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Population Distribution in Guizhou's Mountainous Cities: Evolution of Spatial Pattern and Driving Factors

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Abstract: Guizhou is a typical mountainous province and is also one of the lowland regions in China that has attracted a population influx. Here, using population density data from 2000 to 2020 as the basic dataset and the coefficient of variation method and standard deviation ellipse analysis, we investigated the spatial characteristics across different years. The results show: Firstly, Guizhou's population has a distinct spatial distribution, characterized by a lower population density in the southeast and a higher density in the northwest as well as an increasing polarization of population concentration toward the centers of prefecture-level cities and provincial capitals. Fluctuations in population density resemble a central siphon effect, which is particularly pronounced in the provincial capital and show a significant gravitational pull. Secondly, the coefficient of variation in population density across Guizhou's counties is spatially divided by Guiyang, showing higher values in the east and lower values in the west. Furthermore, the ellipse of the standard deviation of population density is gradually shrinking, indicating an increasingly concentrated population distribution. Thirdly, the explanatory power of the population and socio-economic systems on the population distribution in Guizhou is significantly greater than that of the natural systems. Population distribution and migration patterns have shifted from purely "economic driven" to coexisting with "economic and comfort-oriented" trends, and there is an urgent need to improve the comfort level of public services as a typical supply, in order to boost Guizhou's population attraction.

Keywords: population distribution; spatial pattern evolution; GeoDetector; standard deviation ellipse

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1. Introduction

Population distribution is a crucial spatial manifestation of human–environment interactions and constitutes one of the central themes in the field of population geography research [1]. In 1991, the total fertility rate reached the replacement level, by 2022, a population decline occurred. This signifies the end of 31 years of slow growth driven by inertia in China, with substantial short-term population rebound unlikely [2]. This foreshadows that populations endowed with socio-economic attributes will become increasingly precious. Consequently, the competition for labor and talent among regions will escalate in China[1], where the geographical characteristics of the population's growth and decline will become more prominent, and mountain cities that are less competitive may be at great risk of demographic resilience dislocation. Against the backdrop of differentiated population distribution, examining the clustering and dispersal patterns of population distribution in mountain cities from a geographical spatial perspective reveals the influences of demographic, natural, and socio-economic environments on population distribution. The above analysis aids in understanding the spatial development process and human–environment relationships in mountain cities, clarifying the driving logic between population (distribution), intrinsic demographic factors, and socio-economic environmental factors as well as among the socio-economic environmental factors. It also reveals

the challenges and dilemmas faced by both population and regional development, facilitating the formulation of development plans and responsive policies that are better aligned with the region's characteristics.

As a unique geographical unit, mountainous areas serve as both a barrier for ecosystem protection and a crucial source of natural resources for human [3]. Exploring the population distribution patterns in mountainous areas is crucial for maintaining ecosystem resilience and ensuring the sustained development of socio-economic systems. From 1975 to 2015, 35% of the population in global submontane areas grew by at least twofold, with its spatial distribution closely related to topography, climate, and protected areas [4]. In China, most studies on population distribution in mountainous areas are conducted from a topographical perspective. On a national scale, the relief degree of land surface (RDLS) ranging from 0 to 3.5. most people in China's mountainous regions reside in areas with relatively mild topographical variations. Notably, when the RDLS is 2, these areas accommodate 98.24% of the total population [3,5]. About a local scale, it is clear that the restrictive influence of topography on population distribution in mountainous areas is demonstrated. In the southern mountainous regions of Anhui, the correlation between population distribution and topography is 0.78 [6], whereas in the western mountainous regions of Henan, this correlation exceeds 90% [7]. Among other natural factors, river network density, temperature, and karst geology also shape the distribution patterns of populations in mountainous areas [8]. Additionally, endogenous population changes and socio-economic factors increasingly impact the population distribution in mountainous areas including GDP levels, healthcare provision, education quality, and the proportion of ethnic minorities [8–13]. However, different disciplines employ varying analytical perspectives. For example, demographic perspectives tend to focus on interpreting the process of population distribution from the standpoint of population itself [14], whereas geography predominantly explains the population distribution outcomes in relation to the natural geographical and socio-economic environments [8–13]. Therefore, in the comprehensive analysis of factors influencing population distribution, it is essential to incorporate the elements of population itself into the discourse of population geography to avoid falling into the endless "environmental determinism" trap. Simultaneously, China's population research in mountainous areas lacks specialization and a systematic approach. While there is considerable discussion on population development issues in mountainous regions of developed areas, there is a notable paucity of focus on the population development and distribution in underdeveloped karst mountainous regions of the western regions. Further clarification is needed regarding new patterns, characteristics, and driving factors.

Since 1935, the spatial development pattern of China's population east of the Aihui-Tengchong Line, characterized by a dense core and sparse periphery, has not undergone fundamental changes [9,11]. Due to its lagging economy, undulating topography and fragile ecology, Guizhou, although located east of the Hu Line, is at a distinct disadvantage in the competition in the national labor and talent markets, resulting in a serious population loss [15]. In 2020, the net outflow of population in Guizhou surged to 7.3082 million individuals, securing the top spot nationwide in terms of the proportion of net outflow population relative to the provincial resident population (18.95%). In the harsh reality of population loss, major cities like Guiyang are forced to participate in domestic competition for population and resources at the expense of exacerbating internal imbalances in development within the province, thereby constraining the development of non-key cities within the province [16]. However, the majority of ethnic minority counties in Guizhou are marginalized in socio-economic development, serving as secondary options in historical and contemporary development decisions. Their populations have dwindled amidst the socio-economic development gap between internal and external regions, showing a trend of relative contraction [9,17], and impacting both the preservation of their unique ethnic cultures and the effectiveness of rural revitalization. What are the population distribution trends at the county level in Guizhou amid the described context? Have there been abrupt internal characteristic changes? How do national and regional policies influence the dynamic evolution of population redistribution? The responses to the aforementioned queries

hold profound significance for the equitable allocation of resources, optimization of industrial structures, equalization of public services, and rural revitalization efforts in underdeveloped regions like Guizhou.

The Seventh National Census in 2020 provides comprehensive and authoritative data for studying the population distribution patterns at the county level in Guizhou during the new era. Therefore, this study utilized data from the national censuses of 2000, 2010, and 2020 to analyze the spatial evolution patterns of population distribution in Guizhou. By applying the macro theory of human–environment interaction, we constructed a three-dimensional indicator system to uncover the driving forces behind these changes. This research aims to enrich the understanding of mountainous population studies in China, deepening insights into the distribution of urban populations in underdeveloped mountainous areas and their interactions with demographic origins, socio-economic factors and natural environments. It seeks to provide a reference for social development planning, human–environment relationship coordination, and rural revitalization in Guizhou's mountainous cities.

