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Evaluation of the natural suitability of human settlements in the Western Sichuan Plateau region of China

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The natural suitability of human settlements is greatly influenced by the distinct ecological environment and natural conditions of the plateau area, which are of great eco-environmental significance. 32 counties in China's Western Sichuan Plateau were chosen as the study's research subjects. The evaluation index system and weight of the natural suitability of human settlements were established, along with the obstacle degree model, using the analytical hierarchy process, the entropy method, and the integrated weight method. In order to conduct a thorough investigation into the natural suitability of human settlements in 32 counties in the Western Sichuan Plateau, ArcGIS and other software were utilized to analyze the spatial and features of tempo-spatial variations as well as establish the values and thresholds of natural suitability. This study has gathered important findings: extracting the nature reserves, the natural suitability of human settlements in the Western Sichuan Plateau ranges from 0.3898 to 0.7178, with the overall spatial decrease from the east to the west; the disaster factor and the resource factor are dominant obstacles in different suitability zones. Geographically, the eastern part of the Western Sichuan Plateau is a high plain area characterized by stable geological activities and abundant resources. In contrast, the western part is the core area of the Hengduan Mountains, marked by frequent geological activities and scarce resource availability. The natural environment solely does not define the natural suitability of human settlements in the Western Sichuan Plateau; rather, this is decided by the interaction of the social and humanistic environments with the natural environment. Thus, this study provides empirical evidence and theoretical direction for the establishment of ecological civilization in the Western Sichuan Plateau from the perspective of evaluation of natural suitability, which is crucial for promoting the area's coordinated development and raising the standard of living for the local population.

Keywords Western Sichuan Plateau, Human settlements, Natural suitability, Obstacle degree

The world faces numerous challenges, including extreme poverty, inequality, climate change, environmental degradation, and social injustice¹. The United Nations proposed the Sustainable Development Goals (SDGs) in 2015, and one of the key elements of the goals emphasizes environmental sustainability². China, as the world's largest developing country, has proposed the Beautiful China Initiative, which aims to explore solutions with Chinese characteristics to promote regional sustainability³. With global climate change and regional development, human settlement evaluation is important for guiding regional planning, ecological protection, and sustainable development⁴.

Human settlement is the place where human beings live together, as well as the surface space that is closely related to human living activities and the principal places where human beings utilize nature to transform it⁵. Wu understood human settlements as evolving on the basis of five major systems, namely, nature, society, human beings, residence, and support⁶. In recent years, research on the suitability of human settlements can be broadly categorized into macro-scale and micro-scale⁷, in which changes in the natural environment at the macro-scale are considered to be one of the dominant factors affecting human settlements⁸, and there is a distinct variation in the spatial distribution characteristics of different types of natural environments⁹. The natural suitability of human settlements is a combination of natural environmental features including climate, topography, soil and

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water resources, atmosphere and land cover, and its suitability for concentrated human habitation⁷. The natural system of human settlements was the subject of a thorough evaluation approach proposed by Feng et al.¹⁰, but the support provided for research at different research scales and specific research areas was limited. In recent years, many scholars in the study of the natural suitability of human settlements have followed the national scale^{11,12}, regional scale^{13–15}, urban space^{16–18}, and community (village and town) units^{19–21} as the study areas. By analyzing factors such as topography and climate and thus constructing a human environment evaluation system that corresponds to the scale, the spatial relationship between the natural environment and the distribution of human settlements is explored, among which some scholars studied the distribution pattern of urban living suitability in the Xerias Stream of Greece from the perspective of natural disaster factors such as landslides²². Hierarchical analysis method, entropy weighting method, principal component analysis method, fully aligned polygon method, and multi-indicator comprehensive evaluation method are commonly employed in constructing the evaluation index system for the natural suitability of the human habitat environment^{23–26}. Advancements in remote sensing and GIS technology also enable multi-factorial and comprehensive quantitative analyses.

Currently, there is relatively scarce research on the natural suitability of habitats in special spatial types of areas. Considered a significant geographic entity in western China, the Western Sichuan Plateau (WSP) possesses unique natural conditions and ecological environments, which hold substantial ecological and environmental importance and significantly affect the natural suitability of habitats. Current research on the evaluation of the natural suitability of human habitats has not succeeded in providing targeted theoretical guidance for the Western Sichuan Plateau region, particularly the frequent natural disasters characteristic of the Plateau, which significantly impact human habitats in the region. Constructing a natural suitability evaluation system for human habitats tailored to the unique natural conditions of the Western Sichuan Plateau to thereby provide data support and theoretical guidance for ecological civilization construction in the region, and to elucidate which areas of the Western Sichuan Plateau region are inhospitable to long-term human survival and habitation? Locating the limited space suitable for long-term human habitation? What are the factors that primarily affect the natural suitability of habitats in the Western Sichuan Plateau region? These questions must be addressed in the evaluation of the natural suitability of habitats.

This study takes 32 counties in WSP, as the research object, and conducts a systematic research on the natural suitability of human settlements. Identification of factors influencing the natural suitability of habitats based on local conditions, and employment of diverse research methodologies to conduct a comprehensive examination of habitats holistically. The purpose of the study is to explore the human-land relationship in plateau regions, constructing a system of index for evaluating the natural suitability of human settlements in WSP (Fig. 1), and revealing the features of human settlements in that region in order to provide a scientific basis for the optimization of living environments in the region and the sustainable development of it.

Materials and methods

The study area

The WSP is located in the western part of Sichuan Province, China, and is part of the southeastern edge of the Tibetan Plateau and the Hengduan Mountains (Fig. 2), with an area ranging from 97° 34'–104° 43' E to 27° 67'–34° 31' N. In order to enable a precise study scope and access to data, the WSP referred to in this paper includes 32 counties in Ganzi Tibetan Autonomous Prefecture, Aba Tibetan and Qiang Autonomous Prefecture, and the Tibetan Autonomous County of Muli in Liangshan Yi Autonomous Prefecture in terms of administrative divisions, with a total administrative area of $2.4 \times 105 \text{ km}^2$, which accounts for 48.67% of the total area of Sichuan Province. The study area, with an average elevation of over 4000 m and obvious seasonal changes, is a transition zone between continental monsoon climate and plateau monsoon climate, mainly dominated by cold-temperate climate²⁷, and the vegetation mainly includes mountain warm-temperate mixed coniferous and broad-leaved forests, subalpine cold-temperate dark coniferous forests, alpine subarctic scrub meadows, etc²⁸. The WSP, as an important ecological obstacle and multi-ethnic clustering area in western China, not only possesses unique natural landscapes, but also has a variety of resources as well as a pristine and intact ecosystem.

