SPATIAL-TEMPORAL EVOLUTION OF ECOLOGICAL VULNERABILITY IN DADU RIVER BASIN, CHINA

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Abstract. This paper selected 14 evaluation indices using SRP model and constructed the Dadu River basin ecological vulnerability assessment system by AHP. (1) The classification of ecological vulnerability from high to low is extremely vulnerable (EVI ≥ 0.50), severely vulnerable (0.46 ≤ EVI < 0.50), moderate vulnerable (0.42 ≤ EVI < 0.46), mild vulnerable (0.38 ≤ EVI < 0.42), and slightly vulnerable (EVI < 0.38). (2) The northern and central parts of the basin are mostly extremely and severely vulnerable areas, and the ecological vulnerability index decreases with altitude. (3) In terms of spatio-temporal transformation, the area of slight vulnerability decreased by 2,033 km², which accounted for 2.74% of the total watershed area. Extremely vulnerable areas increased by 2,649 km², or 3.41%. (4) From the perspective of factor detection, the factors with the strongest explanatory power for ecological vulnerability are GDP, population, annual sunshine, soil viscosity and annual average relative humidity. (5) From the perspective of origin, the extremely and severely vulnerable areas are mostly located in the plateau and mountainous regions, and climate and topography are the important reasons for their ecological vulnerability. Human economic activities are closely related to the degree of vulnerability.
Keywords: *ecological vulnerability, analytic hierarchy process, Dadu River basin, ecological sensitivities - ecological resilience - ecological stress model, geographic detector*

Introduction

Ecological vulnerability is the sensitivity of ecosystems in a given area to external disturbances and their ability to recover, which is a natural inherent property of ecosystems (Tian and Chang, 2012). Currently, environmental protection is a hot topic worldwide, and ecological vulnerability research is a key issue in the field of environmental protection and an important direction for ecological civilization construction and sustainable development (Yao et al., 2016). In recent years, with the continuous acceleration of urbanization in China, the expansion of construction land, and the destruction of the ecological environment caused by unreasonable economic activities, a series of environmental problems have emerged (Liu et al., 2018). The Dadu River Basin is located in the western part of the Sichuan Basin, with a complex geological structure, large topographic fluctuations, and a fragile ecological environment. With the increasingly frequent human economic activities, the ecological environment in the watershed has continued to deteriorate (Li et al., 2020). By analyzing the ecological vulnerability of the study area, not only can we provide direction and guidance for economic development in the watershed, but also reference and guidance for ecological vulnerability research in similar arid river valleys (Ren et al., 2018).

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Many scholars at home and abroad have conducted extensive research on ecological vulnerability. Chen et al. (2019) used correlation diagnostic analysis and combined subjective weighting and objective weighting methods to determine the index weights for quantitative evaluation and temporal-spatial feature analysis of EVI in the study area from 1990 to 2015. Xu et al. (2020) studied the Zhangjiakou area based on the SRP model, using principal component analysis and geographic detector. Zhou et al. (2021) used the analytic hierarchy process and other methods to build an ecological vulnerability evaluation model and conducted a comprehensive and quantitative analysis of the ecological vulnerability situation in Inner Mongolia’s Hu Rijiaqian’er area in 2010 and 2017. Chen et al. (2021) used the integrated coupled coordination degree model to analyze the coupling relationship between village ecological environment and poverty. In terms of content, Guo et al.(2019) studied the ecological vulnerability of the inner flow river in arid areas, Zhu et al.(2019) studied the ecological vulnerability of the Changbai Mountain and its surrounding areas, explored the ecological vulnerability situation in high-altitude mountain areas, the arid valleys (Shang et al., 2021; Santos et al., 2020) and high-altitude areas (Zhang et al., 2018; Wang et al., 2022), which are all important areas for ecological vulnerability research. In addition, many scholars have analyzed and evaluated the ecological vulnerability of different regions using methods such as the analytic hierarchy process (Jin and Xu, 2022), principal component analysis (Sun et al., 2022), geographic detector analysis (Zhang et al., 2022), etc.

The Dadu River Basin is a crucial dry valley distribution area in the Jinsha River Basin, and is a typical area for studying ecological vulnerability. The altitude varies greatly, and the river erosion is strong, leading to serious soil loss. In recent years, the economic development, overgrazing, and engineering construction have had a significant impact on the ecological environment in the basin and have been deteriorating, causing serious impact on the sustainable social and economic development in the study area (Shao et al., 2016). Based on this, this paper constructs the ecological sensitivity-ecological resilience-ecological pressure (SRP) model (Wei et al., 2015; Xu et al., 2016) and selects 14 indicators, including wind speed, annual precipitation, annual average temperature, relative humidity, sunshine hours, elevation, slope, aspect, evaporation, soil organic carbon content, soil clay content, NDVI, population density, and GDP, based on the actual situation of the study area, using the analytic hierarchy process to calculate the weights, and constructs an evaluation model of ecological vulnerability indicators for the study area. The ecological vulnerability index of the Dadu River Basin is calculated, and the ecological vulnerability of the basin is analyzed and evaluated. Thus, it can provide reference for ecological environment protection and policy making in the study area.