2. Research Design

2.1. Study Area

Guizhou, situated in the southwestern hinterland of China, is the only province without wide plains (Figure 1). It is characterized by numerous plateaus and mountains, significant terrain undulation, abundant water and heat resources, but also high levels of rocky desertification [18]. The end of 2016, the rocky desertification area in Guizhou was 2.47 million hm^2, accounting for 24.5% of the total rocky desertification area in China. Compared to 2011, the rocky desertification area in Guizhou decreased by 554,000 hm^2, but the rocky desertification situation still remains very severe[2]. The complex ecological environment, characterized by karst desertification and high-altitude mountainous terrain, continues to exert a significant influence on population distribution and economic development in Guizhou. Until the end of 2020, Guizhou covered a total land area of 17.62 thousand km^2, comprising 88 county-level administrative divisions, with a permanent population of 38.56 million people. The province's gross domestic product (GDP) reached RMB 1782 billion, ranking 20th among the 31 provinces and regions[3]. As one of the first provinces to experience a net population outflow, Guizhou witnessed a net outflow of 2.09 million people during the decade from 2000 to 2010. However, this outmigration doubled to 4.02 million people during the decade from 2010 to 2020. Among all provinces experiencing net outmigration, Guizhou's ranking for net outmigration shifted from eighth in 2000 and 2010 to fourth in 2020, indicating a progressively severe pattern of population loss[4]..

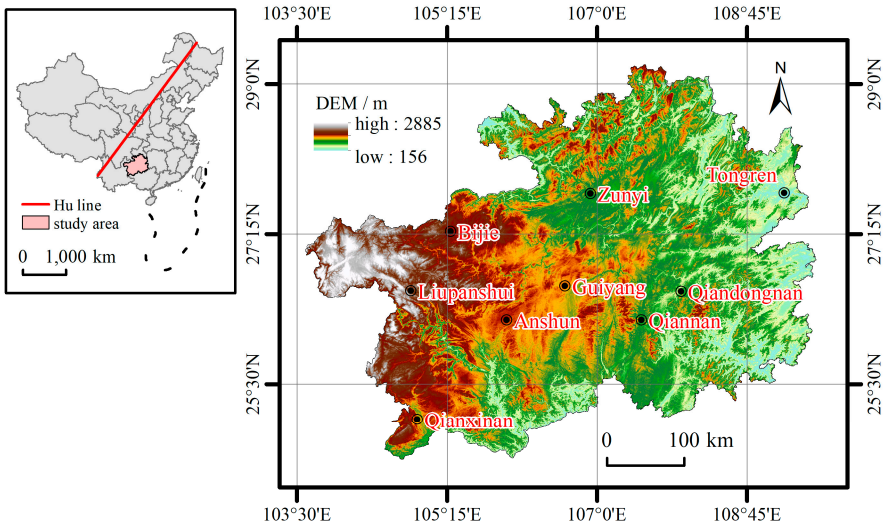


Figure 1. Overview of the study area.

2.2. Data Sources

The county-level resident population data for Guizhou in 2000 and 2010 were from 70 Years of Guizhou, and for 2020 from the China Population Census County-Level Data. Land area data were sourced from the Ministry of Civil Affairs map data (Surveying Number: GS(2022)1873). Population density was calculated by dividing the resident population by the land area of each county. The urbanization rate, derived from the proportion of urban population to the total rural–urban population, was based on data from the China Population Census County-Level Data for 2000, 2010, and 2020. The GDP and the proportions of value added by the primary, secondary, and tertiary industries for the years 2000, 2010, and 2020 were sourced from the Guizhou Statistical Yearbooks 2001, 2011, and 2021. The bed capacities of healthcare institutions were obtained from the China County (City) Social and Economic Statistics Yearbooks for 2001 and 2011, and the China County Statistical Yearbook (County and City Volume) for 2021. Additionally, the data for some counties were sourced from the respective annual 'Statistical Bulletin on National Economic and Social Development' of each county. The number of primary and secondary schools was sourced from the Guizhou Statistical Yearbooks for 2001, 2011, and 2021. Data on the area of rocky desertification land were obtained from the Comprehensive Prevention and Control Atlas of Karst Rocky Desertification in Guizhou (2006–2050). The terrain relief was derived from the China 1 km Terrain Relief dataset published by Youzhen et al. [19]. The temperature and precipitation data originated from the Chinese Academy of Sciences' Resource and Environment Science Data Center, specifically the China Meteorological Elements Annual Spatial Interpolation Dataset. Zonal statistics were then employed to compute the average temperature and precipitation indicators at the county level. The 70 Years of Guizhou has provided retroactively adjusted county-level administrative data since 2000. To ensure the coherence of the study units, the analysis of influencing factors excluded Guanshanhu District, Bozhou District, and Huichuan District. Consequently, the final number of units included in the factor analysis was 85.

2.3. Construction of Evaluation Indicators

Previous studies have indicated that the combined effects of demographic factors, natural environment, and socio-economic factors influence population distribution, leading to continuous spatial pattern changes [8–13,17,20]. Specific indicators of this article are listed in Table 1.

Table 1. Data selection and description.

System Category	Influencing Elements	Indicators	Explanation and Elaboration
Population	Population proliferation	X_1: Natural growth rate (‰)	The inherent growth dynamics of population distribution.
	Population influx	X_2: Proportion of inflow population (%)	The external population supplement for population distribution.
Economic	Economic level	X_3: Per capita GDP (¥Per capita/per person)	To measure the level of regional economic development, the higher the economic level, the more attractive it is to population aggregation.
	Economic structure	X_4: Proportion of primary sector value added X_5: Proportion of secondary sector value added X_6: Proportion of tertiary sector value added	Key indicator of regional economic structure status.
Social	Urban level	X_7: Urbanization rate	Measure of urban development level and the foundation of public services.
	Medical conditions	X_8: Number of beds in healthcare institutions	Indicators for measuring medical environment and resources.
	Educational conditions	X_9: Average years of schooling	Characterization of population cultural quality, effective measurement of educational resources and environment quality.

Table 1. *Cont.*

System Category	Influencing Elements	Indicators	Explanation and Elaboration
Natural	Environmental stressors	X_{10}: Area of rocky desertification (hm^2)	Serving as an environmental stressor factor for regional population distribution.
	Topographical conditions	X_{11}: Terrain relief	Characterizing the undulating conditions of the underlying surface for human habitation.
	Meteorological conditions	X_{12}: Temperature (°C) X_{13}: Precipitation (mm)	Indicators reflecting regional climatic conditions.

The population system exhibits a dual effect on population distribution. The endogenous effect of the population system refers to the inherent drive in population distribution caused by changes in natural growth rates, while the exogenous effect pertains to population redistribution resulting from population mobility. Under the influence of both factors, the population exhibits distinct spatial development patterns. Therefore, we used the natural population growth rate to characterize internal population proliferation, while the proportion of incoming population represents the external population supplement status [9,17].

