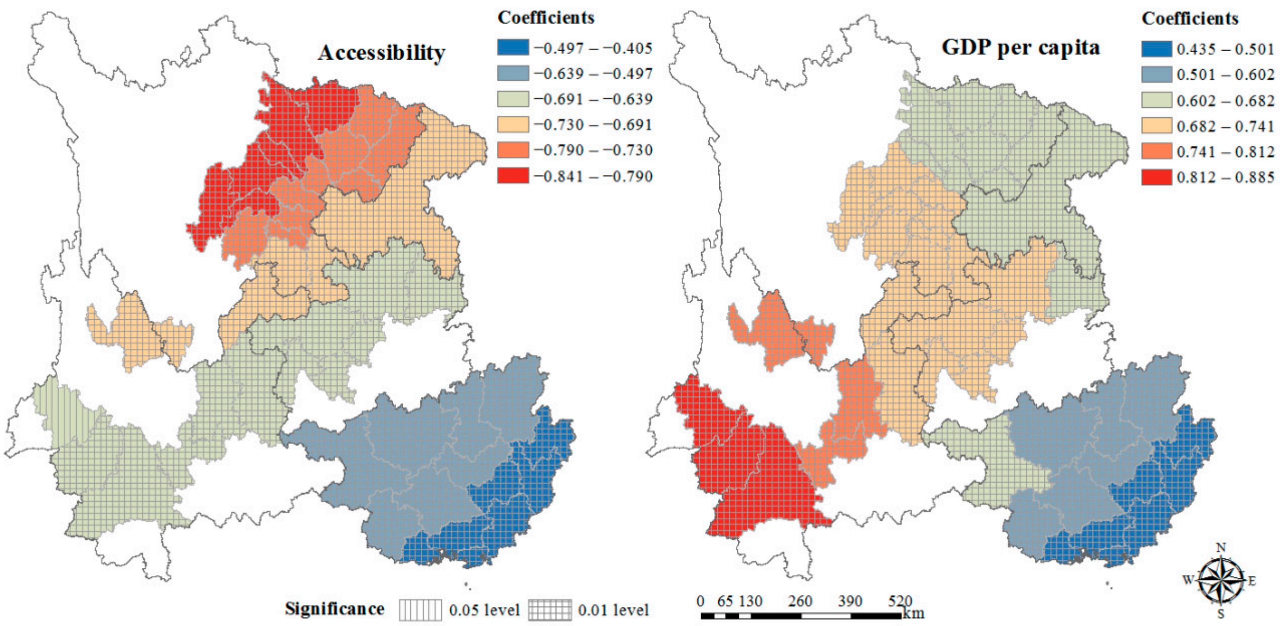


Figure 7. Spatial distribution of regression coefficients between WRUE and influencing factors.

The GWR regression coefficient of the GDPpc in different cities varied from −0.435 to 0.885, and all cities passed the significance test. From the spatial distribution of regression coefficients, the correlation gradually decreased from the west to east areas. The areas with high coefficients were mainly concentrated in Yunnan, and the area with the maximum value is in Baoshan City, Yunnan Province, indicating that its GDPpc had a relatively great impact on WRUE. The areas with low coefficients were mainly concentrated in Guangxi, and the minimum was in Beihai City, Guangxi Province. The GDPpc in all cities was positively correlated with WRUE, which was consistent with the results of the OLS model. With the improvement of cities' economic development level, the economic structure had been optimized and adjusted, which was conducive to strengthening the effective management of water resources and improving WRUE by promoting advanced water-saving technology and strict wastewater discharge management.

The impacts of WRA and GDPpc on WRUE had obvious spatial differences. The impact of economic developments on the WRUE in Yunnan was higher than that of WRA, indicating that the relatively backward economic development was the main reason for the low WRUE of most cities in Yunnan Province. The WRUE of Sichuan and Chongqing cities was more affected by WRA. These cities generally had the characteristics including poor water resource endowment and high WRUE. It is necessary to strengthen the effective control of water resources to achieve the goals of socio-economic developments with simultaneously less water resource input costs. The WRUE of Guizhou ranked at the medium level, which was affected by both WRA and economic development levels. Southeastern Guangxi is characterized by high water resource endowment, backward economic development, and relatively low WRUE, which meant that in these cities, high water resource input was used to produce low GDPs and relatively more wastewater. There was more room for improvement with respect to the WRUE.

