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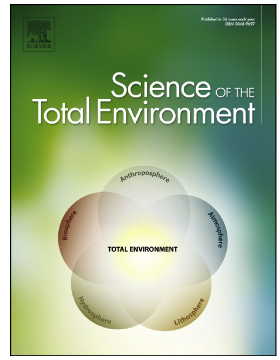

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Spatial differentiation and driving mechanism of rural water security in typical "engineering water depletion” of karst mountainous area——a lesson of Guizhou, China.

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Spatial differentiation and driving mechanism of rural water security in typical "engineering water depletion" of karst mountainous area——a lesson of Guizhou, China.

Abstract: Southwest China gets abundant rainfall, but in its rural areas, there is a severe shortage of water resources for irrigation and drinking. A case study was conducted in the Guizhou Province, which has the most concentrated karst distribution worldwide. The rural water security index was constructed, and Geodetector and ArcGIS were employed to systematically analyze the status quo, spatial differentiation, and driving mechanism of water security in rural areas of Guizhou in 2016. The results showed that (1) there was obvious spatial variation in the rural water security index in the study area, with only 3.85% of areas being maximally safe, and 20.51%, 35.89%, 15.38%, and 24.36% being sub-optimally safe, moderately safe, unsafe, and extremely unsafe, respectively. The spatial distribution of the rural water security index, it generally coincides with a gradual decay from the economically developed areas to the periphery. The water security of the geographical environment is inferior to those of domestic water and water for agricultural production. (2) For Guizhou Province, economic and social factors, such as the disposable income of rural residents and the incidence of impoverishment, were critical factors influencing rural water security. The critical influencing factors vary

greatly among prefectures; however, there are some common factors that affect rural water security, such as the incidence of impoverishment, the penetration rate of rural piped water, the percentage of primary industry, and the percentage of karst area. The maximum value of the interactive driver of the percentage of groundwater and the disposable income of rural residents was 0.812, indicating that the interaction between the high percentage of groundwater caused by karst development and the low disposable income of rural residents was the primary reason for the low rural water security. (3) Rural water security was largely influenced by poor socioeconomic development, resulting in a low level of security and the availability of public water facilities and domestic water in rural areas. Significant improvements in rural water security depend on ameliorating the water security of agricultural production and domestic water, rather than improving the geo-environmental conditions of water resources at extremely high costs.

Key words: karst mountainous area, rural water security, driver, driving mechanism, Guizhou Province

1. Introduction

Water is at the heart of sustainable development and plays a vital role in socioeconomic development, food production, and ecosystems (UNESCO, 2009; UNEP, 2010). Water conservation measures to improve water quality and conserve water have previously been reported to be effective (Sepehri and Sarrafzadeh, 2018). The Millennium Development Goals (MDGs) for drinking water and sanitation state that people from poor and rural areas are more likely to be disadvantaged in terms of access to clean drinking water, especially in developing countries (WHO, 2000, 2002). China is the world's largest developing country, 41.48% of its population live in rural areas, and face severe drinking water security problems (Cho, 2011). In the past, the issue of water security received widespread attention in the industrial development and environmental protection of large- and medium-sized cities; however, rural areas, which account for nearly 90% of the country's total area, have been neglected, with a lack of attention and research on rural water security (Evans et al, 2019). In rural areas, many factors have contributed to the deterioration of the water environment, posing serious hidden dangers to rural water security. For instance, there is a lack of water supply and disinfection equipment, complex and diverse agricultural non-point source pollution, and many chaotic phenomena in the form of rural domestic waste and sewage, which are mostly discharged directly into the environment without treatment. In addition, in the context of rural revitalization, the growth of rural eco-tourism, livestock and poultry breeding, and other industries has promoted the development of the rural economy, but has also increased pollution of the water environment. A growing number of factors are challenging the development, management, and water security of remote or marginal rural areas (Dickson et al, 2016). Thus, it is critical for policymakers to invest more resources into improving water security in these areas. Although the karst mountainous areas of southwest China are located in a subtropical monsoon climate zone with abundant rainfall, surface water easily leaks underground because of the special geological topography of funnel fissure development and the seriously degraded ecological environment formed by karst development, resulting in the ineffective use of surface water resources. The exploitation of groundwater and the construction of water conservancy infrastructure are difficult and expensive, resulting in a typical engineered water shortage area, especially in mountainous rural areas. Moreover, surface groundwater is susceptible to linked pollution, turning point source pollution into non-point source pollution, and expanding the area of pollution. The rural economy of the southwestern karst mountainous area is poorly developed, with a high rural population density. Nearly half of China's poverty-stricken population is concentrated in this region, and the conflicts between people over resources (water and land) are acute (Yang et al, 2016). Rural water security issues in the karst mountainous areas of southwest China are diverse and complex; in 2010, there were still 17 million people in this region who did not have a fundamental solution to their drinking water problem (CAGS, 2012).

The impact of water resources on social development has attracted widespread attention both domestically and internationally. Water management has always been highly valued by governments. Water security has also become a focus of research in the fields of hydrology and water resources science (Jiang, 2015; Liu et al, 2014). Since the definition of "water security" first appeared in the Stockholm Water Forum in 2000, scholars have studied it in depth. The main types of studies on rural water security are 1) the evaluation of rural water security based on the "indicator research framework" (Dickson et al, 2016), such as the conceptual framework proposed by Penn, which includes the availability, accessibility, utility, and stability of water resources (Penn et al, 2017). Xu used the Water Poverty Index (WPI; including the environment, capacity, utilization, approach, and resource) model to quantitatively evaluate rural water security in the Chaoyang area (Xu, 2018). 2) The influencing factors of rural water security and the relationship between water security and disaster risk and prevention (Xu et al, 2019; Ho et al, 2017) have also been widely studied. Ho et al. (2017) reported that water availability is a major factor affecting long-term water security, and Penn et al. (2017) pointed out that complex water resources management is important for water security in the rural areas of Alaska, as well as for other management methods and water security plans (Fitzgibbon and Mensah, 2012; Barrington et al., 2013; Torell et al., 2010). In addition, some studies have focused on the main problems of rural water security and the corresponding management policies and measures, as well as on practical technologies for sewage treatment (Hasan et al., 2011; Li, 2011). Kuriqi et al. (2021) and Suwal et al. (2020) noted that environmental flow assessments can be effective in mitigating the environmental impact of anthropogenic factors such as hydropower plants. Ali investigated post-distribution chlorine decay and household water safety in refugee camps with the aim of demonstrating a method for generating site-specific and evidence-based chlorination targets to better ensure household water safety above the Sphere guidelines (Ali et al,2021).

Notably, there are few previous studies on rural water security; these are essential, particularly in ecologically sensitive areas, such as karst mountainous areas. Furthermore, there are no studies on the influencing factors and driving mechanisms of rural water security. Therefore, there is an immediate need to provide a long-term solution to rural water security by analyzing the core influencing factors, exploring their spatial differentiation, and revealing the deep-seated influencing factors and driving mechanisms of rural water security. This study selected Guizhou Province, the most concentrated and typical karst region in China, as the case study area. The aim is to realize a panoramic portrait and systemic analysis of the status quo, spatial differentiation characteristics, and driving mechanism of rural water security in the region. This will help solve the problem of rural water security and promote the integration of urban and rural development in China.

Specifically, the objectives of this study were 1) to identify the current situation and spatial differentiation characteristics of rural water security in the counties and states of Guizhou Province; 2) to detect the social, economic, and environmental drivers affecting rural water security; 3) to distinguish the core drivers and their directions of action; 4) to reveal the mechanisms affecting the dynamics of rural water security in the karst mountainous areas in Guizhou; and 5) to provide theoretical guidance and decision-making references for the effective utilization of rural water and water security management in this type of region.

2. Research area

The karst area of southwest China is one of the three major karst distribution areas worldwide, and karst development is most typical in Guizhou Province. Guizhou Province is located in the hinterland of southwest China, at latitude 24°37′ N–29°13′ N, 103°36′ E–109°35′ E, with a subtropical monsoon climate and an average annual rainfall of 1178.6 mm. The topography of the territory is high in the west and low in the east, sloping from the center to the north, east, and south. There are three basic types of landforms in the province, including plateau mountains, hills, and basins, of which mountains and hills account for 92.5%. In Guizhou Province, the fragility of the ecological environment and the strong development of karst, which causes rugged and broken surfaces, soil erosion, rock desertification and other ecological problems, have profoundly affected the water resource system and its distribution. Although natural water resources are abundant, the amount of water resources that can be exploited and utilized conveniently and the amount of water that can be supplied is insufficient, making it a typical engineering water shortage area. In addition, there is a large population in rural areas, with relatively weak rural infrastructure, low availability and security of water, and growing water pollution problems.