Data sources

In this study, the location of each county government was used as the geographic coordinates of the county to calculate its topographic and climatic data. The following data were used: Digital Elevation Model (DEM) from Geospatial Data Cloud (<https://www.gscloud.cn/>) with a 30 m spatial resolution for WSP; based on the DEM data, the topographic factors of the study area were calculated by the extraction function of ArcGIS (ArcGIS 10.8, <https://www.esri.com/>): elevation, aspect and angle of slope, and relief degree; and land use intensity was calculated based on the LUCC dataset with a 1 km spatial resolution provided by the Resource and Environment Science Data Center (<http://www.resdc.cn/data.aspx>). Meteorological data were obtained from the basic data of 126 meteorological stations on the Resource Discipline Innovation Platform (http://www.data.ac.cn/list/tab_climate), and the average precipitation, average annual temperature, average annual evaporation, sunshine duration, and average annual wind speed of the vegetation cover of the area from 2010 to 2020 were extracted by using the relevant software, such as ArcGIS. The Normalized Difference Vegetation Index data were extracted from the GIMMS-NDVI dataset provided by the global vegetation cover laboratory of the University of Maryland at a resolution of 8 km × 8 km (<https://ecocast.arc.nasa.gov/data/pub/gimms/>). Data on disaster sites in Sichuan Province were obtained from Geographic Data Sharing Infrastructure, global resources data cloud (www.gis5g.com).

Selection and construction of evaluation indices

The natural environment is the foundation of human settlements, and human life as well as specific construction of living environments cannot be separated from the broad background of the background of the natural environment²⁹. The study area has a complex geological structure and strong motion and is a geologically

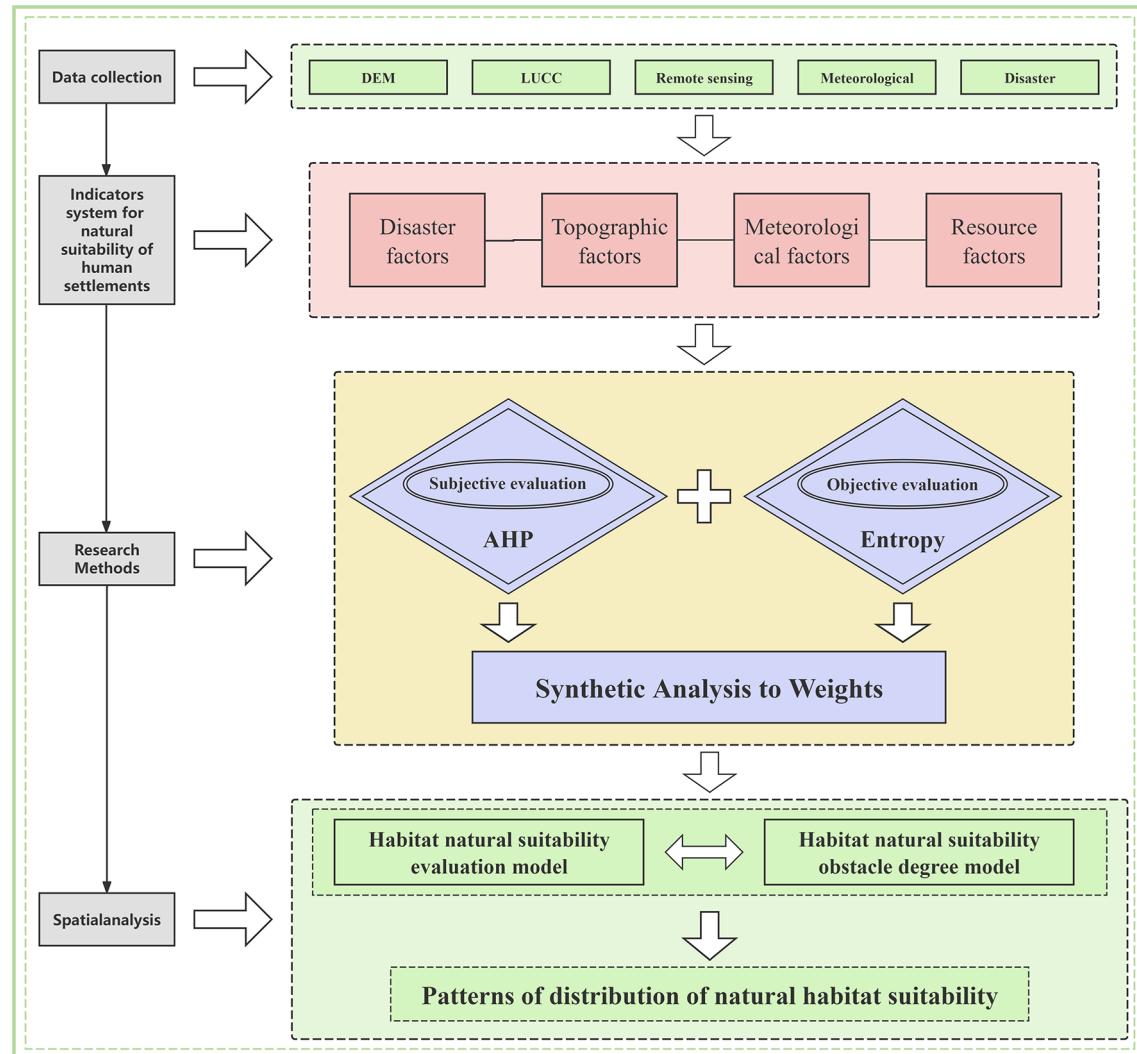


Fig. 1. Research framework.

hazardous region where mudslides, landslides, and collapses frequently occur³⁰, of which the above three types of geological disasters account for more than 90% of the total in WSP, especially mudslides throughout the region of each county and city³¹. The average altitude of the study area is more than 4000 m. According to the topography, it can be roughly divided into two parts: the Northwest Sichuan Plateau (northern part) and the West Sichuan Mountain (southern part)³², and the climate type is mainly subtropical plateau climate and the middle-subtropical monsoon climate³³, so the region has an abundance of natural resources. Through the above investigation and integral analysis of the human settlements in the study area, following comprehensive, systematic, and applicable principles, 15 indices in the natural environment were selected, and a natural suitability evaluation index system for human settlements of WSP in terms of counties was established (Table 1).

Research methods

Dimensionless quantification of index data

Firstly, the original index data are dimensionless, and the formula is as follows:

$$X_{ij} = (x_{ij} - x_{ij \min}) / (x_{ij \max} - x_{ij \min}) \quad (1)$$

$$X_{ij} = (x_{ij \max} - x_{ij}) / (x_{ij \max} - x_{ij \min}) \quad (2)$$

$$X_{ij} = x_{ij} - x_o \quad (3)$$

where X_{ij} refers to the score (i.e. index evaluation coefficient) after the dimensionless processing of the original index data; x_{ij} refers to the actual value of the sample; $x_{ij \max}$ refers to the maximum value of the indicator sequences; $x_{ij \min}$ refers to the minimum value of the indicator sequences; and x_o refers to the ideal value of the indicator and then this paper adopts the weighted average as a reference. When applying formula (1), an indicator that is higher corresponds more closely to the natural suitability of human settlements; when applying