The natural environment is a fundamental constraining factor in population distribution. In the context of Guizhou, the abundance of mountainous terrain, scarcity of flat land, and widespread prevalence of rocky desertification serve as critical natural constraints on population distribution. These factors collectively influence land productivity and the formation of settlements. Research indicates that there is a positive correlation between population distribution and rocky desertification in northwest Guangxi. They found that as rocky desertification worsens, the population density decreases [8]. Additionally, the region shares significant geological similarities with Guizhou. Constrained by the topographical undulations, the population in Guizhou is predominantly concentrated in hilly areas and mountain basins [15,21], indicating a pronounced "channeling" effect of terrain on population distribution. Thus, we utilized the extent of rocky desertification land as an environmental stressor factor in population distribution, while terrain relief represents the undulating conditions of the underlying surface for human habitation. Additionally, the survival and distribution of populations are influenced by factors such as temperature and precipitation. Areas with more favorable climatic conditions tend to exhibit more pronounced population aggregation and distribution patterns [12].

Socio-economic factors serve as significant disruptive factors in population distribution. Generally, the higher the level of economic development, the stronger the attraction and agglomeration effects on the population. Per capita regional gross domestic product (GDP) is commonly used as a measure [9]. Regional disparities in industrial composition are also a key determinant of population shifts. Typically, the value added by the primary sector is lower than that of the secondary and tertiary sectors. In the pursuit of greater returns and profitability, individuals tend to gravitate toward regions with a higher concentration of secondary and tertiary industries [22]. Urbanization levels are typically linked to the provision of public services, local living comfort, and convenience in a region. These factors are crucial considerations influencing population migration and settlement decisions [23,24]. Medical facilities are vital resources for ensuring population health. The more abundant they are, the greater the willingness of the population to congregate. Bed capacity in healthcare institutions can be used to characterize the medical environment [25]. Education is a critical but scarce social resource. Under competitive pressures, populations tend to aggregate in areas with superior educational environments and resources, leading to the formation of new population distribution patterns [9,11]. Based on previous research, this study utilized the average years of schooling as a measure to assess the quality of educational resources and environment [9,11].

2.4. Methodology

2.4.1. Coefficient of Variation

The coefficient of variation (CV), also known as the standard deviation ratio, is a statistical measure that assesses the degree of variation among a set of data. The coefficient of variation not only eliminates the influence of different units and means on comparing the variability of the observed data, but also quickly identifies outlier fluctuations [26]. Typically, the coefficient of variation falls between 0 and 15%. A smaller value indicates a smaller deviation in population density and less population fluctuation. In contrast, if the coefficient of variation is greater than 15%, a larger value indicates a greater deviation in population density and more significant population fluctuations. The formula for the coefficient of variation is:

$$CV = (S/\overline{x}) \times 100\% \quad (1)$$

where S is the standard deviation of the population density, and $\overline{x}$ is the mean population density.

2.4.2. Standard Deviation Ellipse

The standard deviation ellipse (SDE), also known as the Lefever directional distribution, was first proposed by Professor D. Welty Lefever. The standard deviation ellipse is one of the classic methods for analyzing the directional characteristics of spatial distributions in geographic phenomena and has been widely applied in population geography [27]. The long axis of the SDE indicates the direction of data distribution, while the short axis describes the range of data distribution. A larger difference between the long and short axes indicates a more pronounced directional distribution characteristic of the data. The standard deviation ellipse in this article was calculated using the directional distribution (standard deviation ellipse) tool in ArcGIS 10.8. The spatial projection coordinate system was WGS 1984 UTM Zone 48N, with a central meridian of 105° E. The longitude range was from 102° to 108° E, covering the entire research area required. Given the maturity of the standard deviation ellipse application, the specific formula and principles can be found in reference [27].

2.4.3. GeoDetector

GeoDetector (GD) is a novel statistical tool for detecting spatial differentiation, characterized by its superior resistance to collinearity interference. It mainly involves four aspects of detection: differentiation and factor detection, interaction detection, risk zone detection, and ecological detection [28]. Today, GD has been widely applied in analyzing the influencing factors of population distribution [8,12,29]. In factor detection, q-values are used to measure the degree of explanation of the independent variable on the dependent variable. A higher q-value indicates a greater explanatory power of the independent variable on the dependent variable. In addition, p-values or Sig values can determine whether the independent variable is significant. When the p-value or Sig value is less than 0.1, it indicates that the independent variable passes a significance test of over 90%. Before using the GeoDetector model, the data need to be discretized. Typically, methods such as equal intervals, quantiles, natural breaks, and K-means clustering are used for discretization. However, there is currently no unified standard for grouping discretization. Considering the issue of inconsistent data discretization and the selection of optimal discretization methods, this study utilized the gdm algorithm in the GeoDetector package "GD", developed by scholar Song Yongze in R language [30], to achieve the autonomous classification and selection of discretization methods. The general mathematical expression for factor detection in GeoDetector is:

$$q = 1 - \frac{1}{N\sigma^2} \sum_{i=1}^{L} N_i \sigma_i^2 \quad (2)$$

where q represents the degree of influence of explanatory variables, L denotes the classification of the dependent variable and the independent variable, N_i represents the i-th county,

N represents the total number of counties, and σ_i^2 and σ^2 denote the variance of the i-th county and the whole region with respect to the dependent variable, respectively. The value of q ranges from 0 to 1. When q equals 0, it indicates that the factor has no influence on the explained variable.

3. Results

3.1. Population Spatial Distribution Characteristics

Prefectural cities and provincial capitals are crucial economic nodes within a region. On the one hand, they are prioritized locations for policy support and development. On the other hand, they also serve as key points for significant changes in population status within the region [31–33]. Whether it is the '100 Industrial Parks' plan proposed around 2010 or the 'Major Function Oriented Zoning' enacted in 2013, Guizhou has prioritized the development of prefectural city centers and provincial capitals. Meanwhile, the southeastern and southern regions of Guizhou have mostly been designated as ecological protection zones and development prohibition areas. This significant economic development gap has naturally led to a gradual population shift toward the prefectural city centers and provincial capitals. Additionally, following the trend of upward population movement, prefectural city centers are relatively accessible aggregation points for county populations, with local culture, customs, and economy serving as key bonding factors. Conversely, provincial capitals are popular destinations for both internal and external populations, where the economy and public services act as major attraction points.

The population distribution in Guizhou exhibited a pattern of being more concentrated in the northwest and less in the southeast, with a tendency to gather in urban areas and provincial capital cities (Figure 2) from 2000 to 2020. In 2000, approximately 23.86% of counties in the province exhibited a population density surpassing 300 people/km^2, predominantly clustered around Guiyang, Anshun, and their northern vicinities. The districts of Nanming and Yunyan in Guiyang are the only two areas in the province with a population density exceeding 1000 people/km^2, with Yunyan District reaching a remarkable density of 8530 people/km^2. This phenomenon is attributed to Yunyan District's role as the core area of the old city of Guiyang, alongside hosting the administrative seat of the Guizhou Provincial Government. With its early urban development, favorable business environment, well-developed infrastructure, and the concentration of numerous provincial government institutions, it exerts a considerable siphon effect on population mobility [34].

