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Analyses on Characteristics of Spatial Distribution and Matching of the Human–Land–Water–Heat System on the Yunnan Plateau

Jinming Chen [1,2], Xiao Yang [2], Haiya Dao [2], Haowen Gu [3], Gang Chen [2], Changshu Mao [2], Shihan Bai [2], Shixiang Gu [2,*], Zuhao Zhou [4] and Ziqi Yan [4]

1 State Key Laboratory of Water Resources Engineering and Management, Wuhan University, Wuhan 430072, China; chenjinming187@163.com
2 Yunnan Institute of Water & Hydropower Engineering Investigation, Design and Research, Kunming 650021, China
3 School of Engineering and Technology, China University of Geosciences (Beijing), Beijing 100083, China
4 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
* Correspondence: 13078773756@163.com

Abstract: Water, soil, and heat are strategic supporting elements for human survival and social development. The degree of matching between human-land-water-heat elements directly influences the sustainable development of a region. However, the current evaluation of the matching of human-land-water-heat elements overlooks the influence of elevation factors on the matching results, especially evident in mountainous areas. Taking the Yunnan Plateau with distinctive mountainous features as the research subject, divided into 11 elevation ranges, the Lorenz Gini coefficient, asymmetry coefficient, matching distance, and imbalance index are used to assess the spatial matching and balance of human-land-water-heat elements. A projection tracing model is employed to analyze its water resource carrying capacity. Analyses revealed that the Gini coefficient of monthly precipitation from the 1950s to 2022 on the Yunnan Plateau increases with increasing latitude, whereas the correlation with elevation is notably lower. The asymmetry coefficient increases gradually from west to east with change in longitude. The mismatch of the human–land–water–heat system in regions at different elevations is in the order 1800–2000 m > 2000–2200 m > 1400–1600 m > 800 m > other areas. The matching of the human–land–water–heat system in different wet–dry years and seasons also fluctuates with elevation, resulting in serious seasonal drought and water shortage problems in mountainous areas with elevations of 1200–1600, 1800–2000 m, and >2600 m. The spatial equilibrium of temperature and precipitation in regions of different elevations is best, followed by that of cultivated land, while that of the population is the worst. The Gini coefficients for different water cycle processes of precipitation, surface runoff, and regulating storage capacity for water supply continue to increase. Specifically, the Gini coefficient of industrial water supply is the highest, reaching 0.576, and that of agricultural irrigation is the lowest (0.424). Through artificial regulation of lake and reservoir water, seasonal changes in the demand for agricultural irrigation water are offset to achieve a demand–supply balance and matching of land and water resources. The water resource capacity of different elevation ranges is evenly underloaded. However, the potential of the water resource capacity varies obviously with elevation in the order 2000–2200 m < 1800–2000 m < 1600–8000 m < 1400–1600 m < other areas. It appears that the greater the human–land–water–heat system mismatch, the smaller the regional potential of the water resource capacity.

Keywords: Yunnan Plateau; interconnected river–lake–reservoir system; water network engineering; water resources; spatial distribution; capacity evaluation; equilibrium; matching

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1. Introduction

Climate change accelerates the terrestrial hydrological cycle, intensifies global drought, and increases the probability of sudden drought [1]. Southeast Asia is a hotspot of drought migration globally. Drought migration tends to move rapidly with long duration and high severity, while land–atmosphere feedback mechanisms such as precipitation recycling play important roles in the evolution of local and downwind droughts [2]. Climate change caused by human activities has led to negative effects, such as increases in the frequency, intensity, and duration of droughts in China, and the scope of both moderate and extreme drought events has expanded [3]. Climate change and increased atmospheric CO_2 concentration affect land runoff through radiation and biotic stress. Of the total increase in runoff globally, 73–81% is attributed to land surface changes [4]. Owing to global warming, increased evaporation, and human water use, the water storage capacity of 53% of the world's lakes has decreased substantially in the past 30 years, prompting large-scale dam construction to restore water storage capacity [5]. Sustainable irrigation is well adapted to climate change and is a key factor in supporting global food security. It increases global food production by 6–8%, provides food for 620–840 million people, and promotes global food and water security. Water deficiency in the agricultural economy can be resolved by reducing soil evaporation, increasing soil permeability, reducing surface runoff loss, and planting drought-tolerant crops. However, long-term water shortage problems persisting for more than one month can only be resolved by building storage facilities such as ponds and reservoirs [6,7]. Determining the impact of future climate change on the water cycle lies in clarifying the water cycle process, assessing regional and seasonal changes, and analyzing the interference attributable to human activities [8]. Doeffinger and Hall revealed the spatial heterogeneity of water security assessments at national, state, and county levels in the United States from the aspects of population, the economy, and the environment [9].

Owing to the randomness of precipitation and the uneven aggregation of economic and social units, the distribution of water resources in time and space is inconsistent with regional economic development and human activity, resulting in water shortages and supply–demand contradictions that can seriously affect regional economies and high-quality social development [10]. China has a high proportion of mountainous areas, which presents many challenges to the construction of water conservancy and agricultural infrastructure, industrial and agricultural economic development, and ecological and environmental protection [11]. Determining how best to overcome the constraints caused by mismatch between water resources and socioeconomic development and achieving sustainable water resource utilization is China's second centenary goal. Moreover, food security, urban clusters, major strategic areas, energy base construction, ecosystem protection, and improvement of human settlements all face water security problems that must be settled urgently [12,13]. China has built many cross-regional interconnected water systems for water regulation and storage to control the uneven spatiotemporal distribution of national water resources. In the future, the national water network will be densely knitted by connecting transboundary rivers with domestic rivers. Western water transfer and the overall planning of major rivers in southwestern regions of China will promote the construction of China's "Double T"-shaped water network economic zone. Furthermore, the major southwestern rivers, i.e., the Yuanjiang-Honghe River, Lancang River, Nujiang River, Irrawaddy River, Yangtze River, and Yellow River, together with the northwestern rivers, will be connected to form the main framework and arteries of the national water network [13–16]. Earlier studies investigated the matching of water resources with various factors, such as land, population, the economy, energy, and urban space, e.g., the matching relationship between regional water resources and land resources [17–21], and the inherent coordination and correlation with the population, economy, and cities [22–24]. Existing research results have provided a good theoretical basis for promoting regional sustainable development, but improvements should be made in following areas: (1) Existing studies analyze the matching relationship between water resources and other elements from a two-dimensional perspective and overlook the impact of elevation factors on the results of matching evaluation. If elevation is not considered as one of the factors, it is assumed that water resources at any elevation can be used to meet the needs of land, people, and economic water use at any other elevation, even if the elevations differ by 1000 m or more.

However, water resource development is not cost-free. In the case of water, lifting is needed to utilize water resources, and the water lifting height should be within the user's affordability range of water lifting costs. Generally, agricultural irrigation users can only afford the water lifting cost within 200 m. Excessive water lifting heights will lead to water prices that exceed the cost that water users can afford, and human beings will not build projects to utilize the portion of water resources with a price that exceeds their affordability capacity. Therefore, in analyzing the matching of water resources with other element resources, if the influence of elevation on the results is not considered, the matching analysis will not correspond with reality. In other words, erroneously considering the portion of water resources that cannot be utilized by humans as available for economic and social development will result in a biased preference in the matching analysis results, which is more obvious in regions with high mountains and deep valleys. (2) Existing studies mostly analyze the matching of water resources with elements of economic and social development, failing to reflect the matching relationships after the impacts of human activities, i.e., the changes in spatial and temporal distribution of water resources due to the construction of new water conservancy projects, which may lead to distorted matching evaluation results. Therefore, it is necessary to introduce indicators reflecting human activities, such as water supply volume and regulating storage capacity.

The Yunnan Plateau is in the southern extension of the Qinghai–Tibet Plateau and in the western parts of the Yunnan–Guizhou Plateau (Figure 1). Yunnan is a typical mountainous province with soaring mountains, deep valleys, and significant elevation differences. Over 94% of the province's area is mountainous plateau, while basins and intermountain valley dam areas account for only approximately 6% of the total area [25]. The latter areas are major industrial-agricultural economic and urban zones located in the source areas of the second- and third-level tributaries of the six major river systems, i.e., the Yangtze River, Pearl River, Yuanjiang-Honghe River, Lancang River, Nujiang River, and Irrawaddy River. The phenomenon of water resources being in lower regions while people and cultivated land are in higher regions is extremely common in these areas, with the elevation difference between population, cities, farmland, and economic aggregation areas and the major rivers often exceeding several hundred meters. Therefore, this study selects the Yunnan Plateau as the research object, introducing indicators such as water supply volume and regulating storage capacity to reflect human activities into the matching evaluation model. Using 200 meter elevation intervals, the distribution characteristics and their matching characteristics of human-land-water-heat elements within different elevation ranges are analyzed. This approach can not only avoid the distortion of evaluation results caused by the inclusion of water resource volumes that are not suitable for utilization in the total water resource index but also reflect the real matching situation after taking into account the impact of human activities. It represents an improvement upon existing research and fills a gap in this field. The research results can provide technical support for improving the matching of water resources with land, population, economy, and other elements in the Yunnan Plateau, as well as for promoting the sustainable development of the economy and society.

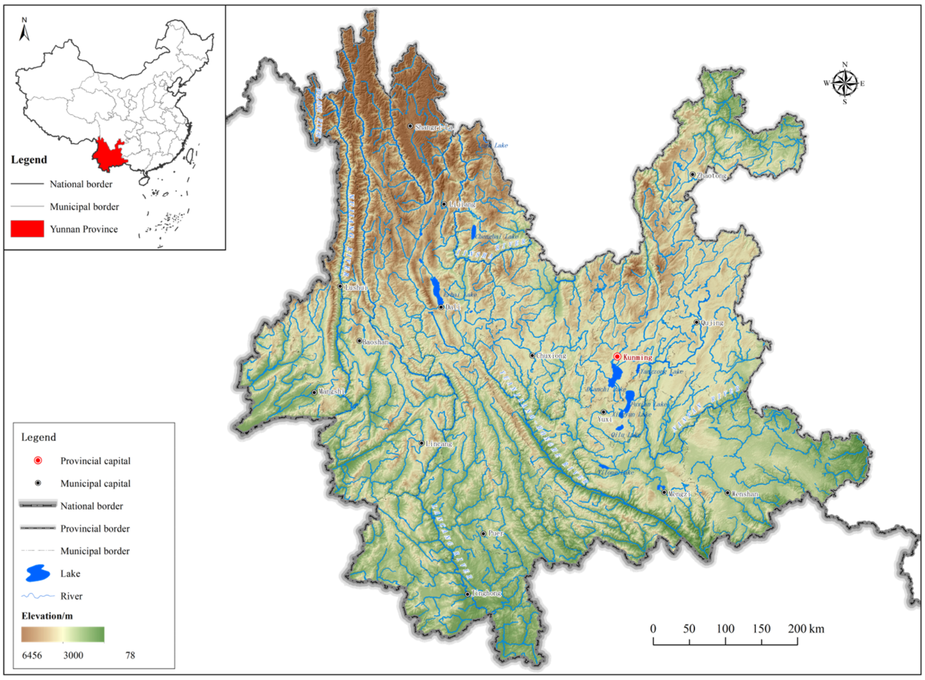

Figure 1. Geographical location of the Yunnan Plateau.