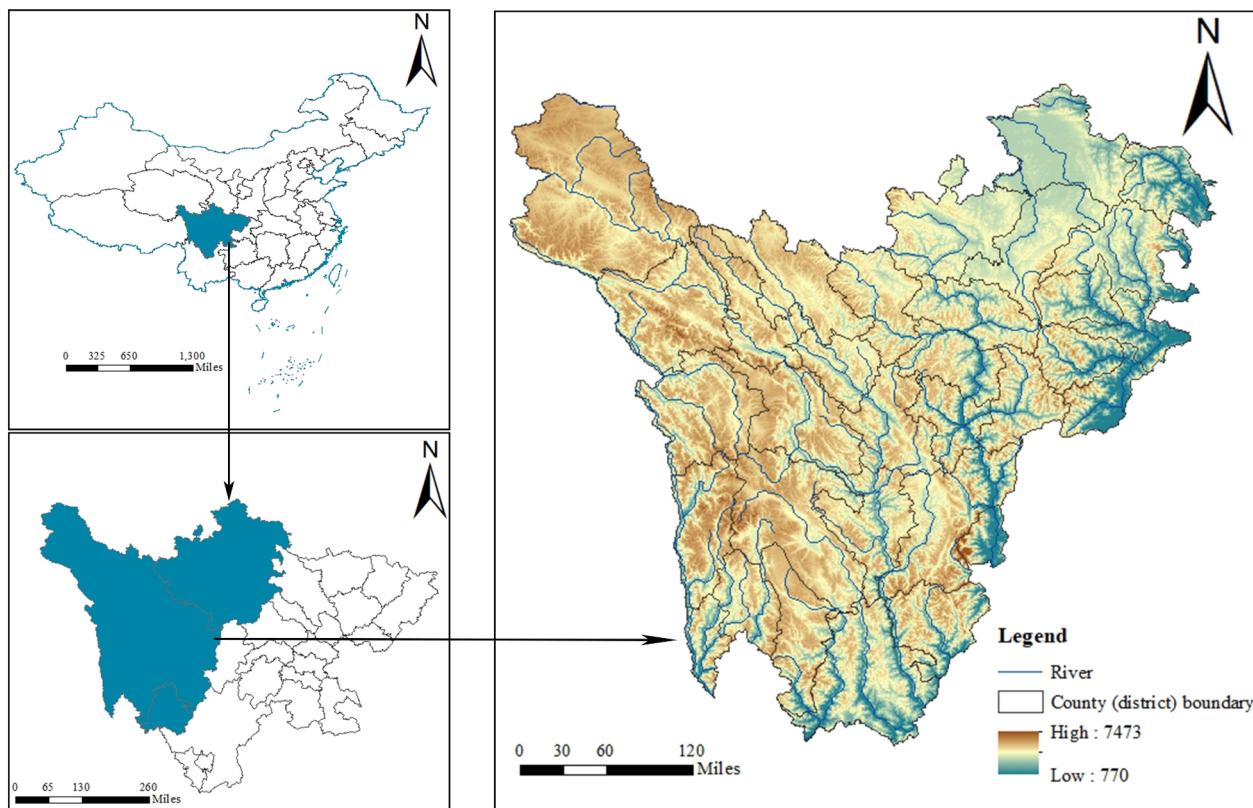


Fig. 2. Location of the study area (Mapped by ArcGIS 10.8 software, <https://www.esri.com/>).

Target layer	Standardized layers	Index layers
Evaluation of the natural suitability of habitat on the Western Sichuan Plateau	Disaster factors	Disaster frequency (X1), Disaster coefficient (X2)
	Topographic factors	Elevations (X3), Slope (X4), Direction slope (X5), Undulate (X6)
	Meteorological factors	Average annual rainfall (X7), Average annual temperature (X8), Wind speed (X9), Daylight hours (X10), Evaporation (X11)
	Resource factors	Plant normalized difference vegetation index (NDVI) (X12), Land use intensity (X13), Plant net primary productivity (NPP) (X14), Cropland area (X15)

Table 1. Natural suitability evaluation system for human settlements in the Western Sichuan Plateau.

formula (2), an indicator that is lower corresponds more closely to the natural suitability of human settlements; for the neutral indicator, the formula (3) is applied to calculate the difference between the sample values and the weighted average, and the living environment is more appropriate the smaller the difference, then the formula (2) is applied again, and this paper does not exist any neutral indicator.

Determination of index weight

Determining the weights of indicators is an important basis for evaluating the natural suitability of human settlements. At present, the methods of index weight mainly include analytic hierarchy process, the Delphi method, the mean square weighted deviation method, the entropy method and so on. In order to improve the accuracy and credibility of index weights, this paper adopts the combination of analytic hierarchy process and the entropy method³⁴ to assign weights to the evaluation index system of natural suitability of human settlements in WSP.

The rationale for this approach is that the distinctive geographical and ecological characteristics of the study area can be effectively addressed through the use of a subjective hierarchical analysis method. This method allows for the complex multi-objective decision-making problem of the study area to be viewed as a system, decomposing the objectives into multiple goals or criteria and then into several levels of multi-indicators. This enables the problem to be solved through the use of qualitative indicators. Furthermore, the objective entropy weighting method can, to a certain extent, circumvent the potential arbitrariness and randomness associated with a single subjective assignment method.

Analytic hierarchy process Analytic hierarchy process (AHP) is a scientific and practical approach to decision making on complex problems. It decomposes the relevant elements related to decision making into a hierarchical structure, quantifies human subjective judgment with certain scales, and conducts layer-by-layer tests to compare the reasonableness of results³⁵.

The entropy method Entropy is derived from thermodynamics. In general, greater information presented, more weight, and a higher degree of variability in the index value correspond with smaller information entropy of the evaluation index³⁶. So, the weight L_j refers to each evaluation index of natural suitability of human settlements, which can be calculated according to the entropy value.

- (1) With m evaluation indicators and n evaluation objects, the original data matrix $R = (r_{ij})_{m \times n}$ is formed. The entropy for the i th indicator is defined as:

$$f_{ij} = f_{ij} / \sum_{j=1}^n r_{ij} \quad (4)$$

$$H_i = -k \sum_{j=1}^n f_{ij} \ln f_{ij}, \quad k = 1 / \ln n \quad i = 1, 2, 3, \dots, m; \quad j = 1, 2, 3, \dots, n \quad (5)$$

where when $f_{ij} = 0$, make $f_{ij} \ln f_{ij} = 0$. f_{ij} is the weight of the j th evaluation object under the i th indicator in this indicator; n is the number of evaluation objects; H_i is the entropy of the i th indicator.

- (2) After defining the entropy of the i th indicator, the entropy weight of the i th indicator is defined as:

$$w_{2i} = \frac{1 - H_i}{n - \sum_{i=1}^m H_i} \quad (6)$$

where $0 \leq w_{2i} \leq 1$, $\sum_{i=1}^m H_i$ is the entropy of the i th indicator; m is the number of evaluation indicators; w_{2i} is the entropy weight of the i th indicator.

Synthetic analysis to weights In this paper, the weights are determined according to two methods: analytic hierarchy process and the entropy method, and there is no preference, so the preference coefficient $\mu = 0.5$ is used to calculate the final weights of each indicator W_j .

$$W_j = \mu L_j + (1 - \mu) Q_j \quad (7)$$

where j is the j th evaluation indicator; Q_j is the weight of the j th indicator calculated according to analytic hierarchy process; L_j is the weight of the j th indicator calculated according to the entropy method; W_j is the final weight of the j th indicator.

