

TEMPORAL AND SPATIAL EVALUATION OF ECOLOGICAL SECURITY IN THE DRY AND HOT VALLEY AREA OF THE JINSHA RIVER IN YUNNAN PROVINCE, CHINA, FROM 2000 TO 2020

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Abstract. The Jinsha river valley in Yunnan Province is a typical dry and hot area in China. By introducing landscape pattern indices, we conducted a spatio-temporal evaluation of regional ecological security from 2000 to 2020 and quantitatively analyzed the influence of its driving factors. Those results showed that: (1) the indices that could characterized the landscape pattern were Division (DIVISION), Mean of Contiguity (CONTIG_MN), Patch Density (PD), and Area Weighted Mean of Shape (SHAPE_AM). (2) From 2000 to 2020, the regional ecological security resulted from cooperative effects of landscape pattern indices and normalized difference vegetation index (NDVI). In 2000, in addition, ecological security resulted from the effects of water quality indices. (3) In 2000, most areas in Yuanmou, Wuding County, and Dongchuan District were in an unsafe or relatively unsafe state. In 2020, some areas of Yuanmou, Wuding, and Yongsheng County were in an unsafe or relatively unsafe state. (4) From 2000 to 2020, the impact of human activity intensity gradually strengthened. Compared with social and economic driving factors, natural driving factors like rainfall and altitude have a greater impact. Our findings can provide theoretical basis and scientific guidance to formulate regional ecological development strategies.

Keywords: *landscape pattern indices, Jinsha River, area of dry and hot valley, ecological security, driving factors*

Introduction

A dry-hot valley is a local special geographical landscape and climate type and belongs to a valley savannah climate. The Jinsha River Basin (Yunnan section) is mainly located in the northwest, north, and northeast of Yunnan Province, and includes 26 counties (cities or districts) in six cities of Lijiang, Dali, Chuxiong, Zhaotong, Kunming, and Qujing. The area of dry and hot valley of Jinsha River is the middle reaches of the Jinsha River, a typical dry and hot area in China and known as an “inland tropical enclave” (Xiong et al., 2005). Under the influence of special terrain type and the southwestern monsoon, the warm moist flowing from the Bay of Bengal is blocked and formed a typical dry and hot valley climate (He et al., 2016). The dry and hot valley area of the Jinsha River is more than 800 km and runs east-west through the northern Yunnan Plateau. In this area the valley is deep, ridges and peaks raise one after the other, and the natural conditions are complex. Due to the

harsh climate and soil conditions, coupled with long-term human disturbance, the ecosystem in this area is very fragile; water and soil loss is serious (Jiang et al., 2015; Xu et al., 2023).

The dry and hot valley area of the Jinsha River is located in the main stream of the upper reaches of the Yangtze River. Its ecological quality relates not only to the regional ecological security, but also has great significance to the ecological and environmental protection of the entire Yangtze River Basin. Previous studies on vegetation, hydrology, soil, and geological disasters in this area illustrated significant ecological security risks (Liu et al., 2021; Ou et al., 2018; Pan et al., 2004; Rong et al., 2006; Wang et al., 2012; Yang et al., 2021, 2002). The lack of an effective quantitative evaluation for comprehensive ecological security to reveal the ecological security status, trends, and driving factors makes providing scientific guidance and a theoretical basis for regional ecological environment regulation difficult. This study reveals changes and factors that influence ecological security in this area by evaluating and analyzing the ecological security state. The research results provide a theoretical basis and scientific guidance for the state to master the ecological security status, develop ecological security, implement regional ecological regulation measures, and formulate a regional ecological development strategy. It also provides a technical reference for the research and evaluation of complex mountainous environments in Southwestern China.

Materials and methodology

Study area

Located in northern Yunnan Province, China, the study area includes parts of six cities—Lijiang, Dali, Chuxiong, Kunming, Qujing, and Zhaotong, and 17 counties (Heqing County, Yongsheng County, Huaping County, Binchuan County, Xiangyun County, Dayao County, Yongren County, Yao'an County, Mouding County, Yuanmou County, Lufeng County, Wuding County, Luquan County, Dongchuan District, Huize County, Qiaojia County, and Ludian County). The study area is approximately 23,317 km², and accounts for ~5.92% of the total area of Yunnan Province. The maximum relative height difference is ~3812 m. The land use is mainly forest land. The average annual precipitation is 700–1000 mm, but precipitation in some dry and hot river valleys is < 600 mm. There are many people (about 112 people per km²) and more cultivated land (24.03% in land area) in this area, and most of them are slope cultivated lands with high land reclamation indices. The secondary natural forest formed by excessive felling of primitive natural forest had been seriously degraded. Forest coverage, soil conservation and water storage capacity are low. The area of water and soil loss is 2.4339 million hectares, with a loss rate of 32%, which is the most serious area of water and soil loss in Yunnan. The rocky desertification land covers an area of 803,800 ha, and accounts for 26.4% of the total rocky desertification land in Yunnan. The dry and hot valley has high evaporation intensity, and the long drought caused an acute shortage of ecological water (*Fig. 1*).