In 2010, the low-population areas in the southeast of Guizhou continued to experience low development, with the number of counties with a population density below 100 people/km^2 increasing from 7 to 15, accounting for 17.05% of the total. The number of counties in the province exhibiting a population density surpassing 300 people/km^2 declined to 17. However, the tally of counties surpassing the threshold of 1000 people/km^2 witnessed an increment by two compared to the statistics of 2000. These additions comprise Honghuagang District in Zunyi City, recording 1066 people/km^2 and the Zhongshan District in Liupanshui City, registering 1236 people/km^2. This underscores a further consolidation of population aggregation within urban precincts.

The overall change in the spatial distribution pattern of the population in Guizhou from 2010 to 2020 was relatively minor. The trend of population concentration continued to grow, primarily centered around urban districts of prefecture-level cities and the provincial capital. These three newly added counties, with a population density of over 1000 people/km^2 (Guanshanhu District, Baiyun District, and Huaxi District), are all situated within Guiyang City. During the intervals of 2000, 2010, and 2020, prefectural-level cities in Guizhou exhibiting consecutive increments in extreme population density accounted for 55.56%. Notably, Guiyang serving as the provincial capital, boasted a population density several times higher than that of other prefectural-level cities, underscoring the amplified siphon effect exerted by prefectural-level city centers and provincial capitals on the province's population.

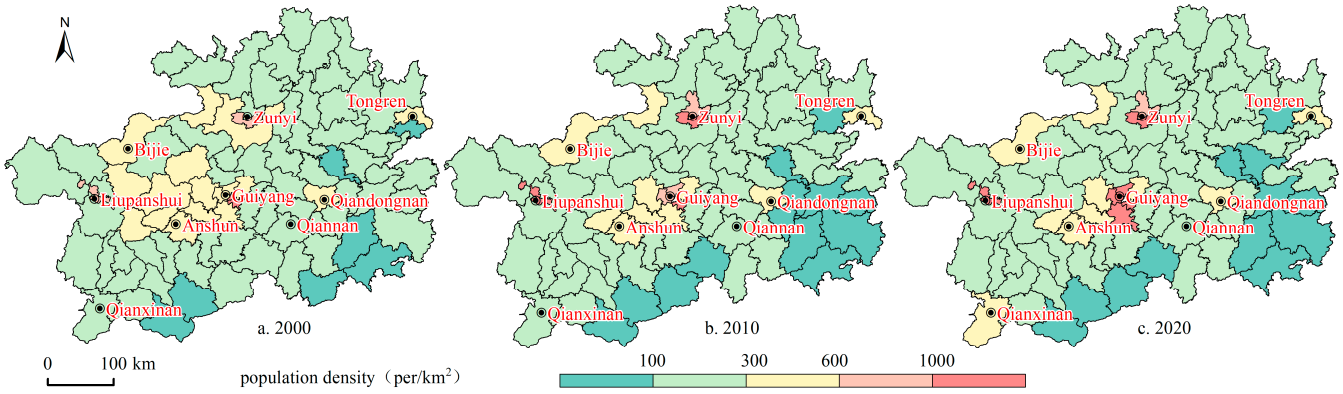


Figure 2. The spatial distribution of population density in Guizhou counties from 2000 to 2020.

3.2. Spatial Dynamics of Population Distribution Characteristics

From 2000 to 2020, the fluctuation in population density across counties in Guizhou generally revealed a pattern of growth in prefectural-level city centers and provincial capital, accompanied by either decelerated growth or negative growth in the surrounding areas (Figure 3).

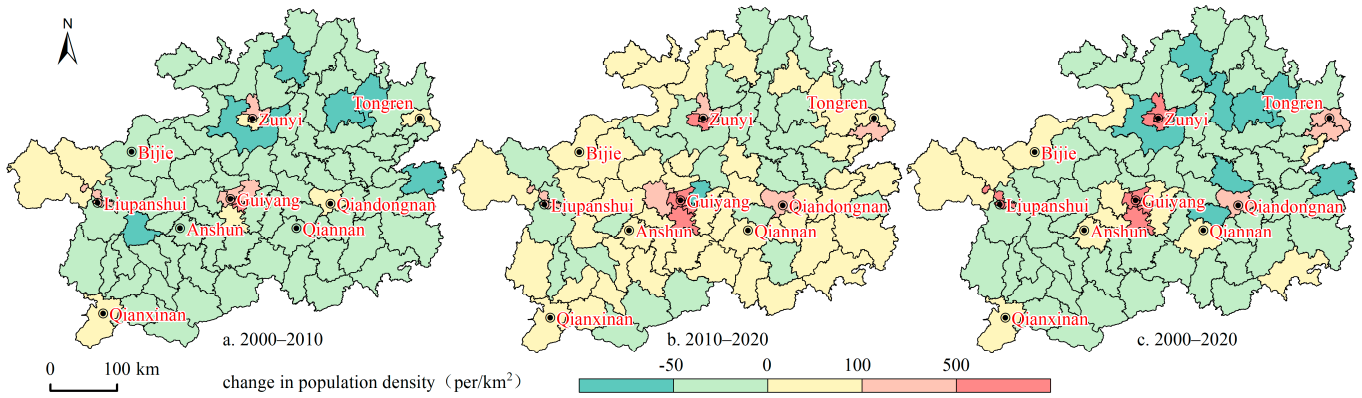


Figure 3. The characteristics of spatial changes in the population density of Guizhou counties from 2000 to 2020.

During the period from 2000 to 2010, the regions where population density increased included the central areas of the Guiyang, Zunyi, Tongren, Qianxinan Prefectures, Qiandongnan Prefecture, and Liupanshui, collectively accounting for 66.67% of the prefectural-level cities. Among them, Yunyan District in Guiyang City stood out as the area with the highest increase in population density province-wide, registering a relative increase of 7052 inhabitants per km^2. The areas where negative growth was more prevalent were predominantly in the surrounding counties of prefecture-level cities, accounting for 84.09% of all counties in the province. During the period from 2010 to 2020, the number of central urban areas in prefecture-level cities experiencing a positive population density growth increased from 6 to 7. However, a negative population density growth trend was observed in the central urban areas of Liupanshui and Tongren. During this period, the number of counties experiencing negative growth in population density decreased from 74 to 29 province-wide, indicating an overall increase in the resident population in most counties of Guizhou. In particular, Yunyan District in Guiyang City continues to exhibit the highest increase in population density across the province. During the period from 2000 to 2020, the prevailing trend in Guizhou was a decrease in population density across the majority of counties (constituting 72.73% of the total), juxtaposed with a consistent rise in population density observed in the central districts of prefecture-level city. Districts such as Yunyan, Nanming, Guanshanhu, Baiyun, Huaxi in Guiyang City, Zhongshan in Liupanshui

City, and Honghuagang, Huichuan in Zunyi City have become prevalent destinations for internal population migration within the province.