Study area

The Dadu River basin is located in (98.39°E-104.25°E, 27.76°N-34.25°N) (As shown in *Figure 1*). The Dadu River is a secondary tributary of the Yangtze River. It originates from the Guoluo Mountain in Yushu Prefecture of Qinghai Province, flows through Guoluo Prefecture, Aba Prefecture, Ganzi Prefecture, Liangshan Prefecture and Leshan City of Sichuan Province, and enters the Minjiang River at Xiaogongzui of Leshan City. The Dadu River Basin flows through the transition zone of Qinghai-Tibet Plateau and Sichuan Basin, with large topography, high terrain in the northwest and low

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terrain in the southeast. It is rich in hydraulic resources, and many hydropower stations are built in the main tributaries. The geological conditions in the study area are complicated, and geological disasters occur frequently, such as debris flow, landslide and earthquake. The Dadu River is upstream from Luding County of Garze Prefecture, middle reaches from Luding County to Leshan City, and downstream from Tongjiezi. The precipitation in the basin is mainly concentrated in summer, and the river valleys are mostly arid. The vegetation coverage rate is low, the land degradation is serious, and the soil and water conservation ability are not high.

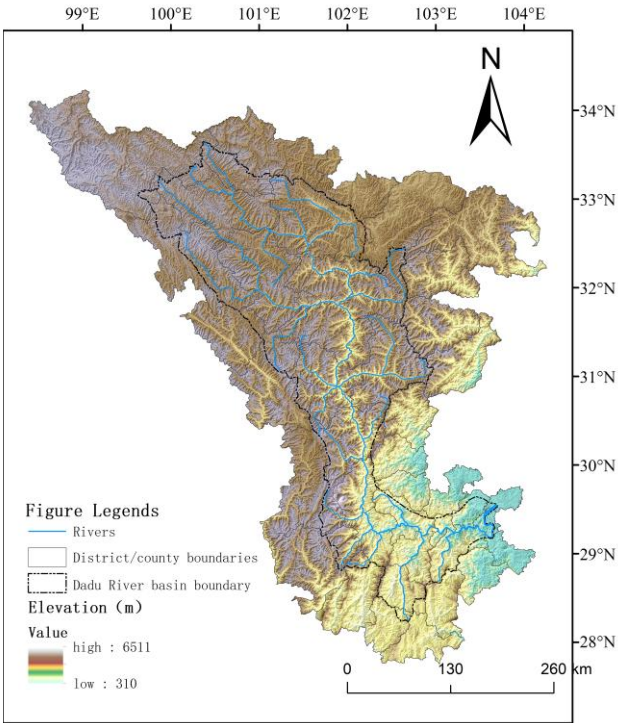

Figure 1. *Overview of the study area (Data source: Geospatial Data Cloud)*

Evaluation system construction

Selection of indicators

The SRP model is a regular method for evaluating the ecological vulnerability of an environment, which includes three evaluation dimensions: ecological sensitivity, ecological resilience, and ecological pressure. Ecological sensitivity refers to the sensitive response of the ecosystem to external interference, ecological resilience refers to the self-regulatory and adjustment ability of the ecosystem under external interference, and ecological pressure refers to the ecosystem in the study area receiving external interference, mainly from human factors. According to the actual situation, this paper selects five factors in the aspects of meteorological factors, topographic factors, soil factors, vegetation factors, and social factors. Meteorological factors include wind speed, annual precipitation, annual average temperature, relative humidity, and sunshine hours. Topographic factors include elevation, slope, slope direction, and evaporation. Soil factors include soil organic carbon content and soil clay content (as shown in *Table 1*). Vegetation factors include NDVI (normalized vegetation index). Social factors include population and GDP.

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Table 1. *Ecological vulnerability assessment index and AHP weight of Dadu River Basin*

Index class	Index group	Index item	Weight
Ecological sensitivity	Meteorological factor	Wind speed	0.0920
		Annual mean temperature	0.0187
		Annual precipitation	0.1311
		Relative humidity	0.1304
		Sunshine number	0.0280
	Terrain factor	Elevation	0.1703
		Slope	0.1564
		Aspect of slope	0.0269
		Evaporation capacity	0.0183
	Edaphic factor	Soil organic carbon	0.0498
		Clay content	0.0364
Ecological resilience	Vegetation factor	NDVI	0.0699
Ecological pressure	Social factor	Population density	0.0421
		GDP	0.0297

Data sources

This paper selects three periods of meteorological, topographic and geomorphic data, vegetation, soil, social and economic data in 2000, 2010 and 2020, and the specific sources of each data are as follows:

(1) Digital Elevation data (DEM): The DEM data used in this paper are all from the website of “Geospatial data Cloud” with a resolution of 30 m.

(2) Administrative divisions, district, county resident data, meteorological data, NDVI, soil texture and other data are all from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences, with a resolution of 1 km.