Data sources and processing

Data sources include land cover data, land use data, meteorological monitoring data, socio-economic statistics, and environmental quality data from 2000 to 2020 (*Table 1*).

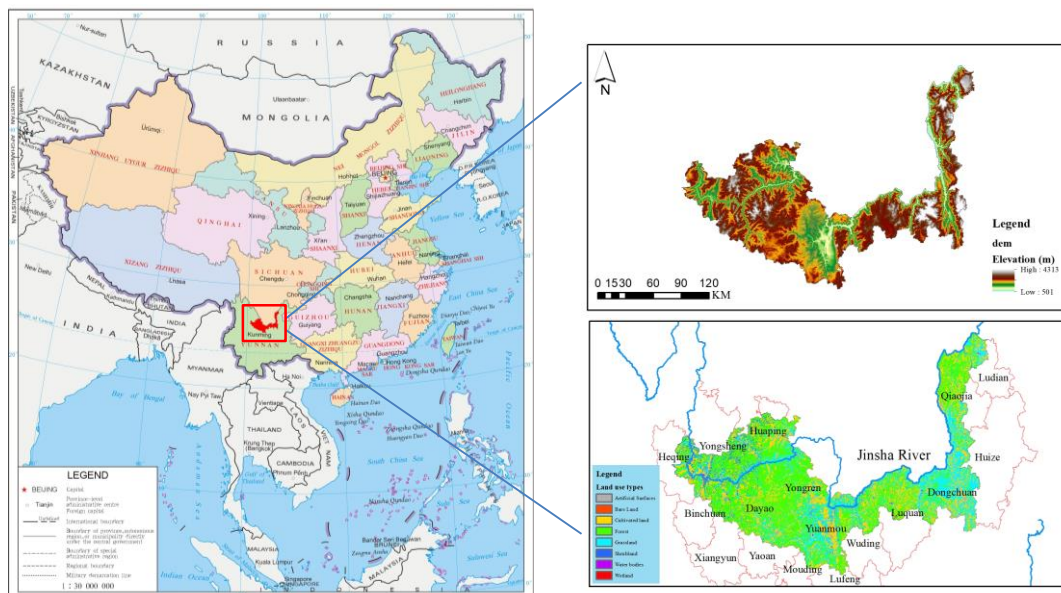


Figure 1. Location of the dry and hot valley area of the Jinsha River in Yunnan Province, China

Based on the land use data set, this study used the evaluation scheme of a comprehensive ecosystem human disturbance index to develop the intensity data of human activities. When the land use type was unused land, permanent glacier, or snow, the coefficient was 0. When the land use type was forest, grassland, or water areas, the coefficient was 0.25. When the land use was paddy field and dry land, the coefficient was 0.5. When land use was urban, rural residential area, industrial or mining land, transportation land or other construction land, the coefficient was 1.

The modified universal soil loss equation RUSLE model (Kumar et al., 2022) estimated potential soil erosion in the watershed as the soil and water loss parameter of Yunnan Province. The calculation data came from soil, terrain, rainfall, land use, and other data.

Methods

Calculation of landscape pattern index

Using the 30 m spatial resolution global land cover data (globeland30) developed in China in 2000 and 2020, considering the calculation needs and referring to research results of relevant literature (Ding et al., 2019; Shi et al., 2021), the grid size used was 100×100 m, calculation grid size $5 \text{ km} \times 5 \text{ km}$. In the landscape computing software FRAGSTATS, there are two basic metrics on the landscape scale. The first involves the composition and spatial distribution of the landscape. The second includes statistical distribution values including mean (MN), area weighted average (AM), and coefficient of variation (CV) among others. According to the characteristics of different landscape indices, 42 indices were selected from five aspects—area and edge index, shape index, spread/dispersion index, and diversity index (Table 2). A detailed introduction to these landscape pattern indices can be found in the help documentation of software FRAGSTATS.