The spatial trend of population density further validates the existence of a siphoning effect of population from prefectural city centers and provincial capitals, which is more closely related to regional policy skews and historical foundations. In the future, the sharp and blunt distribution of population in Guizhou will become more pronounced. This may pose challenges to the sustainable development of mountainous cities. The provincial capital, in particular, needs to carefully balance the relationship between population, ecology, and economy to avoid excessive "headquarters-style" development and the negative effects of uneven concentration.

3.3. Spatial Variability Characteristics of Population

The coefficient of variation calculates the stability index of population density data for the years 2000, 2010, and 2020. In Figure 4, from 2000 to 2020, the coefficient of variation for population density across Guizhou's counties exhibited a spatial pattern where, with Guiyang as the dividing line, the eastern part had a higher population density and the western part had a lower density, reflecting significant population distribution disparities within the province. Guizhou has a total of 22 county-level regions where the coefficient of variation of population density exceeded 15%, accounting for 25% of the province. Among them, there were a total of 21 county-level regions located in Guiyang and its eastern areas, indicating significant fluctuations in population and frequent population migration in the eastern region of Guizhou. Specifically, the central areas of Guiyang and Zunyi are significant destinations for inward population migration in the province, while the eastern regions of Guiyang are notable areas experiencing outward population migration. This population distribution pattern may be associated with the relatively gentle terrain, lower elevation, and predominantly mild or potential rock desertification in areas like the east of Guiyang as well as their historically stronger economic foundations.

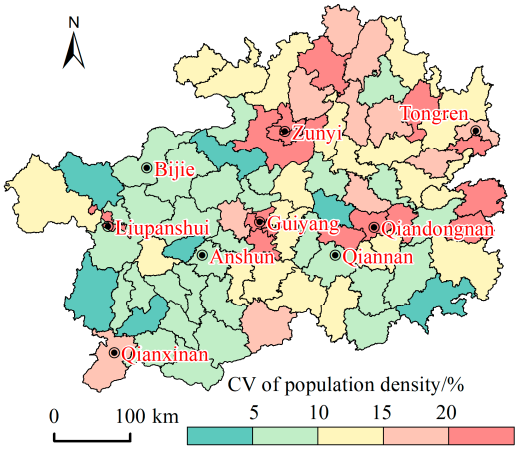


Figure 4. The coefficient of variation of population density in Guizhou counties from 2000 to 2020.

Across the province as a whole, there were a total of 12 counties where the coefficient of variation for population density was below 5%, primarily concentrated in the western region of Guiyang. Additionally, counties in Guizhou with a coefficient of variation below 10% were also predominantly distributed in this area. This observation suggests that most counties in this region experience relatively modest fluctuations in population and maintain a relatively stable distribution of residents. However, this stable distribution may largely result from low growth in the resident population, reflecting a balance between high birth rates and high emigration rates. Meantime, the substantial spatial disparity in population density underscores the influential role of Guizhou's distinctive geological characteristics, particularly karst terrain, which has profoundly limited the spatial scope for human settlement and development. Consequently, the environmental capacity is

predominantly determined by the most vulnerable component of the natural environment—land [21], alongside the socio-economic agglomeration effects it engenders. Specifically, the western part of Guiyang, particularly the Bijie- Qianxinan area, which has rugged terrain, high elevation, and severe rock desertification, limits the quality of life and thus further drives population outflow [21].

3.4. Characteristics of Standard Deviation Ellipse of Population Distribution

Over the period from 2000 to 2020, there was a gradual reduction in the range of standard deviation ellipses for population density across Guizhou's counties, while the direction of their distribution remained consistent (Figure 5). The major semi-axis measurements for the years 2000, 2010, and 2020 were 153.80 km, 131.28 km, and 127.69 km, respectively. These figures suggest a declining trend in the spatial distribution of population across counties over the course of 20 years. The spatial aggregation of population within counties also exhibited a trend of gradual reduction over successive periods. Over the minor semi-axis length, which was the longest in 2000 (93.31 km), followed by 2010 (80.23 km), and the shortest in 2020 (78.02 km), indicates a progressively significant centripetal force in the spatial distribution of population within counties over the twenty-year period, with a growing tendency for population concentration in the central regions of Guizhou.

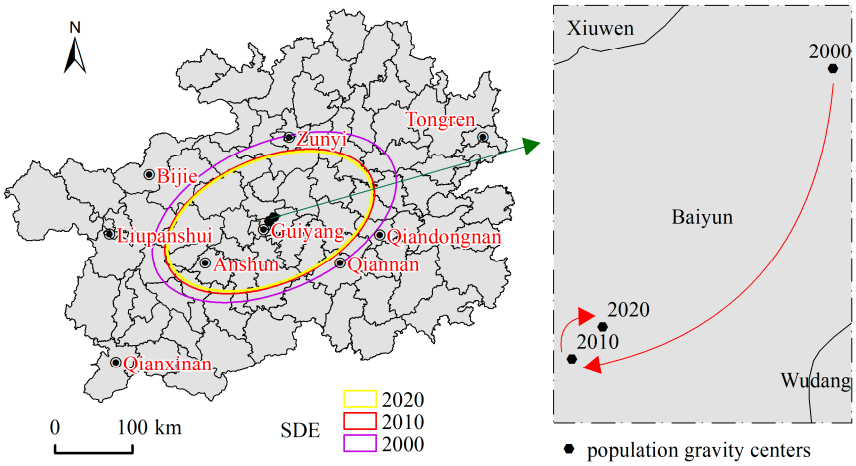


Figure 5. The standard deviation ellipse of the population density of Guizhou counties from 2000 to 2020.

From 2000 to 2020, the area of the standard deviation ellipse exhibited a decreasing trend, shrinking from 45,082.71 km^2 to 31,296.40 km^2, further indicating an intensification of the population distribution clustering trend. In terms of the direction of population change, the standard deviation ellipse underwent a westward shift followed by an eastward shift in the longitudinal direction, and a southward shift followed by a northward shift in the latitudinal direction. The decrease in the difference between the long and short axes of the ellipse from 60.49 km to 49.68 km further indicates a reduction in the directional characteristics of population distribution. Regarding orientation and direction, the standard deviation ellipse consistently maintained a northeast-southwest orientation, with azimuth angles of 59.78°, 61.03°, and 61.63° for the years 2000, 2010, and 2020, respectively. This suggests a trend toward a northeast-north and southwest-south orientation shift in the population distribution across counties in Guizhou.