3.3. Analysis of WICL

There were significant differences in the WICL among different areas in the study area (Figure 8), with a maximum of 0.498 and the minimum of 0.080. Guangxi and central Sichuan, due to a large number of artificial channels (e.g., canals and dikes) and the large coverage of hydraulic construction, performed better in water supply facilities, and their WICLs were relatively high. Chongqing performed well in the guarantee of water supply and the investment of water storage projects. The areas with a low-value of WICL were mainly located in eastern Sichuan, northeastern Yunnan, and northern Guizhou, and they were lacking in the construction of artificial ditches, hydraulic structures, and water supply pipelines. In addition, Yunnan and southeast Sichuan needed to improve raw water guarantee capacities by strengthening the protection of water sources and the implementation of reservoir projects, respectively.

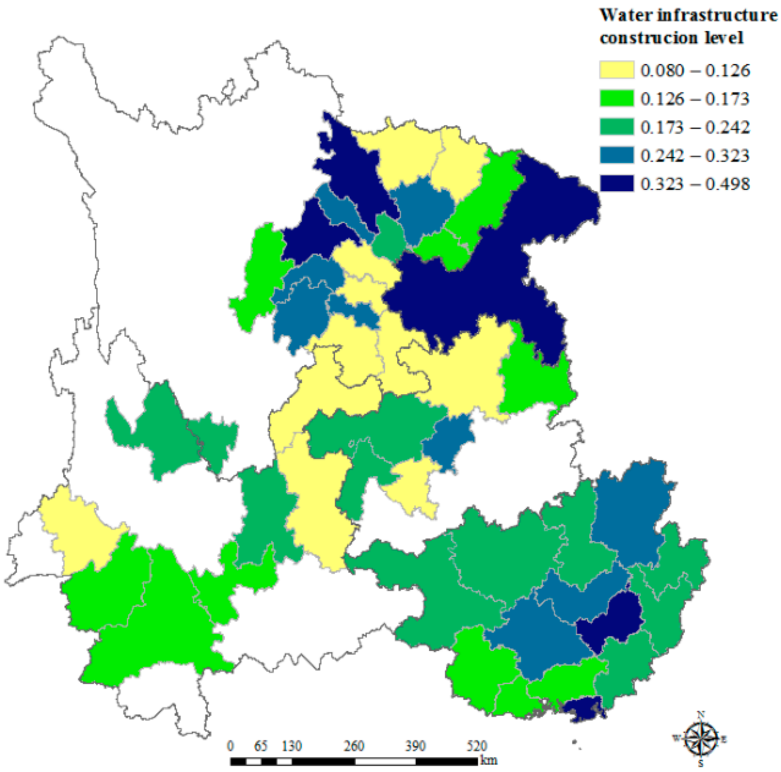


Figure 8. Spatial distribution of WICL.

3.3.1. Relationship with WRA and GDPpc

The relationship of WICL with WRA and GDPpc in Southwest China was discussed (Table 6). GDPpc was positively correlated with WICL, with a regression coefficient of 0.397. WRA did not passed the significance test and was not significantly related to WICL on the whole.

Table 6. Parameter and estimation results of OLS model.

	WICL
WRA	0.253
GDPpc	0.397 **
Intercept	0.096
AICc	−2.25
Adjusted R^2	0.200

Note: ** Significance at 1% level.

The adjusted R^2 of the GWR model was 0.304, and the AICc was −6.51, which were better than the OLS model, suggesting that the GWR model fitted better. The GWR regression coefficient of WRA in different cities varied from −0.047 to 0.400. From the spatial distribution of regression coefficients (Figure 9), the correlation was gradually decreasing from southeast to northwest. In 22 southern cities, WRA had a significant positive impact on WICL. In 15 northern cities, the impact of WRA was not significant, and the WRA of four cities in Sichuan Province had an insignificant negative impact on WICL. The regression coefficient of water WRA in the study area varied greatly, which might be the main reason that the independent variable of WRA failed to pass the significance test in the OLS model, further indicating that the influencing factors of water supply, water conservation and other supporting facilities construction in northern cities were relatively complex.