Evaluation model of natural suitability of human settlements

According to the integrated weight of the indicator W_j and the standardized value of each county and county-level unit after the dimensionless quantifying of the indicators Y_{ij} , the suitability level of the living environment is measured by using the weighted sum method, and the results of the evaluation of the natural suitability of the human settlements in the 32 counties(cities) of WSP can be obtained.

$$f_{ij} = W_j \times Y_{ij} \quad (8)$$

$$F_i = \sum_{j=1}^n f_{ij} \quad (9)$$

where f_{ij} is the evaluation value of the j th indicator of i county or county-level unit, and F_i is the overall evaluation of the natural suitability of human settlements in i county or county-level unit.

Obstacle degree model

Obstacle degree model³⁷ is a mathematical statistical method to effectively determine the key factors that hinder the development, in order to deeply understand and analyze the natural suitability of human settlements in WSP, to further assess which factors play a dominant role in the evaluation of the natural suitability of human habitats, as well as to supplement and verify the established evaluation model of the natural suitability of human habitats, thereby rendering the study's results more robust and comprehensive. Consequently, the obstacle degree model of the natural suitability of living environments is formed to explore the obstacle factors that affect the natural suitability of human settlements, and the formulas are as follows:

$$P_j = \left[(1 - X_{ij}) \times W_j / \sum_{j=1}^m (1 - X_{ij}) \times W_j \right] \times 100\% \quad (10)$$

$$V_j = \sum P_j \quad (11)$$

where P_j refers to obstacle degree of single index to the resilience of the rural living environment system; X_{ij} is the standardized value of single index; $m=15$; V_j is the degree of obstacle of each subsystem layer to the resilience of the rural habitat system.

Results and analysis

Synthetic evaluation and analysis of the natural suitability of human settlements in the Western Sichuan Plateau

Analysis of evaluation index weights

There are 4 standardized layers and 15 index layers for the natural suitability of human settlements in the study area. The disaster factor (0.2435), topographic factor (0.2382), meteorological factor (0.2601), and resource factor (0.2582) were among the standardized layers and their corresponding weights. In contrast, disaster coefficients (0.1294), disaster frequency (0.1142), vegetation NPP (0.0788), annual rainfall (0.0748), and cultivated area (0.0674) were given greater weights in the index layers (Table 2). The other standardized layers were made up of four or more index layers, of which the meteorological factor accounted for 26.01% and the resource factor, for 25.82%. The disaster factor, which was composed of the disaster coefficient and disaster frequency, accounted for 24.35% of the total weight of the whole evaluation system. The sum of the weights of the resource factor and the meteorological factor accounted for 51.83% of the total weight, which constituted the main elements in the evaluation system of the natural suitability of human settlements in WSP.

Results of the overall evaluation of the natural suitability of human settlements

According to the findings of the assessment of the natural suitability of human settlements in WSP (Fig. 3), the northeastern and southern regions of the Plateau have better evaluation results than the western and eastern regions, with the highest evaluation results being 0.7178 in Hongyuan County and 0.6123 in Tibetan Autonomous County of Muli. The lowest evaluation results are found in the western and eastern regions of the Plateau, with the lowest results being 0.3898 in Dege County and 0.4049 in Xiaojin County. The geography of WSP is primarily made up of high plains and valleys, which are relatively flat in comparison to other regions, and the climate and tourism are the main reasons why there are less disasters in these regions than in others.

Since 2000, China has created a number of nature reserves to resolve possible conflicts between the preservation of the natural environment and human development and survival³⁸. The Giant Panda National Park, Gongga Mountain Nature Reserve, and Siguniang Mountain Nature Reserve are a few of the nature reserves located in the Western Sichuan Plateau³⁹. When zoning a location for a human settlement, the nature reserves should be removed because large-scale human activities are prohibited there. The environmental suitability of human settlements following the removal of the nature reserves is divided into five levels, as illustrated in Fig. 4. Table 3 displays how the results of the natural suitability index of human settlements following the removal of the nature reserve are divided into five grade ranges by using the natural breaks method⁴⁰. This allows for the establishment of the regional grading and spatial pattern of the natural suitability of human settlements in counties (cities), where the areas marked with I, II, III, and V are highly suitable, comparatively suitable, general-suitable, low-suitable, and unsuitable, respectively. Of the nature reserves, 53.61% are in low-suitable zones and 1.92% are in

Target layer	Standardized layers	Index layers	Nature of indicators	Entropy weights	AHP weights	Combined weights
Evaluation of the natural suitability of human settlements in the Western Sichuan Plateau	Disaster factors 0.2435	X1	– ^b	0.1068	0.1190	0.1142
		X2 ^c	–	0.1269	0.1310	0.1294
	Topographic factors 0.2382	X3	–	0.0412	0.0735	0.0606
		X4	–	0.0608	0.0714	0.0671
		X5	+ ^a	0.0608	0.0428	0.0499
		X6	–	0.0575	0.0624	0.0605
		X7	+	0.0474	0.0930	0.0748
	Meteorological factors* 0.2601	X8	+	0.0491	0.0551	0.0528
		X9	+	0.0768	0.0511	0.0614
		X10	+	0.0647	0.0285	0.0429
		X11	+	0.0372	0.0223	0.0283
		X12	+	0.0481	0.0576	0.0538
	Resource factors* 0.2582	X13	+	0.0676	0.0518	0.0581
		X14	+	0.0604	0.0910	0.0788
		X15	+	0.0947	0.0492	0.0674

Table 2. Evaluation index system of the natural suitability of the habitat in the Western Sichuan Plateau.

*The index layer data of meteorological factor and resource factor all adopt the average value of 2010–2020.

^a“+”indicates a positive indicator, one that favors the outcome of the habitat assessment. ^b“–”indicates a negative indicator, one that is not conducive to the outcome of the habitat assessment. ^cDisaster coefficient function model $A = \log_{10}(P + 10 + E/W)$, A is the disaster coefficient, P is the number of casualties (unit: person), E is the direct economic loss (unit: million yuan), and W is the weight value, taking 100, i.e., 1 casualty is regarded as 1 million yuan of economic loss.