(3) Socio-economic data: Population and GDP data are derived from relevant provincial and municipal statistical yearbooks and national economic and social development bulletins, with a resolution of 1 km.

Research methods

Analytic hierarchy process (Cheng, 2019)

Analytic hierarchy process is an important method to assign index weights, which is widely used in ecological environment assessment and sustainable development research. The analytic hierarchy process (AHP) combines quantitative and qualitative data, divides complex problems into multiple layers of simple problems, and obtains the result through calculation to determine the weight. This method not only fully considers people’s subjective initiative, but also can conduct qualitative analysis of things.

(1) Standardized processing of data

Different evaluation indicators have different properties, different units, and different scales, so they cannot be directly compared across different regions. According to the

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different impacts of positive and negative indicators on the ecological vulnerability of the study area, the article uses different standardization processing formulas to normalize the indicators:

$$\text{Forward indicator: } X_i = \frac{I_i - I_{min}}{I_{max} - I_{min}} \quad \text{(Eq.1)}$$

$$\text{Negative indicator: } X_i = \frac{I_{max} - I_i}{I_{max} - I_{min}} \quad \text{(Eq.2)}$$

where, X_i is the standardized value, I_{max} is the maximum value in a single indicator, I_{min} is the minimum value in a single indicator, and I_i is a specific indicator.

(2) Determination of weight

According to the expert's judgment of the importance of different indicators, different weights are assigned to the indicators, so as to construct the judgment matrix. For the *NTH* index, a pairwise comparison judgment matrix can be obtained:

$$A = (A_{ij})_{n \times n} \quad \text{(Eq.3)}$$

where, A_{ij} represents the importance of the two indicators i and j relative to the target.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad \text{(Eq.4)}$$

where, the judgment matrix uses the 1-9 scale method, wherein $A_{ij} > 0$, $A_{ii} = 1$, $a_{ij} = 1/a_{ij}$ (i,j = 1, 2, 3 … n).

The weights are calculated by analytic hierarchy process (AHP). The specific steps are as follows:

1. The index of matrix *A* is normalized by column
2. Add each row after normalization
3. Divide the addition result by the result, that is, the eigenvector weight

(3) Consistency check

After the weights are obtained, in order to verify whether the results are correct, the weights need to be tested for consistency. When calculating whether different judgment matrices have relatively satisfactory consistency, it is necessary to reference the *RI* value. When the consistency index *CI* of the judgment matrix is compared with *RI*, *CR* is obtained:

$$CR = \frac{CI}{RI} \quad \text{(Eq.5)}$$

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where, if $CR \leq 0.1$, the constructed judgment matrix is reasonable. *RI* is determined by the number of selected indicators and can be obtained by looking up the table.

The expression for CI is as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad \text{(Eq.6)}$$

where, $\lambda_{\max}$ is the largest eigenvalue, and *n* is the index order.

The weights of indicators calculated through analytic hierarchy process are shown in *Table 1*.

Construct evaluation model

According to the obtained weights, an evaluation model is constructed and the formula of ecological vulnerability index (EVI) is calculated as (An et al., 2019):

$$EVI = \sum_{i=1}^{n} W_i \times X_i \quad \text{(Eq.7)}$$

where, *EVI* is the ecological vulnerability index, W_i is the weight of different evaluation indicators, *n* is the number of evaluation indicators, X_i is the normalization result of each indicator, *EVI* is from 0 to 1, and the larger the value, the higher the vulnerability degree.

In this paper, according to the actual situation, the natural break point grading method is used to classify the vulnerability into five levels: slight, mild, moderate, severe and extremely severe vulnerability (Wei et al., 2015).

Geographic detector

The geographical detector is a way used in recent years to explore spatial variability and reveal factor driving forces. It is divided into four parts: factor detector, ecological detector, interactive detector, and risk detector. The causes of ecological vulnerability in the study area are various, and the spatial distribution has obvious spatial analysis. In this paper, the factor detector and interactive detector are chose, which can not only detect the driving factors of the change in the ecological vulnerability of the study area, but also explore the causal relationship between factors.

(1) The formula of factor detector is calculated as (Wang and Xu, 2017):

$$q = 1 - \frac{1}{N\sigma^2} \sum_{i=1}^{L} N_i \sigma_i^2 \quad \text{(Eq.8)}$$

where, *q* represents the explanatory degree of the factor to the ecological fragili, and the range is [0,1]. The larger the value of *q*, the stronger the explanatory power of the factor, and the smaller the value of the other. n is the number of samples, *L* is the number of index classifications, N_i represents the sample size of layer *i* and σ_i^2 represents the variance of the ecological vulnerability index of Layer *i*.