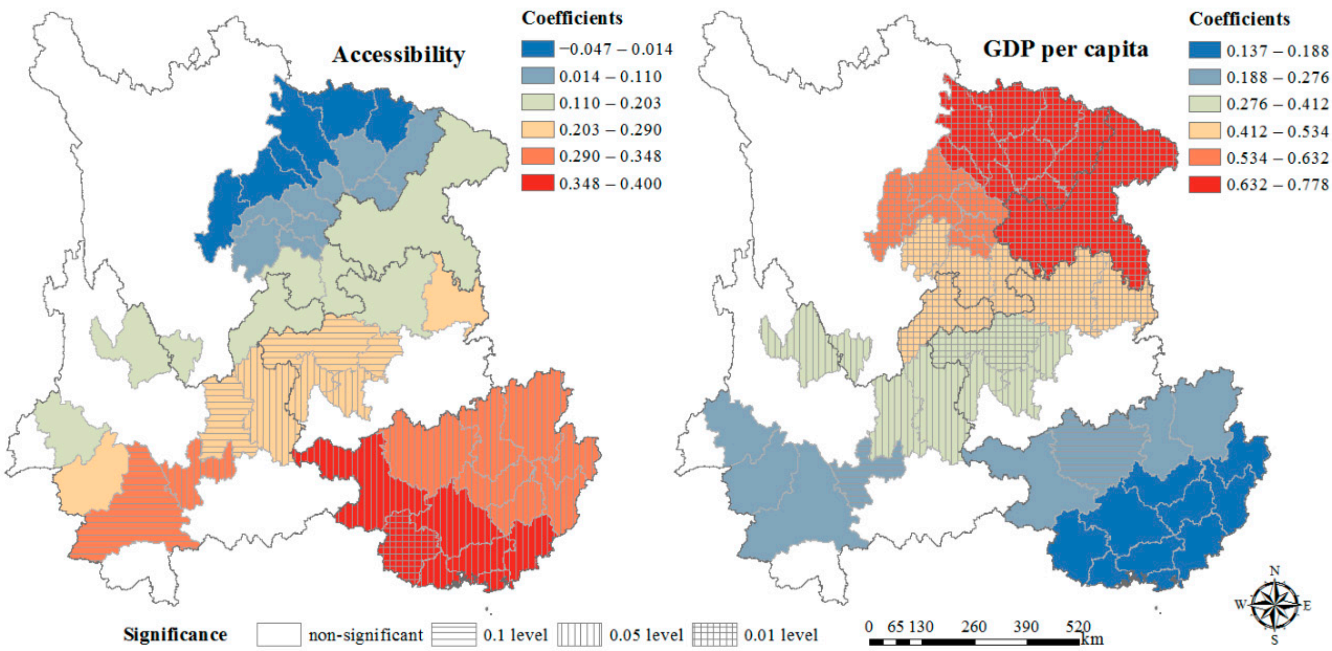


Figure 9. Spatial distribution of regression coefficients between WICL and influencing factors.

The GWR regression coefficient of GDPpc in different cities varied from 0.138 to 0.778. The correlation was gradually decreasing from north to south. In 31 northern cities, GDPpc had a significant positive impact on WICL. The higher the level of cities' economic development, the more perfect the construction of water infrastructure, among which Chongqing and northeastern Sichuan were the most obvious. The cities with a GDPpc that had no significant impact on WICL were mainly located in Guangxi and southwestern Yunnan, indicating that there was little relationship between WICL and economic level in these cities.

The GWR regression coefficients between WICL and different influencing factors were compared and discussed. The results showed that in Sichuan, Chongqing, Guizhou and northern Yunnan, the WRA was relatively low, and the level of economic development was the main factor affecting water infrastructure construction. The higher GDPpc, the more capital investment in the facilities of water supply and water conservancy, and the more complete the water infrastructure. In Guangxi and southwestern Yunnan, GDPpc was relatively low, which might limit the construction scale of water infrastructure to a certain extent. However, due to the high WRA, more facilities were needed to effectively use water resources. Therefore, in these areas, WRA had a higher impact on WICL than economic development level.