There is a strong correlation between landscape pattern indices, which increases the complexity of the analysis. Therefore, a Pearson correlation analysis was conducted on

the above 42 landscape indices. Then, using the idea of principal component analysis in factor analysis, taking the correlation matrix of analytical variables as the basis for extracting factors, the eigenvalues and corresponding eigenvectors of the correlation matrix were calculated.

Table 1. Data source and pre-processing

Data type	Data sources	Remarks
Land cover data	Includes normalized vegetation index (NDVI) and total primary productivity of vegetation (GPP), derived from a geospatial data cloud platform (https://www.gscloud.cn/)	The data type is grid data, the spatial resolution is 500 m, and the projection is WGS84
Meteorological monitoring data	Includes precipitation data and temperature data, which are from the national science and technology basic conditions platform-National Earth System Science Data Center (http://www.geodata.cn)	The data type is grid data, the spatial resolution is 1 km, and the projection is WGS84
Land use data	The land use data is 30 m global surface coverage data derived from GlobeLand30 (http://www.globallandcover.com)	The data type is grid data with a resolution of 30 m. The data adopts WGS84 coordinate system, including 10 first-class types: cultivated land, forest land, grassland, shrub land, wetland, water body, tundra, artificial surface, bare land, glacier and permanent snow
Socio-economic statistics	Includes population density and economic density. The population density kilometer grid data comes from the world population worldpop website (https://www.worldpop.org/). The GDP kilometer grid data comes from the resource and environmental science and data center of the Chinese Academy of Sciences (https://www.resdc.cn/)	The data type is grid data, the resolution is 1 km, and the projection is WGS84
Environmental quality data	The water environment quality data comes from the ecological environment quality report of Yunnan Province. PM2.5 data comes from https://weijing-rs.github.io/product.html	The water environment quality data comes from section water quality data. Based on DEM data, Yunnan Province was divided into 231 subbasins for rasterization; According to surface water environmental quality standards (GB 3838-2002) water quality category was assigned to each subbasin. The data type of PM2.5 is grid data, the resolution is 1 km, and the projection is WGS84
Other data	The data of DEM comes from the geospatial data cloud platform of the computer network information center of the Chinese Academy of Sciences (http://www.gscloud.cn). The soil data comes from the “Heihe project data management center” (http://westdc.westgis.ac.cn)	The digital elevation model (DEM) uses aster GDEM V2 data product with a spatial resolution of 30 m. The soil data type is grid data, the spatial resolution is 1 km, and the projection is WGS84

Table 2. Landscape pattern index

Type	Abbreviation
Area and Edge metrics	NP, PD, LPI, TE, LSI, AREA_MN, AREA_AM, AREA_CV, GYRATE_MN, GYRATE_AM, GYRATE_CV
Shape metrics	SHAPE_MN, SHAPE_AM, SHAPE_CV, FRAC_MN, FRAC_AM, FRAC_CV, PARA_MN, PARA_AM, PARA_CV, CIRCLE_MN, CIRCLE_AM, CIRCLE_CV, CONTIG_MN, CONTIG_AM, CONTIG_CV, PAFRAC
Aggregation metrics	CONTAG, PLADJ, IJI, COHESION, DIVISION, MESH, SPLIT, AI
Diversity metrics	PR, SHDI, SIDI, MSIDI, SHEI, SIEI, MSIEI

Ecological security evaluation

The determination of multi-index comprehensive evaluation factor weight is key to the entire evaluation. Weight determination methods generally are divided into subjective or objective weighting methods according to the original data sources. Subjective weighting comes primarily from the subjective judgment of experts based on their experience, such as the Delphi and AHP methods. These methods have been around longer and used extensively, but their objectivity is poor. The weight of objective assignment comes from the actual data of each index in the evaluation unit and does not depend on subjective human judgment. Therefore, these methods are more objective, and include methods such as principal component analysis, mean square deviation method, and entropy method. This study selected the mean square deviation decision and entropy methods to objectively and comprehensively weigh the ecological security evaluation indicators.

(1) Entropy method

Entropy quantitatively describes the uncertainty of an event. In the evaluation of ecological security, entropy determined the contribution of each index to the information of regional ecological security. Entropy determined the weight of each index in the evaluation index system (Sun et al., 2017; Zhang et al., 2014). The calculation method is as follows:

(a) Calculate the information entropy of the j -th index of the standardized data:

There are m samples and n indices, we recorded the value of the j -th index of the i -th sample as X_{ij} ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$). Calculate the information entropy of the j -th index of the standardized data matrix:

$$E_j = -k \sum_{i=1}^m P_{ij} \ln(P_{ij}) \quad (\text{Eq.1})$$

In Equation 1, k is a constant, and related to the sample number m of the system.