2. Materials and Methodology

2.1. Fundamental Data

The data used in this study comprised China high-resolution satellite remote sensing imagery (GF-2 and GF-3 satellites, spatial resolution of 0.8 and 2.0 m, respectively) of Yunnan Province and information from the provincial projects of core reservoirs built or under construction and interconnected lake–reservoir water systems, including the first national water conservancy survey, the third water resource survey, and the third land resource survey Each water source and its elevation, the distance between the water source and the water supply object, the elevation of water users, and the actual water supply of each industry were analyzed based on the hydrometeorological data, materials, and other spatial information. Additionally, the social and economic (or agricultural) statistical annual reports and water conservancy statistical yearbooks (or reports) of 16 prefectures (cities), 129 counties (cities, districts), and 1380 townships (towns, streets, offices) in Yunnan Province were considered [26–28]. Table 1 lists the characteristics of the interconnected lake–reservoir water systems involved in this study. The interconnected water system accounts for 51.2% of the total water supply, and the remainder is provided by small river water diversion, underground wells, rainwater harvesting, and other projects.

Table 1. Information of the interconnected lake–reservoir systems on the Yunnan Plateau.

Type of Water Engineering	Number	Total Storage /10^8 m^3	Utilizable Capacity /10^8 m^3	Elevation Range/m		Actual Water Supply/10^8 m^3					
				Lowest	Highest	Industrial	Urban	Rural	Agricultural Irrigation	Ecology of River-Lake	Total Water Supply
Large reservoir	17	34.08	22.40	995	3225	3.18	4.70	0.18	6.21	5.75	20.02
Moderate reservoir	321	66.03	51.14	649	3426	7.50	6.21	1.74	33.51	0.15	49.11
Comprehensive utilization of hydropower station	15	39.99	24.34	370	2221	1.08	1.13	0.06	2.59	0.00	4.85
Plateau lakes *	18	60.82	14.95	1273	3180	2.95	1.57	0.06	4.00	0.16	8.74
Total	371	200.93	112.83	---	---	14.71	13.61	2.04	46.30	6.06	82.72

Note: * Includes natural lakes built into reservoirs.

2.2. Water Resource Allocation

Yunnan is a province inhabited by many ethnic groups. Ethnic minority autonomous regions account for 70.2% of the total area of the province, and 25 ethnic minorities, including the Yi, Bai, Dai, Hani, and Naxi, account for 33.4% of the total population of the province. The population density is high in valley dam areas but low in mountainous areas [27]. The province currently has 93.13 million mu (667 square meters) of farmland, with 1.97 mu of farmland per capita. The per capita farmland also reflects the characteristic of more farmland in mountainous areas than in plains and more in the interior than in border areas. The total irrigated area of farmland in the province is 30.72 million mu. To date, 12 large-scale irrigation districts of more than 0.3 million mu and 103 key medium-sized irrigation districts of 0.05–0.3 million mu have been established [28].

Taking the national fourth water resource regionalization within county-level administrative regions as the calculation unit, in accordance with the national development goal of realizing rural revitalization and modernization, the total water consumption is intended to be controlled at 22.682 billion m^3 by 2035. Based on analysis of the water supply and demand of priority water conservation, spatial balance, and ensuring the health of river–lake systems, a planned simulation model of the water resource system of Yunnan Province was established based on the MIKE BASIN platform. After three time balance analyses, water use quota and efficiency management was strengthened and the total amount of sewage discharged into rivers and lakes was strictly controlled, while promoting the protection and restoration of water ecosystems. For the entire province, the water resources are rationally allocated between socioeconomic systems and ecological–environmental systems, between different river basins and regions, and between different water use industries [29]. A "four-level interconnected water systems" layout for joint management of rivers and water engineering projects is gradually being built, which focuses on the key economic zone. It is based on the six major water systems, with the "Central Yunnan Water Diversion Project" as the backbone, the comprehensive utilization of a hydropower station project as the supplement, and large reservoirs and core medium-sized reservoirs as the water sources. The main streams and tributaries are utilized jointly and complementarily. Eventually, achieving a three-dimensional comprehensive interconnected river–lake water system on the Yunnan Plateau is expected, with the multifunctional characteristic of "river–lake connection, west–east water diversion, upper–lower linkage, multisource complementarity, regional–mutual assistance, and coordinated functions."

Large and medium-sized hydropower stations or reservoirs (storage capacity: >50 million m^3) on the main streams and tributaries within the province have been gradually developed into comprehensive water utilization–conservancy hubs, forming a balance of water demand–supply with the densely distributed water users in the surrounding socioeconomic areas. The interconnected river–lake water systems are planned and implemented through various large and medium-sized reservoirs (storage capacity: >10 million m^3), plateau lakes (including those that have been transformed into storage facilities), and large and medium-sized hydropower stations (storage capacity: >50 million m^3) that can regulate changes in river runoff and increase water supply for socioeconomic development during dry periods. These projects can realize the hydraulic connection and mutual exchange with cities, villages, industrial and mining enterprises, irrigation areas, and rivers through gravity flow or water withdrawal. The continuous promotion of such water engineering projects will result in the replacement of a large portion of diversion projects with low water supply guarantee rates with reservoir projects with high water supply guarantee rates, which will gradually build a three-dimensional cross-regional water network system on the Yunnan Plateau.

2.3. Methodology

To reveal the matching between the distribution of the population and the cultivated land, light, heat, and water resources on the Yunnan Plateau, as well as the coordination between the water engineering projects and the human–land–heat system, the matching distance d is used to analyze the matching and the advantages among the factors. The imbalance index I is used to analyze the overall matching between two factors. The main formulas can be expressed as follows [30]:

$$d_i = \sqrt{2}(a_i - b_i)/2, \quad (1)$$

$$I = \sqrt{\sum_{i=1}^{n} \sqrt{2}(a_i - b_i)^2/2n}, \quad (2)$$

where a_i is the proportion of factor a in region i in terms of the total amount of the province, b_i is the proportion of factor b in region i in terms of the total amount of the province, and n is the number of regions. The larger the imbalance index, the more notable the mismatch of factors.

The Lorenz curve, Gini coefficient, concentration degree, and asymmetry coefficient were used in this study. The spatial balance of the water resource-related factor indicators in different elevation intervals (divided into 11 levels: ≤800, 800–1000, 1000–1200, 1200–1400, 1400–1600, 1600–1800, 1800–2000, 2000–2200, 2200–2400, 2400–2600, and >2600 m), and the spatial elevation difference between water supply projects and water consumers (divided into six levels: ≤50, 50–100, 100–150, 150–200, 200–300, and >300 m) were analyzed using the aforementioned coefficients. The specific calculation method can be found in the literature [31–34]:

$$Gi = \sum_{i=1}^{n-1} (M_i P_{i+1} - M_{i+1} P_i), \quad (3)$$

where Gi is the Gini coefficient, M_i is the cumulative percentage of a certain measure in the i-th elevation interval, P_i is the cumulative percentage of a certain measure in the i-th elevation interval, and n is the number of elevation intervals. The Gi value ranges from 0 to 1; the closer the value is to 0 (1), the more equal (unequal) the distribution.

For the ordered sequence $x_1 \leq x_2 \leq ,\ldots, \leq x_n$, the asymmetry coefficient S can be calculated using the following formulas:

$$S = F(\mu) + L(\mu), \quad (4)$$

$$\delta = \frac{\mu - x_m}{x_{m+1} - x_m}, \quad (5)$$

$$F(\mu) = \frac{m + \delta}{n}, \quad (6)$$

$$L(\mu) = \frac{L_m + \delta x_m}{L_n} = \frac{\sum_{i=1}^{m} x_i + \delta x_m}{\sum_{i=1}^{n} x_i}, \quad (7)$$

where S is the Lorentz asymmetry coefficient, x is the cumulative percentage, μ is the mean value, n is the total number of data, and m is the number of data with values less than the mean value. A value of $S > 1$ means that the area on the right side (right side of the symmetry line) enclosed by the Lorentz curve and the uniform line is greater than the area on the left side, and vice versa for a value of $S < 1$.

The framework of this study is shown in Figure 2.