Historically, the central Guizhou region, encompassing Guiyang, Zunyi, and parts of Bijie, was among the first areas governed by the Han ethnic group, where thriving agriculture and economic activities led to sustained population growth, thereby establishing the overall northern bias in modern Guizhou's population distribution. Since 2000, under the policy emphasis on the Western Development Strategy and the Strong Provincial Capital Strategy, Guiyang has gained significant development advantages. The rapid concentration of logistics, capital, and information within the city has spurred a dramatic

increase in economic growth, drawing more people to Guiyang and leading to a shift in the population distribution center from north to south. After 2010, with the expansion of the Guiyang Economic Development Zone, there has been an eastward shift in Guiyang's economic center and industrial layout. This shift has stimulated industrial development in surrounding counties while also causing a population expansion toward the east, resulting in a slight eastward movement of the population distribution center. Additionally, the center coordinates in 2010 and 2020 showed negligible difference, indicating that the population aggregation center (the core urban area of Guiyang City) remained essentially unchanged after 2010. In the short-term, the pattern of population distribution in Guizhou is unlikely to change significantly. The central Guizhou region around the provincial capital will continue to be the primary choice for population inflow both within and outside the province.

3.5. Driving Factors of Population Distribution

The "GD" package in R-studio was utilized to invoke the geographical detector, where three commonly employed methods ("geometric", "natural", and "quantile") were employed for data classification. The group settings varied from 3 to 10, and the discretization function utilized was "gdm". The results indicate that the automatic grouping categories of the influencing factors from 2000 to 2020 mostly fell within the range of 9–10, suggesting that a higher number of groups may lead to better detection efficiency. Furthermore, the natural breakpoint method and the quantile method were the primary classification methods in the model's autonomous selection process, indicating that these methods can effectively distinguish data sample differences and achieve the optimal model fitting performance.

According to the model results, from 2000 to 2020, the influence of population, socioeconomic, and natural systems on population distribution varied from year to year. Based on the significance and q-values, the population distribution in Guizhou's counties was primarily affected by factors such as the proportion of incoming population, urbanization rate, precipitation, temperature, per capita GDP, and the shares of primary and secondary industry outputs. Other factors were either significant only in 2020 or did not pass the 10% significance level test at all (Table 2).

The proportion of incoming population is a key factor in the differentiation of Guizhou's population distribution. It passed the 5% significance level test only in 2000. All other years, it passed the 1% significance level test, with q-values around 0.6. This underscores the substantial impact of population influx in reshaping the regional demographic landscape. The higher proportion of incoming population in districts and counties not only reflects the region's substantial human attraction capital, but also represents the intense spatial coupling of people's pursuit for better employment opportunities and quality of life. As a comparatively underdeveloped province, Guizhou has had to adopt a concentrated and biased policy of "small-scale experimentation leading to large-scale production", focusing investment in provincial and prefecture-level urban centers to afford them significant early advantages. This strategy has created a differentiated competitive environment for both internal and external migration into the province. Therefore, this leads to a population development scenario where low population density corresponds to a low inflow of population, while high population density aligns with a high inflow of population. Although most counties in Guizhou still maintain relatively high levels of population reproduction, the momentum of population growth is gradually declining amid competition from both internal and external population surges. It can be said that the correlation between population density in Guizhou and the influx of external populations is becoming more crucial. As shown in Table 3, except for Guiyang and Liupanshui, migration into other prefecture-level cities mainly relies on the population within the same prefecture-level city, with minimal influx from other prefecture-level cities or provinces. This indirectly indicates that these cities are more severely affected by population outflow in Guizhou. Furthermore, the proportion of population inflow from other prefecture-level cities within the province to Guiyang has been steadily increasing. Meanwhile, the influx of population from other

provinces has gradually become the largest in both volume and proportion within the province, further highlighting the population agglomeration effect under the policy of strengthening the provincial capital in Guizhou.

Table 2. Factor detection results of the spatial differentiation of population distribution in Guizhou.

Variables	Year of 2000		Year of 2010		Year of 2020	
	Value of q	Value of Sig	Value of q	Value of Sig	Value of q	Value of Sig
Natural growth rate (X_1)	0.214	0.125	0.214	0.125	0.128	0.473
Ln proportion of incoming population (X_2)	0.607	0.015 **	0.569	0.008 ***	0.673	0.000 ***
Ln per capita GDP (X_3)	0.616	0.130	0.634	0.023 **	0.615	0.004 ***
Ln Proportion of primary sector value added (X_4)	0.716	0.060 *	0.705	0.197	0.803	0.000 ***
Ln Proportion of secondary sector value added (X_5)	0.299	0.003 ***	0.299	0.003 ***	0.181	0.810
Ln Proportion of tertiary sector value added (X_6)	0.398	0.164	0.412	0.232	0.386	0.445
Ln Urbanization rate (X_7)	0.597	0.044 **	0.608	0.029 **	0.632	0.000 ***
Ln beds per thousand people (X_8)	0.549	0.999	0.549	0.999	0.565	0.076 *
Ln average years of education (X_9)	0.691	0.579	0.691	0.579	0.713	0.007 ***
Ln rocky desertification area (X_{10})	0.529	0.935	0.529	0.935	0.548	0.557
Ln terrain undulation (X_{11})	0.133	0.396	0.133	0.396	0.124	0.438
Ln temperature (X_{12})	0.222	0.081 *	0.222	0.081 *	0.279	0.006 ***
Ln precipitation (X_{13})	0.237	0.014 **	0.237	0.014 **	0.393	0.050 **

Note: The q value indicates the explanatory power of the independent variable on the dependent variable. *, **, *** denote significance at the 10%, 5%, and 1% levels, respectively. Since the natural growth rate has negative values and relatively small differences, this variable has not been logarithmically transformed.

Table 3. Proportion of various inflows of population in Guizhou from 2000 to 2020.

City	Year of 2000			Year of 2010			Year of 2020		
	PPIP/%	PPIOP/%	PPOP/%	PPIP/%	PPIOP/%	PPOP/%	PPIP/%	PPIOP/%	PPOP/%
Guiyang	37.13	44.65	18.22	22.21	59.78	18.01	21.64	65.1	13.26
Liupanshui	40.2	40.95	18.85	43.43	40.04	16.53	51.68	39.15	9.18
Zunyi	54.7	31.83	13.47	51.27	36.12	12.6	57.38	34.52	8.1
Anshun	57.5	29.01	13.49	51.93	31.83	16.24	55.9	33.95	10.15
Bijie	66.83	20.5	12.67	66.38	18.12	15.5	69.72	23.06	7.22
Tongren	60.42	20.28	19.3	62.89	20.85	16.26	58.5	33.18	8.32
Qianxinan	57.28	25	17.71	55.85	25.37	18.78	56.86	34.46	8.68
Qiandongnan	66.83	20.5	12.67	66.38	18.12	15.5	62.16	30.27	7.56
Qiannan	54.88	28.35	16.77	50.82	31.13	18.06	57.22	32.82	9.96

Note: PPIP denotes the proportion of population inflow originating from counties within the prefecture-level city, PPIOP denotes the proportion of population inflow originating from other prefecture-level cities in Guizhou Province, and PPOP denotes the proportion of population inflow originating from outside Guizhou Province.