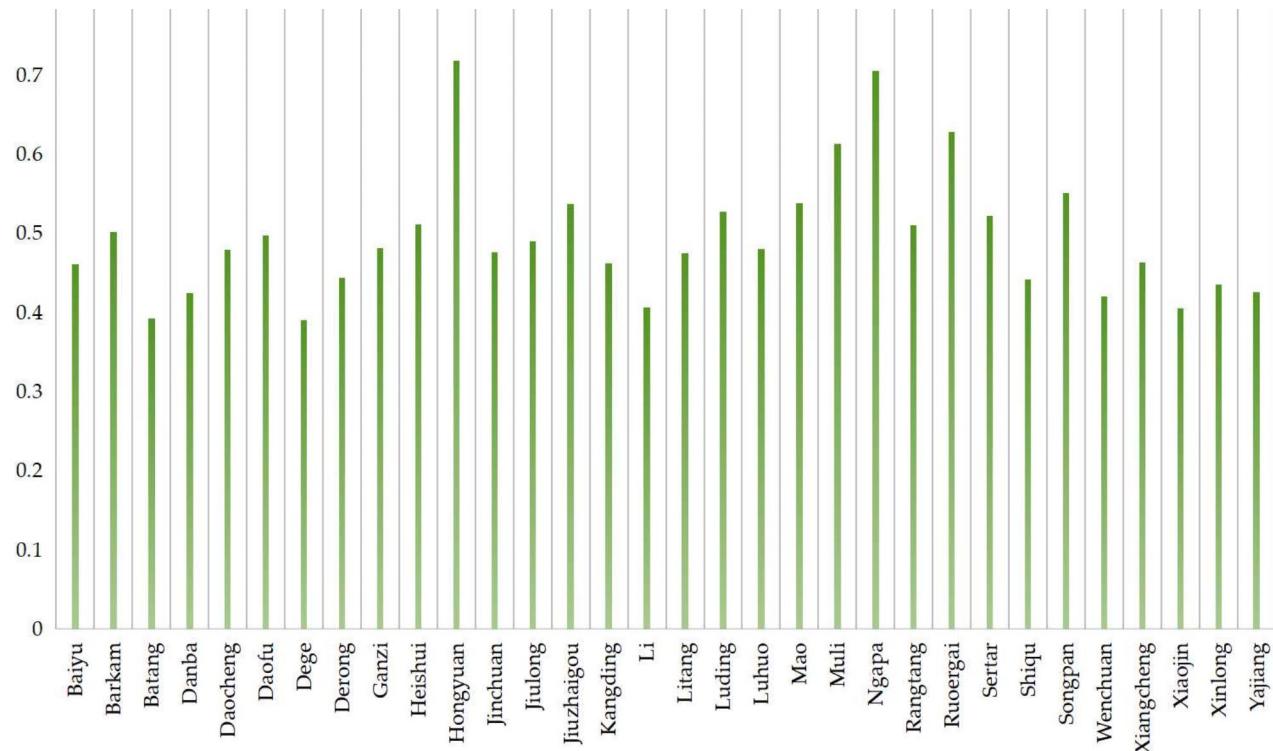


Fig. 3. Evaluation of indicator results of the natural suitability of the human habitat in each county (city).

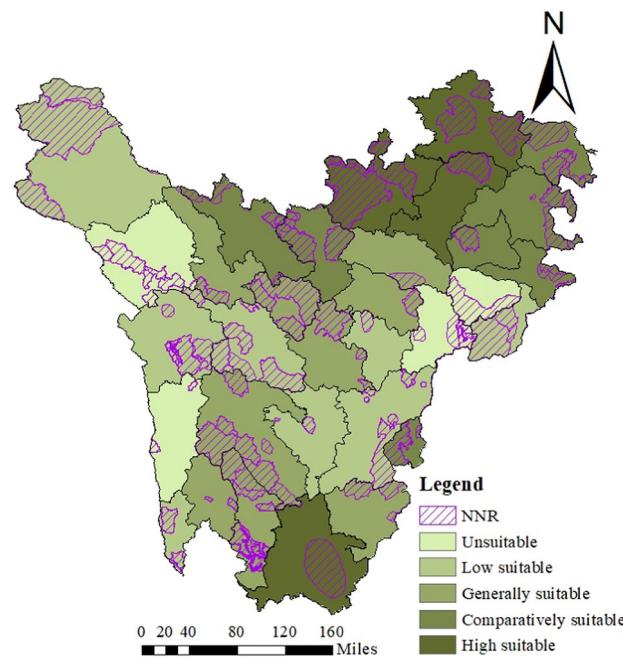


Fig. 4. Habitat natural suitability zoning. Highly suitable area (Zone I), Comparatively suitable area (Zone II), Generally suitable area (Zone III), Low- suitable area (Zone IV), Unsuitable area (Zone V).

unsuitable zones (very suitable area: 0.5503–0.7178; comparably suitable area: 0.5013–0.5502; generally suitable area: 0.4621–0.5012; low suitable area: 0.4201–0.4620; unsuitable area: 0.3898–0.4200). Consequently, over half of WSP is located in unsuitable and low-suitable zones, which is better for protecting nature reserves. The percentage of land appropriate for human habitation improved from 55.92 to 58.03% based on the categorization

Suitability level	Habitat natural suitability index		Description of habitat suitability	Theoretical area (km ²)	Percent (%) ^a	NNR* (km ²)	Percent (%) ^b	Practical area (km ²)	Percent (%) ^c
	Range	Averages							
Highly suitable area Zone I	0.5504–0.7178	0.6655	Good natural environment, optimal for human habitation	42,414	17.67	4430	11.81	37,984	18.76
Comparatively suitable area Zone II	0.4965–0.5503	0.5277	Less constrained by natural factors, more suitable for human habitation	47,033	19.61	10,610	28.29	36,423	17.99
Generally suitable area Zone III	0.4621–0.4964	0.4796	Somewhat affected by natural factors, generally suitable for human habitation	44,731	18.64	1640	4.37	43,091	21.28
Low-suitable area Zone IV	0.4201–0.4620	0.4386	Highly constrained by natural factors, generally suitable for human habitation	76,830	32.01	20,100	53.61	56,730	28.01
Unsuitable area Zone V	0.3898–0.4200	0.3982	Poor natural environment, unsuitable for human habitation	28,992	12.07	720	1.92	28,272	13.96

Table 3. Habitat natural suitability grading thresholds for the Western Sichuan Plateau. *NNR is Nature conservation. ^aProportion of the theoretical area at different suitability levels. ^bProportion of the National Nature Reserve area at different suitability levels. ^cProportion of the practical area at different suitability levels.

of several categories of suitable lands, although the coverage slightly fell by 16,680 km². The area shrank by roughly 20,820 km², and the percentage of low-suitable and unsuitable areas in the total area dropped to 41.97%.

Analysis of the results of the evaluation of the standardized layers in different types of areas

The spatial distribution of the evaluation indicators was calculated according to the natural suitability evaluation model of human settlements (Fig. 5), and the evaluation results were categorized into disaster factor, topographic factor, meteorological factor, and resource factor according to the standardized layer in the evaluation system.

Evaluation and analysis of disaster factors

In this paper, two indicators, disaster coefficient and disaster frequency, which directly reflect the evaluation results of disaster factor, were extracted through the analysis of geohazard data in Sichuan Province. From Table 4, it can be concluded that the evaluation results of disaster factor in different types of zones are between 0.0964 and 0.1800, and with the decrease of suitability, the evaluation results of disaster factor also decrease. Among them, the difference between the comparatively suitable area and the generally suitable area is small, and the evaluation result of the generally suitable area is slightly better than that of the comparatively suitable area.

Evaluation and analysis of topographic factors

Table 5 demonstrates that the evaluation results of the topography factor in different types of zones range from 0.1215 to 0.1636, with a rising trend as suitability increases. Among them, the data of the topographic factor index layer of Zone I are higher than those of other types of zones because the four counties of Zone I are in the northeastern part of the WSP as well as the southern part of the region, have a lower average elevation than those of other counties, and belong to the high plains in terms of terrain. Slope direction indicator (0.0182–0.0257) and topographic factor evaluation results in different types of zones have significant differences; slope indicator in the unsuitable area of the indicator results are better than other types of zones. It indicates that the results of slope direction for different types of suitability are less significant than the results of other indicators on their influence, but there is a positive correlation trend on the overall topographic factor evaluation.