(2) Interactive detector: To explore whether the interaction of the two indicators enhances or weakens the explanatory power of ecological vulnerability. The types of interactions between indicators are shown in *Table 2*:

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Table 2. *Discriminant table of interaction relation of index factors*

Basis	**Interactive relationship**
$q(X_1 \cap X_2) < Min(q(X_1), q(X_2))$	Nonlinearity attenuation
$Min((X_1), q(X_2)) < q(X_1 \cap X_2) < Max((X_1), q(X_2))$	The single-factor nonlinearity decreases
$q(X_1 \cap X_2) > Max((X_1), q(X_2))$	Two-factor enhancement
$q(X_1 \cap X_2) = q(X_1) + (X_2)$	Independent
$q(X_1 \cap X_2) > q(X_1) + (X_2)$	Nonlinear enhancement

In this paper, ArcGIS software is used for data processing and visualization.

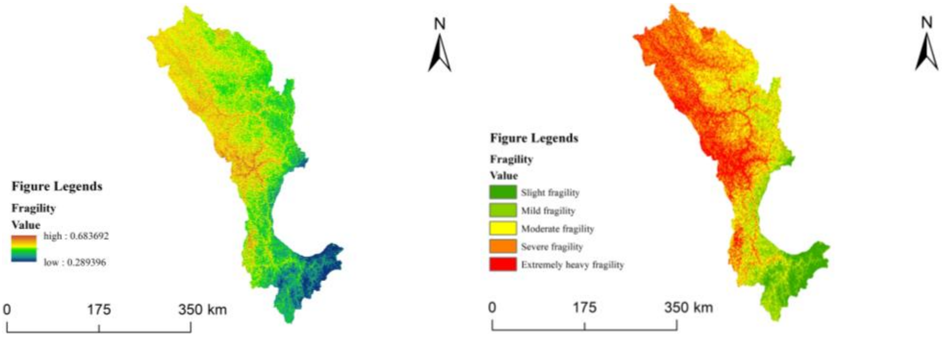
Result analysis

Ecological vulnerability classification

According to ArcGIS and using the reclassification tool and raster calculation tool, *Figure 2* and *Table 3* are obtained.

Figure 2a shows the ecological vulnerability index of Dadu River, with *EVI* values is from 0.289 to 0.684, and the average value is 0.487. On the whole, the ecological environment in the research area is relatively fragile, showing a trend of higher in the northwest and lower in the southeast, and the vulnerability index of the valley is also relatively high, and the ecological environment quality in the northwest is lower than that in the southeast.

According to the natural discontinuance point classification method, the ecological vulnerability of Dadu River region was divided into 5 levels from high to low (see *Table 3*). *Figure 2b* is the ecological vulnerability classification map of Dadu River Basin in 2020. It can be seen that the extremely and severely vulnerable areas are mostly dispersed in the eastern and northeastern parts of the study area, the moderately vulnerable areas are primarily distributed in the central and eastern parts of the research area, and the mildly and slightly vulnerable areas are mainly distributed in the lower reaches of the southeastern valley. Some extremely heavy and severely vulnerable areas are distributed in the middle and upper reaches of rivers, mostly in the northern part of the western Sichuan Plateau, with high altitude and thin air. The ecological vulnerability index displayed a decreasing trend with the decrease of altitude, that is, from the extreme vulnerability in the upper reaches of high altitude to the slight fragility in the lower reaches of low altitude.



(a) Fragility index (b) Fragility classification

Figure 2. *Ecological vulnerability distribution map of Dadu River Basin in 2020*

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Table 3. *Vulnerability classification of Dadu River Basin*

Vulnerability level	Vulnerability index
Slight fragility	< 0.38
Mild fragility	0.38~0.42
Moderate fragility	0.42~0.46
Severe fragility	0.46~0.50
Extremely heavy fragility	≥ 0.50

Spatial and temporal transformation characteristics of ecological vulnerability

This can be seen from *Figures 3* and *4* and *Table 4*, the vulnerability of Dadu River basin is relatively high, and the spatial distribution difference is large, on the whole study period. The moderately vulnerable area accounts for 75.88% of the whole basin area, and the mild and slight vulnerable area only accounts for 24.12%. Among them, the mild and slight vulnerable areas are mainly in Leshan and Ya'an. These places are mainly located in the lower reaches of the river, and the flow rate of the river is relatively gentle, and the scouring effect on the valley is weakened. The moderately vulnerable areas are mainly distributed in the northern plateau areas, mainly in Serda County and Rangtang County of Sichuan Province and Banma County of Qinghai Province. These areas are located in plateau mountainous areas with an average altitude of more than four kilometers and relatively thin air. In 2000, the economic development of the region was backward, human economic activities were not frequent, and the impact on the environment was small, and the ecological environment remained stable. The extremely heavy and severely vulnerable areas are mainly distributed in the middle of the basin, located in Daofu, Danba, Jinchuan, Luhuo and other counties. These areas are in the Western Sichuan basin, with high mountains and deep valleys, high relative elevations and large river drops. Moreover, human activities in these areas have a greater impact on the environment, and the ecological environment is more fragile than other areas. In 2010, the extremely heavy and severe vulnerable areas were mainly dispersed in the upper stream in the high altitude and high cold area. These areas are high in altitude, thin in air, mostly animal husbandry, and the environment is fragile. In addition, during this period, the economic development and human activities in the upstream area gradually increased, and the impact of human economic activities led to the decline of the ecological environment in the area, and the degree of ecological vulnerability continued to rise. In the whole period of 2010, the distribution of ecological vulnerability was different from north to south, higher in the north and lower in the south, and higher in the upper reaches and lower in the lower reaches, showing a decreasing trend with the decrease of altitude.