Generally, $k = \frac{1}{\ln(m)}$, $P_{ij} = \frac{X_{ij}}{\sum_{i=1}^m X_{ij}}$.

(b) Calculate the information utility value (C_j) of the index through information entropy:

$$D_j = 1 - E_j \quad (\text{Eq.2})$$

(c) Calculate the weight of each index using the proportion of information utility value, the weight of the j -th index is:

$$W_j = \frac{D_j}{\sum_{j=1}^n D_j} \quad (\text{Eq.3})$$

(2) Mean square deviation decision method

The most important and commonly used index to reflect the dispersion degree of random variables is the mean square deviation of random variables. The basic idea of this method uses each evaluation index as a random variable (Dong et al., 2015; Ren et al., 2019). The mean square deviation of these random variables gets calculated, those mean square deviations are normalized, and that result is the weight coefficient of each index. The steps involved include:

(a) Finding the mean value of the j -th index: $E(G_j)$

$$E(G_j) = \frac{1}{n} \sum_{i=1}^n X_{ij} \quad i = 1, 2, \dots, n; j = 1, 2, \dots, m \quad (\text{Eq.4})$$

(b) Finding the mean square deviation of G_j : $\sigma(G_j)$

$$\sigma(G_j) = \sqrt{\sum_{i=1}^n [X_{ij} - E(G_j)]^2} \quad i = 1, 2, \dots, n; j = 1, 2, \dots, m \quad (\text{Eq.5})$$

(c) Finding the weight coefficient W_j of G_j

$$W_j = \frac{\sigma(G_j)}{\sum_{j=1}^m \sigma(G_j)} \quad j = 1, 2, \dots, m \quad (\text{Eq.6})$$

Analysis of driving factors

Referring to relevant literature (Chen et al., 2020; Chen and Wang, 2020; Huang et al., 2021; Li et al., 2019; Liu et al., 2022; Ma et al., 2019; Wang and Zhu, 2016) and combined with regional reality, the main natural driving factors affecting the ecological security comprehensive index change include elevation, slope, and rainfall while social driving factors include per capita GDP, population density, and intensity of human activities. Based on an ArcGIS geographically weighted regress toolbox, the fixed distance method (fixed) was used for core type parameters, which generated a smoother core surface. The AIC method was used as the core bandwidth parameter, and the optimal bandwidth was determined by the minimum information criterion. The simulation effect of the geographical weighted regression model was measured using an adjusted R-squared, Cond, and stdresid. The calculation of the corrected R-squared value normalized them according to the degrees of freedom in the numerator and denominator. Its value varied from 0.0 to 1.0; larger values are desirable. A standard deviation greater than 2.5 times indicates a problem, and this diagnosis was used to evaluate local multicollinearity. If the condition number $< 0, > 30$, or set to “null”, it means there is strong local multicollinearity and the associated results may be unreliable. After normalizing the driving factor data, a quantitative relationship between the comprehensive index of ecological security and driving factors was established by using the geographically weighted regression model.

Results and analysis

Index system construction

Firstly, we used principal component analysis to extract the main component indicators. The cumulative variance rate of the first five principal component variables in 2000 and 2020 accounted for more than 90% of the 42 variables, which indicated the first five principal components contained more than 90% of all landscape structure information. Due to the strong linear relationship between many landscape indices within each of the first five principal component variables. When the correlation coefficient is greater than 0.7, some indicators are eliminated. Consolidated selection of representative indicators in four dimensions (Area and Edge metrics, Shape metrics, Aggregation metrics, Diversity metrics), the indices that represent the landscape pattern in the dry and hot valley of Jinsha River include DIVISION, CONTIG_MN, PD, and SHAPE_AM (*Table 3*).

Table 3. Average of correlation coefficients of landscape index for 2000 and 2020 of landscape index

NAME	DIVISION	CONTIG_MN	PD	SHAPE_AM
DIVISION	1	0.198	0.500	-0.17
CONTIG_MN	0.198	1	-0.448	-0.203
PD	0.500	-0.448	1	0.078
SHAPE_AM	-0.17	-0.203	0.078	1

From an ecological environment perspective, nine indicators including water environment quality, atmospheric environment quality, landscape pattern index, NDVI index, soil and water loss intensity, and total primary productivity formed an ecological security evaluation index system to evaluate the state of ecological security in real time. Among them, positive indicators are: NDVI, CONTIG_MN, GPP, negative indicators are: Water quality categories (abbreviation “SZLB”), PM2.5, PD, SHAPE_MN, DIVISION, soil and water loss intensity (abbreviation “STLS”).