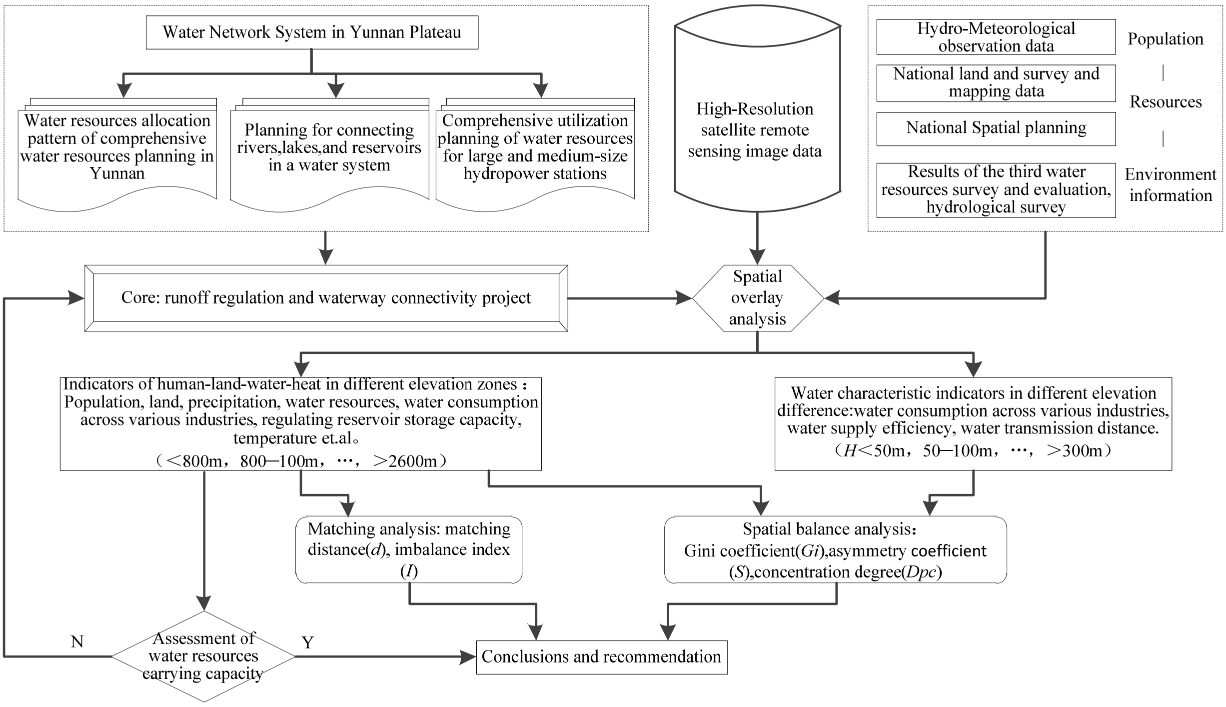

Figure 2. Research framework.

3. Spatial Distribution Features

3.1. Spatial Distribution Characteristics of Human–Land–Water

Based on the third water resource survey and regulation in the Yunnan Plateau, combined with precipitation and runoff observation data, the spatial distributions of water resources per capita and per mu water resources of cultivated land at the township level in the province are shown in Figure 3. It is evident that the water crisis areas with per capita water resources of <500 m^3/people are concentrated in Dianchi Lake, Fuxian Lake, Qilu Lake, and other surrounding areas (Figure 3a). Areas between the resource-type and the general water shortage-type are mainly distributed south of Kunming, east of Yuxi, north of Honghe, central Chuxiong, east of Dali, and west of Qujing, all located in central Yunnan Province. Other areas in the province that greatly exceed the water balance line of 3000 m^3/people are regarded as relatively rich in water resources.

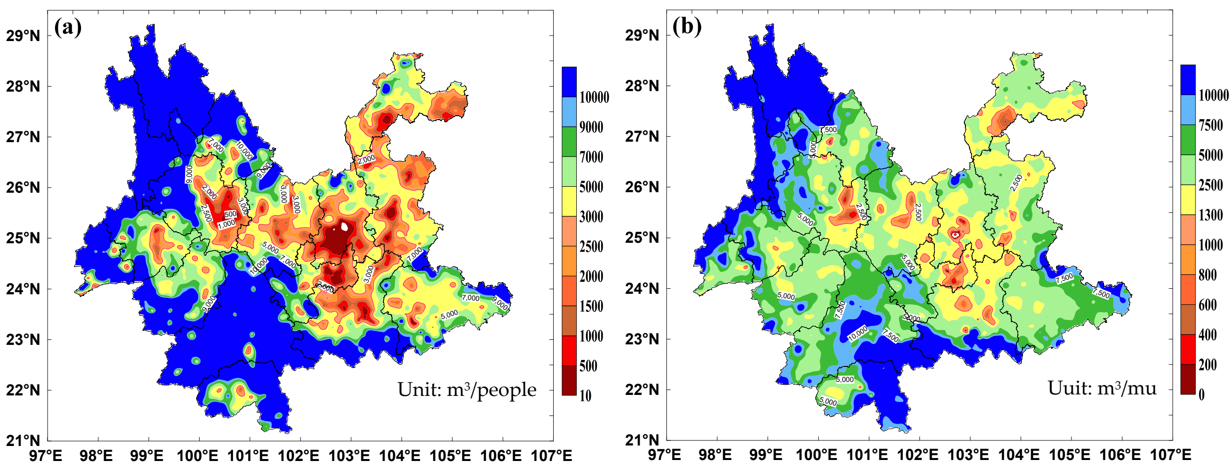

Figure 3. Spatial distribution of water resources (**a**) per capita and (**b**) per mu of cultivated land in the Yunan Plateau.

In terms of water resources per mu of cultivated land (Figure 3b), the spatial distribution trend is similar to that of the per capita water resources. It indicates that the lake basin area of the central Yunnan Plateau, where cultivated land is concentrated and contiguous, has the lowest water resources per mu. The northwestern and southern regions of the Yunnan Plateau, with sparse population and fragmented cultivated land, have high water resources per capita and high water resources of cultivated land per mu. The water resources in the central Yunnan Plateau are inherently restricted owing to the agglomeration effect of population and industry in the Central Yunnan Plateau Economic Zone (Kunming as the center), together with the natural endowment of water resources and cultivated land. The contradiction between water demand and supply within the area has existed for a long time, which has resulted in the area having the highest density of water network projects.

Correlation analysis was conducted on the spatial change trends of indicators such as population, cultivated land, water resources, and storage capacity in various elevation areas of the Yunnan Plateau, as shown in Figure 4. Population increases with expansion of cultivated land (Figure 4a), with a correlation coefficient as high as 0.90 (significance level, $p < 0.01$), indicating that cultivated land is a vital and fundamental resource for human survival. The regulating storage capacity index, which reflects the human transformation of nature and abundant–dry changes in river runoff, has an approximately linear relationship with population growth (Figure 4b), with a correlation coefficient of 0.86 (significance level, $p < 0.01$). The main reason is that humans need to build reservoirs to effectively utilize water resources. The larger the population, the greater the required regulating storage capacity. The spatial relationship between cultivated land and water resources also shows a linear growth trend (Figure 4c), with a correlation coefficient of 0.81 (significance level, $p < 0.01$), indicating that the capacity constraints of regional water resources are prerequisite for expansion of cultivated land, while cultivated land resources have become the basic condition for human survival and development.

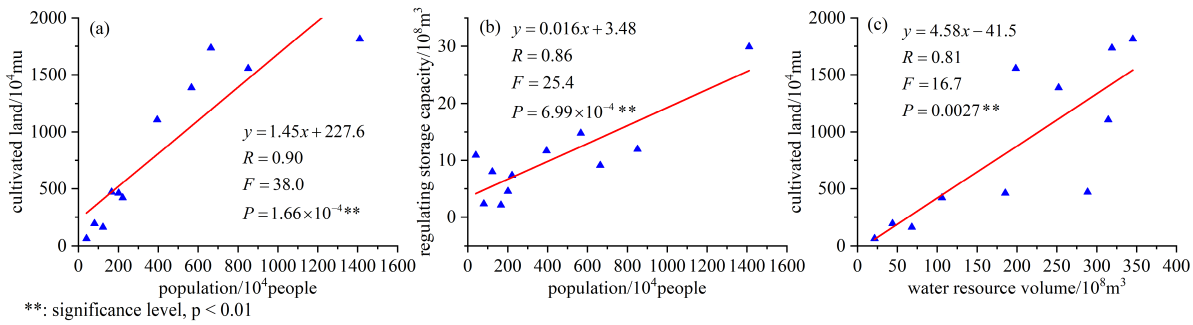

Figure 4. Spatial correlations of the human–land (**a**), the human–water (**b**), the land–water (**c**) in different elevation ranges on the Yunnan Plateau.

3.2. Spatial Distribution Features of Precipitation

The Yunnan Plateau is a typical plateau mountainous area, for which runoff mainly relies on precipitation. Hence, the spatiotemporal patterns of variation in precipitation are broadly consistent with the variation characteristics of runoff and regional water resources. The third Chinese water resource survey revealed that water resources were severely depleted during 2009–2012 owing to four years of severe drought in southwestern China. Analysis of water resources from 1956 to 2015 revealed that the total amount of water resources in the province was 214.1 billion m^3, which was 3% less than the average value from 1956 to 2000. However, owing to the effects of topography, monsoon sources, and the local environment, the change in water resources varies across different regions.

The long-term trend was analyzed using observed precipitation data from the 1950s to 2022 from eight meteorological stations in Kunming, Zhaotong, Mengzi, Dali, Jinghong, Shangri-La, Yuanjiang, and Yuanmou, obtained since their establishment. Precipitation in Kunming, the provincial capital, showed a slight trend of reduction overall, but with notable annual variation. In the past 20 years, two periods of reduced precipitation with one intervening period of increased precipitation were observed, i.e., 1999–2012, 2018–2022, and 2013–2017, respectively. These characteristics of periodic continuous abundant precipitation or dry periods are prominent. In the remaining areas, annual precipitation also showed a slight trend of reduction in Mengzi and Shangri-La, whereas annual precipitation declined notably in Dali, Zhaotong, and Jinghong.

Further analysis of the Gini coefficients of the monthly precipitation distribution balance within a year revealed that the average Gini coefficient of the eight stations is 0.48–0.56 and that the average asymmetry coefficient (*S*) is 0.85–0.94, as shown in Figure 5. Generally, the Gini coefficient of each station presents a trend of decline. The asymmetry coefficients show a trend of increase in Kunming, Zhaotong, Dali, Yuanjiang, and Yuanmou, whereas they show a gradual reduction for the other three stations. It shows that the balance of precipitation distribution within a year gradually increases and that the asymmetry weakens. However, the interannual changes are large, and the abundant–dry difference of rainfall affected by the monsoon climate does not change, resulting in increase or decrease in runoff. Therefore, it is necessary to rely on water storage projects such as lakes and artificial reservoirs to reduce the abundant–dry difference in natural water to satisfy the demands for water associated with daily life and industrial/agricultural production.