3.3.2. Relationship with WSC and WRUE

The relationship of WICL with WSC and WRUE in Southwest China was discussed (Table 7). WICL was positively correlated with WSC, with a regression coefficient of 0.548. WRUE did not pass the significance test, the correlation coefficient was small, and the adjusted R^2 was negative. It indicated that the relationship between cities' water infrastructure construction level and the efficient use of water resources was weak.

Table 7. Parameter and estimation results of OLS model.

	WSC	**WRUE**
WICL	0.548 **	0.069
Intercept	0.255 **	0.362 **
AICc	−32.93	17.94
Adjusted R^2	0.40437	−0.018

Note: ** Significance at 1% level.

The standardized residuals of GWR model were completely randomly distributed in space, indicating that the model fitted better, and the correlation decreased from the north to the south. It is noteworthy that the difference in the GWR correlation coefficients between different cities is very small, and the value of AICc and adjusted R^2 is very close to the OLS model's results. Further analyses of the results of the GWR model showed that the optimal bandwidth was large, and most elements in the study's area became the adjacent elements of the model. To a certain extent, it showed that the relationship between WFC and WSC in the study's area was relatively stable, and the spatial heterogeneity of the correlation coefficient was not obvious, resulting in no significant differences with respect to the GWR results from the OLS model. Combining the impacts of WRA and GDPpc on WICL and WSC, it can be observed that the WRA in the north of the study area was low, while the WSC is relatively high, and there is no significant correlation between the two. Via an analysis of WICL, it was found that the improvement in the WSC of these cities was mainly affected by the improvement of the WICL brought about by economic development. In view of the stable and significant correlation between WICL and WSC, the city's water resource endowment was poor, and their water supply security could be improved by developing the economy and strengthening the construction of water infrastructure and implementing other methods.

4. Discussion

4.1. Influencing Factors of WRUE

WRUE is an important comprehensive indicator reflecting the effectiveness of water resource development, utilization and management. In this study, WRA and GDPpc were analyzed as the natural and economic influencing factors of WRUE, respectively. WRA was significantly and negatively correlated with WRUE. For example, the WRA of Hezhou, Laibin and Guigang ranked third, fourth and sixth, respectively, while their WRUE ranked last, third last and fifth last, respectively. This might be attributable to the impact of the "Resource Curse" which implied that people living in cities with rich water resources endowment had relatively weaker aware-ness of water conservation [45]. On the contrary, in Ziyang City, Yuxi City and Neijiang City, where it was difficult to obtain water resources, the WRUE ranked first, fifth and eighth, respectively, indicating that these cities with relative water shortage had higher water intake costs, paid more attention to the efficient use of water resources, improved water-saving measures, and had stronger capabilities of water resource management and resource allocation, resulting in a higher WRUE, which is consistent with the conclusion of other research studies on water resource endowments and WRUE [37,55]. There are different opinions on the impact of economic development. In this study, the level of cities' economic development, as an important influencing factor of WRUE, had a very significant positive correlation with it. Cities that have difficulty obtaining water resources (e.g., Lijiang City, Bijie City and Zhaotong City), ranked low in terms of the WRUE due to their low economic levels. However, some studies suggested that WRUE was related to the stage of economic development, but they not directly related to the level of economic development. [56], some other studies believed that the level of economic development had a significant effect on WRUE [28,31,57], and the specific effects might be the opposite showing a "U-shaped" relationship [31] and satisfying the environmental Kuznets curve theory.

WRUE is also affected by many other practical factors (e.g., population, industrial structure, urbanization level and land use). Urban expansion is positively correlated with the WRUE except in small cities [27], and cities with a higher population density generally have a relatively higher WRUE [31]. Since flood irrigation is often adopted in China's agricultural production, the ratio of the added value of agricultural sectors has negative impacts [28,38]. Cities in the comprehensive function category have a higher WRUE than those in the industry specialization category [27]. The urbanization ratio has a positive influence on WRUE due to the different water use patterns and quantities in rural and urban areas [58]. The WRUE of dry farming field is more efficient than that of paddy fields [59], and the WRUE can be improved by implementing transformations from grasslands to croplands and deciduous broadleaf forests [60], indicating that changing the land-use patterns might be a method for increasing WRUE.