Using the entropy and mean square error methods, the weights of nine indices were calculated and averaged, and the comprehensive ecological security index in the dry and hot valley of Jinsha River was calculated. *Figure 2* shows the weight of each ecological security index.

Among them, indicators with greater weight in 2000 were DIVISION, SZLB, NDVI, and GPP. Indicators with greater weight in 2020 were DIVISION, GPP, CONTIG_MN, and NDVI. This shows the main stress factors of ecological security in 2000 for the dry and hot valley area of the Jinsha River were the intertwined effects of water environment security factors, landscape pattern factors, and vegetation coverage factors. In 2020, the main stress factors of ecological security were the intertwined effects of landscape pattern factors and vegetation coverage factors. In both 2000 and 2020, the entropy weight and the mean square deviation weight of the DIVISION indicator were larger, indicating that the indicator provides more information about the ecological security of the watershed. NDVI and GPP were also the main stress characteristic factors, which indicated the vegetation cover change in this area was large or sensitive to the disturbance of ecosystem security.

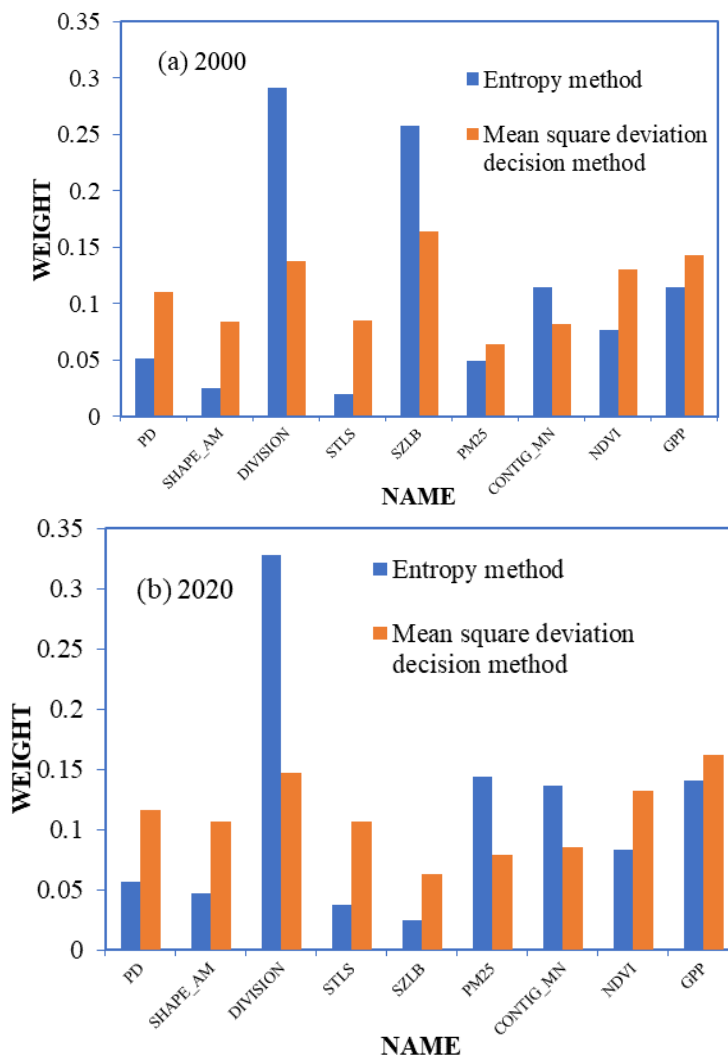


Figure 2. Weight of each index in 2000 and 2020

Temporal and spatial evolution of ecological security

Using the weighted index system, comprehensive ecological security indices for 2000 and 2020 were calculated with the results shown in Figure 3. Using the natural breakpoint method in GIS, each of the indices was categorized into five categories based on the magnitude of the values, in that order: Extremely Low, Low, Medium, High, Extremely High. The composite index of ecological security was categorized into five categories, in that order: Extremely Safe, Safe, Medium, Unsafe, Extremely Unsafe.