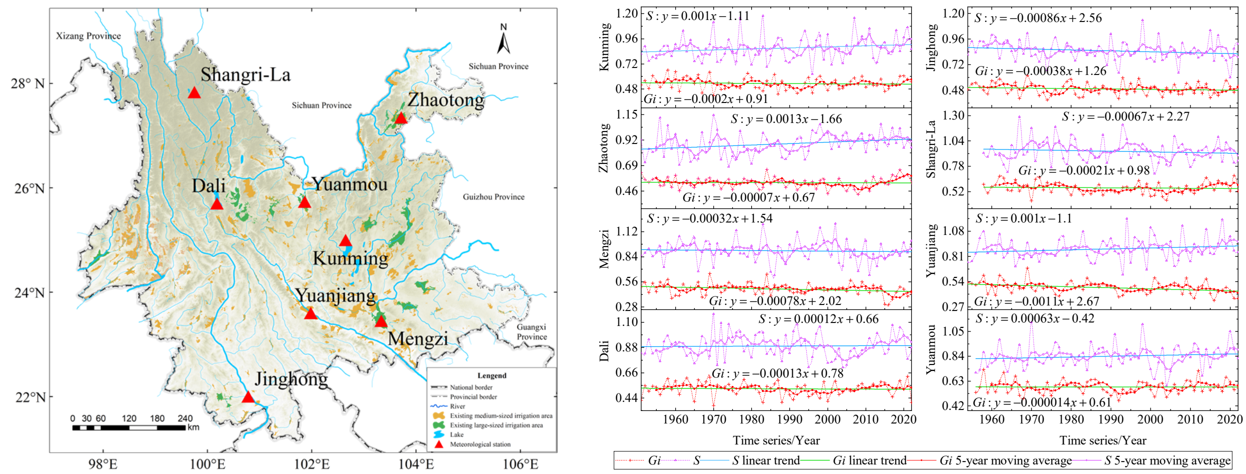

Figure 5. Variations in the Gini coefficient and the asymmetry coefficient (*S*) of precipitation within a year at typical meteorological stations on the Yunnan Plateau from the 1950s to 2022.

The spatial changes in the mean values of the Gini coefficient and the asymmetry coefficient were further analyzed, referring to the monthly precipitation observational data of 70 meteorological stations at various latitudes and longitudes and elevations in the Yunnan Plateau from the 1950s to 2022, as shown in Figure 6. Reflecting the different sources of water vapor for precipitation on the Yunnan Plateau, the data were divided on the basis of two warm and humid airflows: the southeast monsoon in the North Pacific Ocean and the southwest monsoon in the Bay of Bengal in the Indian Ocean. Figure 6a shows that irrespective of whether the stations are in the southeast monsoon area or the southwest monsoon area, the Gini coefficient of monthly precipitation for each meteorological station increases with increasing latitude. The correlation coefficients are as high as 0.849 (significance level, $p < 0.01$) in the southeast monsoon region and 0.715 (significance level, $p < 0.01$) in the southwest monsoon region. Similarly (Figure 6b), the Gini coefficients of monthly precipitation in the southeast monsoon area and the southwest monsoon area increase with increasing elevation; however, the correlation coefficient is 0.432 (significance level, $p < 0.01$), which is less than that associated with the change in latitude. The underlying reason is the geomorphic features of the Yunnan Plateau. The terrain of the Yunnan Plateau gradually declines from the northwest to the southeast. Thus, the southeast and southwest warm and humid airflows flow northward and westward along the southwestern and southeastern valleys, in an area broadly divided by the Yuanjiang-Honghe River and the Ailao Mountains. To the east of the boundary lies the source of the warm and humid airflow current in the North Pacific Ocean, and to the west is the water vapor source in the Bay of Bengal in the Indian Ocean. From the south to the north, the transport distance of both major water vapor sources is lengthened with increasing latitude, and thus the water vapor content available to produce precipitation gradually diminishes [35]. Not only is the total annual precipitation gradually declining, but the uniformity of the water vapor distribution within a year is also getting worse, which leads to the gradual annual increase in the Gini coefficient of precipitation. The uplift of local terrain at the various meteorological stations can promote the formation of precipitation, i.e., the precipitation within a certain range (such as the windward slope and leeward slope of mountains) increases with the increase in elevation [29]. It weakens the imbalance caused by the gradual weakening of water vapor with elevation during the long-distance transport process, which means the Gini coefficient of the overall monthly precipitation during a year on the Yunnan Plateau is not as closely related to the increase in elevation as it is to the increase in latitude. It is also evident from Figure 6a,b that at the same latitude or elevation, the Gini coefficient of precipitation change in the southwest monsoon area is higher than that in the southeast monsoon area. Because the Yunnan Plateau is at the end of the range of influence of the East Asian monsoon in summer, it can be attributed to the fact that the source of the rainfall-producing water vapor is weaker than that of the southwest monsoon region of the Indian Ocean, and, accordingly, the magnitude of its change is much smaller. As show in Figure 6c, irrespective of whether the stations are in the southeast monsoon area or the southwest monsoon area, the Gini coefficient of monthly precipitation shows no clear pattern with change in longitude, indicating that the intra-annual variation in precipitation is not significantly influenced by longitude, which is consistent with the research results of Liu et al. [36].

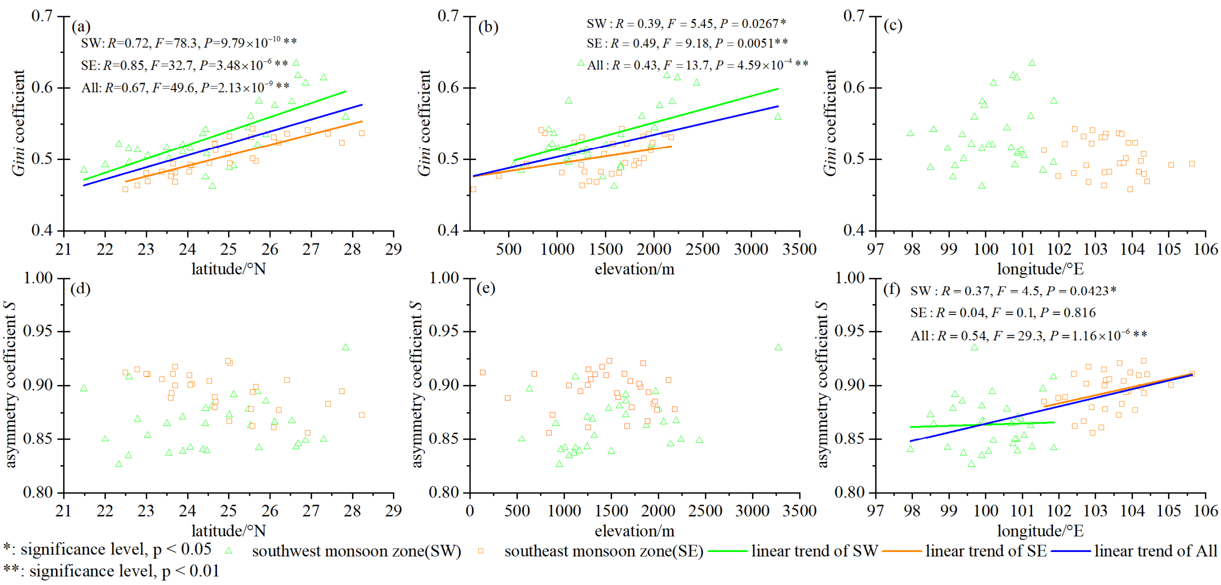

Figure 6. Spatial patterns of the Gini coefficient and the asymmetry coefficient (S) of the annual distribution of precipitation on the Yunnan Plateau ((**a**–**c**) represent the relationship between the Gini coefficient and latitude, elevation, longitude, respectively. (**d**–**f**) represent the relationship between the asymmetry coefficient and latitude, elevation, longitude, respectively).

Particularly in the areas of Gongshan, Weixi, and Fugong in the northwest of the Yunnan Plateau, owing to the transport of Indian Ocean water vapor from the Enmeikai River to the northeast and "the rainfall in spring" [37] flood season during March–April annually, two peaks in precipitation are evident during the year. This feature markedly slows the phenomenon of precipitation depletion in the dry season. The Gini coefficients of the annual monthly precipitation in these places are 21–42% lower than those in other places at the same latitude.

Deqin is the area with the highest elevation and latitude in the northwest of the Yunnan Plateau. The water vapor source of precipitation, whether it be the southeast monsoon or the southwest monsoon, is at the furthest transport distance. The precipitation in this area is only equivalent to that of dry and hot valleys such as the Yangtze River valley, Yuanjiang-Honghe River valley, and other rainless areas. Affected by the Qinghai–Tibet Plateau and the Himalayas, the Gini coefficient of monthly precipitation in the Deqin area is only 0.484.

Other than that derived from water vapor associated with the East Asian monsoon, precipitation in the areas of Weixin, Zhenxiong, and Yanjin in the northeast of the Yunnan Plateau is also caused by the uplifting of evaporation owing to high temperatures and to increased water vapor in the northern Sichuan Basin moving along the Wumeng Mountains. This represents a greater source of precipitation than that in other northern areas of Yunnan Province, and it greatly promotes even distribution of precipitation throughout the year. The Gini coefficients of monthly precipitation are also 11–28% lower than those in other places at the same latitude.

As shown in Figure 6d,e, for different monsoon climate regions, the variations in the monthly precipitation asymmetry coefficient with elevation and latitude are chaotic, indicating irregularity. However, it generally increases from the west to the east with increasing longitude (Figure 6f), where the correlation coefficient reaches 0.541 (significance level, $p < 0.01$), i.e., the asymmetry of the annual distribution of precipitation in the west of the Yunnan Plateau is lower than that in the eastern and central parts. The main reason is that the water vapor source on the Yunnan Plateau in the late rainy season every year follows the basic pattern of that of the East Asian monsoon, i.e., gradual weakening and retreat, followed by the advance of the southwest monsoon. Thus, it affects the trend of the asymmetry of the annual distribution of precipitation in relation to longitude.

3.3. Spatial Distribution Features of Interconnected Lake–River Water Systems

Based on the first national water conservancy survey and the third water resource survey, the actual water supply volume of the interconnected water system in different elevation regions was studied. It should be noted that the water supply volume in this study refers to the actual supply volume of water storage projects with a certain spatiotemporal regulation ability (including large and middle-sized reservoirs, plateau lakes, and comprehensive utilization projects of large and middle-sized hydropower stations) and the interconnected lake–river water systems. The water supply volume is subdivided into five categories for statistical survey: urban, rural, industrial, agricultural irrigation, and ecological. The actual water supply volume of the interconnected water system in different elevation regions is shown in Figure 7a. The water supply of projects between 1200 and 2200 m accounts for 82.9% of the total water supply of all projects. Among them, the water supply of interconnected water systems in the range of 1800–2000 m is largest, accounting for approximately 25.3% of the total water supply of the project, followed by the range of 1600–1800 m, which accounts for approximately 20.1% of the total.

