

Research on eco-environmental vulnerability evaluation of the Anning River Basin in the upper reaches of the Yangtze River

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Abstract The Anning River Basin is located in the transitional zone of the Qinghai-Tibet Plateau, Yunnan-Kweichow Plateau and Sichuan Basin. This transitional zone is an important ecological barrier of the upper reaches of the Yangtze River and plays a significant role in the ecological security and ecological construction of Sichuan Province. However, the innate vulnerability of the eco-environment combined with the unreasonable development and use of minerals, hydropower, agriculture and animal husbandry resources contribute to prominent eco-environmental problems. In support of remote sensing and geographical information system, this study uses the spatial principal component analysis (SPCA) method to build the evaluation model for the vulnerability evaluation and analysis of the eco-environment in the Anning River Basin. The following indicators are selected for the SPCA: elevation, slope, vegetation index, land use, soil type, soil erosion, precipitation, temperature, and population density. Thereafter, the first four principal components are selected and their corresponding weights are determined. The eco-environmental vulnerability comprehensive index of the Anning River Basin is calculated by using these data. According to the calculated results, the eco-environmental vulnerability of the

Anning River Basin is divided into five levels, namely, potential vulnerability, slight vulnerability, light vulnerability, moderate vulnerability, and high vulnerability. Eco-environmental changes for the past 20 years (from 1990 to 2010) are discussed and analyzed as well as the driving forces. The analysis shows that the eco-environmental vulnerability of the Anning River Basin is at the moderate level, and exhibits obvious vertical distribution characteristics. The main reasons that cause eco-environmental changes are mainly human factors, socioeconomic factors, and environmental protection policies like “Natural Forests Protection” and “Grain-for-Green”. Based on the vulnerability classification results, the Anning River Basin is divided into three partitions for different degrees of eco-environmental reconstruction and protection, which provides foundation for the local eco-environmental reconstruction so as to reconstruct in order of the importance and urgency.

Keywords Eco-environmental vulnerability · The Anning River Basin · GIS · RS · SPCA

Introduction

The Anning River Basin is located in the transitional zone of the Qinghai-Tibet Plateau, Yunnan-Kweichow Plateau, and Sichuan Basin. The transitional zone is an important ecological barrier of the upper reaches of the Yangtze River and plays significant role in the ecological security and ecological construction of Sichuan Province (Sichuan Outline of the 12th Five-Year Plan). However, this eco-environment is innately vulnerable because of its complex geological structure, broken rock, steep slopes, deep valleys, and concentrated rainfall. The combined interference of unreasonable development and improper use of minerals,

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hydropower, agriculture and animal husbandry resources also contribute to the vulnerability of this eco-environment. Thus, the transitional zone does not function as an ecological barrier effectively and has become a prominent area with eco-environmental problems. Eco-environmental problems in the Anning River Basin pose a threat to the ecological security of Sichuan Province and the entire Yangtze River basin. So it has a very important strategic significance of the eco-environmental protection and construction in this area.

In order to carry on environmental protection and ecological construction, current ecological conditions and development trends should be analyzed to evaluate the eco-environmental vulnerability of the area. The results should be taken as reference for ecological construction. These results are significant to not only understand, protect and transform the eco-environment, but also promote the harmonious development of man and nature. (Cai et al. 2009; Huang et al. 2010; Phillips 2012; Manfre et al. 2013). To date, many studies have been conducted on eco-environmental vulnerability evaluation approaches, such as artificial neural network (Park et al. 2004; Kia et al. 2012; Sun 2012), fuzzy decision analysis (Enea and Salemi 2001; Tran et al. 2002; Yao et al. 2003; Navas et al. 2012), landscape ecology approach (Kangas et al. 2000; Gómez-Sal et al. 2003; Mortberg et al. 2007), Environmental Sensitivity Index (ESI) method (Lavado et al. 2009; Mao et al. 2013), the P-S-R model (Wang et al. 2010; Liu et al. 2011), the analytic hierarchy process (Li et al. 2009; Donevska et al. 2012; Huang et al. 2012; Aryafar et al. 2013; Bagdanavičiūtė and Valiūnas 2013), Environmental Sensitivity Areas (ESA) approach (Ferrara et al. 2012), and gray evaluation (Guan et al. 1998). There is a certain degree of subjectivity in the index selection and index weights determined by using these methods. For example, the selection of indicators of artificial neural network (Kia et al. 2012; Sun 2012) is based mainly on prior knowledge and experience of the researchers, so individual experience of researchers will affect results. The analytic hierarchy process is based on an expert scoring method to determine the indicator weight, which is not objective, and the results are greatly influenced by expert level and knowledge (Aryafar et al. 2013; Li et al. 2006). Principal component analysis (Wotling et al. 2000; Parinet et al. 2004; Wang et al. 2008; He et al. 2011; Xu et al. 2011; Jung et al. 2012; Pacheco et al. 2013) obtains principal components by the cumulative contribution ratio which is calculated by the eigenvalue and eigenvector. Thereafter, principal components with high contribution ratios are selected, and relevant contribution ratios are used as indicator weights for comprehensive analysis. The principal component analysis is more objective and advantageous in selecting indicators and determining indicator weights over other methods.