Table 4. *Area transformation table of vulnerability level*

Vulnerability level	Area in 2000 (km²)	Percentage of area in 2000 (%)	Area in 2010 (km²)	Percentage of area in 2010 (%)	Area in 2020 (km²)	Percentage of area in 2020 (%)
Slight fragility	7270	9.66	7053	9.29	5237	6.92
Mild fragility	10886	14.46	11024	14.53	10867	14.35
Moderate fragility	22114	29.38	18788	24.76	21093	27.86
Severe fragility	23638	31.41	24200	31.89	24522	32.38
Extremely heavy fragility	11352	15.08	14824	19.53	14002	18.49

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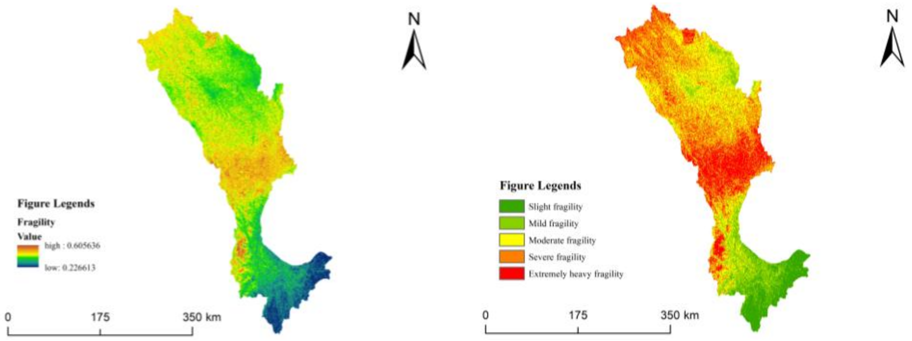
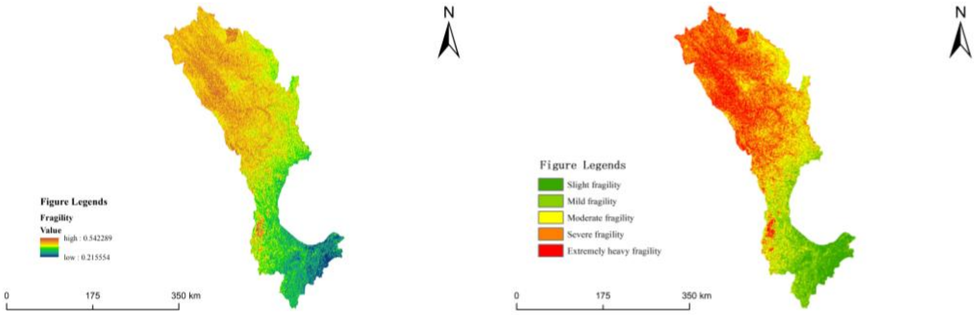


(a) Fragility index (b) Fragility classification

Figure 3. *Distribution of ecological vulnerability in Dadu River Basin in 2000*



(a) Fragility index (b) Fragility classification

Figure 4. *Distribution of ecological vulnerability in Dadu River Basin in 2010*

From the aspect of spatio-temporal transformation, in the 20 years from 2000 to 2020, the slightly vulnerable areas have decreased by 2033 km², accounting for 2.74% of the entire basin area. The reduction areas are mainly dispersed in the downstream of the river in Yuexi County, Ganluo County, Shimian County and other places, and most of them are transformed into moderate and severe vulnerable areas. The slight vulnerable area decreased by 18.86 km², and the reduction area accounted for 0.11%, which did not change much on the whole. Moderately vulnerable areas decreased by 1021 km², accounting for 1.53% of the total area of the basin. The transformation areas were mainly distributed in the north and south of the basin, and the northern areas were mainly transformed from moderately vulnerable to severe and extremely severe vulnerable areas, mainly located in the plateau areas of Seda County, Rangtang County and Banma County. The southern region is mainly transformed from mild and mildly vulnerable areas. Compared with 2000, the severely vulnerable areas increased by 883.18 km², accounting for 0.98% of the total area of the whole basin, and the overall change was small, mainly distributed in the middle and upper reaches of the river, and these areas are relatively fragile ecological environment areas. Compared with 2000, the extremely heavy and vulnerable areas increased by 2,649 km², accounting for 3.41% of the area. The major change areas of the extremely heavy and vulnerable areas were in the northern and central parts of the basin, and the increase areas were distributed in the northern Seda County, Luhuo County, Rangtang County and Banma County, as well as some river valley areas. In the past 20 years, many extremely vulnerable areas in Danba County and Jinchuan County changed to moderate and mild vulnerable areas, and the

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extremely vulnerable areas in southern Jiulong County also decreased correspondingly. From the perspective of the three time scales, the mildly vulnerable areas are decreasing continuously, and the extremely heavy and severely vulnerable areas are increasing. On the whole, the ecological vulnerability degree of the study area is increasing continuously. It shows that the ecological environment of Dadu River basin is relatively fragile on the whole and still has a trend of continuous deterioration.