Evaluation and analysis of meteorological factors

In this study, the meteorological factors adopt average values from 2010 to 2020, and the corresponding index layer data are more accurately derived through the spatial and temporal dimensions. Table 6 shows that the evaluation results of the meteorological factors of different types of zones are in the range of 0.1058–0.1784, which demonstrates a rising tendency as suitability increases. Among them, the results of annual average temperature (0.0221–0.0334), wind speed (0.0110–0.0412), and sunshine duration (0.0249–0.0370) are positively correlated with suitability. The results of annual average rainfall (0.0249–0.0506), evaporation (0.0123–0.0207), and evaluation of meteorological factors in the study area are dramatically various in different types of zones, and the results of the annual average rainfall indicator are the highest in the comparatively suitable zone and the lowest in the generally suitable zone, and the evaporation indicator is the lowest in the low-suitable zone. The reason for this is that the climate type in the eastern and southern parts of the study area is a middle subtropical monsoon climate with higher annual rainfall than in other areas.

Evaluation and analysis of resource factors

The average values of the index layer data for each county in the study region from 2010 to 2020 were employed based on different types of suitability zones. and it can be seen from Table 7 that, as suitability increases, so do the results of the resource factor evaluation in the study area (0.0744–0.1436), the plant NDVI indicator (0.0212–0.0424), and the land use intensity indicator (0.0098–0.0381). The results of the cultivated land area indicator (0.0220–0.0293) and the plant NPP indicator (0.0205–0.0373) differed in various zones, in which the plant NPP indicator had the highest results in a more suitable zone and the cultivated land area indicator had the

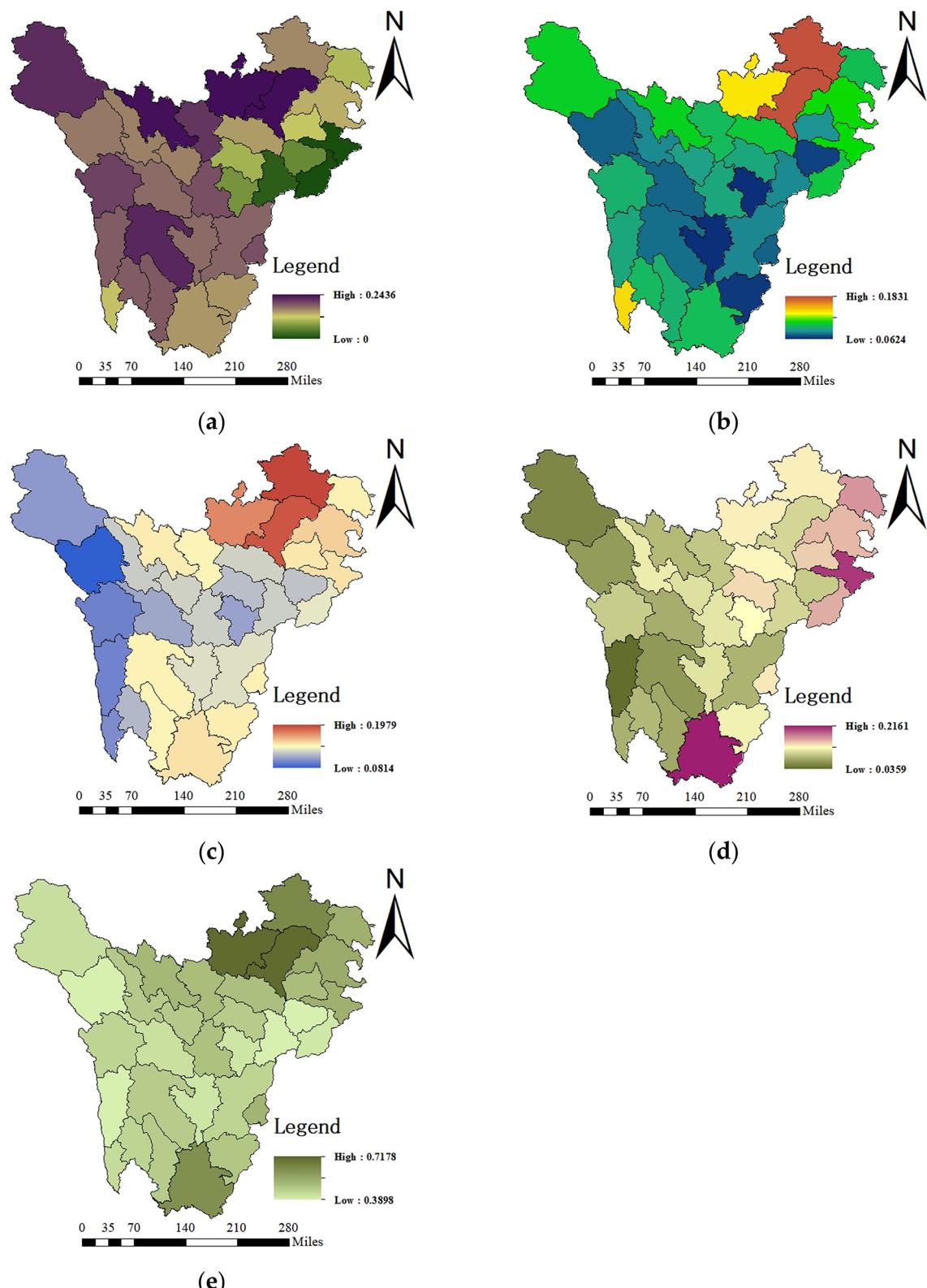


Fig. 5. (a) Disaster factors; (b) Topographic factors; (c) Meteorological factors; (d) Resource factors; (e) Spatial distribution of natural suitability of the overall habitat at the county level. Suitability of the overall habitat at the county level.

Typology area	Average value of indicators		Disaster factors	
	X1	X2		
Zone I	0.1048	0.0752	0.1800	
Zone II	0.0909	0.0213	0.1122	
Zone III	0.1011	0.0223	0.1234	
Zone IV	0.0828	0.0231	0.1059	
Zone V	0.0790	0.0174	0.0964	

Table 4. Evaluation results of disaster factors.

Typology area	Average value of indicators				Topographic factors
	X3	X4	X5	X6	
Zone I	0.0339	0.0495	0.0197	0.0605	0.1636
Zone II	0.0364	0.0181	0.0182	0.0605	0.1332
Zone III	0.0165	0.0296	0.0194	0.0605	0.1260
Zone IV	0.0225	0.0241	0.0228	0.0529	0.1223
Zone V	0.0177	0.0176	0.0257	0.0605	0.1215

Table 5. Evaluation results of topographic factors.

Typology area	Average value of indicators					Meteorological factors
	X7	X8	X9	X10	X11	
Zone I	0.0461	0.0334	0.0412	0.0370	0.0207	0.1784
Zone II	0.0506	0.0324	0.0331	0.0253	0.0189	0.1603
Zone III	0.0249	0.0281	0.0245	0.0370	0.0156	0.1301
Zone IV	0.0255	0.0299	0.0194	0.0273	0.0123	0.1143
Zone V	0.0299	0.0221	0.0110	0.0249	0.0180	0.1058

Table 6. Evaluation results of meteorological factors.