Based on remote sensing (RS) technology, vulnerability indicators' data are updated timely, and in support of

geographical information system (GIS) technology, the ecological vulnerability and temporal and spatial variations are analyzed by using mathematical models, so as to achieve the real-time monitoring and dynamic evaluation of vulnerable ecosystems. This method has gradually become an important direction of regional ecological vulnerability assessment study (Jabbar and Zhou 2011; Akgun et al. 2012; MacMillan et al. 2004; Kia et al. 2012). In support of RS and GIS, this study takes Anning River Basin as a study area. The Anning River Basin has typical landform transition characteristics, an important ecological status and innate vulnerable eco-environment. Along with high spatial resolution of thematic mapper (TM) data of this area, the present study uses a method that combines supervised classification with visual interpretation to obtain land use data and vegetation coverage data in 1990, 2000 and 2010. Thereafter the eco-environmental vulnerability of the Anning River Basin is evaluated comprehensively by quantitative methods to provide a scientific basis for the governance and development of regional eco-environment. This paper aims to accomplish the following objectives: (1) establishing an eco-environmental vulnerability evaluation model of the Anning River Basin by using principal component analysis method, (2) classifying results by using clustering principle, (3) analyzing the spatial distribution and eco-environmental vulnerability changes for past 20 years of the Anning River Basin and discussing the cause of the distribution and changes, and (4) according to the results and taking present situation into consideration, making some suggestions for the future eco-environmental reconstruction, management and protection of the Anning River Basin (Li et al. 2006).

Methods

Study area

The Anning River Basin (Fig. 1) is located in the southwest of Sichuan Province and in the main part of the well-known Great Rift Valley of Panxi, between 102°06'51"E–102°10'14"E and 26°38'11"N–29°02'24"N. The total length of the Anning River is 337 km, and it flows through Xichang, Mianning, Dechang and Miyi, four counties with a drainage area of approximately 11,150 km². The altitude of the Anning River Basin is high in the north and west while low in the south and east, with an elevation between 900 m to 4,750 m. The landform comprises high and medium mountains with denuded and eroded structures, high mountains with denuded and melted glacier, aggradational plain and river valley plain, and intermountain down-faulted basins. The perpendicular band spectrum phenomenon of the climate in the study area is apparent. The alpine cold temperate zone, which is 4,000 m above