The elevation distribution of water supply of projects is broadly consistent with that of the population in the Yunnan Plateau. In terms of water use, the trends of urban, industrial, and agricultural water supply in different elevation ranges are similar to the trend of the total water supply, which is mainly distributed in the range of 1800–2200 m. Many important cities and towns are located in the two elevation ranges, as are the core economic zones of central Yunnan Province, including Kunming, Qujing, Yuxi, Chuxiong, Dali, Zhaotong, Baoshan, Lincang, and other prefectures (cities). In particular, industrial water use accounts for a large proportion in the elevation range of 1200–1400 m, which encompasses the locations of important smelting and mining industrial parks such as Honghe and Wenshan in southeastern Yunnan Province. The abovementioned elevation range is also the main water-receiving area of the water diversion project of central Yunnan

Province. The rural water supply varies little in the different elevation ranges, which shows that the rural population lives in scattered areas owing to the different living habits and farming practices of the various ethnic groups that live in Yunnan Province. Mountain ethnic groups such as the Miao, Tibetan, and Dulong, mid-mountain ethnic groups such as the Yi and Zhuang, and ethnic groups in the dam area such as the Dai, Hui, and Bai exhibit little difference in terms of distribution at various elevations. The rural water supply in Yunnan Province is mainly from springs or from mountain streams near villages. The ecological water supply, available only within the elevation range of 1600–1800 m, is mainly associated with the Niulan River–Dianchi Lake water diversion project, the Fuxian Lake diversion, and the Xingyun Lake ecological water diversion project.

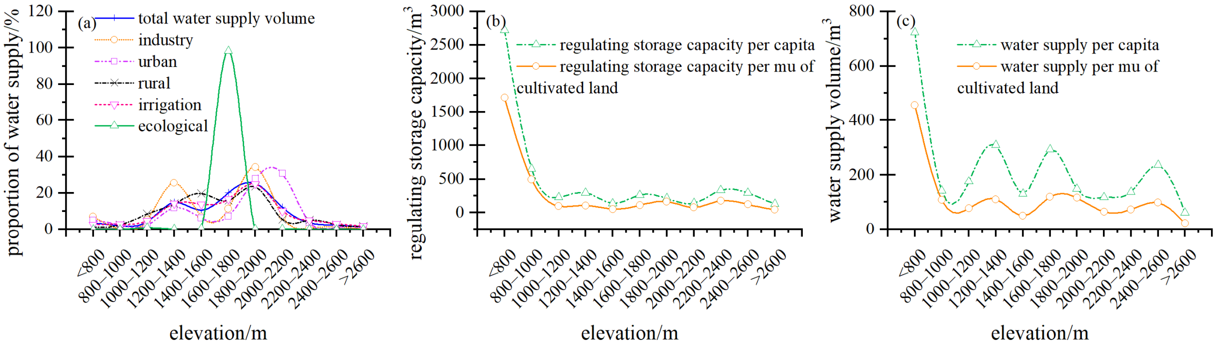

Figure 7. Variations in the proportion of water supply (**a**), the regulating storage capacity per mu of cultivated land and per capita (**b**) and the water supply volume per mu of cultivated land and per capita (**c**) in different elevation ranges on the Yunnan Plateau.

The regulating storage capacity and water supply of lakes and reservoirs in each elevation range and the corresponding population and cultivated land resources were further analyzed. The changes in the water supply and regulating storage capacity per mu of cultivated land and per capita with elevation difference are shown in Figure 7b,c. To determine the value of regulating storage capacity, the regulating storage capacity is used for the reservoir. Lake volume between the highest and lowest operating control water levels is taken for plateau lakes. The storage for comprehensive utilization projects of large and middle-sized hydropower stations is only calculated according to their tasks of supplying water to surrounding industrial and agricultural production. Since 2009, the Yunnan Plateau, especially in central and southeastern areas, has suffered multiple winter–spring–early summer droughts [38]. With ecological and environmental problems such as declining water quality and falling water levels of regional lakes, Fuxian Lake, Yilong Lake, Xingyun Lake, Chenghai Lake, and other lakes have stopped providing useful water to the surrounding areas. Instead, long-distance ecological water projects are planned to replenish the water in these lakes or replace their water supply tasks. It is evident from Figure 7b that the regulating storage capacity per capita and per mu of cultivated land decreases from 2716 and 1713 m^3, respectively, in the hot and dry valley areas below 800 m, to 128–332 and 46–175 m^3, respectively, in areas above the elevation of 1000 m. The per capita water supply (Figure 7c) also drops from 723 to 61–170 m^3 and reaches 236–308 m^3 in three elevation zones: 1200–1400, 1600–1800, and 2400–2600 m. The trend of the water supply per mu of cultivated land (Figure 7c) is similar to that of the regulating storage capacity, which rapidly drops from 456 to 50–120 m^3 in the dry and hot valley areas below the elevation of 800 m. In alpine mountainous areas above the elevation of 2600 m, only cold-resistant, low-yielding dry crops can be grown, and the average water supply per mu is only 20 m^3. These results quantitatively reflect the topographic water shortage on the Yunnan Plateau, with the characteristics of water resources being in lower regions, while people and cultivated land are in higher regions.

3.4. Spatial Distribution Characteristics of Water Consumers

Among all types of water consumers, the average water transmission distance between the water source and the water consumer is sorted as follows (from shortest to longest): rural < irrigation < industrial < urban. It indicates that the water diversion distance to the water consumer is directly proportional to the affordability of water supply costs by consumers. The relative difficulty of water supply is measured by the water transmission distance required to obtain a water supply (unit: per million m^3), as shown in Figure 8c. It is evident that the average water transmission distance for a rural water supply is 5.89 km/million m^3, while the absolute distance is only 2–8 km. It indicates that rural water supply is affected by factors such as water supply costs, and that it is typically supplied from the nearest water supply source, which is the most expensive in terms of transportation. The average water delivery distance is 2.02 km/million m^3 for industrial water supply (Figure 8c), and the absolute value is between 4 and 16 km. The industrial water supply is relatively large within the elevation range of 1200–2200 m (Figure 8a), which means that the water supply distance is longer. The locations of industries are mostly based on mineral resources, topography, transportation, and other factors, whereas water source conditions are not considered as limiting factors. Therefore, in addition to adjusting and utilizing water supplies such as nearby reservoirs and lakes, many industrial water supplies require long distances for self-provided water. Water supply by pumping projects account for a large proportion of industrial water use. The average water transmission distance for the urban water supply is 1.80 km/million m^3 (Figure 8c); however, the absolute distance is generally longer, i.e., 6–23 km. This is attributable both to the large demand for urban water usage and to the difficulty of finding suitable water sources. It is also related to the strong water price affordability of the urban water supply. Especially in the elevation range of 2200–2400 m, the average water transmission distance is 23 km in terms of the urban water supply. Two of the targets of the urban and irrigation water supply are Ninglang and Yongsheng Counties, with a corresponding large reservoir (Guanquaping Reservoir) under construction, for which the water transmission distance is up to 52 km. In terms of agricultural irrigation, the average water transmission distance is 0.70 km/million m^3 (Figure 8c), and the absolute value is 5–11 km. From the perspective of individual projects, few projects have agricultural irrigation water transmission distances of <1 or >10 km. This is because the water supply for agricultural irrigation is relatively concentrated, i.e., it supports irrigation in an area of concentrated cultivated land where the water demand is relatively large. Finding a water source project that can meet the water demand while comprehensively considering factors such as hydrology, geology, and the ecological environment is difficult; thus, the location of its construction is generally not close to the irrigation area. Although the construction of water source projects with agricultural irrigation tasks has national investment subsidies, the cost affordability of agricultural irrigation water supply is still not high, resulting in few long-distance agricultural irrigation projects. Currently, China's fee revenue for agricultural water accounts for only approximately one third of the production cost of the water supply. In most areas, the price level is lower than the operation and maintenance costs of the irrigation facilities. The inability and unwillingness of water users to pay for a water supply have become constraints in the implementation of policies related to the reform of agricultural water pricing [39]. The average distance for ecological water replenishment is only 0.296 km/million m^3, but the absolute water diversion distance is 17–116 km.

From Figure 8b, it can be observed that there are differences in the difficulty of water supply to water consumers in different elevation ranges. In the elevation ranges of 2000–2400 m, 2200–2400 m, and 1600–1800 m, the difficulty of water supply ranks from difficult to easy in the following order: rural > industrial > urban > irrigation > ecological. In other elevation ranges, except for the elevations of 800–100 m and >2600 m, in most areas, the difficulty of water supply is sorted as follows (from difficult to easy): rural > urban, industrial > irrigation > ecological. Only the ranking of urban and industrial sectors differs.

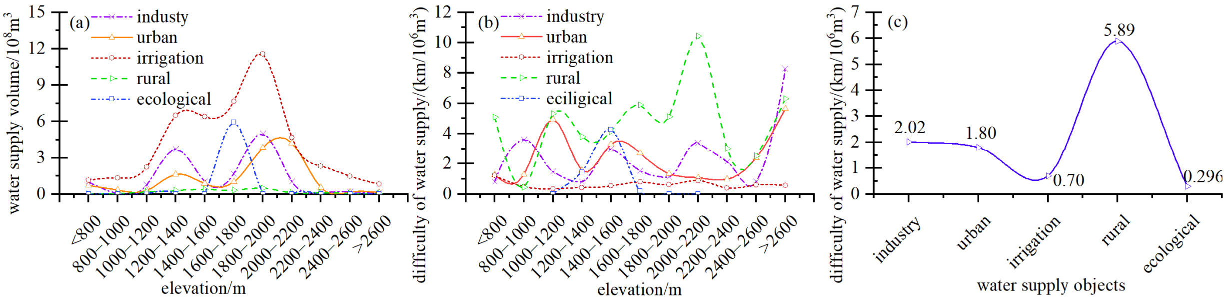

Figure 8. Variations in volume (**a**) and difficulty (**b**) of water supply in different elevation ranges, and variations in difficulty of water supply (**c**) in different water consumers.