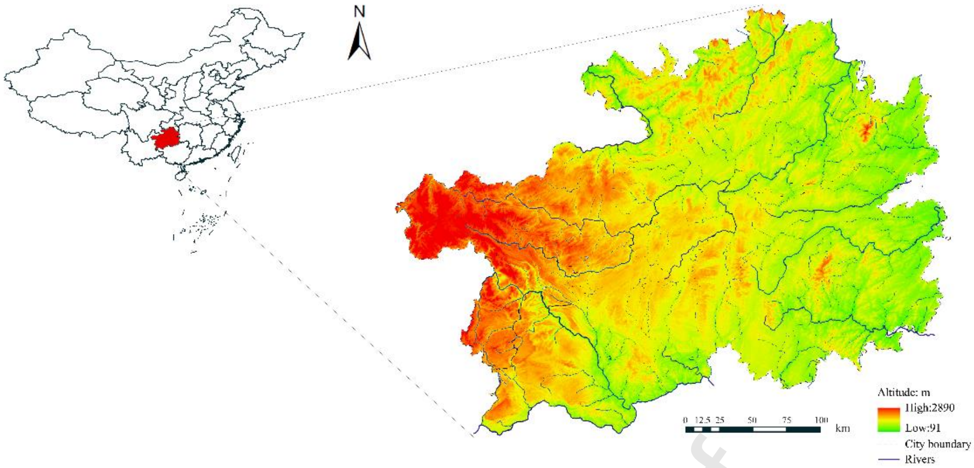


Figure 1. Location of Guizhou Province

3. Research data and methods

3.1 Data sources

The 78 districts and counties under the jurisdiction of eight cities and prefectures (Guiyang City, Liupanshui City, Zunyi City, Anshun City, Bijie City, Qianxinan Prefecture, Qiandongnan Prefecture, and Qiannan Prefecture) were taken as the research objects. The research data were mainly adopted from the Statistical Yearbook of Guizhou Province (2017); the Third Agricultural Census Report, Water Resources Bulletin, and National Economic and Social Development Bulletin of each city and state in 2016; and the National Economic and Social Development Bulletin of each district and county in 2016. The relevant statistics for Tongren City were excluded because they were not timely. Other data, such as surface fluctuation, surface river network density, and hill area percentage, were obtained by remote sensing interpretation.

3.2 Research methods

(1) Rural Water Security Index

Rural water security refers to the ability to obtain sufficient and reliable water for domestic life to meet agricultural needs and to claim water rights from other rural parties (Sinyolo et al., 2014). To explore the current situation of and spatial differences in rural water security, the rural water security index (RWSI), which can reflect the status of rural water security in karst mountainous areas and has long-term universal applicability, was constructed based on the relevant references (Dickson et al., 2016; Penn et al., 2017) and combined with the natural socioeconomic characteristics of the study area, such as mountain distribution, karst development, and industrial development. The RWSI is comprehensively embodied by the geographic environment water security index (GEWSI), agricultural production water security index (APWSI), and domestic water security index (DWSI). The water security of the geographic environment subsystem reflects the situation of the geo-environment on water resources and water conservancy construction (Zhang et al, 2005). The water security of the agricultural production subsystem mainly refers to the ability of agricultural water quality, agricultural water consumption, and water conservancy facilities to secure agricultural production (Liu et al., 2006; Wu et al., 2007). The domestic water security subsystem refers to the ability to obtain sufficient, good quality, easily accessible water to meet daily water needs, and the ability to claim water rights in relation to domestic water use (Sinyolo et al., 2014; He et al., 2019). The domestic water security subsystem mainly reflects the quality, quantity, and accessibility of water for residential use (Siwar and Ahmed, 2014).

Each subsystem contained several specific indices (Table 1). The calculation steps of the GEWSI, APWSI, DWSI, and RWSI were as follows: 1) clarify the decision issues and establish a hierarchical structure model (Table 1); 2) clear the positive and negative characteristics of each index, and standardize using the range method; 3) determine the weight (W) of each index using the entropy weight method (Table 1); and 4) calculate GEWSI, APWSI, DWSI, and RWSI using the "modular addition" method. See references (Zhou et al., 2019ab) for specific steps.

The indices of drivers with significant impacts on rural water security (Table 2) were selected mainly from social, economic, and environmental perspectives; however, this list is not exhaustive. The drivers that can affect the quantity, quality, and convenience of water were selected from the following perspectives: population scale, social input at the social point, industrial structure, agricultural development, and farmers' income at the economic point; and special geological features and fertilizer use at the environmental point. The various factors work further to affect overall rural water security in terms of agricultural production, domestic life, and geo-environment subsystems.

Table 1 Evaluation rural water security indices

Destination	Subsystem	Index	Implication	Weight
RWSI	GEWSI	Forest coverage	Capacity of water conservation	0.019
		Density of surface river network	Degree of water aggregation	0.021
		Per capita possession of water resources	Abundance of precipitation and per capita water resources	0.069
		Percentage of plain area	Impact of surface conditions on the cost of water conservancy construction	0.071
	APWSI	Percentage of agricultural business households	Water demand for agricultural production	0.01
		Per capita possession of grain yield	Grain output of per unit water	0.011
		Number of large livestock per 10,000 rural residents	Water demand of livestock	0.005
		Irrigation water on per unit farmland	Utilization efficiency of agricultural water resources	0.103
		Percentage of cultivated area	Water demand of cultivated land	0.003
		Number of electromechanical wells per 10,000 rural residents	Ability to pump groundwater	0.196
		Number of irrigation and drainage	Large facilities to safeguard	0.116

	stations per 10,000 rural residents	agricultural irrigation and drainage	
	Number of irrigation ponds and reservoirs per 10,000 rural residents	Capacity of reservoir to guarantee irrigation	0.067
DWSI	Annual water consumption by rural residents	Water for domestic life	0.009
	Percentage of villages without toilets	Influence of no toilet on water quality	0.003
	Percentage of villages with centralized water supply	Convenience of water utilization	0.003
	Percentage of villages with centralized treatment of domestic waste	Influence of domestic waste discharge on water quality	0.024
	Percentage of villages with centralized treatment of domestic sewage	Influence of domestic sewage discharge on water quality	0.047
	Percentage of villages where drinking water is purified tap water	Excellent water quality and easy access to water	0.045
	Percentage of villages where drinking water comes from a protected well/spring	Moderate water quality and low water accessibility	0.016
	Percentage of villages where drinking water comes from a natural well	Unsafe water quality and low accessibility	0.01
	Percentage of villages where drinking water is stored in barrels	Excellent water quality but high water costs	0.143
	Percentage of villages where drinking water comes from rivers and lakes	Unsafe water quality and low accessibility	0.007

Table 2 Drivers of rural water security

Field	Symbol	Direction	Detected factors	Index
Society	D1	-	Rural population size	Percentage of population in rural areas
	D2	-	Coercion of poverty on water investment	Incidence of impoverishment
	D3	+	Degree of efficient and intensive utilization of agricultural water resources	Percentage of large-scale agricultural business households
	D4	+	Ease and stability of access to water	Penetration rate of rural piped water
	D5	+	Degree of water pollution caused by the lack of toilets	Percentage of villages that have completed toilet renovation
Economic	D6	-	Industrial structure	Percentage of primary industry
	D7	+	Disposable income level of rural residents	Disposable income of rural residents
	D8	+	Level of agricultural development	Gross value of agriculture production per capital
Environment	D9	-	Influencing factors of infrastructure construction	Percentage of hilly areas
	D10	-	Factors that cause soil erosion and other stress to ecological environment	Percentage of karst areas
	D11	-	Factors influencing the accessibility of water resources	Surface roughness
	D12	-	Percentage of water resources in difficult exploitation and utilization	Percentage of groundwater
	D13	-	Impact of agricultural production on water quality	Fertilizer consumption per unit area
	D14	+	Abundance of water resources	Annual average precipitation

Note: + indicates that the index has a positive influence within a certain range, and - indicates that the index has a negative impact within a certain range. D1 to D14 represent the symbols for each index. The four index factors in Table 2, including the percentage of hilly area, the percentage of karst area, the degree of surface roughness, and the percentage of groundwater, directly or indirectly reflect the influence characteristics of karst geological and geomorphological environments.

(2) Geodetector method

The Geodetector statistical method detects spatial differentiation and reveals the driving forces behind phenomena, including differentiation and factor detection, interaction detection, risk area detection, and ecological detection (Wang and Xu, 2017). Other methods, such as system dynamics (Su et al., 2016) and logistic regression models (Song et al., 2016), in water security assessment, suffer from a tension between the diversity of assumptions and the rarity of real cases that fit the assumptions, which can affect the effectiveness of the model. However, Geodetector does not have too many assumptions and can effectively overcome the limitations of traditional statistical analysis methods dealing with category variables, and have functional diversity (Wang and Xu, 2017; Zhan et al., 2015). Geodetector also has the limitation of requiring the independent variable to be a type quantity and cannot be applied in analytical studies with continuous-type independent variables (Wang and Xu, 2017; He et al., 2019). This study intends to employ this model to detect the impact of social, economic, natural environmental, and other relevant factors on rural water security differentiation.

In this study, differentiation and factor exploration were used to measure the interpretation degree of different drivers, and ecological detection was used to detect the interaction and superimpose influence among various factors.