The urbanization rate is the second critical factor, following the proportion of incoming population. During the three-year period, it not only passed the 5% significance level test, but also showed a slight increasing trend in q-values. This indicates that the influence of urbanization on population distribution has been strengthening. Per capita GDP is another important factor affecting population distribution. It only passed the significance test in 2010, and its q-values have shown a relative decrease. This suggests that the economic level's attractiveness for migration has diminished compared to other factors, indicating that people no longer consider economic factors as the sole consideration for migration. Urbanization and economic level have historically been key variables influencing population distribution in China [9,12,17]. Higher urbanization and economic levels imply the provision of more job opportunities and comprehensive social public services, thereby

being able to better meet people's aspirations for improving their material living standards. After 2010, under the policies of new urbanization construction, the dual-core city plan (Guiyang-Zunyi), and the development of the Central Guizhou Urban Agglomeration, the Central Guizhou region has experienced significant economic benefits. This development has provided opportunities for urban renewal and improved the quality of public services, contributing to central Guizhou becoming a "highland" in the population distribution of Guizhou. Conversely, other regions have formed relatively lower population density areas. Meanwhile, with the advancement of rural revitalization and tourism poverty alleviation, community development in Guizhou's rural areas has improved significantly. Residents in tourism-rich villages can now achieve ample employment locally, which helps narrow the economic gap between urban and rural areas. This shift encourages population movement from highly pressured mega-cities to more scenic and pleasant areas [35].

Indeed, industrial structure is a crucial factor in population distribution. The significant impact of the primary and secondary industries on Guizhou's population distribution was confirmed in 2000 and 2020 for the primary sector and the secondary sector. The third sector did not pass the significance test. This suggests that the influence of primary and secondary industries on population distribution remains significant, though the impact of the secondary sector has been weakening over time. Guizhou's unique mountainous environment and fragile ecosystem have made agriculture, representing the primary sector, relatively prosperous, while industrial development remains constrained. However, during the Western Development campaign, Guizhou attracted significant industrial transfers from partner provinces and, before 2010, actively promoted the construction of industrial parks in a hundred counties. These factors contributed to the growth of the secondary sector, leading to a notable increase in its impact on population distribution by 2010. With the rise of green eco-tourism and rural tourism poverty alleviation, the impact of agriculture, representing the primary sector, on population distribution significantly increased among the three major industries by 2020. Although Guizhou has actively developed the tertiary sector supported by "big data", the impact of this sector on population distribution is less pronounced compared to others. This is due to the relatively immature industrial clusters, a shortage of high-quality talent, and a lack of innovation platforms [36]. As the big data industry clusters continue to mature, mountain cities centered around Guiyang are expected to gain greater urban appeal in the future.

The average years of education and the number of hospital beds per thousand people were only found to be significant in 2020, with q-values among the highest of all significant factors. This indicates that the influence of educational and medical resources on population distribution has become increasingly pronounced. Within the constraints of historical and contemporary development, the educational center and resources in Guizhou exhibit a pattern of aggregation around the provincial capital. Particularly, higher education institutions are predominantly located in the provincial capital and prefecture-level city centers. Amidst the ongoing optimization of education support policies including initiatives like migrant students sitting for college entrance exams in cities and disciplines being included in the "double world-class project", the population in Guizhou is increasingly gravitating toward regions endowed with high-quality educational environments such as the provincial capital and key cities. This trend underscores the influential role of education in shaping population distribution [37]. Medical resources have consistently been essential factors in ensuring the level of public health. Their abundance and quality are conducive to enhancing the willingness of residents to stay and attract incoming populations [38]. Before 2010, Guizhou's economy, social insurance system, and educational levels were relatively low, which hindered the improvement of public health awareness. Additionally, the affordability of modern medical resources was low, leading people to prioritize basic necessities over healthcare. Since 2010, with the deepening of poverty alleviation policies and the implementation of the Western Development Strategy, the residents of Guizhou have experienced significant improvements in their material standard of living. However, the extensive economic development has also led to environmental pollution, resulting in

an increase in endemic diseases. Consequently, this has strengthened the willingness of the population in Guizhou to aggregate around advantageous medical resources.

Among natural factors, temperature and precipitation significantly affected the population distribution at the 10% significance level across all years, while topographic and geological factors did not pass the significance tests. This indicates that climate conditions have had a more noticeable impact on population distribution since the turn of the century compared to topography and geology. Human have always sought favorable climate, topography, and geological conditions, making geographic factors fundamental elements of population distribution. Guizhou's natural environment can be broadly described as "80 percent of the land is mountainous, 10 percent rivers and lakes, and 10 percent arable land", characterized by mountainous terrain, fragmented landscapes, and prevalent rocky desertification. Therefore, in situations where overall topographic and geological variations are relatively small, these factors might have larger q-values but may not show statistical significance. This occurs because the impact of topography and geology on population distribution might be less pronounced compared to other factors when differences are minimal. A favorable water–heat ratio benefits both industrial and agricultural production as well as human habitation and aggregation. In Guizhou, temperatures and precipitation typically show a pattern of higher in the south and lower in the northwest [39,40]. This ratio is optimal in the central region of Guizhou, while other areas experience relatively less favorable conditions. As a result, climatic conditions have a more significant impact on population distribution. Despite progress in rocky desertification control in Guizhou, the widespread rocky desertification environment still significantly affects the population distribution.

4. Discussion

Many studies have confirmed that population distribution is the result of the combined constraints of natural geographical factors and socio-economic factors [9,11,12,17,38], but a few have considered the dynamics of internal population factors. Ultimately, population distribution is the product of changes within the population system itself. Overemphasizing socio-economic and geographical factors while neglecting the intrinsic role of population can lead to a superficial understanding, limiting the ability to gain a more diverse and multi-dimensional perspective on the underlying dynamics. Therefore, building upon previous research, this study integrated population factors, natural geographical elements, and socio-economic factors into the determinants of population distribution, aiming to explore the multidimensional mechanisms underlying the population distribution in counties of Guizhou. The study found that socio-economic factors exhibited a stronger explanatory power on the population distribution in counties of Guizhou compared to natural geographical elements. Moreover, among the demographic factors, the influx of population emerged as a crucial driver of population concentration, while the influence of natural population growth on the population distribution gradually diminished. This represents a deepening of existing research in this field. With the massive social mobility and economic upheaval, a low-fertility social environment has been established, leading many regions to experience negative population growth. This has heightened the importance of the impact of migrant populations on population distribution. Currently, the natural population growth rate in Guizhou remains relatively high, but it also maintains a declining trend. In 2020, there are 20 counties have entered a phase of negative population growth, with a predominant concentration observed in Bijie and the ethnic minority autonomous prefectures situated along provincial borders. It could be argued that the contribution of natural population growth to the distribution of population in Guizhou has been gradually decreasing amidst the competition for population between internal and external regions. Under the circumstance of low external population replenishment, the return migration of the population within the province and the outflow from other provinces will become key factors in the population growth and distribution patterns in Guizhou.