4.2. Relationship among WICL, WSC and WRUE

Ensuring water supply security and improving water use efficiency are of great significance for the sustainable utilization of water resources and the construction of water-saving cities. The water infrastructure is the basis of ensuring water supplies. The results showed that there was a significant positive correlation between WICL and WSC. Under the background of the uneven distribution of water resources, for cities with less precipitation, poor water resource storage capacity or low water supply security capacity, measures such as expanding the scale of water plants, updating water supply equipment and water distribution network can be taken to improve the construction of water storage and water transfer facilities, so as to alleviate the water supply pressure faced by cities in the dry season. However, WRUE was not directly related to WICL and WSC. Water supply guarantees and WRUE improvements are both important for the sustainable use of water resources and the promotion of water-saving city construction, but they have different emphases.

In this study, the evaluation system of WICL mainly included the number of water sources, the number of water sources, the number of large reservoirs, the density of ditches, the density of land for hydraulic construction and the density of water supply pipelines in built-up areas, which corresponded to facility investments in the storage, regulation, treatment and the transmission of water resources in the water supply process. The evaluation system of WICL mainly included indicators such as the urban production capacity of tap water supply, tap water access rate, effective irrigation rate of farmland

and water supply per capita, which is a direct reflection of the regional water supply guarantee in designs, populations and farmlands. WICL and WSC focus on improving the available water resources in urban, agricultural and industrial areas, and they aim at "water intake". However, WRUE refers to taking fixed asset inputs, the number of employees and water consumption as input indicators in the Super-SBM model, and taking GDP and wastewater discharge as the desirable output and undesirable output, respectively. It not only focuses on the input scale and economic output, but also considers the environmental pollution caused by production activities. It can reflect whether the input-output ratio of water resources is optimal, in other words, whether the current technological upgrades and water resources recycling can achieve the maximization of benefits and the minimization of pollution with the least amount of water input, aiming toward "water use". Therefore, there is no direct correlation between water supply and water utilization efficiency due to the different index system construction and focus. Only by taking into account the optimization and improvement of "water intake" and "water use" can we better meet the urgent needs of social and economic development for water resources.

4.3. Measures to Improve WSC and WRUE

In regions with a low WRA (e.g., Bazhong, Bijie and Zhaotong), under the fierce market competition, limited water resources will be allocated to the most effective production activities under the fierce market competition, and the WRUE will be maximized via water-saving operations, sewage treatment recycling and other technologies. For these cities, it is more urgent to strengthen water supply security than to improve the WRUE. Strategies for implementing appropriate water diversion and replenishment projects via water source planning and water allocation and optimizing the layout of water plants and pipe networks, to alleviate urban water shortage or insufficient water supply guarantee rates are recommended.

In regions with a high WRA (e.g., Laibin, Guilin and Liuzhou), due to the advantages of water resource endowment, the water supply pressure is lower. However, due to the non-scarcity of water resources, there is a possibility of water waste, and there is still room for improving WRUE. It is suggested that the resource supervision system should be strictly enforced by providing enterprises with policy and technical support (e.g., water conservation and emission reduction). In addition, economic tools can also be used to improve WRUE. The current price of water in China is generally low, making it easy for water to be wasted. The regulation of water prices and imposing a pollution charge as a standard is an important method for improving WRUE [59,60]. Regions with rich water resource endowments should guard against the "resource curse" trap, and efforts should focus on the coordinated and sustainable development of the economy and resources rather than short-term economic growth [61]. Combined with the proactive strategy of water resources protection and storage, the level of water resources management will improve, the development of water resources recycling technology will accelerate, and the WRUE will further improve. In addition, regions with rich water resources can actively respond to water transfer projects to jointly ensure water security and the sustainable use of water resources.

In regions with a relatively developed economy (e.g., Chongqing, Kunming and Yuxi), due to the advantages of industrial structure, technical personnel and water-saving equipment, an industrial agglomeration effect and higher management technology levels are observed. Moreover, the investment capacity in the water supply and pollution control facilities is strong. The virtuous circle of high-level of water saving and water conservation relieved their water supply pressure and improved their WRUE. On the premise of meeting the needs of their own development, developed cities should be encouraged to provide certain financial and technical assistance to developing cities. Moreover, we suggest strengthening the cooperation between cities with high economic development and resource-intensive cities to realize complementary ad-vantages [62].