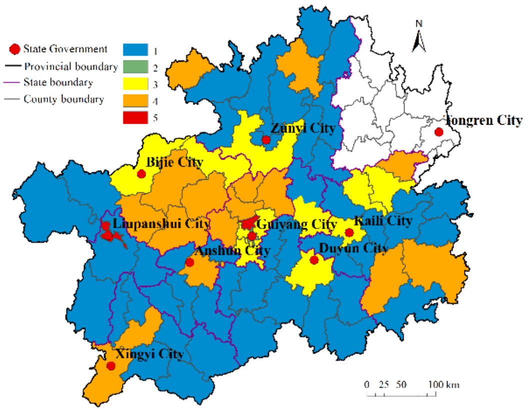
The calculation formula is as follows:

$$P_{D,E} = 1 - \frac{1}{N\sigma_E^2}\sum_{h=1}^{m} n_{D,h}\sigma_{E_{D,h}}^2,$$

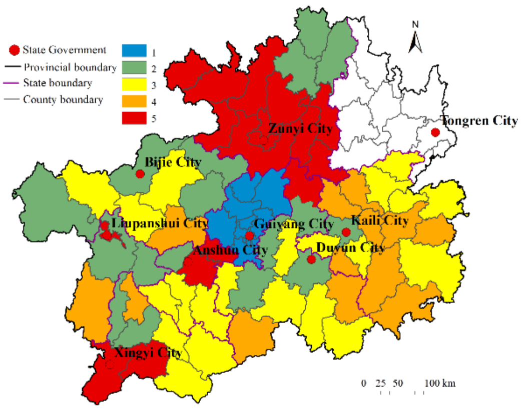
where D is the independent variable and E is the dependent variable; $P_{D,E}$ is the influence of factor D on rural water security; N is the regional sample number; σ_E^2 is the variance of rural water security, N = 78; $n_{D,h}$, $\sigma^2_{E_{D,h}}$ is the sample size of the h (h = 1, 2,..., m) layer and the variance of rural water security; $P_{D,E} \in [0,1]$, with the increase in $P_{D,E}$, the interpretation of the spatial differentiation of rural water security by the impact factor is higher, and the impact on rural water security is greater. $P_{D,E}$ = 0 indicates that the spatial distribution of rural water security is not influenced by factors, while $P_{D,E}$ = 1 indicates that it can be fully explained.

Interaction detection is used to identify interactions between different factors D_i (i, = 1, 2, ⋯, 14) and D_j (j, = 1, 2, ⋯, 14), whether factors D_i and D_j work together to increase or decrease the explanatory power of the dependent variable E, or whether the effects of these factors on E are independent of each other. If $P(D_i \cap D_j)$ < min [$P(D_i)$, $P(D_j)$], factors x and y are nonlinearly reduced; if min [$P(D_i)$, $P(D_j)$] < $P(D_i \cap D_j)$ < max [$P(D_i)$, $P(D_j)$], factors x and y interact, and if $P(D_i \cap D_j)$ > max [$P(D_i)$, $P(D_j)$], the factors D_i and y are bilinear after interaction; if $P(D_i \cap D_j)$ > $P(D_i)$ + $P(D_j)$, factors D_i and y are nonlinearly strengthened after interaction. If $P(D_i \cap D_j)$ = $P(D_i)$ + $P(D_j)$, factors D_i and D_j are independent of each other (Wang et al., 2017).

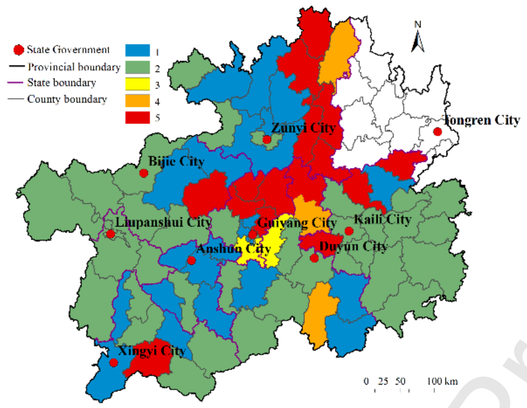
Geodetector is good at analyzing type data, and appropriate discretization is required for sequential, ratio, or interval data (Cao et al., 2013). Therefore, we employed IBM SPSS Statistics 25.0 software to perform K-means clustering to obtain the spatial distribution of each detection factor (Fig. 1). Each factor was divided into five categories based on the 2016 data, and there was no corresponding relationship between the level of the clustering category and the detection factors.



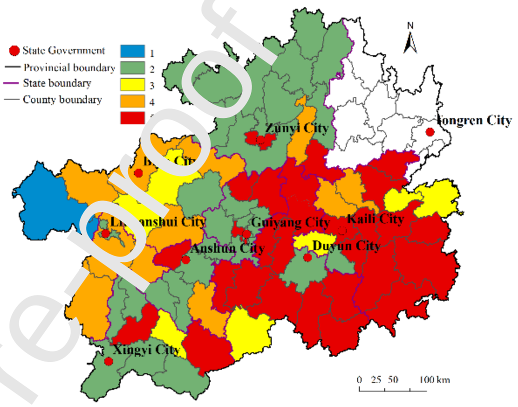
a. Percentage of population in rural areas



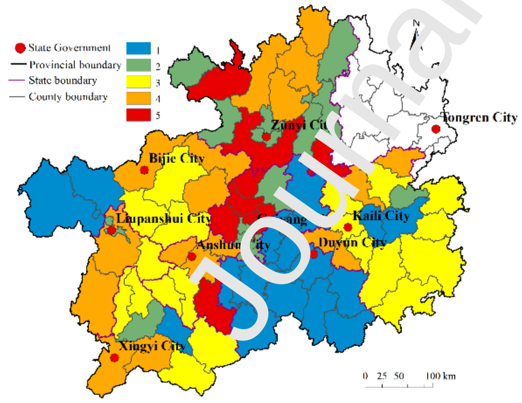
b. Incidence of impoverishment



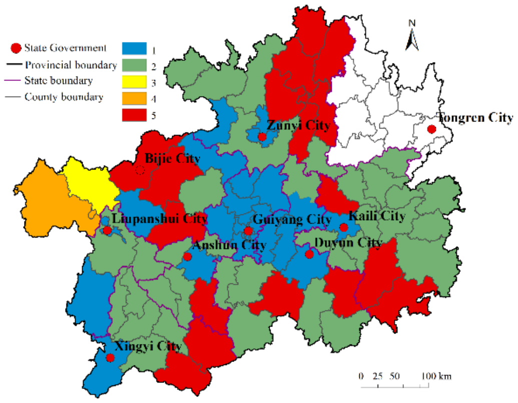
c. Percentage of large-scale agricultural business household



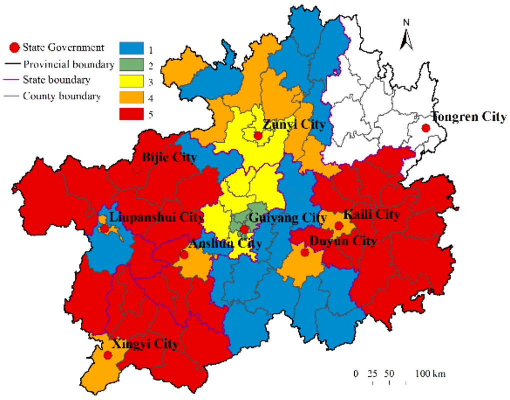
d. Penetration rate of rural piped water



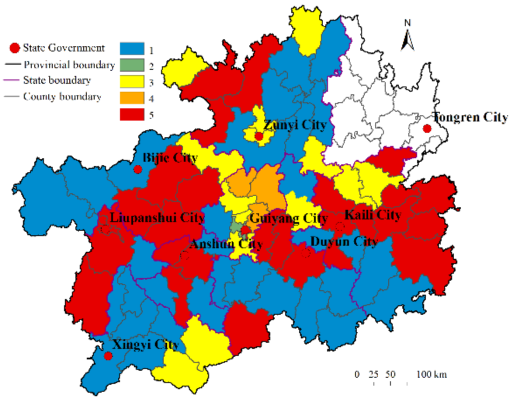
e. Percentage of villages that have completed toilet renovation