Before 2010, Guizhou, as a typical underdeveloped province in western China, experienced a net outflow of population. However, with the deepening of the Western

Development Strategy, the construction of the Guizhou Central City Cluster, the planning of the dual-core cities of Guiyang and Zunyi, and the gradual formation of the regional center of the Southwest High-Speed Railway, the economic level of Guizhou, represented by Guiyang, has continued to rise. As a result, Guiyang has increasingly become the preferred destination for both internal and external migration to Guizhou. Currently, Guizhou, like many other central and western provinces, is adopting similar development strategies. This approach strengthens resource allocation, infrastructure, industrial investment, and public services in the provincial capital, guiding the population toward it. This trend resembles the early patterns of population distribution seen in eastern China [9,11,17,41]. However, Guizhou's natural environment supports a significantly lower population capacity than that of the eastern and central provinces, resulting in a relatively lower population carrying threshold. If practical conditions are ignored and there is a relentless pursuit of a super provincial capital population development strategy, it will face significant constraints. Additionally, an uneven and imbalanced population distribution will impact the high-quality development of the socio-economic sector. Confronting ecological constraints, regions like Guizhou face a significant challenge in optimizing population growth for maximum benefits, while tactfully guiding resource allocation and industrial development to ensure effective and equitable outcomes. Therefore, based on the above issues, this paper offers the following policy recommendations. (1) Major function oriented zoning should be used as a basis, with a focus on achieving spatial balance in the population to support Guizhou's strategy for high-quality economic and social development and optimize population distribution. (2) The urban system structure should be improved and the quality of urbanization enhanced. The Guiyang-Guian-Anshun metropolitan area and the Zunyi metropolitan area should be developed, with these "circles" used to drive and support the growth and strengthening of the central Guizhou urban cluster. (3) A differentiated zoning development path should be implemented, with deep cultivation of the big data industry in Guiyang. Support should be given to the unique ethnic cultures and brand development in minority areas, creating distinctive geographic identification products. (4) It is essential to improve the equality of public services and promote a balanced development of education, healthcare, and cultural infrastructure across the entire province.

By studying the spatial pattern of population distribution in Guizhou and its influencing factors, we can spatially reflect the new pattern and trend of population distribution in Guizhou. This provides certain ideas and references for the major planning of socio-economic development and special planning for population development in Guizhou in the future. However, this study also had certain limitations. For instance, the population data were at the county level, which cannot depict the population changes at finer scales such as township or village levels. Furthermore, due to data availability constraints, this study still had some shortcomings in terms of the selected indicators. For instance, indicators such as power infrastructure, agricultural machinery usage, road network density, urbanization rate, and air quality were not uniformly available due to variations in statistical categories, which limited their inclusion in the analysis. Therefore, in future studies aiming to deepen the research on population distribution in Guizhou, it may be beneficial to utilize gridded population data to further disaggregate the study scale. At the same time, the importance of comfort-oriented factors in population distribution and migration flows is constantly highlighted [42], and future research needs to continue to deepen and improve the indicators of human habitat comfort and excavate the mechanism behind the population distribution in the new period. Finally, since the county-level population inflow data were based on address information from household registration and place of residence, we were unable to identify intra-provincial return migrants. The next step of the study will involve integrating additional survey data to clarify the contribution of intra-provincial return migrants to the population distribution in Guizhou. This effort aims to provide targeted strategic references to attract population and talent to underdeveloped areas.

5. Conclusions

This study, based on population density data and utilizing county-level analysis, employed the coefficient of variation method and standard deviation ellipse to analyze the spatial distribution characteristics of the population in Guizhou. Furthermore, it constructed a comprehensive system of influencing factors including population, socio-economic, and natural systems, and introduced the GeoDetector model to identify key determinants of population distribution. Here are the basic conclusions of this article:

(1) The spatial distribution of the population in Guizhou exhibits the characteristic of being less dense in the southeast and denser in the northwest, with an increasing polarization of population toward the centers of prefecture-level cities and provincial capitals. At the same time, the population density variation in Guizhou's counties generally exhibits a siphon effect, especially the counties in provincial capital. Counties exhibiting a population density surpassing 300 individuals per square kilometer are predominantly situated in the northwestern region of Guizhou and within the central counties of prefecture-level cities. Notably, Guiyang's Yunyan District consistently maintains a population density exceeding 1000 individuals per square kilometer. Additionally, the population density in Guizhou's county-level areas generally shows a pattern of increasing in the central cities and decreasing in the surrounding areas, with a significant siphoning effect.

(2) The coefficient of variation in population density across Guizhou's counties was spatially divided by Guiyang, showing higher values in the east and lower values in the west. Meanwhile, the range of standard deviation ellipses for population density in Guizhou's counties is gradually shrinking, indicating an increasing concentration of population distribution. The coefficient of variation was significantly higher in Guiyang and the eastern region, indicating notable population fluctuations in this area after the year 2000. The area of the standard deviation ellipse decreased from 45,082.71 km^2 to 31,296.40 km^2, while the ellipse's center point remained relatively stable in the core area of Guiyang. This further indicates the increasing trend of population concentration toward the core area of Guiyang. In conclusion, the pronounced variability coefficient in Guiyang and its eastern regions signifies a notable population fluctuation in this area since 2000.

(3) The explanatory power of population and socio-economic systems on the population distribution in Guizhou was significantly higher than that of the natural system. The proportion of inflowing population > urbanization rate > precipitation > temperature > per capita GDP > primary sector output ratio > secondary sector output ratio, with the significance of average years of education and the number of hospital beds per thousand people gradually increasing. On the one hand, in the context of persistent fertility decline and population siphon effect by external provinces, the forthcoming dynamics of population distribution and growth in Guizhou may increasingly rely on intra-provincial return migration and internal population movements as the driving force of natural population growth gradually diminishes. On the other hand, the heightened attractiveness of public services such as healthcare and education underscores a shift in population distribution and migration dynamics from a predominantly "economically driven" model to one characterized by the coexistence of "economic and comfort" considerations. In the future, competition among populations will also pertain to the comfort of living environments. Less developed areas like Guizhou need to actively improve the quality of public services and prioritize attracting the return of local populations as a key strategy.

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

Notes

[1] The aforementioned description is based on calculations derived from relevant data provided by the "2022 United Nations World Population Prospects".

[2] The data were sourced from Bulletin of Rocky Desertification in Karst Area China 2018.

[3] The data were sourced from the China Statistical Yearbook 2021.

[4] The data were sourced from the Population Census Yearbook 2020

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