In 2000, most areas of Yuanmou County, Wuding County, and Dongchuan District were in an unsafe or relatively unsafe state and these tied directly to SZLB, DIVISION, and NDVI. The water quality in Yuanmou County, Wuding County, Luquan County, and Dongchuan District is relatively poor. The separation index DIVISION reflects the complexity of patch types. The regional values of Yuanmou County, Wuding County, and Dongchuan District were large, which indicated a more irregular patch shape. The vegetation coverage of Yuanmou County and Dongchuan district is low, as were the NDVI and GPP values. In 2020, some areas in Yuanmou County, Wuding County, and Yongsheng County were all an unsafe or relatively unsafe state, and primarily related to

the landscape indices DIVISION, CONTIG_MN, NDVI and GPP. Due to significant regional water quality improvements in 2020, Dongchuan District is relatively safe. Due to the decline of NDVI and GPP indicators, some areas of Yongsheng County were unsafe in 2020. The research by Zhang, et al. (2023) showed that the area of high risk zone in the western and middle sections was much higher than that in the eastern section from the perspective of landscape ecological risk, and the research conclusion is similar to our research.

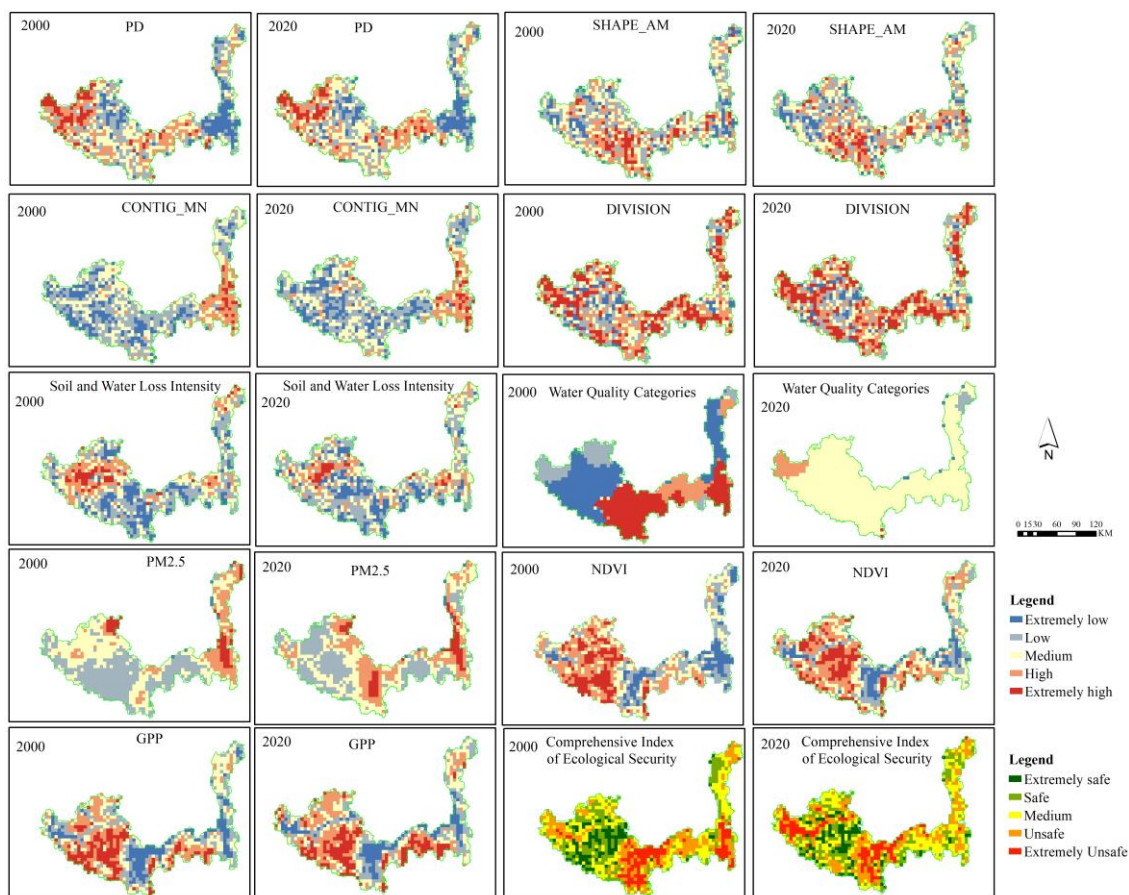


Figure 3. Ecological security assessment of Jinsha River dry and hot valley in 2000 and 2020

Driver analysis

Using a geographical weighted regression model, analysis results showed that in both 2000 and 2020, the adjusted R^2 values exceeded 0.57, the std. residual values were ~ 2.5, and the cond values ranged from 0–30. Therefore, the GWR model was suitable for fitting the relationship between comprehensive ecological security indices and driving factors. *Figure 4* shows that the local R^2 values in Yongsheng, Binchuan, Dayao, Yongren, Yuanmou, Mouding, and Wuding counties were > 0.5 in both 2000 and 2020, which indicated a good fitting effect. We counted the changes in the influence coefficients for these regions over the period 2000-2020 in *Table 4*.