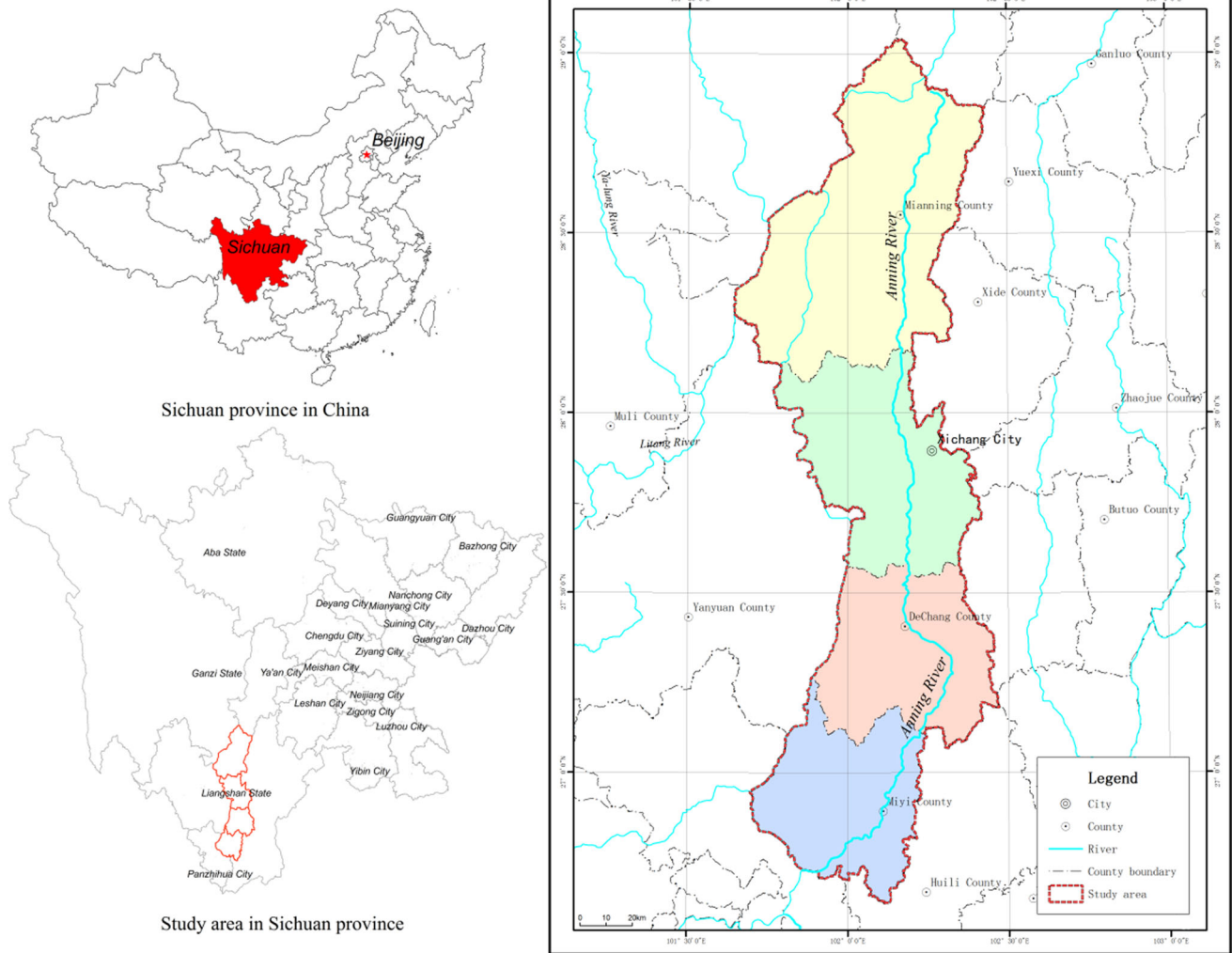


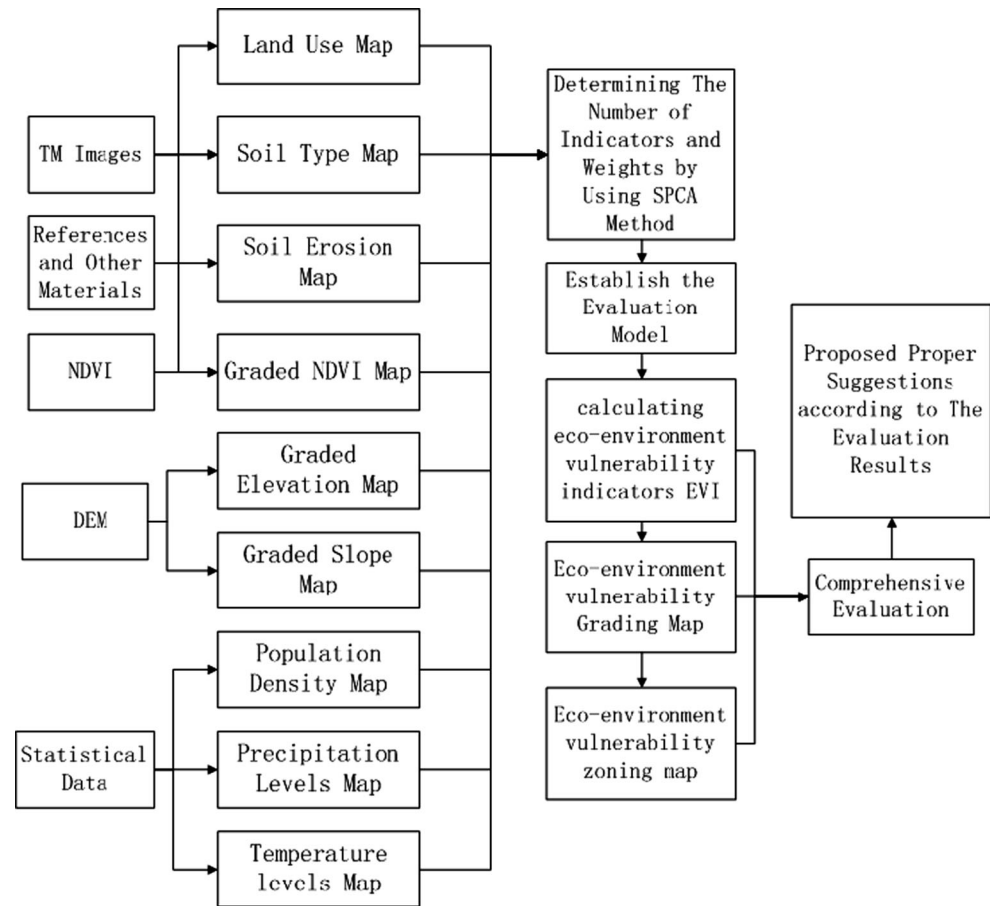
Fig. 1 Location map of the Anning River Basin showing the relationship between the study area, Sichuan Province, and Yangtze River

sea level, and has an annual average temperature below 0 °C; the temperate mountain, which is 2,500–4,000 m above sea level and has an annual average temperature below 8 °C, it is cloudy throughout the year and summer is short; the low mountain valley zone in the north subtropical zone, which is 1,550–2,500 m above sea level and has an annual average temperature between 9 and 15 °C. The valley zone is in the central Asian tropical region, which is 1,330–1,640 m above sea level and has an annual average temperature 17.4 °C. The precipitation in the Anning River Basin has clear seasonal variations that cause rainy weather in summer and autumn and dry weather in winter and spring with 1,133 mm average annual rainfall. The rainy season begins from May to October and accounts for 90 % of the rainfall of the whole year. The elevation of rainfall has great difference with that higher in mountain land than in the neighboring valleys. The Anning River Basin is the second largest valley plain and granary in Sichuan Province followed by Chengdu Plain.