In regions with relatively backward economy, the urbanization rate is low, the proportion of agriculture is relatively high, and the corresponding financial, financing and new technology popularization capabilities are generally lacking. Cities with rich water resources (e.g., Wuzhou, Guigang and Hezhou), cannot make the best of their natural endowment advantages, while cities with water shortage (e.g., Baise, Chongzuo and Lincang), have more pressure on the supply and demand of water resources. While this situation can be improved by adjusting the industrial structure and reducing the proportion of the primary industry, the high ratio of primary industry and low ratio industry introduce adverse effects on the efficient utilization of water resources [58]. The upgrading of the industrial structure can decrease water consumption by optimizing the water use structure [63]. Effectively adjusting the agricultural planting methods and irrigation pattern also contribute to water conservation [64]. In addition, the tilt of investments and policies in water resource utilization and management is very important. Financial support and technical assistance should be provided for relatively backward regions to build better water system networks and locate water sources and water treatment plants more efficiently [64].

Communication between different cities and learning from each other are of great significance for alleviating the pressure on water resources in Southwest China and even the entire country. Moreover, the impact of climatic conditions should be considered in the practical applications since global warming has negative effects on water supply sanitation, agriculture and water infrastructure [65,66]. Characterized by multiple mountains and plateaus, Southwest China has been greatly affected by climate change [67]. For climate change adaptation, the water infrastructure needs to be updated to reduce losses in water conveyance networks; low-loss irrigation systems and closed system for irrigation channels could be implemented to reduce irrigation water; an increase in grain cultivation can reduce the irrigation water requirement [65]. In addition, strengthening the monitoring and management of water quality is an effective method to improve the availability of water resources. Aldrees et al. [68] used machine learning algorithms, including the individual and ensemble learners to predict the total dissolved solids (TDS) and electrical conductivity (EC) of water quality indexes more accurately and conveniently. Shah et al. [69] applied AI and regression methods for EC and TDS prediction, and the performance of the gene expression programming model was the most accurate, which could assist in the management of surface water bodies. Water quality control and prediction can not only improve water supply security for drinking, industrial, and irrigation purposes, but also improve WRUE with respect to pollutants control.

5. Conclusions

Exploring WSC and WRUE and their spatial relationships with water resource endowments, economic development levels and water infrastructure construction is of great significance for effectively alleviating the contradiction between water supply and demand and promoting the sustainable development of water resources. WSC and WRUE in Southwest China had obvious spatial heterogeneities, which were significantly affected by WRA and the level of economic development. It showed that when there is a lower difficulty of obtaining water resources, the WSC is higher, and there might be insufficient utilization and a waste of water resources, leading to a decline in WRUE. The high level of economic development, to a certain extent, determines the advantages of the city in terms of industrial structure, WICL, human resources and technology, and it has a positive impact on WSC and WRUE. The effects of different factors on WSC and WRUE had obvious spatial differences. Therefore, it is of great significance for Southwest China to alleviate the problem of water resources by improving the water storage and transfer facilities to reduce the difficulty of obtaining water resources, rationally optimizing the allocation of water resources to solve local water supply difficulties, and introducing advanced technologies to improve the recyclability of water resources. This paper has proposed future water resources management plans and suggestions for sustainable development from different conditions of water accessibility and economy.

This study can help establish the direction and goal of the sustainable development of water resources of cities in the future. There are still some limitations in this article that need to be covered in the future. The factors affecting WSC and WRUE are more complex. Limited by the available data and applicable conditions of the method, we only examined the impact of water resource accessibility, GDP per capita and water infrastructure. While the water quality was not specifically evaluated and analyzed in this paper, the only content related to water quality was the undesirable outputs (wastewater discharge) in the WRUE's evaluation process; moreover, the economic rationality and feasibility of improving water supply and utilization efficiency have not been assessed yet since water quality is an important aspect related to public health, and economic sustainable development is a necessary condition for sustainable development. With the improvement of data and the expansion of methods, the complexity of the water resource system, such as water quality management and cost–benefit evaluations, will be further investigated in the future.

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