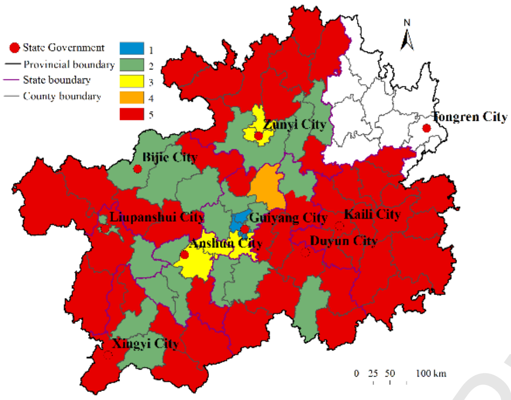
f. Percentage of primary industry



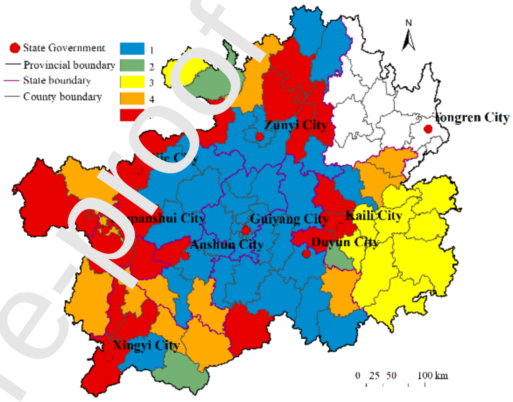
g. Disposable income of rural residents



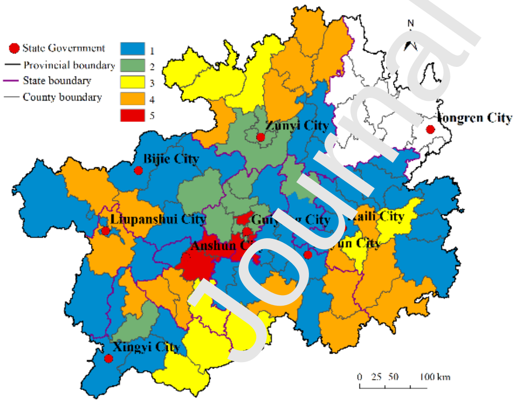
h. Gross value of agriculture production per capital



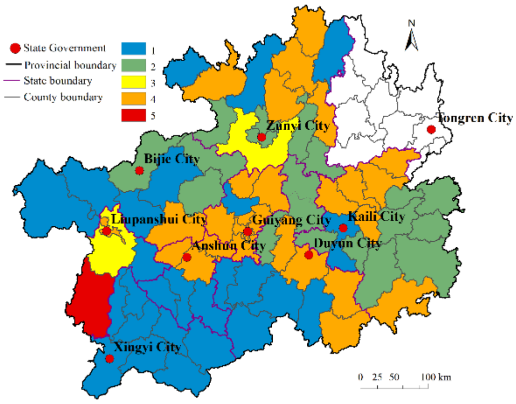
i. Percentage of hilly area



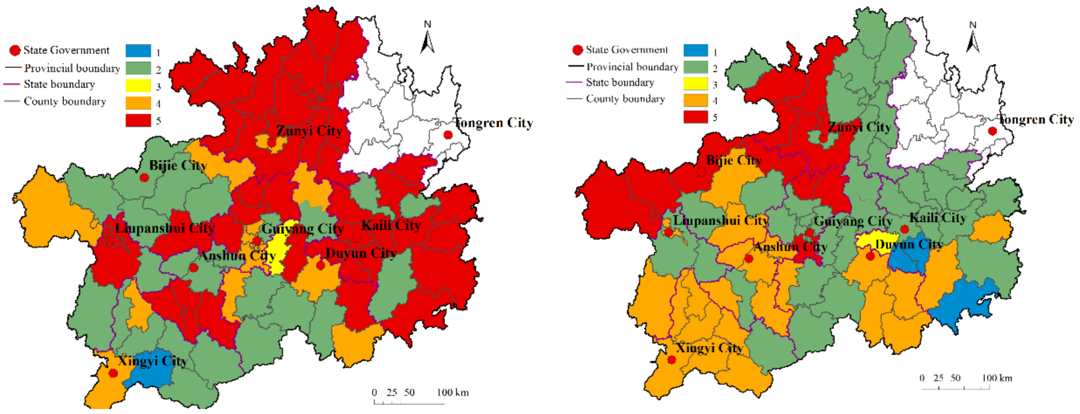
j. Percentage of karst area



k. Surface roughness



l. Percentage of groundwater



m. Fertilizer consumption per unit area

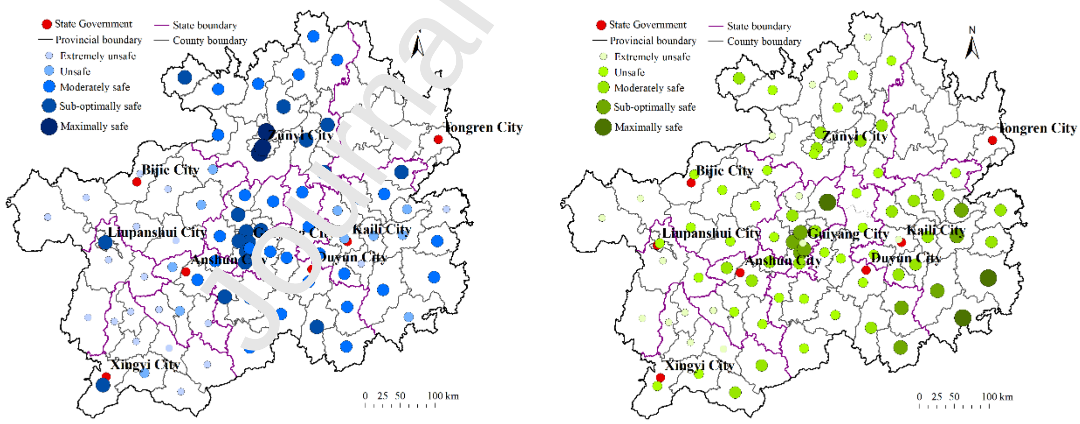
n. Annual average precipitation

Figure 2 Spatial distribution of geographic detection factor categories

4. Results

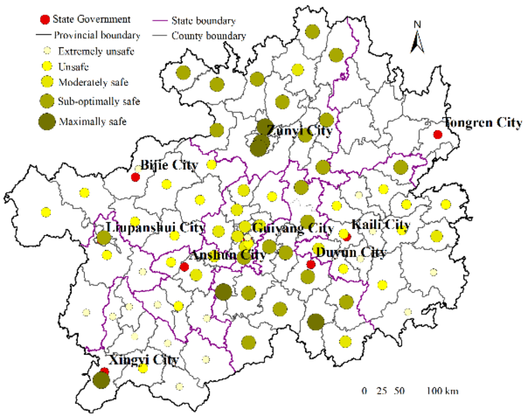
4.1 Spatial differentiation of rural water security

Using ArcGIS 10.2 software, the RWSI, GEWSI, APWSI and DWSI in 2016 were classified using the natural breakpoint method, and each index was divided into five levels: extremely unsafe, unsafe, moderately safe, sub-optimally safe, and maximally safe.

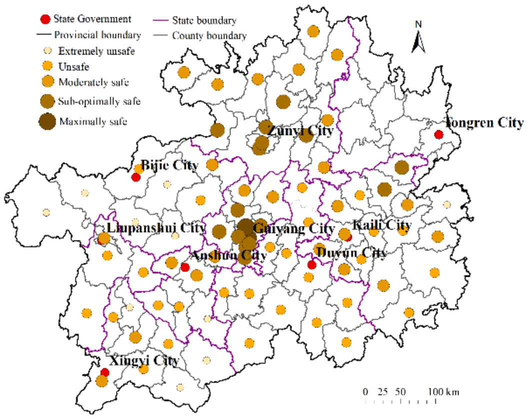


a. Spatial distribution of the rural water security index (RWSI)

b. Spatial distribution of the geographic environment water security index (GEWSI)



c. Spatial distribution of the agricultural production water security index (APWSI)



d. Spatial distribution of the domestic water security index (DWSI)

Figure 3 Spatial distribution of rural water security and subsystem water security in 2016

4.1.1 Rural water security

The RWSI showed remarkable spatial heterogeneity (Figure 2a). The RWSI accounts for 24.36% and were maximally safe and sub-optimally safe, mainly in the municipal districts of Guiyang and Zunyi, which have a high level of economic development. The distribution of the RWSI and economic development is roughly the same, indicating that the spatial differentiation of rural water security may be affected by the spatial differentiation of economic development in rural areas. In addition, the APWSI and DWSI in these areas are both sub-optimally safe and maximally safe, respectively, but the geographical environment security of water resources is low. The RWSI is unsafe and extremely unsafe, accounting for 15.38% and 24.36%, respectively. Most of them are in Bijie City, Qianxinan Prefecture, and other districts and counties with low economic development and fragile ecological environments. The geographical environment of water resources is unsatisfactory, with low APWSI and DWSI. For the RWSI, 35.89% of the areas classed as moderately safe are concentrated in areas with high water security for agricultural production, such as northern Zunyi City, Guiyang City, and Qiannan Prefecture. Overall, the

RWSI gradually extended from the centers of Guiyang and Zunyi to the periphery. Moreover, the areas with the highest RWSI were concentrated in the center of the north–south line between Guiyang City and Zunyi City, followed by the eastern areas of Qiandongnan Prefecture and Qiannan Prefecture and the western areas of Bijie City, Liupanshui Prefecture, and Qianxinan Prefecture at low levels.