As the difficulty of implementing new water source projects gradually increases, and the affordability of water supply costs gradually increases, it is expected that the water transmission distance to each water supply object will also show a trend of increase in the future. The Yunnan Plateau is dominated by large-scale agriculture; however, the steep mountains and canyons pose huge obstacles to the livelihoods and productivity of the population. Particularly for those cities and towns that are developing secondary and tertiary industries, topography has become the primary factor of focus. The nine plateau lakes and the surrounding areas, together with the valleys and basins, have become key areas for the development of cities and industrial parks. However, problems such as water shortages, low per capita arable land, deterioration of river and lake water environments, and the fragile water ecology have become increasingly prominent, resulting in changes in water resource allocation plans for the development of cities and industrial parks and the water supply guarantee measured from adjacent drainage to long-distance cross-drainage water transport. For example, the planned and constructed Central Yunnan Water Diversion Project [40] is the core axis of the regional water network on the Yunnan Plateau, connecting the main stream of the Yangtze River with 36 counties (cities, districts) in six prefectures (cities) including Dali, Lijiang, Chuxiong, Kunming, Yuxi, and Honghe. Four major water systems, i.e., the Yangtze River River, Lancang River, Yuanjiang-Honghe River, and Pearl River, are connected by the Central Yunnan Water Diversion Project through the interconnection of 108 reservoirs and 111 water plants with the main canal. This system mainly ensures the safety of the water supply for cities, industries, key irrigation areas, and plateau lakes. Large reservoirs such as Deze, Songhuaba, Yunlong, Qingshanzui, Chaishitan, Chemabi, Heitanhe, Haishao, Xiaoshimen, and other large reservoirs represent the primary nodes of the water network in central Yunnan Province, forming connections between the main streams and the tributaries. The network connects rivers with counties and towns, realizes the regulation of abundance and dryness, supports regional mutual assistance, improves the river water ecological environment, and integrates the Yangtze River Economic Belt, the Western Economic Belt, and the national Double T-shaped water network into an organic entity [13].

According to the distribution of differences in water delivery elevation, the changing patterns of water supply volume of various water consumers were classified statistically, as shown in Figure 9a. It is evident from Figure 8b that, irrespective of whether lifting or natural flow water supply, the water supply for agricultural irrigation, rural daily life, and industrial production based on the built interconnected water system is mainly concentrated within the elevation difference of 100 m, accounting for 67.5–72.2% of the total industrial water supply volume. The urban and ecological water supply is relatively concentrated in several elevation ranges, e.g., <50, 150–200, 200–250, and >300 m. Because of long-term water shortages in urban areas and the vulnerability of the water ecology of plateau lakes such as Dianchi Lake, the population is forced to bear greater water supply costs to provide water for urban life and ecological restoration of lakes. From the perspective of water supply objects, the elevation difference of the rural and agricultural irrigation water supply is generally smaller than that of the urban and industrial water supply. This can be attributed to the water transmission distance, because the distance between the objects of rural and agricultural irrigation water supply and the water source is relatively small, and the elevation difference is also relatively small. The water supply efficiency for industrial/agricultural production, urban, and rural areas is at its maximum value for the elevation differences of <50 and 50–100 m, except for the abnormal phenomenon of the ecological water replenishment affected by the Niulan River–Dianchi Lake water diversion project, which has a much larger water supply than other similar projects. Overall, the water supply efficiency gradually diminishes as the elevation difference of water delivery increases. For example, the representative agricultural irrigation water supply accounts for 56.0% of the total water supply, and the water supply efficiency (Figure 8c) gradually reduces from 1.97 million m^3/km to 0.66–0.96 million m^3/km. Overall, the average water supply efficiency of the interconnected water systems in the Yunnan Plateau is 0.83 million m^3/km, although it varies among the various industries (as shown in Figure 9b). The ecological water supply efficiency is highest, i.e., 3.38 million m^3/km, followed by that of agricultural irrigation at 1.43 million m^3/km. It is broadly the same for the industrial and urban water supply, i.e., 0.5–0.55 million m^3/km. Rural areas have the lowest water supply efficiency, i.e., only 170,000 m^3/km (Figure 9c).

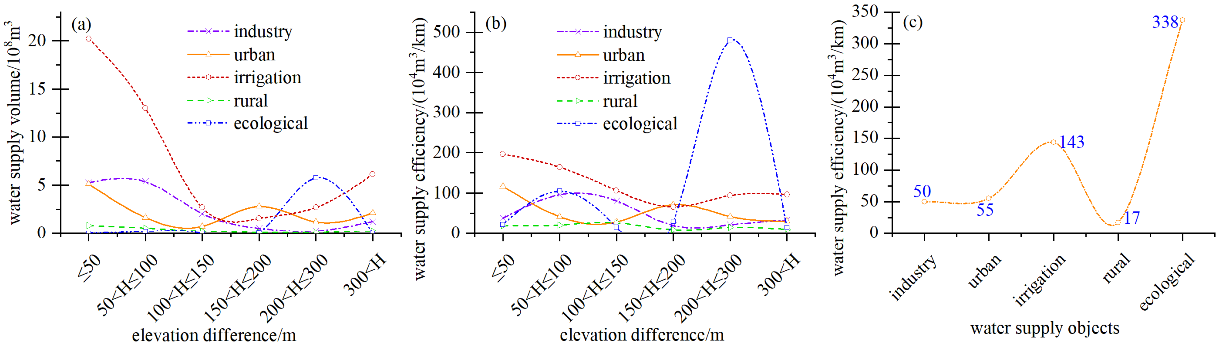

Figure 9. Variations in volume (**a**) and efficiency (**b**) of water supply in various ranges of elevation difference, and the water supply efficiency of different water consumers (**c**).

4. Spatial Matching and Equilibrium

4.1. Matching Analysis of Human–Land–Water–Heat in Various Elevation Ranges

Based on the aforementioned data, spatial overlay analysis was used to extract the distribution characteristics of basic information such as population, cultivated land, heat, precipitation, water resources, regulating storage capacity, water supply volume, and other factors in each elevation range, as shown in Figure 10. Temperature and precipitation generally show a gradually trend of decline with increasing elevation, as shown in Figure 10a. It is evident from Figure 10b that the cultivated land resources on the Yunnan Plateau are concentrated in the elevation range of 1400–2200 m, while the water resources are mainly distributed in three elevation ranges: 1200–1600, 1800–2000, and >2600 m. There is certain synchronicity between cultivated land, light, and heat. The indicators reflecting human activities such as the population, regulating storage capacity, and water supply volume are mainly concentrated in the elevation range of 1800–2000 m, e.g., Kunming, Qujing, Yuxi, and other cities, corresponding to industrial parks, plateau lake basins, and valley dam areas. The overall level of socioeconomic development is high in these areas. Affected by the transit water resources of the main rivers, the regulating storage capacity and water supply per capita and per mu of cultivated land show marked downward trends with increases in the dry and hot valley areas at elevations of <800 m. Conversely, most of the areas at an elevation of 2400–2600 m are characterized by steep mountains and canyons with harsh natural conditions. The proportion of light, heat, cultivated land resources, and indicators reflecting human activities is approximately 2%, which is even lower than that of alpine mountainous areas at elevations of >2600 m.

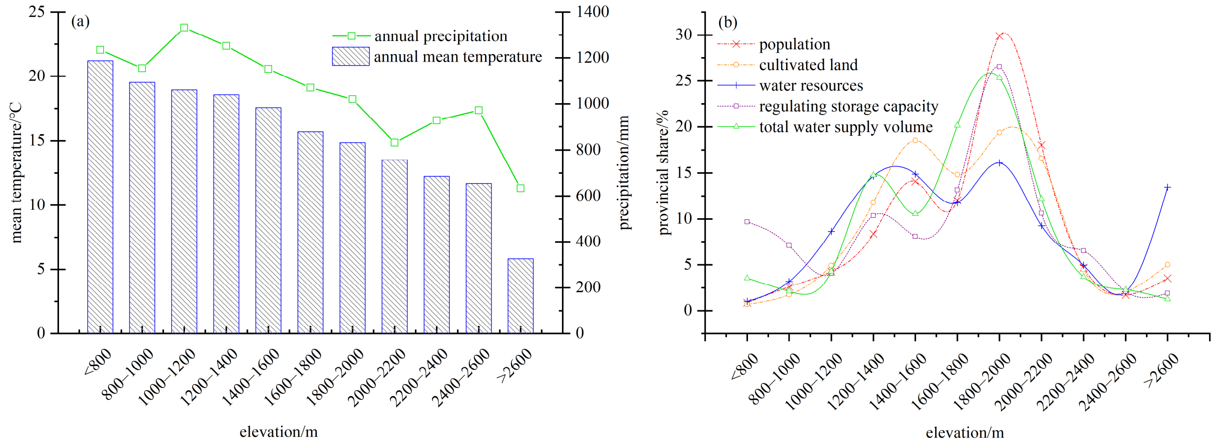

Figure 10. Spatial distributions of annual precipitation and mean temperature (**a**), and provincial share of the population, cultivated land, water resources, regulating storage capacity, and total water supply volume (**b**) on the Yunnan Plateau.

The imbalance index was adapted to analyze the matching characteristics of related factors of the human–land–water–heat system in various elevation ranges on the Yunnan Plateau, as presented in Table 2. The results show that the mismatch between population and various factors such as land, temperature, precipitation, cultivated land, water resources, and water supply is markedly higher than that of other factor combinations. The imbalance between population distribution and light-heat-land resources is the most serious, followed by the mismatch between heat (temperature) and water supply, which is reflected in the hot and dry valley areas. The light and heat resources are abundant, whereas the water resources are in lower regions while people and cultivated land are in higher regions, meaning that the water supply is seriously inadequate. From the perspective of resource utilization, humans still have to satisfy their own needs of development through resource allocation, even when factor endowments and their matching characteristics are poor (especially the two factors of population and water). It improves the balance between the population and the land, while increasing the cost of water supply security accordingly, further confirming the importance of promoting coordinated development of the human–land–water–heat system [30].

Table 2. Imbalance index of the human–land–water–heat system on the Yunnan Plateau.