Figure 4 and *Table 4* show that: (1) from 2000 to 2020, the impact of GDP on ecological security gradually weakened, the impact of population density changed little, but the impact of human activity intensity gradually strengthened. This showed an

increased interference of human activities on land use, especially in Yuanmou County, northern Mouding County, northwest Wuding County, southeast Dayao County, and Yongren County. These areas are located near the main stream of Jinsha River, at relatively low altitudes and high land use intensities. (2) Compared with socio-economic impact driving factors, natural driving forces had a greater impact on rainfall and altitude. The research by Ou et al. (2018) showed that structural natural factors dominated by terrain and climate were still determinants of the spatial distribution of regional landscape ecological security. The negative correlation between rainfall and ecological security index was more obvious in Yuanmou County, northern Mouding County, and northwest Wuding County. The positive correlation between altitude and ecological security index was more obvious in Yuanmou County, northwestern Mouding and Wuding Counties. These areas have low forest coverage and concentrated human activities. Increased rainfall led to the aggravation of soil erosion.

Table 4. *the changes in the influence coefficients for these regions over the period 2000-2020*

Driver	2000		2020	
	Range of influence coefficients	Name of the region	Range of influence coefficients	Name of the region
Per capita GDP	0-0.88	Southern Yongsheng and northern Binchuan	0-0.59	Southern Yongsheng, northern Binchuan and eastern Heqing
	-1.8-0.32	Eastern Dayao, western Yongren, southern Yuanmou, and northern Mouding	-0.2-0	Eastern Dayao, Yongren, northern Yuanmou, and Mouding
	-0.32-0	Northern Wuding	-0.53-0.2	Southern Yuanmou and northwestern Mouding
Population density	-0.32-0	Southern Yongsheng and northern Binchuan	-0.18-0	Southwestern Yongsheng, western Heqing, and northern Binchuan
	0-0.27	Southeastern Dayao, Yongren, southern Yuanmou, northern Mouding, and northwestern Wuding	0-0.15	Southeast Dayao, Yongren, northern Yuanmou, and northern Wuding
	0.16-0	Northern Yongren	-0.1-0	Northern Mouding and southern Yuanmou
Rainfall	0-0.37	Southern Yongsheng	-0.68-0	Southwestern Yongsheng and the center of Binchuan
	-0.78-0	Northern Binchuan	0-0.59	Eastern Heqing and western Yongshen
	0.36-1.02	Southeastern Dayao and Yongren	0-0.59	Southeastern Dayao and Yongren
	-0.78-0	Southern Yuanmou, northern Mouding, and northwestern Wuding	-0.98--0.41	Yuanmou, northern Mouding, and northwestern Wuding
Slope	0-0.13	Southern Yongsheng	-0.08-0.07	Yongsheng, Binchuan, Dayao, Yongren, Yuanmou, Mouding, and Wuding counties
	-0.11-0	Northern Binchuan		
	0.13-0.47	Southeastern Dayao, Yongren, and northern Mouding		
	-0.11-0	Southern Yuanmou and northwestern MOUDING		
Elevation	0.47-0.84	Southern Yongsheng and northern Binchuan	0.72-1.03	Southwestern Yongsheng, eastern Heqing, and northern Binchuan
	0-0.48	Northeastern Dayao and Yongren	0.72-1.27	Northeastern Dayao and Yongren
	0.84-1.90	Southern Yuanmou, northwestern Mouding, and northwestern Wuding	1.27-1.73	Yuanmou, northern Mouding, and northwestern Wuding
Intensity of human activities	0-0.04	Southern Yongsheng and northern Binchuan	-0.25-0	Southern Yongsheng, northern Binchuan, and eastern Heqing
	-0.05-0	Northeastern Dayao and western Yongren	-0.25-0	Northeastern Dayao and Yongren
	0.02-0.07	Southern Yongren, southern Yuanmou, and northern Mouding	0.04-0.22	Yuanmou, northern Mouding, and northwestern Wuding
	-0.05-0	Northwestern Wuding		