Typology area	Average value of indicators				Resource factors
	X12	X13	X14	X15	
Zone I	0.0424	0.0381	0.0339	0.0293	0.1436
Zone II	0.0394	0.0355	0.0373	0.0230	0.1352
Zone III	0.0240	0.0286	0.0232	0.0244	0.1002
Zone IV	0.0222	0.0257	0.0261	0.0220	0.0961
Zone V	0.0212	0.0098	0.0205	0.0229	0.0744

Table 7. Evaluation results of resource factors.

lowest results in a less suitable zone. The reason is that plant NPP indicators are directly related to meteorological factors, such as rainfall, temperature, evaporation, and other meteorological factors that affect plant NPP, and cultivated land area is related to man-made factors.

Analysis of the spatiotemporal evolution characteristics of natural suitability of human settlements in the Western Sichuan Plateau

Based on the evaluation model of the natural suitability of human settlements, the evaluation results in 32 counties (cities) in the Western Sichuan Plateau were calculated in 2010, 2015, and 2020, and the spatial and temporal evolution maps were plotted using ArcGIS software (Fig. 6). In the spatial dimension, the overall level of the natural suitability of the habitat in WSP declined from 15.7140 in 2010 to 14.9675 in 2015, and then to 14.9473 in 2020. There is a downward trend in the overall suitability level. The reason is that during the 12th Five-Year Plan period, Sichuan Province vigorously develops the regional economy and improves the quality of industries, so the management of the ecological environment is weakened, which leads to a decrease in the overall suitability level of the human habitat in the study area during this period. During the 13th Five-Year Plan period (The Central Committee of the Communist Party of China has issued recommendations for the

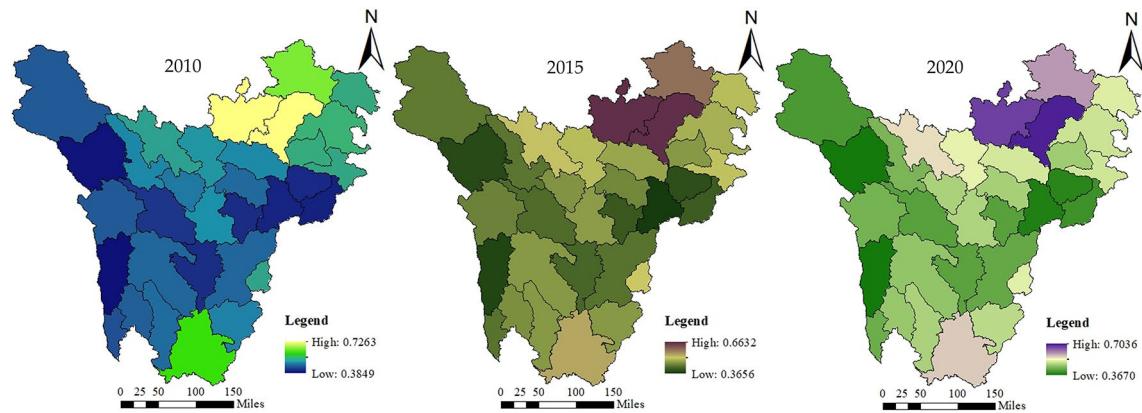


Fig. 6. Spatial and temporal evolution of the natural suitability index of the habitat in the Western Sichuan Plateau.

Standardized layers	Obstacle factors	High suitable area	Comparatively suitable area	Generally suitable area	Low-suitable area	Unsuitable area
Disaster factors	X2	X2	X2	X2	X2	X2
	X1	X1	X1	X1	X1	X1
Topographic factors	X5	X4	X3	X4	X4	X5
	X3	X5	X4	X3	X3	X3
Meteorological factors	X7	X9	X7	X7	X9	X7
	X8	X7	X9	X9	X7	X8
Resource factors	X14	X15	X14	X14	X14	X14
	X15	X14	X15	X15	X13	X15

Table 8. The main obstacles to the natural suitability of human settlements.

formulation of the 13th Five-Year Plan for National Economic and Social Development), Sichuan Province put eco-environment protection and management in an important position, and the overall natural suitability level of the human habitat remained basically unchanged during the period of 2015–2020. In the spatial dimension, the level of natural suitability of human settlements decreases from east to west, as well as from north to south, which is due to the fact that the terrain in the east and south is lower in elevation than that in other areas, and the climate environment is better and rich in resources.

Analysis of obstacle factors to natural suitability of human settlements in different types of zones

Analysis of obstacle factors to natural suitability of human settlements

According to formula (8), the degree of obstacle factors for each suitability zone in the Western Sichuan plateau was calculated, and the top 2 obstacle factors were listed. The results are shown in Table 8. Among the disaster factors, the disaster coefficient X2 and the disaster frequency X1 were the main obstacle factors in all types of areas, and therefore, improving disaster prevention is the key to improving the natural suitability of human settlements in the study area. Among the topographic factors, slope direction X5 and elevation X3 are the main obstacle factors in the highly suitable area; slope X4 and slope direction X5 are the main obstacle factors in the more suitable area, which indicates that the plateau area has an important influence on the residents' lives; and elevation X3 and slope X4 are the main obstacle factors in other types of areas. Among the meteorological factors, average annual rainfall X7 and average annual temperature X8 are the main obstacle factors in highly suitable areas; average annual rainfall X7 and wind speed X9 are the main obstacle factors in other types of areas. Among the resource factors, land use intensity X13 and plant NPP X14 are the main obstacle factors in unsuitable zones; plant NPP X14 and cultivated land area X15 are the main obstacle factors in other types of zones, so land use as well as plant ecology in plateau areas have an important impact on the human habitat.

The degree of obstacle of the four standardized layers calculated according to formula (9) for each suitability type is shown in Fig. 7. The resource factor is the dominant obstacle in highly suitable, generally suitable, low-suitable and unsuitable zones; the disaster factor is the dominant obstacle in more suitable zones.

Discussion

The natural environment of WSP is complex and diverse, involving many factors such as climate, geomorphology, hydrology, and biology. The high altitude of the region leads to the obvious vertical distribution of its climate, while the complex and varied topography makes the natural environment of different counties (cities) differ significantly. In the Western Sichuan Plateau, as a multi-ethnic clustering region, the Tibetan people mostly live