Data

According to whether the initial data has spatial coordinates or not, the datasets in this paper are divided into spatial data and non-spatial data (attribute data) (Farhan and Lim 2012). Spatial data include the following: (1) TM imagery of Landsat 5 satellite with a spatial resolution of 30 m × 30 m, obtained from the International Science Data Services Platform, the Chinese Academy of Sciences for Earth Observation and the Digital Earth Science Center and the University of Maryland; (2) digital elevation model (DEM) data, with a spatial resolution of 90 m obtained from the International Science Data Services Platform; (3) normalized difference vegetation index (NDVI) data obtained from the International Science Data Services Platform MODIS data products; (4) spatial data of soil types with scale 1:100,000 in study area, provided by the Sichuan Provincial Academy of Environmental Sciences; (5) soil erosion data derived from the first, the second and

Fig. 2 Schematic representation of the eco-environmental vulnerability evaluation



the fourth soil erosion RS survey results of Sichuan Province. Non-spatial data include the following: (1) population density data obtained from the Panzhuhua Yearbook and Liangshan Yearbook; (2) the data of annual average temperature and annual average precipitation obtained from China meteorological data sharing service system.

Further processing of the collected data mainly includes the following steps: (1) Acquisition of thematic data: SPOT5 images are taken as reference for interpretation, land use data are obtained by using TM images and combining unsupervised classification with visual interpretation. During the interpretation, land use types are divided into arable land, forest land, shrub land, open forest land, grassland, low coverage grassland, urban construction land, rural settlement, river, lake, glacier, mine area, bare rock and bare land, and almost 150 points of different land use types are selected for field verify in the whole region. By statistics, the interpretation accuracy of different land use types surpasses 90 %; elevation and slope data are obtained based on DEM data; the data of population density, annual average temperature and annual average precipitation are processed then converted to spatial data in ArcGIS software; (2) Projection coordinate and other information. In order to ensure good spatial coincidence of different thematic data,

this study uses equal area projection, the specific projection parameters for: initial longitude 110°E, initial latitude 0°, double standard parallel 25° and 47°, 1954 Beijing geodetic datum and Krassovsky ellipsoid. (3) Generation of raster data. Considering that GIS raster data has good spatial analysis capabilities, this study converts all thematic data into raster data to achieve a variety of algebraic and logical operations, with a grid size of 250 m × 250 m.

Evaluation process

This paper performs three steps to evaluate the eco-environmental vulnerability of the Anning River Basin: (1) selection and establishment of an evaluation indicator system; (2) determination of the weight of each factor in the indicator system; (3) analysis and computation by using mathematical model. The evaluation process is shown in Fig. 2.

Evaluation indicators and model

Based on present study (Villa and McLeod 2002; Li et al. 2006; Wang et al. 2008; Xu et al. 2011; Bagdanavičiūtė and Valiūnas 2013), considering the representative,

holistic, scientific, and operational principles, along with the real eco-environmental problem of Anning River Basin, nine indicators (i.e., elevation, slope, vegetation, land use, soil type, soil erosion, precipitation, temperature and population) are selected as the eco-environmental vulnerability evaluation indicators in study area. The reasons for the selection are shown in Table 1.

For the eco-environmental vulnerability evaluation indicators, comparability cannot be ensured because their dimension is not unified. Although the actual values of these indicators can be used to determine the degree of their effect on the environment, they still fail to reflect the exact effect because of the lack of a comparable standard (Xu et al. 2011). In order to determine the effect of different values of each factor on the eco-environmental vulnerability, the degree of effect of each factor is divided into five levels. This paper uses two methods to divide the degree of effect of each factor:

1. *Classification by referring to existing research results.* In terms of land use data (Huang et al. 2003; Wang et al. 2008), river, lake, and other water bodies are graded as Level one. Forest land are graded as Level two. Grassland, shrub land, and open forest land are graded as Level three. Low coverage grassland and arable land are graded as Level four. Urban construction land, rural settlement, glacier, mine area, bare rock and bare land are graded as Level 5. For soil type data, the degree of the effect of different soil types on eco-environmental vulnerability are determined by using the soil erodibility (K) value of different soil types (Lv and Shen 1992; Liang and Shi 1999; Deng et al. 2003; Song et al. 2012). Soil erosion intensity from existing soil erosion data is divided into five levels, namely, unobvious erosion, slight erosion, mild erosion, moderate erosion, and deep erosion. The present study directly uses these classification standards.
2. *Classification by the principal of cluster analysis.* Elevation, population, slope, vegetation, rainfall, and temperature are graded by the natural breaks classification method according to the clustering principles. The natural breaks classification method is a statistical method in which grades and classifications are based on the law of numerical statistical distribution. This method can maximize the difference between different classes (Wang et al. 2008; Xu et al. 2011).