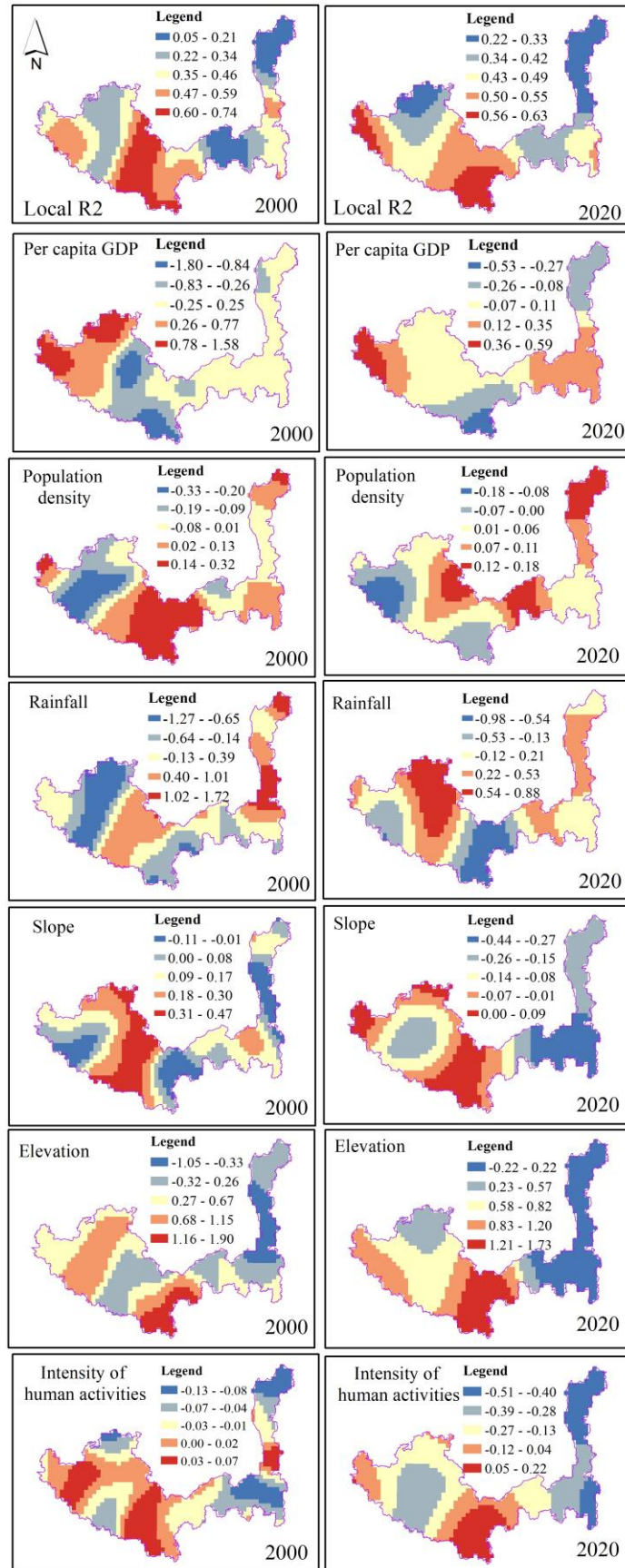


Figure 4. Influence coefficients of driving factors in the dry and hot valley of Jinsha River

Conclusions

(1) These indices (DIVISION, CONTIG_MN, PD, SHAPE_AM) comprehensively described the landscape pattern state of the dry and hot valley area of the Jinsha River in Yunnan Province.

(2) The dominant stress factors of regional ecological security changed between 2000–2020. The ecological security state in 2000 was affected by water environment security, landscape pattern, and vegetation cover, but only by landscape pattern and vegetation cover in 2020. From 2000 to 2020, DIVISION, NDVI and GPP were the main stress characteristic factors and showed the landscape pattern and vegetation cover changes were more sensitive to ecosystem security.

(3) Due to the influence of regional water quality, DIVISION and NDVI, most areas in Yuanmou, Wuding, and Dongchuan Counties were unsafe or relatively unsafe in 2000. Due to the influences of DIVISION, CONTIG_MN, NDVI, and GPP in 2020, some areas of Yuanmou, Wuding, and Yongsheng Counties were in an unsafe or relatively unsafe state. In 2020, due to the great improvement of regional water quality, Dongchuan district is generally in a medium safe state. Due to declines of NDVI and GPP indicators, some areas of Yongsheng County were in an unsafe state in 2020.

(4) From 2000 to 2020, the impact of GDP on ecological security gradually weakened, the impact of population density changed little, but the impact of human activity intensity gradually strengthened. Compared with socio-economic impact drivers, natural drivers (rainfall and altitude) had greater impacts. This showed the extensive land use mode, coupled with the low regional forest coverage, rainfall, and altitude became the main driving factors of regional ecological security.

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Conflict of interests. The authors declare no conflict of interests.

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APPENDIX

This article has an electronic appendix.