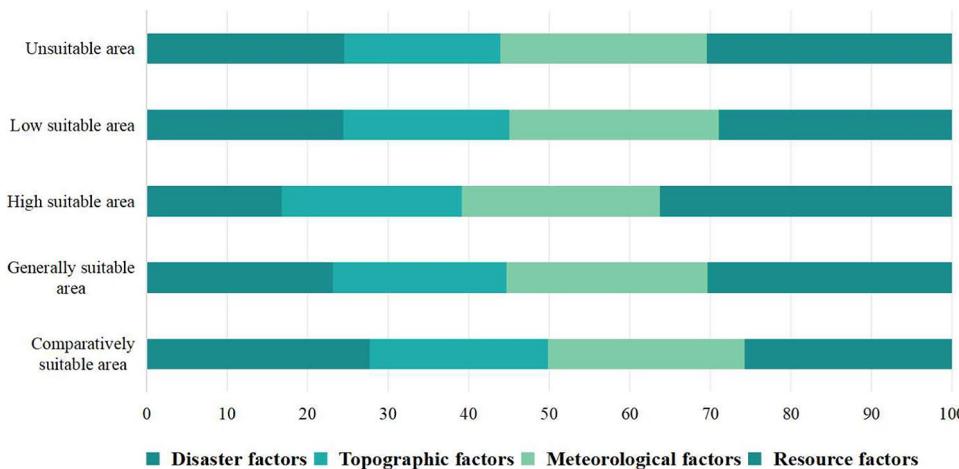


Fig. 7. Obstacles in the standardized layer in different types of areas of the Western Sichuan Plateau.

in higher altitude areas, adapted to the plateau oxygen-deficient environment, while the Yi and Qiang people are mostly distributed in the river valley area, with a strong dependence on water resources⁴¹. Therefore, the Western Sichuan Plateau region is an ideal place to conduct research on the evaluation of the natural suitability of regional human settlements. On this basis, the findings of this paper are of great practical significance and application value for guiding regional sustainable development, tourism planning, and eco-civilization construction in WSP.

In this paper, in the evaluation of each standardized layer and obstacle degree analysis, it was found that Zone I is mainly distributed in the northeastern part of WSP, which has a climate type of Central Subtropical Monsoon Climate, with an average annual rainfall of about 900–1200 mm, the number of days during the period of $\geq 10^{\circ}\text{C}$ ranging from 120 to 180 days, an abundant source of surface water, good hydrothermal conditions, and a high degree of vegetation, with an abundance of oxygen⁴². Topographically, it is an upland plain with a relatively low average elevation compared to other areas. Zone II is mainly distributed in the northern and southern areas of WSP; the climatic conditions compared to highly suitable areas have decreased significantly; the average altitude is slightly higher than highly suitable areas; the river valley area has superior topography and good soil conditions, which is the major advantage of comparatively suitable areas. With favorable water and heat conditions, crops can be up to single cropping or three crops in two years. The topography of the region is, however, highly undulating, and there are many geological disasters such as soil erosion and landslides⁴³, which leads to the disaster factor as the dominant obstacle in the region. Zone III and Zone IV are located in the central region of WSP, and the temperature is lower than Zone I and Zone II on average. Their day-night temperature difference is obvious because the winter is long with cold and dry weather and the summer is short. Moreover, their average elevation is relatively high, which is not suitable for crop planting; thus, the local residents mainly focus on animal husbandry. Zone V is primarily located in the western region, with low temperatures reaching -20°C and frequent frosts, freezes, and hailstones. It has a tough environment and relatively scarce resources.

Regional sustainable development is mainly divided into three dimensions: economic, social, and environmental⁴⁴. The development of regional tourism in WSP under favorable natural conditions as well as in a social and humanistic environment is the direction to realize regional sustainable development in it. By integrating resources such as the natural landscape, ethnic culture, and historical heritage, it promotes the integral development of tourism with agriculture, pastoralism, and other industries to enhance the regional economy. Therefore, the natural suitability of living environments should be comprehensively considered in tourism development planning to protect the eco-environment and realize sustainable development. During the 14th Five-Year Plan period (The Central Committee of the Communist Party of China has issued recommendations for the formulation of the 14th Five-Year Plan for National Economic and Social Development), the planning and construction of WSP will focus on ecological protection, infrastructure construction, industrial upgrading, social governance, etc⁴⁵, and encourage the promotion of green development and circular economy in WSP through scientific planning. As the human settlements system is an open complex giant system, this paper studying, respectively, the disaster factor, topographic factor, meteorological factor, and resource factor is not enough; it should also strengthen the overall cognition of the natural suitability of high-altitude human settlements from the interaction among various standardized layers. In addition, the results of the evaluation of the natural suitability of the habitat environment in WSP, employing a comprehensive evaluation method, more effectively capture the spatial heterogeneity of the influence of various local factors on the natural suitability of the habitat environment. However, there are uncertainties in the selection of conditions, as well as limitations pertaining to data acquisition methods and the diversity of processing techniques. Furthermore, strengthening field research in the region will continuously improve the evaluation system of the natural suitability of the habitat environment in WSP. We will strengthen the field research in the region and continuously improve the evaluation system of the natural suitability of the human habitat in WSP. The comprehensive index evaluation method utilizing composite weights remains a mainstream and efficient approach, yet the challenge of reasonably defining the weights of each sub-index remains a critical scientific question in this research.

Conclusions

This paper combines the unique geographic location of the Western Sichuan Plateau and the natural environment to build a harmonious coexistence between human beings and nature through ecological construction. The following conclusions are drawn from the study:

- (1) The main indices influencing the differences in natural suitability of human settlements on the Western Sichuan Plateau are disaster frequency, disaster coefficient, plant NPP, annual rainfall and cultivated land area, whose weights result in the top five of index system. Through the function model for evaluating natural suitability of human settlements, extracting nature reserves, the habitat natural suitability index of WSP lies between 0.3898 and 0.7178.
- (2) The analysis of the obstacle degree of each suitability type area through the four standardized layers concludes that: the disaster factor is the dominant obstacle in the more suitable areas ; the resource factor is the dominant obstacle in other types of zones.
- (3) From the analysis of the spatiotemporal evolution of the habitat natural suitability index of 32 counties (cities) in WSP from 2010 to 2020, it is concluded that in the time dimension, the overall level of natural suitability of human settlements in WSP is diminishing. In the spatial dimension, the level of natural suitability of human habitat is decreasing from east to west and from north to south.
- (4) The high plains around Ruoergai, Hongyuan and Ngapa are distributed in the northeastern part of WSP and the Muli Gorge area in the south of it. Their natural suitability shows the best results making them the highly suitable area, which accounted for 18.76%. The more suitable area accounted for 17.99% is mainly distributed at the upper reach of Minjiang River and in Sertar, Zamthang and Barkam which are all northern parts of WSP. The distribution of the generally suitable area and low-suitable area accounted for 49.29% close to nearly half of WSP, amounting to 99,821 km², distributed in the Western Sichuan Plateau Dadu River Basin and the eastern part of the Hengduan Mountains. Unsuitable areas are mainly distributed in the core area of the Hengduan Mountains, Lixian and Xiaojin, whose natural environment is severe with frequent geologic disasters, and unsuitable for long-term human habitation, processing an area accounting for 13.96%, the smallest in each area.

This study can provide data support and theoretical guidance for the construction of ecological civilization in WSP, which is of great significance in promoting the coordinated development of the region and improving the quality of life of the people.

Data availability

All the data used for several analyses are freely available, and resources are mentioned within the paper.

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Author contributions

Conceptualization, W.F., H.L. and M.X.; methodology, W.F. and M.X.; software, W.F.; validation, H.L. and M.X.; formal analysis, W.F.; resources and data curation, W.F.; writing—original draft preparation, W.F. and M.X.; writing—review and editing, H.L. and M.X.; visualization, W.F.; supervision, H.L.; project administration and funding acquisition, H.L. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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