The key of eco-environmental vulnerability evaluation is the conversion of a number of characteristic indicators into a comprehensive evaluation indicator (Munda et al. 1994; Li et al. 2006). To solve this issue, we tend to select more than one characteristic indicator for observation to ensure more accurate judgments, because each characteristic indicator will reflect information on the research

question in varying degrees (Wang et al. 2010; Xu et al. 2011). Characteristic indicators are usually numerous, thus, as mentioned above we select nine characteristic indicators. When the number of characteristic indicators is considerable that the analytical complexity of the problem increases (Yao et al. 2003; Xu et al. 2011), therefore a small number of integrated features indicators that contain more information should be selected. Principal component analysis (Khatun 2009; Jung et al. 2012; Pacheco et al. 2013) is a method that integrate the original characteristic indicators into several indicators as few as possible, and requires several indicators can not only fully reflect the information which multiple characteristics indicators can reflect, but also make these indicators unrelated. In this study, spatial principal component analysis (SPCA) is used for eco-environmental vulnerability evaluation. SPCA is a method that support by GIS software, in the GRID module of ARC/INFO by using PRINCOMP function through the rotation of the original space axis, and conversion of multivariate spatial data that are correlated into a small number of unrelated indicators. The method ultimately determines the final small number of indicators that are need in the establishment of the evaluation model. SPCA follows the following steps: (1) standardization of original data, (2) establishment of the covariance matrix R of each variable, (3) calculation of each eigenvalue λ_i and its eigenvector ai of matrix R , and (4) classification by using a linear combination of ai to extract m principal components.

Standardization of original data is as the following linear formula 1:

$$Y_{ij} = \frac{x_{ij} - x_{i,\min}}{x_{i,\max} - x_{i,\min}} \quad (1)$$

In this formula, Y_{ij} represents the standardized value in grid j of indicator i (range 0–1), x_{ij} represents the actual value in grid j of indicator i , $x_{i,\max}$ represents maximum value of all grids of indicator i , and $x_{i,\min}$ represents minimum value of all grids of indicator i .

In this paper, nine evaluation indicators of the regional eco-environmental vulnerability evaluation index system are selected for SPCA. The selection is based on the cumulative contribution of the principal component. Ultimately, the four principal components are determined for eco-environmental vulnerability evaluation (Table 2). Based on the extracted four principal components, an evaluation function is constructed to compute the comprehensive evaluate index to obtain comprehensive evaluation results. In this paper, we mainly use the eco-environmental vulnerability index (EVI) to show the degree of eco-environmental vulnerability in a quantitative way. EVI is defined as the weighed sum of principal components, and while each weight is determined as the contribution ratio of each principal component. EVI is

Table 1 Eco-environmental vulnerability evaluation indicators in the Anning River Basin

Indicator	Basis and conditions for the selection of indicators	Time of indicators
Elevation and slope	Elevation and slope are two important environmental indicators that influence surface runoff, soil erosion and land use. Anning River Basin, with an elevation between 900 m and 4,750 m, is featured by undulating terrain, steep slope and deep valley, and alternating between valley and basin. Therefore, the influences of elevation and slope on eco-environmental in study area are of significant importance	Data come from the digital elevation model (DEM) with a spatial resolution of 90 m in 1990, 2000, and 2010
Vegetation coverage	Vegetation coverage is a measurement of the ground vegetation condition, vegetation cover which affects directly and can even determine the status and function of ecological system such as primary biological production, ecological capacity, the intensity of water loss and soil erosion, and so on, it is of important significance for regional eco-environmental vulnerability study	NDVI data come from MODIS data products in May 1990, 2000, and 2010
Land use types	Regional vulnerable eco-environment such as water loss and soil erosion, forest vegetation degradation, desertification and salinization of land are related to human land use types (the way how people use land). Due to unreasonable exploitation of land, destruction of vegetation, and general reclamation of steep slope, before the 1990s the problem of water loss and soil erosion of Anning River Basin is worse. In the late 1990s, “Natural Forests Protection” and “Grain-for-Green” the two ecological projects are carried out one after another in the study area, which have an important effect on increasing forest vegetation coverage, alleviating the problem of water loss and soil erosion, and improving eco-environment effectively. Accordingly, land use types and their changes are vital indicators that affect regional eco-environmental vulnerability	Land use data come from TM images of February 2, 1988; April 8, 2000; and April 16, 2009 (path 130 row 040); and TM images of March 11, 1990; August 15, 2000; and April 5, 2008 (path 130 row 041)
Soil types and soil erosion	Soil plays an important role in maintaining the terrestrial ecological balance. Poor soil often leads to vulnerable ecosystem. The major soil types in Anning River Basin are red soil, yellow brown soil, meadow soil, purple soil, etc. The common characteristics of these soils are poor quality, bad water retention, low erosion resistance and easy degradation, which cause different kinds of defects and soil fertility problems. Hence, soil types and degree of soil erosion are fundamental indicators that affect eco-environmental vulnerability in study area	Soil type data are provided by the Sichuan Provincial Academy of Environmental Sciences. Soil erosion data derived from the first (in 1990), the second (in 2000) and the fourth (in 2010) soil erosion RS survey results of Sichuan Province
Temperature and precipitation	Climatic factors (temperature and precipitation) are the facilitated factors of natural environment component and are also the energy foundation of ecosystem. When the energy feature, transmission and transformation are not in accordance with other factors in time and space, it will cause ecological degradation. For the Anning River basin, on the one side, the rainfall is abundant and intense, which results in high erosion of the river, heavy rainfall, high vulnerability, on the other side, along with the heavy rainfall and uneven distribution, and there exists seasonal drought which causes the constraint of the growing plants in the drought and vegetation degradation that is difficult to recover. So the more obvious of the seasonal drought, the more intensified of the vulnerability	The annual average temperature and annual average precipitation data in 1990, 2000, and 2010 are from statistical data in China meteorological data sharing service system.
Population density:	Population density and education level, human recognition of natural laws and etc. constitute the regional vulnerable eco-environmental effect factors. Human activities that lead to the ecological degradation of Anning River Basin are mainly reclamation of slope and over-exploitation. In study area, development is focused on agriculture and animal husbandry development, while the resource of arable land is limited. Due to rapid population growth, destruction of vegetation and reclamation of steep slope was general and made the phenomenon that water loss and soil erosion serious, which aggravated eco-environmental vulnerability. Therefore, population density is an important eco-environmental vulnerability indicator in study area	Population density data come from statistical data on the Panzhuhua Yearbook and Liangshan Yearbook