4.1.2 Water security of subsystem

(1) GEWSI

GEWSI showed significant spatial differentiation (Figure 2b). The number of districts and counties at the maximally safe, sub-optimally safe, moderately safe, unsafe, and extremely unsafe levels accounted for 3.85%, 11.54%, 29.49%, 35.9%, and 19.23%, respectively. This is consistent with the high spatial heterogeneity of the geological environment in Guizhou Province, which is a typical karst mountainous region. The maximally safe and sub-optimally safe areas are mainly distributed in relatively flat terrain areas, such as Guiyang, and areas with better ecological environments, such as Liping County and Cong Jiang County. Unsafe and extremely unsafe areas are mainly distributed in areas with high altitudes and severe rocky desertification, such as Bijie City, Liupanshui City, Qianxinan Prefecture, and the northern part of Zunyi City. There were large differences compared to the regional distribution of the RWSI.

(2) APWSI

As shown in Figure 2c, the spatial distribution of the APWSI is similar to that of the RWSI. The number of districts and counties with maximally safe, sub-optimally safe, moderately safe, unsafe, and extremely unsafe levels accounted for 7.69%, 28.2%, 15.38%, 26.92%, and 21.79%, respectively. The highest percentages of maximally safe and sub-optimally safe areas were mainly distributed in Zunyi City, Guiyang City, and Qiannan Prefecture, which are relatively economically developed, have more water conservancy facilities, and have relatively flat terrain. The unsafe and extremely unsafe areas were mainly distributed in Bijie City, Qianxinan Prefecture, western Anshun City, and most districts and counties in Qiandongnan Prefecture, with low agricultural water use efficiency and few farmland water conservancy facilities.

(3) DWSI

The DWSI also shows remarkable spatial differentiation. With economic development areas, Guiyang, Zunyi, and surrounding districts and counties, as the two cores, presented safe and sub-optimally safe areas, other unsafe and extremely unsafe distributed in areas outside of the more economically developed areas, such as Ceheng County and Wangmo County in Qianxinan Prefecture. The number of areas that are maximally safe, sub-optimally safe, moderately safe, unsafe, and extremely unsafe accounted for 2.56%, 17.95%, 30.77%, 35.9%, and 12.82%, respectively. There were only a few maximally safe areas (only Yunyan District and Baiyun District in Guiyang City) where water quality and quantity can be guaranteed. The sub-optimally safe areas were mainly distributed in the southern part of Zunyi City, Guiyang City, and several districts and counties in Qiandongnan Prefecture, where water supply is concentrated and environmental protection is strong. The unsafe areas were mainly distributed in Qianxinan Prefecture, Qiannan Prefecture, and Qiandongnan Prefecture, where environmental protection is low and drinking water conditions are poor. The extremely unsafe areas were mainly distributed in Bijie City and Qianxinan Prefecture. In this part of the area, there were few water resources that can be used efficiently and few areas where drinking water is treated.

4.2 Drivers of rural water security

4.2.1 Impact of drivers in Guizhou Province

The geographic detector method was used to calculate the impact of drivers on rural water security (Table 3). For Guizhou Province, the drivers' influences on rural water security were as follows: disposable income of rural residents (D7), incidence of impoverishment (D2), percentage of villages that have completed toilet renovation (D5), percentage of hilly areas (D9), surface roughness (D11), penetration rate of rural piped water (D4), percentage of karst area (D10), percentage of primary industry (D6), percentage of groundwater (D12), fertilizer consumption per unit area (D13), percentage of large-scale agricultural business households (D3), gross value of agricultural production per capita (D8), annual average precipitation (D14), and percentage of population in rural areas (D1). D7, D2, and D5 are dominant drivers ($P_{D,E}$ > 0.3); D9 and D11 are secondary drivers (0.2 <$P_{D,E}$< 0.3); D4, D10, D6, D12, D13, and D3 are common drivers (0.1 < $P_{D,E}$ < 0.2); and D8, D14, and D1 are minimum drivers (0 < $P_{D,E}$ < 0.1).

4.2.2 Impact of drivers in each city and state

The geographic detector method was used to calculate the driver capacity ($P_{D,E}$) affecting the rural water security in each municipality (Table 3). As some of the influencing factors were at the same level across districts and counties, there were no differences. Therefore, factor detection was not performed for these factors and had no effect on the $P_{D,E}$ values of other factors in each district and county.

To compare and analyze the differences in the ability to influence each of the detection factors in different regions, the $P_{D,E}$ of each detection factor was ranked in various regions (Figure 3). As the rank value increased, the influence of each driver decreased.

The decisive power of each factor on rural water security in different regions showed obvious similarities and differences (Figure 3). D2, D4, D5, D6, and D10 were relatively consistent in their decisive power on rural water security in each city and state, while D1, D3, D7, D8, D9, D11, D12, D13, and D14 showed differences. Drivers had a greater impact on rural water security in Liupanshui City, Anshun City, Qianxinan Prefecture, and Zunyi City, followed by Guiyang City, Bijie City, Qiannan Prefecture, and Qiandongnan Prefecture.

Table 3 Influence detection results of rural water security drivers in 2016

Driver	Guizhou Province	Guiyang	Liupanshui	Anshun	Bijie	Qianxinan	Qiandongnan	Qiannan	Zunyi
D1	0.078	0.598#	0.993	0.347	0.186	0.465	0.335#	0.001	0.245
D2	0.457#	/	0.994	0.900#	0.277	0.634#	0.114	0.086	0.215
D3	0.144	0.564#	/	0.014	0.7[illegible]5#	0.230	0.249	0.340#	0.194
D4	0.197	0.209	0.993	0.368	0.538	0.096	0.049	0.034	0.089
D5	0.369#	0.011	0.996#	0.791	0.460	0.621	0.267#	/	0.173
D6	0.173	/	0.302	0.587	0.741#	0.921#	0.053	0.195	0.333
D7	0.604#	0.113	1.000#	0.801	0.308	0.920#	0.053	0.024	0.911#
D8	0.130	0.741#	0.140	0.133	0.506	0.057	0.015	0.101	0.170
D9	0.278	0.464	0.282	0.910#	0.031	0.000	/	0.454#	0.798#
D10	0.263	0.243	0.064	0.958#	0.582#	0.245	0.128	0.254#	0.935#
D11	0.174	0.087	0.302	0.728	0.485	0.311	0.432#	0.024	0.260
D12	0.153	0.000	1.000#	0.733	0.454	/	0.014	0.213	0.547
D13	0.148	0.405	0.415	0.733	0.075	0.266	0.010	0.073	0.175
D14	0.092	0.053	0.302	0.014	0.170	0.053	0.166	0.133	0.082

Note: The top three values of $P_{D,E}$ are the dominant drivers, represented by #.

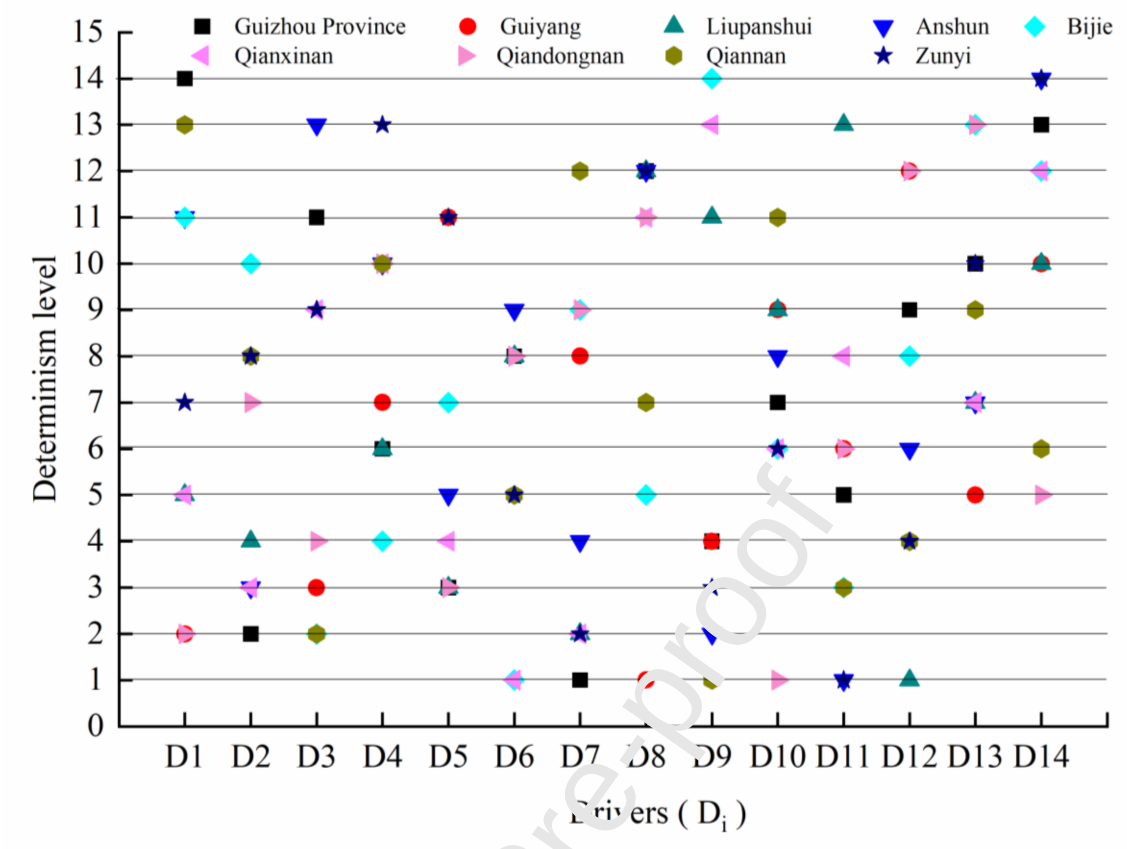


Figure 4 Determining power levels of drivers in each region

4.2.3 Drivers interactive detection

The results of the interaction detection of each factor (Table 5) show that the $P_{D,E}$ values for each combination factor are greater than those for a single factor, indicating that the interaction between the factors causes low water security in rural areas. In contrast, D2 and D7, which reflect poverty, have greater $P_{D,E}$ values than other single factors or combinations of factors, and are significantly different from other drivers. This further suggests that D2 and D7 are the main factors influencing rural water security. The maximum interaction driver value for D7 and D12 was 0.812.