Factor Indicator	Land	Population	Cultivated Land	Temperature	Water Resources	Precipitation	Water Supply
Land	0.0000	0.0437	0.0257	0.0546	0.0501	0.0131	0.0491
Population	--	0.0000	0.0316	0.0749	0.0744	0.0523	0.0597
Cultivated land	--	--	0.0000	0.0618	0.0610	0.0343	0.0518
Temperature	--	--	--	0.0000	0.0104	0.0528	0.0529
Water resources	--	--	--	--	0.0000	0.0477	0.0506
Precipitation	--	--	--	--	--	0.0000	0.0518
Water supply	--	--	--	--	--	--	0.0000

Taking water supply (water), average temperature (heat), total population (people), and cultivated land (land) as representative indicators, the single matching distance of each indicator in different elevation ranges of the Yunnan Plateau was calculated. The matching distance (absolute value) was summed to obtain the comprehensive matching distance of each factor for comparison with the others. In this way, a comprehensive matching distance of various factors can be achieved, as shown in Figure 11a. The results show that the mismatching order of the human–land–water–heat system in different elevation ranges is as follows: 1800–2000 m > 2000–2200 m > 1400–1600 m > 800 m > other areas, where the minimum value is in the elevation range of 2200–2400 m. The comprehensive matching distances of the top four areas are 1.643, 1.076, 1.017, and 0.902, respectively, and the minimum value is only 0.418. This is mainly because of the large population in the elevation range of 1800–2000 m and the rich heat resources in the dry and hot valleys at an elevation of <800 m, which are mismatched from the other factors. As shown in Figure 11b, except for the water supply indicator, the mismatching order of the other three indicators in different elevation ranges is consistent with the comprehensive mismatch distance indicator. The water supply indicator also has a different ranking only in the elevation ranges of <800 m, 800–1000 m, and 1000–1000 m.

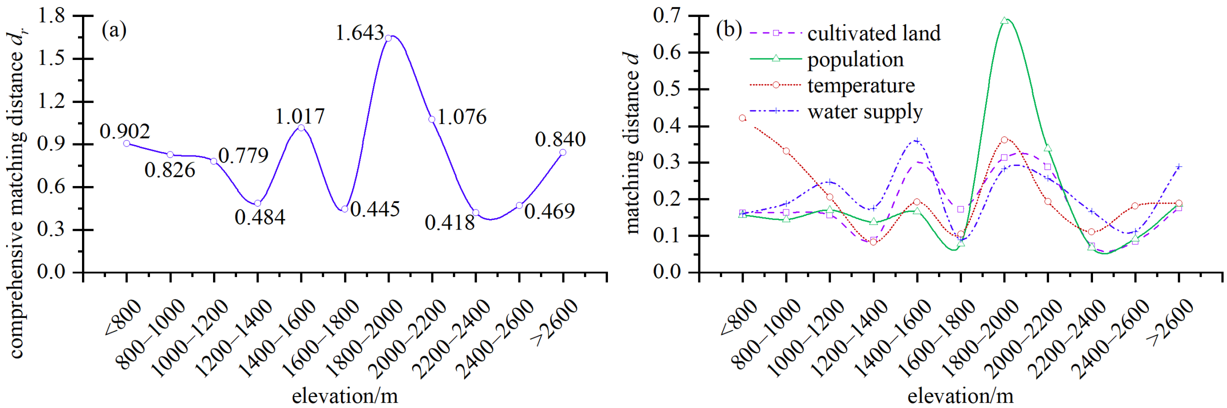

Figure 11. Variations in comprehensive matching distance d_r (**a**) and matching distance d (**b**) in different elevation ranges on the Yunnan Plateau.

If further refined to interannual and intra-annual scales, because factors such as light, heat, and cultivated land are relatively stable, the matching of the human–land–water–heat system in different periods of abundant–dry years or wet–dry seasons also fluctuates, while water resources vary greatly interannually and are unevenly distributed intra-annually. In mountainous areas with abundant water resources in elevation ranges of 1200–1600, 1800–2000, and >2600 m, there are serious seasonal drought and water shortage problems. Tina's [41] and Jin et al.'s [42] research also indicates that there is winter and spring drought in the central and northwestern parts of Yunnan Province. The elevation in the central and northwestern parts of Yunnan Province is basically within the above-mentioned elevation range. For hot and dry valleys at an elevation of <800 m and alpine valleys in the elevation range of 2400–2600 m with poor background water resources, the matching of the human–land–water–heat system is even worse in dry years and seasons. Hence, the contradiction between demand and supply of water resources is more prominent owing to engineering-related water shortages.

4.2. Analysis of the Equilibrium of the Human–Land–Water–Heat System

Table 3 lists the Gini coefficient and the asymmetry coefficient of each factor of the human–land–water–heat system in different elevation ranges. Obviously, the equilibrium of temperature and precipitation in the various elevation ranges is the best, which is determined by natural geographical conditions such as low-latitude plateaus and longitudinal ridges and valleys. The spatial equilibrium of land and water resources is second best, with a Gini coefficient of 0.330. The equilibrium of the total population distribution, which reflects human activities, is the worst. The main reason is that the basins and valley dam areas of the Yunnan Plateau account for only approximately 22% of the total land area. However, the population, cultivated land, and cities of these areas are all concentrated, exacerbating the imbalance. The Gini coefficient of the regulating storage capacity that can regulate runoff and satisfy the water demands for human survival and development reaches 0.359, exceeding that of water resources, which supports the socioeconomic development of the Yunnan Plateau. Additionally, Table 3 also reveals that the Gini coefficients are constantly increasing for different water cycle processes on the Yunnan Plateau, from precipitation, to surface runoff (water resources), to regulating storage capacity and supply. Owing to the combined effects of the underlying surface conditions (natural environment) and connectivity projects of lakes and reservoirs, the water demand for human survival and development has become increasingly heterogenous, and its asymmetry has weakened while the concentration has gradually increased.

Table 3. Equilibrium evaluation of the human–land–water–heat system in different elevation ranges on the Yunnan Plateau.

Factor	The Gini Coefficient Gi	The Asymmetry Coefficient S	Concentration Degree D_{pc}
Precipitation	0.100	0.994	0.108
Total population	0.484	0.938	0.547
Land area	0.330	0.726	0.316
Cultivated land	0.421	0.860	0.496
Average temperature	0.151	0.923	0.139
Water resources	0.330	0.785	0.290
Regulating storage capacity	0.359	0.961	0.330

The asymmetry coefficient reflects whether patterns of symmetry exist in the changes of factors in the different elevation ranges. As can be seen from Table 3, the asymmetry coefficient of each factor is in the range of 0.726–0.994. The degree of spatial asymmetry of land and water resources is low, while that of precipitation and regulating storage capacity is the highest, revealing that both natural and artificial interventions have substantially affected the spatial distribution of water resources to adapt to the requirements of the uneven spatial distribution of the population. The concentration degree reflects the spatial variation of each factor from another aspect. The concentration degrees of the total population and cultivated land, shown in Table 4, are in the range of 0.496–0.547, while those of the other elements are only in the range of 0.108–0.330, which is not remarkable.

Table 4. Balance evaluation of the water supply in different elevation ranges and elevation differences on the Yunnan Plateau.

Type	Water User	The Gini Coefficient Gi	The Asymmetry Coefficient S	Concentration Degree D_{pc}
Different elevation regions	Industry	0.576	1.111	0.514
	Urban	0.541	1.103	0.531
	Rural	0.456	0.929	0.532
	Agricultural irrigation	0.424	0.900	0.500
	Ecological	0.903	1.017	0.988
	Total water supply	0.462	0.867	0.531
Different elevation differences	Industry	0.459	1.010	0.583
	Urban	0.335	1.164	0.247
	Rural	0.460	1.052	0.567
	Agricultural irrigation	0.412	1.121	0.509
	Ecological	0.808	1.044	0.918
	Total water supply	0.358	1.181	0.415

The equilibrium of the water supply of various industries in different elevation ranges and different elevation differences was further analyzed, which represents the spatial balance of the light, heat, and land resource conditions and the economic affordability of the water supply, as presented in Table 4. Most of the ecological water supply volume comes from the Niulan River–Dianchi Lake water diversion project, which has the highest Gini coefficient and concentration degree and is extremely uneven in space. In comparison, the Gini coefficients of the water supply for various industries and the total water supply in different elevation ranges on the Yunnan Plateau are greater than for those in regions with different elevation differences. It indicates that the spatial imbalance is more prominent when divided by different elevation ranges. The Gini coefficient of industrial water supply is the highest, reaching 0.576, among the various water use industries and different elevation ranges. The lowest Gini coefficient (0.424) is for agricultural irrigation, which is the result of water supplied by the many lakes and reservoirs. Artificial regulation overcomes the seasonal changes in agricultural irrigation water and weakens its spatial imbalance.

The asymmetry of the total water supply in different elevation ranges is weaker than that in different elevation differences. The changing trends among the various water users, such as urban, rural life, and agricultural irrigation, are consistent with those of the total water supply. The asymmetry of industrial and ecological water supply is more prominent in different elevation ranges.

The concentration degree of the total water supply is more notable in the spatial changes in different elevation ranges than in different elevation differences. The concentration degree trends of the urban and ecological water supply are consistent with that of the total water supply, whereas the trends of the industrial, agricultural irrigation, and rural water supply are higher in regions with different elevation differences.

4.3. Evaluation of Water Resource Capacity

Water resource capacity is a comprehensive indicator used to evaluate the coordinated development between water resources, the economy, society, and the ecological environment. The evaluation of water resource capacity uses comprehensive evaluation methods to determine the comprehensive status and differences of water resources capacity in each region based on an evaluation index system. Considering the importance of an evaluation of water resource capacity complying with the principles of objectivity, systematicness, and accessibility, six evaluation indicators were constructed (see Table 5 for details). The classification of each indicator was determined comprehensively by referring to existing research and the actual situation in the Yunnan Plateau.

Table 5. Evaluation indicators and grades.