Table 2 Results of the SPCA in study area

Principal components	P1	P2	P3	P4
2010				
Eigenvalue	4.1176	2.4735	2.0710	1.3288
Contribution ratios	0.3550	0.2132	0.1785	0.1145
Cumulative contribution rate (%)	35.50	56.81	74.67	86.13
2000				
Eigenvalue	4.5670	2.9461	2.2501	1.4343
Contribution ratios	0.3496	0.2255	0.1722	0.1098
Cumulative contribution rate (%)	34.96	57.51	74.73	85.71
1990				
Eigenvalue	4.1723	2.4575	1.8600	1.1458
Contribution ratios	0.3725	0.2208	0.1661	0.1023
Cumulative contribution rate (%)	37.25	59.34	75.95	86.08

computed by formula 2, and the contribution rate is computed by formula 3 as following.

$$EVI = \sum_{i=1}^n W_i P_i = W_1 P_1 + W_2 P_2 + \dots + W_n P_n. \quad (2)$$

In this formula, P_i represents the principal component of number i , and W_i represents the corresponding contribution ratios, n is the number of extracted principal components after SPCA.

$$W_i = \frac{\lambda_i}{\sum_{i=1}^m \lambda_i}. \quad (3)$$

In this formula, W_i represents the contribution ratios of the i th principal component, and λ_i represents the eigenvalue of the i th principal component.

According to the principal components and its corresponding weight, the comprehensive evaluation indexes are calculated to represent the degree of regional eco-environmental vulnerability. A higher EVI corresponds to a more fragile eco-environment.

According to Table 2, in this research EVI is calculated by the following linear formula:

$$EVI_{1990} = 0.355 \times X_1 + 0.213 \times X_2 + 0.178 \times X_3 + 0.115 \times X_4$$

$$EVI_{2000} = 0.349 \times Y_1 + 0.225 \times Y_2 + 0.172 \times Y_3 + 0.109 \times Y_4$$

$$EVI_{2010} = 0.372 \times Z_1 + 0.221 \times Z_2 + 0.166 \times Z_3 + 0.102 \times Z_4.$$

In this formula, EVI represents the degree of eco-environmental vulnerability, $X1$ to $X4$ denote the four principal components extracted from the initial nine spatial variables in 1990. In similar, $Y1$ to $Y4$ are the principal components extracted in 2000, and $Z1$ to $Z4$ are extracted in 2010. The

cumulative contribution rates of the four principal components reach 86.14 % in 2010, 85.17 % in 2000, and 86.08 % in 1990. The rates all surpass 85 % and meet the standards of choosing the principal components.

Gradation of vulnerability

The resulting value of eco-environmental vulnerability obtained from the model is continuous. A classification of the different levels of eco-environmental vulnerability should be made so as to acquire an overall understanding of the regional eco-environmental vulnerability. An objective and logical classification is crucial to evaluate the results (Wang et al. 2008), and it is an objective method that makes a classification according to histogram (Li et al. 2006). This research uses natural breaks classification to make a cluster classification according to the histogram of the eco-environmental vulnerability evaluation results of our study area. Natural breaks classification is a data classification method designed to determine the best arrangement of values into different categories. This is done by seeking to minimize each class’s average deviation from the mean of the category, while maximize each class’s deviation from the means of the other groups. In other words, the method seeks to reduce the variance within classes and maximize the variance between classes (Jenks 1967; McMaster et al. 2002). By calculating the variance of each category and the sum of all the variances, the quality of classification (good or bad) can be determined through comparing the sum of variances of different classification methods. After calculating the sum of variances of all the classification methods, the method with the minimum sum will be selected as the best method (but it is not unique). This is just the principle of natural breaks classification method. Looking at the data distribution histogram, you can find clearly that the break is consistent with the breakpoint (threshold) that calculated by the natural breaks classification. It is concluded that natural breaks classification is a “natural” classification method, which meet “birds of a feather flock together”. The difference is obvious between different categories, while very small inside a category, and there is a more obvious break between category and category. Therefore, natural breaks classification is used to analyze the natural properties of the eco-environmental vulnerability results to find out the breakpoints (thresholds) and thus divide the eco-environmental vulnerability into different levels in study area.