Table 5 Interactive detection results

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14
D1	0.078													
D2	0.535	0.457												

D3	0.262	0.623	0.144											
D4	0.309	0.589	0.370	0.197										
D5	0.547	0.622	0.517	0.605	0.369									
D6	0.258	0.562	0.345	0.366	0.565	0.173								
D7	0.792	0.779	0.786	0.693	0.702	0.655	0.604							
D8	0.233	0.576	0.263	0.306	0.527	0.355	0.749	0.130						
D9	0.405	0.530	0.414	0.414	0.627	0.372	0.726	0.426	0.278					
D10	0.465	0.656	0.470	0.438	0.503	0.415	0.656	0.457	0.425	0.263				
D11	0.369	0.581	0.361	0.407	0.579	0.333	0.626	0.405	0.335	0.342	0.174			
D12	0.349	0.609	0.389	0.421	0.590	0.324	0.812	0.396	0.533	0.428	0.445	0.153		
D13	0.222	0.596	0.326	0.345	0.529	0.292	0.653	0.328	0.494	0.435	0.381	0.258	0.148	
D14	0.183	0.535	0.341	0.413	0.529	0.332	0.652	0.271	0.410	0.446	0.297	0.307	0.355	0.092

5. Discussion

5.1 Analysis on spatial differentiation of rural water security

Owing to the obvious regional differences in GEWSI, APWSI, and DWSI among districts and counties in Guizhou Province, RWSI presents obvious spatial heterogeneity.

The geographical environment is complex and an important physical basis of the natural–society binary water cycle, and the geography of water resources is an important indicator of water security (Dou et al, 2016; Bichai et al, 2016). Water security in the geographical environment is the basis for the water security of both agricultural production and domestic residents. Most districts and counties in Guizhou Province have abundant annual precipitation, but there are typically water shortages because of their geology and geomorphology. Forest cover plays a key role in water conservation. Because of the strong karst development and serious rocky desertification in Guizhou Province, most of the districts and counties—except for most of the districts and counties in Qiandongnan Prefecture—have low forest cover, making it difficult to use water for production and living. The density of the surface river network indicates the degree of surface water resource aggregation, which impacts how efficiently it can be utilized; if it is large, surface water resources can be easily exploited and utilized. In addition, it is relatively easy to build hydraulic facilities, such as ponds and reservoirs, on flat areas compared to on areas with high surface relief (Yang and Su, 2016). Karst areas with high surface relief are characterized by large relative height differences in the landscape, a high frequency of plot division, and large slopes. This makes it difficult to store and lift water, and makes irrigation more fragmented and less effectively utilized. This, coupled with the fact that the natural economic situation is less favorable than that of the plains, makes it difficult to build water infrastructure (Su and Zhang, 2011). However, the slope of the land in karst mountainous areas is mostly steep, and most of the farmland is located in areas with steep slopes, so the benefits of building water conservancy facilities are low. In addition, karst fissures are common, and farmland is easily washed by rainwater runoff. This leads to pollutants such as fertilizers being carried into the surface and groundwater bodies, affecting water safety. Thus, areas with high GEWSIs, such as Guanshanhu District and Nanming District in Guiyang City, show high per capita possession of water resources, high forest coverage, and high density of surface river networks. Otherwise, the reverse is true. Unsafe and extremely unsafe areas account for a low percentage of the plain area (less than 10%); the density of the surface river network is low, mostly at 0.2–0.5 km/km^2, and water resources are less aggregated. At the same time, the karst mountainous rural area also has intense land use and large population concentrations. Agricultural production requires flat land and easy access to irrigation, and not just land or water. Agricultural production is closely linked to physical, geographic, and socioeconomic conditions of the area (Sun et al, 2019). The APWSI is also affected by geographical environment and socioeconomic factors. Therefore, among the indices. the spatial distribution trends of the APWSI were the most consistent with those of the RWSI. The area of cultivated land associated with agricultural production is mainly affected by the natural geographic environment. The water consumption for livestock, the percentage of water used for agricultural production, the output efficiency of water resources, the number of electromechanical wells per 10,000 rural residents, and other farmland water conservancy facilities are also affected by socioeconomic impacts, and indirectly affected by the natural geographic environment (Ma et al., 2019). The water used for agricultural production and agricultural output values in karst mountainous areas is strongly affected by changes in hydrological conditions. Therefore, it is necessary to improve regional regulation and storage capacity and optimize water resource allocation through both engineering and non-engineering measures (Peng et al., 2020). However, the difficulty of building water conservancy facilities in karst mountainous areas, the small number of water conservancy facilities per unit of population, and the scattering of cultivated land have led to a low efficiency of water use for agricultural production, increased agricultural water consumption, and weak regional regulation and water storage capacity. Finally, the water security of agricultural production was affected. In counties with a large number of large livestock per 10,000 rural residents and a high percentage of arable land and a low number of electromechanical wells, irrigation and drainage stations, and irrigation ponds and reservoirs per 10,000 rural residents, the agricultural production water demand pressure is high and the water supply capacity is insufficient. This resulted in a low level of water security for agricultural production, such as that observed in Wangmo County and Qinglong County. The amount of irrigation water for farmland in unsafe and extremely unsafe areas is 450–795 m^3/km^2. Most areas, such as Leishan County, Congjiang County, and Qinglong County, have less than one irrigation facility per 10,000 rural residents.

The calculation of the DWSI mainly focuses on domestic water consumption, water quality, and convenience. As the level of economic development increases, so does the amount of water used, and rural residents are bound to place higher demands on water quality and convenience. Therefore, domestic water security needs to pay more attention to the quality of the water source, in addition to addressing the quantity of water (Yang et al., 2018; Yu et al., 2011). For example, bottled water, protected well water, and spring water are the main embodiments of the residents' water quality requirements; villages with a centralized water supply indicate the convenience of access to water, and the centralized treatment of domestic waste and sewage has a significant impact on the security of the water environment and is related to economic development. Therefore, the water security of domestic residents is also affected by economic development (Sun et al., 2013). This is consistent with the incidence of impoverishment and residents' disposable income as the main drivers detected by Geodetector. The security of rural residents' domestic water is lower in areas where the annual water consumption is smaller, the percentage of villages without toilets is higher, and the quality and convenience of drinking water is poorer, such as in Ziyun County and Weining County. In the unsafe and extremely unsafe areas, the percentages of villages with centralized domestic waste and centralized domestic sewage treatments are below 40% and 10%, respectively, and the percentage of residents drinking water from unprotected wells and springs is between 10% and 40%.

From the distribution ratio of the water security levels of each subsystem, it can be seen that the DWSI is better than APWSI, and both are better than the GEWSI. This shows that the geographical environment of water resources in the cities and prefectures of Guizhou Province is fragile, and water resource problems caused by karst development, rocky desertification, and other ecological environment problems are prominent. Although several policies and measures have been adopted to deal with various ecological and environmental problems, water resources and geographical environment problems exist objectively in karst areas. The cost of improvement is relatively high, and the benefits are low. Therefore, it is important to continue to tap into the perspective of economic development and technological progress to improve water security for agricultural production and domestic water. This is consistent with the study by Su et al. (2021), who reported that the levels of economic development and human capital and technological progress have a significant impact on water security.

5.2 Driving mechanisms of rural water security

Social factors, such as the regional natural environment, degree of economic development, and policy constraints in a single region can lead to differences in drivers across districts and counties. Natural factors, such as D9, D11, and D10, have significant impacts on Liupanshui City, Anshun City, Qiandongnan Prefecture, Qiannan Prefecture, and Zunyi City, but the influence of natural factors is related to the direction of the regional water policy. Economic and social factors, such as D7, D6, and D3, have more significant effects on Guiyang City, which has a more developed rural economy, and Bijie City and Qianxinan Prefecture, which have a high percentage of agricultural primary industries. Among the drivers, the values of the interactive drivers D7 and D12 are the highest, indicating that the superposition of D7 and D12 has the greatest impact on rural water security (Weis et al., 2017). The ability to improve the water dilemma is limited by karst development, the large proportion of groundwater, the difficulties in exploiting water resources and sustaining water abstraction, and the low disposable income of rural residents.