Analysis of driving forces of ecological vulnerability

In this paper, on the strength of the arcgis10.7 platform, a 10 km × 10 km grid was created, and 745 effective grid points were extracted for extracting *X* and *Y* values, so as to conduct quantitative analysis of vulnerability driving factors. ecological vulnerability index was selected as the dependent variable Y value and ecological vulnerability index as the independent variable *X* value. After standardized processing, the data of 2000, 2010 and 2020 were divided into 5 levels by natural breakpoint measure. Finally, the influence of indicators on ecological vulnerability in the study area was analyzed by geographical detector.

Factor detectors are mainly used to explore the impact of indicators on ecological vulnerability, and the detection results are shown in *Table 5*. According to the results, the top five factors with the strongest explanatory power in 2000 were GDP, population density, annual sunshine, soil viscosity and annual mean relative humidity. The highest value of q value was GDP (0.5366), while the lowest value was slope direction (0.0097). The top five factors with the strongest explanatory power in 2010 were annual sunshine, annual mean relative humidity, annual precipitation, GDP and population density, with the highest value being annual sunshine (0.5956) and the lowest value being slope direction (0.0044). In 2020, the top five factors with the strongest explanatory power are annual mean relative humidity, GDP, population density, annual sunshine, and soil viscosity, with the highest value of q being annual mean relative humidity (0.5695) and the lowest value being slope direction (0.0064). It can be seen from the data of the past two years that relative humidity, soil viscosity, sunshine and economic indicators are important driving factors for the change of ecological vulnerability in the study area. The study area is mainly located in the dry and hot river valley area, and air humidity, sunshine and social and economic activities have important effects on the ecological environment, while the impact of slope aspect on the environment is relatively small.

The results of the interactive detector show (*Fig. 5*) that the maximum value of q (X1∩X2) in 2000 is 0.6893 and the minimum value is 0.0893. The interaction results can be divided into two categories: double factor enhancement and nonlinear enhancement, in which the double factor enhancement is 48 items and the nonlinear enhancement is 43 items. In 2010, the maximum value of q (X1∩X2) is 0.6781 and the minimum value is 0.0298, in which the two-factor enhancement is 47 items and the nonlinear enhancement is 44 items. In 2020, the maximum value of q (X1∩X2) is 0.6624 and the minimum value is 0.0438, in which there are 45 items of two-factor enhancement and 46 items of nonlinear enhancement. In 2000, the interaction between GDP and population density and other factors was the strongest, and the explanation of ecological vulnerability in the study area was also the strongest. The interaction between annual mean relative humidity and GDP is strongest in 2010 and 2020. This indicates that socioeconomic factors and meteorological factors are the key driving forces for the change of ecological vulnerability in the study area. On the whole, the

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value of interaction between the factors in the two periods is greater than that of a single factor, which mainly indicates that the impact of indicators on ecological vulnerability is not completely independent of each other, but occurs synergistically. The ecological vulnerability of Dadu River Basin is the result of the comprehensive action of various factors.

Table 5. *Factor detection results of Dadu River Basin*

Influence factor	q		
	2000	**2010**	**2020**
GDP	0.5366	0.5487	0.4492
Population density	0.5210	0.4830	0.3958
Annual precipitation	0.0805	0.5507	0.2265
Annual evaporation	0.3345	0.3381	0.2801
Relative humidity	0.0723	0.5804	0.5695
Sunshine number	0.4710	0.5956	0.3771
Annual mean temperature	0.3544	0.3146	0.1304
Wind speed	0.0655	0.0576	0.0226
NDVI	0.4574	0.0095	0.0212
Soil organic carbon content	0.5055	0.2779	0.1943
Clay content	0.0901	0.4388	0.3325
Elevation	0.0097	0.3779	0.1997
Slope	0.0219	0.0081	0.0132
Aspect of slope	0.4391	0.0044	0.0064

Cause analysis of ecological environment vulnerability in Dadu River Basin

From the perspective of region, the ecological environment of Banma County, Seda County, Rangtang County, Daofu County and Luhuo County, which are located in the upper reaches of the basin, is fragile. Generally speaking, these areas are located at the eastern foot of the Qinghai-Tibet Plateau, with high altitude, thin air, low vegetation coverage, low scrub and alpine meadows, abundant precipitation and concentrated in summer, large temperature difference throughout the year, poor soil and water conservation ability, unreasonable land resource allocation, and bare land and low vegetation cover. With the development of human secondary and tertiary industries, soil erosion has intensified, and the ecological environment in the region has been deteriorating. At the same time, there is a lot of animal husbandry in the region, and overgrazing leads to soil desertification and vegetation destruction. Frequent human activities further increase the ecological pressure on the already fragile plateau, and the ecological environment is extremely vulnerable.