In this standard, the eco-environmental vulnerability in our study area is divided into five levels: potential vulnerability, slight vulnerability, light vulnerability, moderate vulnerability and high vulnerability (Huang et al. 2003; Cai et al. 2009). As shown in Table 3, each level has its own typical characteristics.

Table 3 Results of the eco-environmental vulnerability classification in the Anning River Basin

Levels of vulnerability	EVI	Character description
Potential vulnerability (I)	<4.83	The ecological system is stable with a relatively strong erosion resistance, fertile soil, relatively low altitude, and good vegetation coverage
Slight vulnerability (II)	4.83–5.64	The ecological system is comparatively stable with a general erosion resistance, fertile soil, comparatively low altitude, and good vegetation coverage
Light vulnerability (III)	5.64–6.57	The ecological system is comparatively unstable with a relatively weak erosion resistance, relatively poor soil, and complex vegetation types
Moderate vulnerability (IV)	6.57–7.66	The ecological system is unstable with a weak erosion resistance, poor soil, and few vegetation types
High vulnerability (V)	>7.66	The ecological system is extremely unstable with quite a weak erosion resistance, relatively high altitude, poor soil, and few vegetation types that are mainly composed of hardy plants

Analysis of the whole change trend

In order to analyze the change trend of the eco-environmental vulnerability in a quantitative manner, a composite index that can represent the vulnerable situation of the whole region should be defined. The composite index E is calculated by the following formula:

$$E_j = \sum_{i=1}^n \frac{A_i}{SA_j} \times P_i \quad (4)$$

In this formula, i represents the grade, n represents the number of all grades, A_i represents the area of grade i in the evaluation unit j , SA_j represents the area of unit j , P_i represents the value of grade i . According to the vulnerability level, a quantitative value is used to represent one level: the potential vulnerability is represented by one, slight vulnerability is two, light vulnerability is three, moderate vulnerability is four and high vulnerability is five. A greater eco-environmental vulnerability composite index E leads to a more vulnerable eco-environment.

Results

Distribution of vulnerability levels

According to our eco-environmental vulnerability assessment method, the results of the eco-environmental

vulnerability classification in our study area in different years are shown in Fig. 3. The statistical proportions of different eco-environmental vulnerable grades are shown in Table 4.

According to the analysis results of the percentage of all kinds of vulnerable levels' grid number in the total grid number of the study area in 1990, 2000 and 2010, in general, the percentage of the slightly vulnerable region in the study area is the largest, followed by the lightly vulnerable region, the moderately vulnerable region and the high vulnerable region. The percentage of the potentially vulnerable region is the smallest. For example, in 2010, the slightly vulnerable region has the largest percentage at 30.8 %, the lightly vulnerable region is at 24.7 %, the moderately vulnerable region is at 18.6 %, and the high vulnerable region is at 13.2 %, the potentially vulnerable region has the smallest percentage at 12.7 %. The percentage of the slightly vulnerable region and the lightly vulnerable region exceeds 50 %. Thus, it is concluded that the eco-environmental vulnerability of the Anning River Basin is at the moderate level.

Change trend of eco-environmental vulnerability

Compared with the grid numbers of the study area in 1990 and in 2000, the grid numbers of Levels I, II, III, IV, and V decrease by 0.6, 0.2, 0.5, 0.5, and 0.6 %, respectively. Compared with the grid numbers of the study area in 2000 and in 2010, the grid numbers of Levels I, II, III, IV, and V increase by 0.2, 1.1, 0.5, 0.6, and 1.1 %, respectively (Table 4). It can be clearly concluded from Fig. 4 that the change trend of the percentage of eco-environmental vulnerability occurs in different levels. The percentage of the potentially vulnerable region is smallest in 2000, largest in 1990, and modest in 2010. The percentages of the slightly vulnerable region and the lightly vulnerable region increased from 1990 to 2010 in turn. The percentage of the moderately vulnerable region is smallest in 1990, largest in 2000, and modest in 2010. The percentage of the high vulnerable region decreased from 1990 to 2000 in turn.

According to the formula for calculation of E , the eco-environmental vulnerability index E can be calculated at different times in the whole study area. The value of E of the study area in 1990, 2000 and 2010 are 2.925, 2.928 and 2.888, respectively. This result shows that the whole eco-environmental situation in 1990 is slightly better than that in 2000, and the value of E in 2010 is the largest, thus indicating that the best eco-environmental situation occurs in 2010.