Rural water security is closely related to social and economic development, as well as the natural conditions. This is restricted by various factors. The spatial heterogeneity mechanism of rural water security in the mountainous areas of Guizhou was explored based on the pathways and outcomes of the drivers (Figure 4). Various factors influence rural water security to different degrees and directions from different perspectives. Rural water security is most affected by factors such as individual economic development and social poverty. In general, the levels of socioeconomic development and disposable income of residents are positively related to the level of rural drinking water security, while the opposite is true for the incidence of poverty. The advantages and disadvantages of the environment still account for a large percentage of the influence. According to the pathway of action and results of rural water security drivers, the driving mechanism of rural water security is summarized as follows:

(1) Backward social and economic development has led to the deprivation of rural public water facilities and the lack of water security for rural households. D7, D2, and D5 are the dominant factors in the province, and have the greatest impact on rural water security, which is consistent with the distribution of districts and counties in economically developed areas with higher comprehensive water security. The main reason for this is that the economic factors of rural residents own development levels play an important role in their daily lives. Rural residents with higher disposable income will invest more in water consumption, such as building small water conservancy projects, purchasing modern domestic water facilities, and water purification facilities, to meet their own water needs and improve the efficiency and quality of their domestic water. However, for rural households with lower disposable incomes, the cost of water conservation facilities is a major factor preventing easy access to safe water (Jamison et al., 2006). Social factors reflecting the level of poverty in each district and county pose a threat to rural water security. At higher levels of poverty, social inputs to rural areas will be invested first and foremost

in solving basic subsistence problems, putting pressure on water resources inputs, and resulting in the water demand and quality of water for domestic use and agricultural production not being guaranteed. In more socioeconomically developed areas, large-scale investment in water technology can offset the pressure of water security problems but does not fundamentally address water security issues. However, in economically underdeveloped areas, the lack of investment in water technology does not allow for the ability to fundamentally address water security issues (Vörösmarty et al., 2010). At the same time, lower economic status and livelihood uncertainty make it difficult for rural people to generate enough income to pay for the operation and maintenance of the source (Basu et al, 2020). Low-income households do not receive the same social benefits as wealthier households, including access to clean water and sanitation facilities. Therefore, rural water security problems remain a serious problem. The lack of social insurance for water security, coupled with the low disposable income of rural residents, has led to a low ability of individual farming households to support their own water facilities, a lack of modern household water supply services, an inability to satisfy residents' domestic water needs, and the lack of participation of rural residents in the entire rural water supply process, which is the primary reason for the low level of water security in rural areas, in line with the findings of Ho et al. (2017) and Basu et al. (2020). The low level of individual development and the backwardness of socioeconomic development have compounding effects that exacerbate the impact of inadequate investment in water development and management policies, institutions, and construction; in the context of the fragile natural environment of Guizhou Province, social and economic factors are relatively more important than natural factors in improving rural water safety. Owing to the fragile nature of the natural environment in most of Guizhou Province, improving the natural environment is difficult and slow to accomplish, and the geography of water resources remains poor. Therefore, it is more effective to achieve rural water security through social and economic measures (Qin et al., 2020; Xu et al., 2020). At the same time, rural karst areas in the southwest are backward in terms of water conservancy infrastructure, and the basis for the development of water ecological civilization is relatively weak, which makes it easy to fall into the “low-level balance trap”. While the geography of water resources provides a natural base for water security development, the ability to gradually improve disadvantages and turn them into tangible results depends on sufficient regional attention and investment in institutions, funding, technology, and personnel (Su et al., 2021).

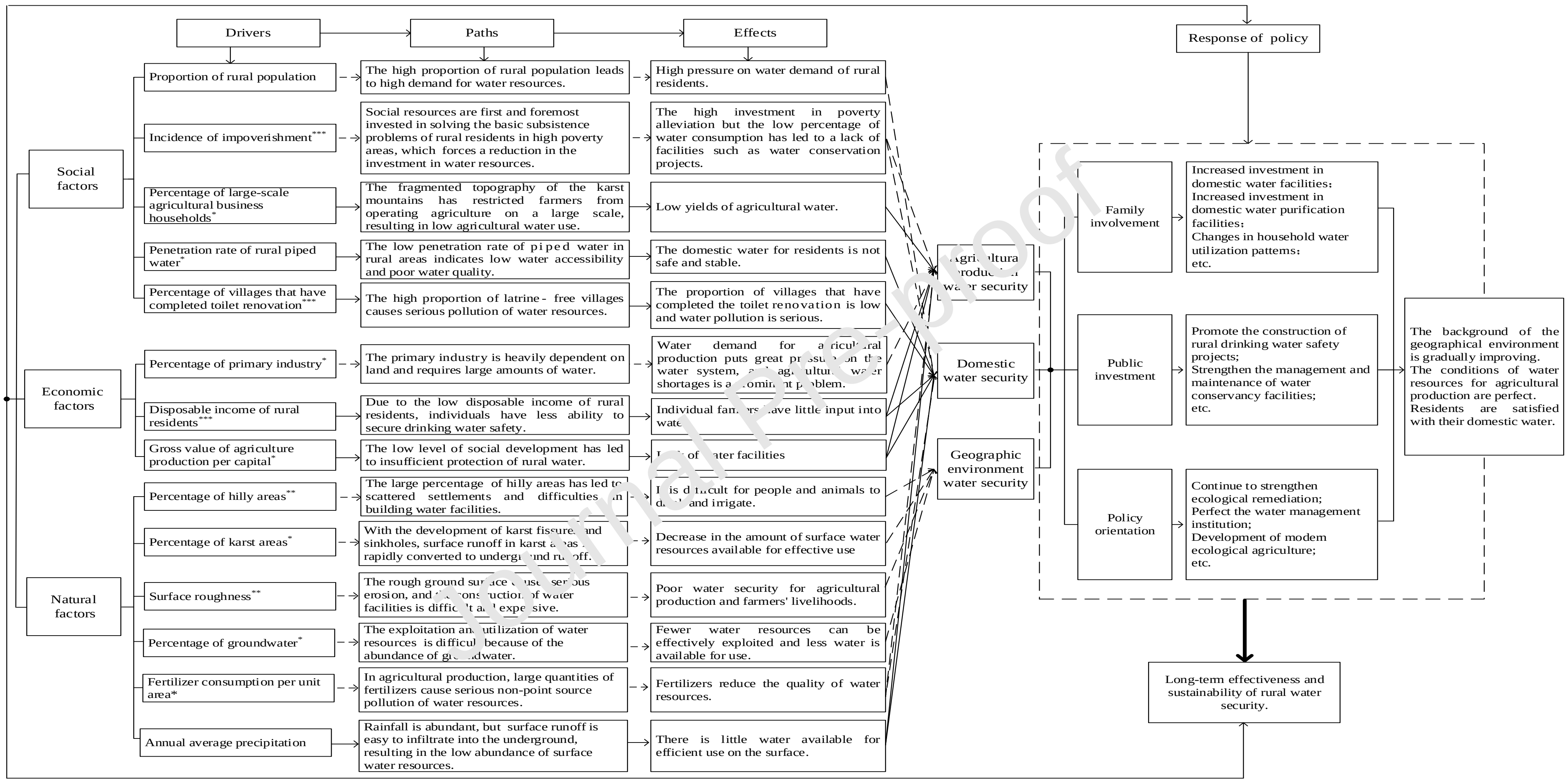
(2) Poor natural resource endowment hinders industrial development and infrastructure construction, and there is a large contradiction between the decentralization of rural residents and the publicity of water conservancy facilities. The secondary drivers (D9 and D11) mainly originate from the topography and geomorphology. Most districts and counties in Guizhou Province are areas with a large percentage of mountains and hills, with large undulations, rugged and broken terrain, and scattered rural residents. There is a large contradiction between the decentralization of residences and the publicity of infrastructure services. The high percentage of groundwater resources and the reduced volume of water make it difficult to exploit and utilize water resources, and it is difficult and expensive to build reservoirs and other water conservancy facilities, domestic sewage and waste disposal systems, and other infrastructure. It is evident that there is a serious engineering water shortage. The lack of water facilities contradicts the needs of people and animals for drinking water, agricultural irrigation, and other living and production needs (Chen et al., 2021). In addition, the development of industries, such as eco-agriculture systems and

plantations, has been affected by poor natural resource endowments, and backward industrial and economic development has deepened the above-mentioned social and economic impacts on rural water security (Jin et al., 2020; Cook and Spray, 2012; Du et al., 2015). In the context of a fragile natural environment, ecosystem protection should be considered, and the self-development and socioeconomic development of rural residents should be enhanced to improve their capacity to address the water security issues arising from environmental constraints.