Jinchuan County, Danba County, Kangding City and Jiulong County in the central and eastern parts of the study area are mostly moderately vulnerable areas. These areas are mainly located in the transition zone between the Qinghai-Tibet Plateau and Sichuan Basin, with high topography and large elevation drop. The precipitation is mainly concentrated in summer, and the vegetation coverage is high and shows vertical zonal differentiation. The geological structure of this region is unstable, with frequent geological disasters such as landslides, mud-rock flows and earthquakes. In addition, this region is located on the lee slope of the monsoon, the foehn effect is significant, and

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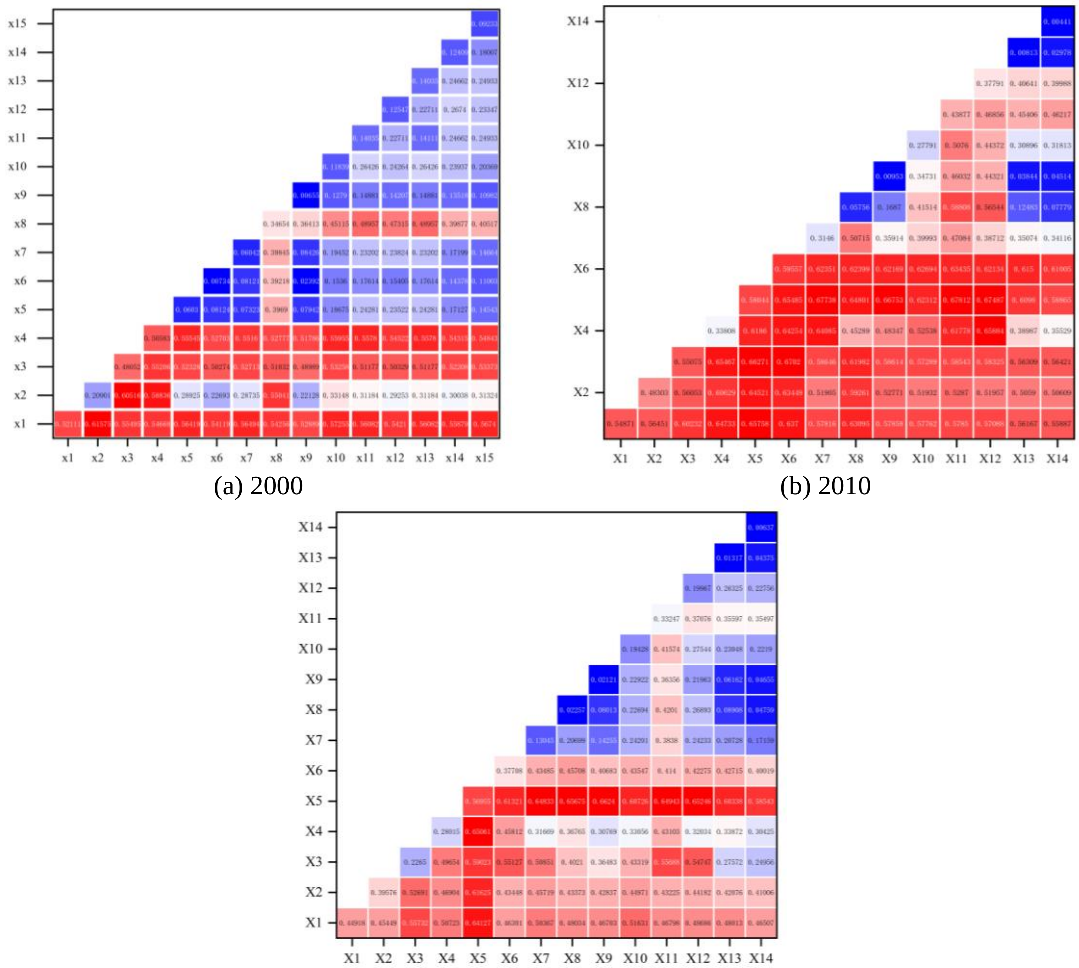
the vegetation is mostly low shrubs, resulting in relatively serious soil erosion and relatively poor soil. In addition, the continuous economic development and the continuous promotion of transportation facilities in recent years have gradually increased the pressure on the ecological environment. Vulnerability is growing.



(a) 2000 (b) 2010 (c) 2020

Figure 5. *Interactive detection results of factors in Dadu River Basin. X1-X12 is GDP, population density, annual precipitation, annual evaporation, annual mean relative humidity, annual sunshine, annual average temperature, annual mean wind speed, NDVI, soil organic carbon content, clay content, elevation, slope and aspect of slope*

Shimian County, Ganluo County, Shawan District, Ebian County and other places in the lower reaches of the basin belong to the mild and slight vulnerable areas. In the downstream area of the river, the flow rate slows down, the erosion effect of the river on the valley is weakened, and the soil and water loss are relatively good. In addition, the altitude is low, the precipitation is abundant and the temperature is suitable, and the vegetation coverage is high. This area is located in the edge of Sichuan Basin, the overall geological structure is relatively stable, the frequency of geological disasters is low, and the impact on the environment is small. In addition, this region is an area with good economic development in the study area, with dense population and frequent economic activities, which will inevitably have a negative impact on the ecological

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environment. If the environmental protection is not strengthened, the ecological vulnerability will continue to increase and the environment will continue to deteriorate.