Evaluation Indicator	Underload	Critical State	Overload	Heavily Overload
Per capita water resources/(m^3/people)	≥3000	2000–3000	1000–2000	<1000
Per capita regulating storage capacity/(m^3/people)	≥267	133–267	111–133	<111
Per capita water supply/(m^3/people)	≥400	200–400	167–200	<167
Per mu water resources of cultivated land/(m^3/mu)	≥1213	607–1213	506–607	<506
Per mu regulating storage capacity of cultivated land/(m^3/mu)	≥224	112–224	93–112	<93
Per mu water supply of cultivated land/(m^3/mu)	≥336	168–336	140–168	<140
Projection value Z_j (Threshold for comprehensive evaluation)	≥1212	808–1212	404–808	<404

To avoid the shortcomings of traditional water resource capacity evaluation methods, e.g., discrete levels, strong subjectivity, and unintuitive results [43], a projection–pursuit evaluation model based on a genetic algorithm [44,45] was used to evaluate the water resources in different elevation ranges. The genetic projection–pursuit model needs a large number of data samples for learning and training. The mathematical model will be inaccurate if too few index samples are used for the evaluation. Given that it is difficult to obtain real data for water resource capacity evaluation, to make the algorithm convincing, the projection curves are dense. The boundary values of each grade interval adopted for water resource capacity evaluation are used as sample values (Table 5). In the ranges of the values at each level, 80 indicator samples are uniformly and randomly generated, forming a total of 320 points, including 80 randomly generated sample points within the "underload" range as samples to find the optimize projection vector. The genetic algorithm was used to optimize the projection index function, the maximum projection function was 351.4673, while the optimal projection direction was $\vec{a_{opt}} = (0.4040, 0.5275, 0.4492, 0.5190, 0.1758)$. In terms of the vector element values, the per capita regulating storage capacity, per mu regulating storage capacity of cultivated land, per mu water resources of cultivated land, and per capita water resources all have relatively large impacts on the capacity of water resources. A grade evaluation method of the projection value was established based on each level and its corresponding projection value. The projection value of the sample to be evaluated was calculated, and the grade of the evaluation sample was obtained using the grade evaluation method of the projection value. The grades of water resource capacity based on the projected values are shown in Table 5.

Projected values Z_j of water resource capacity at different elevations were calculated, as shown in Figure 12. Generally, benefiting from the continuous improvement of the unified water resource allocation system and the patterns of river–lake–reservoir system interconnection projects, water resources at different elevations in the Yunnan Plateau are not overloaded. However, there are obvious differences in the potentials of water resource capacity between different elevations. Among them, the area with the greatest potential for water resource capacity is at an elevation of >2600 m. The region with land at this elevation is mainly located in the area of confluence of the three rivers in the northwestern Yunnan Plateau, with rich water resources, a sparse population, and cultivated land. The area with the second-best potential is the region with an elevation of <800 m, with abundant rainfall and water resources, which is mainly located in Banna, Dehong, and other areas in the southwestern Yunnan Plateau. The areas with the smallest water resource capacity potential are in the areas with elevations of 1800–2000 and 2000–2200 m. The area with land at this elevation is in the central parts of the Yunnan Plateau and other major urban areas. The population and cultivated land of such areas are the densest, accounting for 48% and 36%, respectively, of the provincial total. However, the natural water resource endowment is poor in such areas and the water resources account for only 25% of the provincial total. The projected value of its water resource capacity is close to the critical state threshold, indicating that the water resource capacity potential is small. Other areas with lower water resource capacity potential are concentrated in the elevation ranges of 1400–1600 and 1600–1800 m, including Wenshan, Honghe, and Yuxi. The area has reasonable socioeconomic development with a large population and cultivated land, but precipitation is relatively less, which is the reason for the small potential of the water resource capacity. Zhang's [46] study also found that, in most areas of central Yunnan and eastern Yunnan, the overall water resource carrying capacity is low, while in northwestern Yunnan, represented by the Nujiang River, the water resource carrying capacity is generally better.

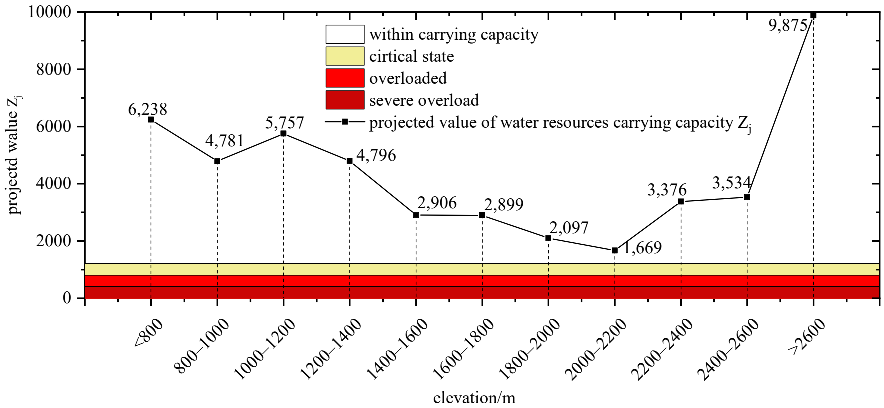

Figure 12. Water resource capacity evaluation in different elevation ranges on the Yunnan Plateau.

5. Conclusions

In view of the significant variations in natural and social elements with elevation on the Yunnan Plateau, the distribution characteristics, water resource capacity, and matching characteristics of human-land-water-heat elements within different elevation ranges are analyzed in this study. The source material comprised hydrometeorology data, Chinese high-resolution satellite remote sensing imagery, the first national water conservancy census, the third water resource survey, the third national land survey, the optimal allocation of water resource systems, and the plan of the interconnected river–lake–reservoir water network system. Geographical spatial overlay analysis was used to extract data such as population, cultivated land, precipitation, water resources, water consumption of industries, regulating storage capacity, temperature, water supply efficiency, and water transmission distance in different elevation ranges, and the following conclusions were derived.

(1) The Gini coefficient of monthly precipitation on the Yunnan Plateau from the 1950s to 2022 increases with increasing latitude. The correlation coefficients of the southeastern Pacific monsoon region and the southwest monsoon region of the Indian Ocean reach 0.849 and 0.715, respectively. The change in the Gini coefficient of precipitation with elevation is notably less correlated than that with latitude. The northwestern and northeastern Yunnan Plateau are locally affected by two water vapor sources: the Indian monsoon and evaporation in the Sichuan Basin. The occurrence of "the rainfall in spring" greatly improves the uneven distribution of precipitation within a year. The Gini coefficient of monthly precipitation in the northwest and northeast Yunnan Plateau is 21–42% and 11–28% lower, respectively, than that in other areas at the same latitude. The asymmetry coefficient mainly increases from the west to the east with the change in longitude, and the correlation coefficient is 0.541. It occurs because the water vapor source in the mid–late rainy season is gradually weakened and retreats with the East Asian monsoon and is then replaced by the advance of the southwest monsoon toward the northeast.

(2) Cultivated land resources are concentrated in the elevation range of 1400–1600, whereas water resources are mainly distributed in three elevation ranges: 1200–1600, 1800–2000, and >2600 m. The indicators reflecting human activities, such as the population, regulating storage capacity, and water supply volume, are mainly concentrated in the elevation range of 1800–2000 m. The natural resources are not matched with the economic and social layout in terms of elevation. The average water transmission distance in different elevation ranges in order from small to large is rural, agricultural irrigation, industrial, and urban, which is directly proportional to the affordability of water supply costs by consumers. In the past, the water supply of various industries was mainly driven by gravity flow, and water withdrawal occurred over an elevation difference of 100 m. In the future, there will be urgent need for the restoration of the aquatic ecological environment of plateau lakes and comprehensive utilization of large and middle-sized hydropower stations. Long-distance water pumping projects with elevation differences of between 200 and 300 m are becoming more common.

(3) The comprehensive matching distance revealed that the mismatching order of the human–land–water–heat system in different elevation ranges is sorted as follows: 1800–2000 m > 2000–2200 m > 1400–1600 m > 800 m > other areas. The minimum value is in the elevation range of 2200–2400 m. The matching of the human–land–water–heat system also fluctuates in different wet–dry years and seasons, resulting in serious seasonal drought problems in mountainous areas at elevations of 1200–1600, 1800–2000, and >2600 m. For hot and dry valleys at an elevation of <800 m and alpine valleys in the elevation range of 2400–2600 m with poor background water resources, the matching of the human–land–water–heat system is even worse in dry years and seasons. Hence, the contradiction between demand and supply of water resources is more prominent owing to engineering-related water shortages.

(4) The Gini coefficient of each factor of the human–land–water–heat system is sorted as follows: population > cultivated > regulating storage capacity > land and water resources > temperature > precipitation. This reveals that the spatial balance of temperature and precipitation in different elevation regions is relatively best, followed by that of land and water resources, and the balance of the population distribution is the worst. The Gini coefficient is constantly increasing for different water cycle processes on the Yunnan Plateau,

from precipitation, to surface runoff (water resources), to regulating storage capacity for water supply. In terms of the Gini coefficients of different water users, the Gini coefficient of the industrial water supply is the highest, reaching 0.576, while that of agricultural irrigation is the lowest (0.424). Artificial regulation offsets the seasonal water demand for agricultural irrigation through use of water stored in lakes and reservoirs, weakening its spatial imbalance.

(5) Evaluation of the water resource capacity reveals that continuous improvement of the unified water resource allocation system and the patterns of the interconnected water system of the interconnected river–lake–reservoir water network system projects mean that water resources in different elevation ranges in the Yunnan Plateau are not overloaded. However, the potential of the water resource capacity varies markedly between different elevation ranges. The potential of water resources capacity is sorted as follows: 2000–2200 m < 1800–2000 m < 1600–8000 m < 1400–1600 m < other areas. The largest area is at an elevation of >2600 m, which is in the region where confluence of the three rivers occurs in the northwestern Yunnan Plateau, with rich water resources, a sparse population, and cultivated land. The region with the second-largest capacity is at an elevation of <800 m, which includes Banna, Dehong, and other areas in the southwest of the Yunnan Plateau. The region has abundant precipitation and water resources. The areas with the smallest water resource capacity potential are in the elevation ranges of 1800–2000 and 2000–2200 m. These areas mainly include the central Yunnan Plateau and other major urban areas, with the densest population and cultivated land and the poorest natural resource endowment. The projected value of water resource capacity in these areas is close to the critical state threshold.

In summary, this article analyzes the distribution characteristics, matching characteristics, and balance of the human–land–water–heat system on the Yunnan Plateau from a new perspective. However, the human–land–water–heat system on the Yunnan Plateau is complex with significant regional differences and intertwined influencing factors that interact with each other. Its matching and balance exhibit many uncertainties and deeper change characteristics, necessitating further consideration of the introduction of new indicators and refined units for in-depth research. Additionally, the relationship between the temporal changes of the human–land–water–heat system and climate change also deserves attention.

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