(3) Insufficient policy guidance on water management, backward agricultural production techniques, and low efficiency in the use of water resources in the study area are evident. The water resource management system and water resource policies in rural areas are imperfect, and the implementation and effectiveness of water resource policies vary greatly from region to region. The primary industry has a high demand for water resources. The output efficiency per unit of water resources in agriculture is low compared to that in the secondary and tertiary industries. The development of the primary industry has a marked impact on the demand and efficiency of water resources (Weis et al., 2017). With the implementation of agricultural support policies in various regions, such as the continuous promotion of large-scale agriculture and the gradual development of modern ecological agriculture, the efficiency of agricultural water use has gradually improved, and the problem of agricultural production water security has gradually been alleviated (Rosegrant et al, 2013). Owing to the large amount of fertilizer applied per unit area, water quality has been seriously affected, and there are multiple water shortage and water pollution pressures. Therefore, there is a need to adopt high production technologies that save water and increase efficiency (Swartjes and Van, 2019; Zhu and Schwartz, 2011) through methods such as improving water management and conservation techniques through the mechanization of agricultural facilities and

efficient water conservation. In the process of achieving these goals, the situation will deteriorate if water management is not adequately or effectively planned (Scott et al., 2021). In this sense, it is critical to involve both managers and rural residents in defining integrated water security management plans and developing policies. Providing local people with knowledge of water use technologies, rainwater harvesting techniques, adaptation strategies, and local geography will also contribute to the development and implementation of sustainable water policies (Basu et al., 2020).

Each driver ultimately affects water quantity, quality, accessibility, and assurance, which in turn gives rise to rural water security issues, such as water insecurity of agricultural production, domestic use, and the geographical environment (Hou et al., 2017). To solve the problem of rural water security, we must first address the plight of rural residents who are deprived of water benefits because of lagging development, and whose limited income is taken up by basic needs, to achieve the development of rural residents and solve the problem of social poverty. Promoting the development of society and individual residents and enhancing the water security capacity of residents and society can be reflected in individual resident investment and government investment to meet water needs. Countermeasures, such as improving the water resources management policy system and developing modern ecological agriculture practices, could guarantee the long-term effectiveness and sustainability of rural water security.



Note: *** represents the dominant driver, ** represents the secondary driver, * represents the common driver, ⟶ represents the positive effect of the driver, and - → represents the negative effect of the driver.

Figure 5 Driving mechanism and policy response of rural water security

6. Conclusion

Districts and counties under the jurisdiction of Guizhou Province (except Tongren City) were selected as a case study. Based on the concept of rural water security, a rural water security evaluation system, including subsystems of the geographic environment, agricultural production, and domestic water resources, was proposed. Using the ArcGIS 10.2 platform, the regional differentiation of comprehensive rural water security and the water security of each subsystem were depicted, and the driving force of rural water security was detected using Geodetector.

(1) Overall, districts and counties with maximally safe, sub-optimally safe, moderately safe, unsafe, and extremely unsafe RWSI levels accounted for 3.85%, 20.51%, 35.89%, 15.38%, and 24.36% of the total, respectively. With Guiyang City and the central districts and counties of Zunyi as the center, the RWSI gradually declines toward the surrounding areas. The counties with higher RWSIs are mainly concentrated in Guiyang City and Zunyi City in the central region, followed by Qiandongnan and Qiannan in the eastern region, while the western regions from Bijie, Liupanshui, and Qianxinan have relatively low levels.

(2) The water security levels of each subsystem were maximally safe, sub-optimally safe, moderately safe, unsafe, and extremely unsafe; the results showed that the GEWSI accounted for 3.85%, 11.54%, 29.49%, 35.9%, and 19.23% of the total, respectively (44.88% were moderately safe or better); the APWSI accounted for 7.69%, 28.2%, 15.38%, 26.92%, 21.79%, respectively (51.27% were moderately safe or better); and the DWSI accounted for 2.56%, 17.95%, 30.77%, 35.9%, and 12.82%, respectively (51.28% were moderately safe or better). Clearly, the level of water security in the geographical environment is not as good as that in domestic and agricultural production. However, the problems of the geographical environment are objective and cannot be

completely changed. We must continue to explore the potential for improving water security in agricultural production and domestic scenarios.

(3) Provincial and sub-regional drivers explain rural water security. The disposable income of rural residents, the incidence of impoverishment, and the percentage of villages that have completed toilet renovation were the dominant drivers ($P_{D,E}$ > 0.3). The percentage of hilly areas and surface roughness were the secondary drivers (0.2 < $P_{D,E}$ < 0.3). The penetration rate of rural piped water, percentage of karst areas, percentage of primary industry, percentage of groundwater, fertilizer consumption per unit area, and percentage of large-scale agricultural business households were common drivers (0.1 < $P_{D,E}$ < 0.2). The gross value of agricultural production per capita, annual average precipitation, and the percentage of the rural population had the lowest influences (0 < $P_{D,E}$ < 0.1). Rural water security is most affected by factors such as individual wealth and social poverty. The maximum value of the interactive driver between the disposable income of rural residents and the percentage of groundwater was 0.812. The large percentage of groundwater caused by karst development interacts with the low disposable income of rural residents and is the primary reason for the low level of water security.

(4) The leading factors affecting rural water security in cities and prefectures differ markedly owing to obvious social, economic, and natural geographical differences. The incidence of impoverishment, penetration rate of rural piped water, percentage of villages that have completed toilet renovation, percentage of primary industry, and the percentage of karst area were relatively consistent among the determining forces of rural drinking water safety in each city and county, while other factors varied considerably among the determining forces of rural drinking water security in each city and county.

(5) In terms of driving mechanisms, social, economic, and natural factors will ultimately affect water security for agricultural production, domestic use, and the geographic environment from the perspectives of water quality, water quantity, water accessibility, and water supply guarantee rate. In the context of a fragile natural environment, it promotes the development of individual residents and society, and enhances the ability of individual residents and the government to ensure water security. On this basis, the policy orientation of ecological environment governance and the improvement of water resource management systems is to realize the long-term effectiveness and sustainability of—and ultimately achieve—rural water security.

Regional differences exist in the selection and weighting of rural water security measurement indices. The results of water security measurements may be affected by the selection of indices and the setting of weights; however, the results of this study can still objectively reflect the current situation of rural water security in the study area. In the future, it is necessary to further explore the transmission effects of factors influencing rural water security in karst mountainous areas, the long-term mechanisms of water security, and the threshold for karst groundwater development in different regions.

Author Contributions

Feng Zhou: data curation, formal analysis, investigation, visualization, and writing–original draft. **Wanshun Zhang:** supervision, methodology, funding acquisition, and conceptualization. **Weici Su:** supervision, conceptualization, writing–review and editing. **Hong Peng:** supervision, writing–review and editing. **Shulin Zhou:** writing **-** review and editing.

Declaration of Competing Interest

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

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Appendices:

Table 1 List of acronyms, symbols, and abbreviations

Abbreviations	Index
MDGs	Millennium Development Goals
WPI	Water Poverty Index
RWSI	Rural water security index
GEWSI	Geographic environment water security index
APWSI	Agricultural production water security index
DWSI	Domestic water security index
D1	Percentage of population in rural areas
D2	Incidence of impoverishment
D3	Percentage of large-scale agricultural business households
D4	Penetration rate of rural piped water
D5	Percentage of villages that have completed toilet renovation
D6	Percentage of primary industry
D7	Disposable income of rural residents
D8	Gross value of agriculture production per capita
D9	Percentage of hilly areas
D10	Percentage of karst areas
D11	Surface roughness
D12	Percentage of groundwater
D13	Fertilizer consumption per unit area
D14	Annual average precipitation

Declaration of Competing Interest

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

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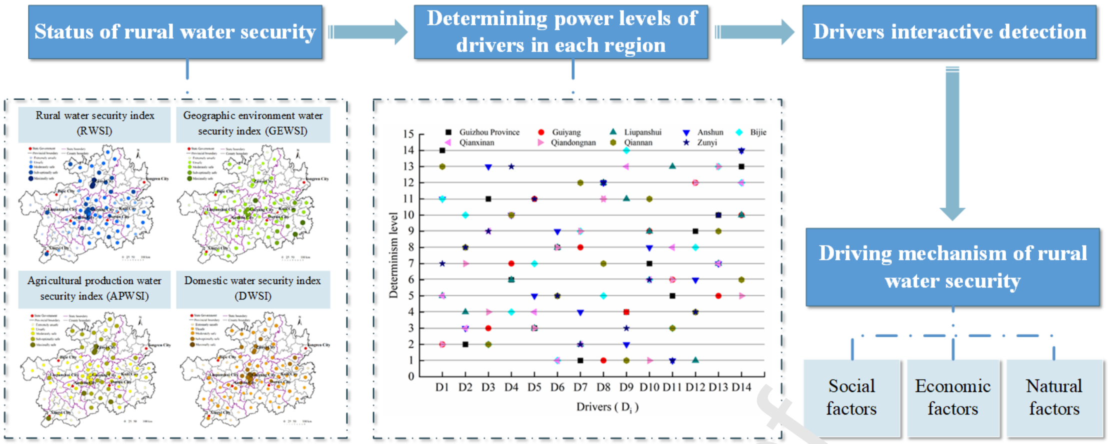
Declaration of interests

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

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract



Highlights:

- Rural water security index was constructed to analyze water security in rural Guizhou
- Spatial characteristics and drivers of water security were analyzed by software tools
- County-by-county analysis supports decision-making in water environmental management