In general, Dadu River Basin is an arid valley area with less precipitation, mainly plateaus and mountains, and large temperature difference between day and night. Such climatic and topographic conditions make the ecological environment of the whole region fragile. With the frequent economic activities of human beings and the continuous increase of population, the whole basin is faced with the risk of continuous deterioration of ecological environment, especially the development of tourism and industry, which has a great impact on the environment. How to achieve the coordinated development of environmental protection and economy is an important issue facing the whole region.

Discussion

This study divides Dadu River Area in different periods. By using SRP model, 14 indicators are selected to calculate the vulnerability degree of different regions in the basin in 2000, 2010 and 2020, and explore the causes and change characteristics of the vulnerability. The results indicated that the environment in the research area was deteriorating and the vulnerability was increasing, which was parallel with the research conclusions of Xu et al. (2021). Since 2000, the area of extremely heavy and severely vulnerable areas in Dadu River Basin has been increasing, especially in plateau and mountain areas. Brooks, et al. (2004) believe that ecological vulnerability is an inherent attribute within the ecosystem, and it is the ability to adapt to external disturbances Zhang et al. (2021), when studying the temporal and spatial evolution of ecological vulnerability in the arid region of Northwest China, also came to the conclusion that severely vulnerable areas in the study area were increasing. The SRP model used in this paper is an important method in vulnerability research, but the selection of evaluation indicators is highly subjective and has certain defects, which is parallel with the consequences presented by Li et al. (2021) when using SRP model to study the evolution characteristics of ecological vulnerability in karst topography in southwestern China. Salvati et al. (2009) used the comprehensive Index of land vulnerability (LVA) to study the city of Radham in Italy and showed that drought, population growth and land use change were the key factors leading to land vulnerability. Based on the study of ecological vulnerability, this paper concludes that the degree of vulnerability will continue to increase over time, and the ecological environment will also become more vulnerable in areas with large elevation fluctuations and frequent economic activities (Tang et al., 2020; Liu et al., 2020). This study focuses on three periods of time: 2000, 2010 and 2020. Although the results are generally not affected, there are still slight differences between the data.

The Dadu River Basin is a principle eco-safety barrier in the upper reaches of the Yangtze River and an principle water conservation area. The main stream develops from the Qinghai-Tibet Plateau, flows through the highland mountains to Leshan and enters the Sichuan Basin. The whole basin has large topographic fluctuations, great differences in temperature and precipitation, unstable geological structure and fragile ecological environment. Of late years, with the development of tourism in western Sichuan, the population of the plateau mountain area is increasing, which brings great pressure to the environment of the whole Dadu River Valley. The study of ecological vulnerability can make the key areas of ecological protection clear in the basin, so as to

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achieve the coordinated and sustainable development of economy and environment. Follow-up studies can focus on the spatio-temporal transformation of land use types in extremely heavy and severely vulnerable areas to explore the impact of land transfer on ecological vulnerability.

Conclusion

(1) The vulnerability classification of Dadu River Basin was calculated by ArcGIS. The vulnerability in the study area was divided into 5 levels from high to low.

(2) In 2000, the extremely vulnerable areas were primarily dispersed in the midst of the basin, the slight and venial vulnerable areas were dispersed in the lower reaches of the river, and the moderate vulnerable areas were primarily dispersed in the upper reaches of the northern river. In 2010, extremely heavy and severely vulnerable areas were mostly situated in the upper reaches of rivers. In 2020, the extremely vulnerable areas are mainly distributed in the midst of the basin, the slight and mildly vulnerable areas are dispersed in the lower reaches of the river, and the moderately vulnerable areas are primarily distributed in the upper reaches of the northern river, and the EVI displays a decreasing trend with the altitude.

(3) From the perspective of spatiotemporal transformation, the slightly vulnerable areas decreased by 2,033 km^2 in the past 20 years, accounting for 2.74% of the total basin area. The area of extremely heavy and vulnerable areas increased by 2,649 km^2, accounting for 3.41%. On the whole, the slightly vulnerable areas are decreasing, the extremely vulnerable regions are increasing, and the ecological environment in the whole research area is deteriorating.

(4) From the perspective of factor detection, the factors with the strongest explanatory power for the ecological vulnerability of the study area are GDP, population, annual sunshine, soil viscosity and annual mean relative humidity. From the perspective of interaction detection, there is a strong interaction between the factors, and the ecological vulnerability is the result of the comprehensive action of various factors.

(5) From the perspective of origin, the extremely heavy and severely vulnerable areas are mostly located in plateaus and mountains, and the climate and topography are important reasons for their ecological vulnerability. In the mildly and moderately vulnerable areas, the vulnerability situation is better due to topographic and climatic advantages, but the vulnerability level tends to increase due to the frequent economic activities of the population.

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