Regionalization of eco-environmental vulnerability

Based on previous research, according to the degrees of vulnerability, the study area should be divided to several

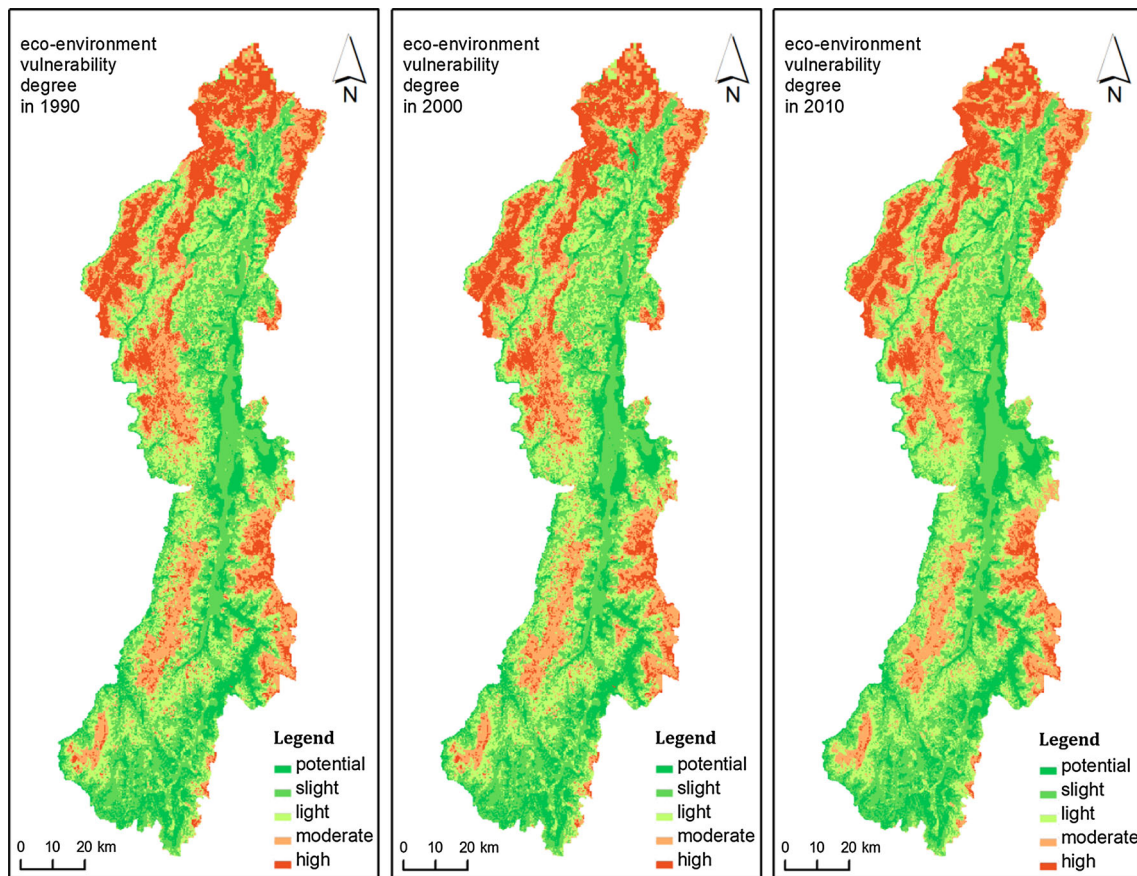


Fig. 3 Distribution map of the eco-environmental vulnerability of the Anning River Basin

Table 4 Percentage of different levels of eco-environmental vulnerability

Vulnerability degree	Vulnerability level	1990		2000		2010	
		Grid number	Percentage	Grid number	Percentage	Grid number	Percentage
Potential	I	23,769	13.1	22,714	12.5	23,084	12.7
Slight	II	53,588	29.5	53,847	29.7	55,891	30.8
Light	III	43,049	23.7	43,974	24.2	44,749	24.7
Moderate	IV	33,911	18.7	34,843	19.2	33,715	18.6
High	V	27,034	14.9	25,970	14.3	23,911	13.2

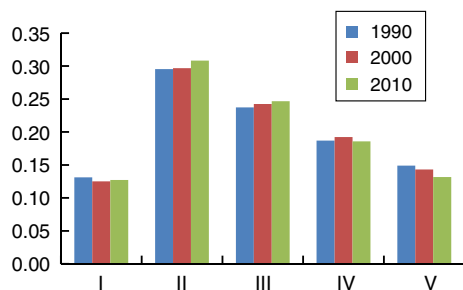


Fig. 4 Eco-environmental vulnerability indicators of different levels in 1990, 2000, and 2010

sub-regions for further study (Li et al. 2006; Cai et al. 2009). The area should be divided through a natural boundary according to the state of the environment (Hall and Arnberg 2002; Li et al. 2006; Furlan et al. 2011). In the present paper, based on the regional characteristics and eco-reconstruction needs, the comprehensive index EVI is used to divide the region. The region is divided into three sub-regions in accordance with the degree of eco-environmental vulnerability (Fig. 5) which provides foundation for the local eco-environmental reconstruction so as to reconstruct in order of the importance and urgency (O’Brien et al. 2004; Bagdavičiūtė and Valiūnas 2013; Manfre et al. 2013).

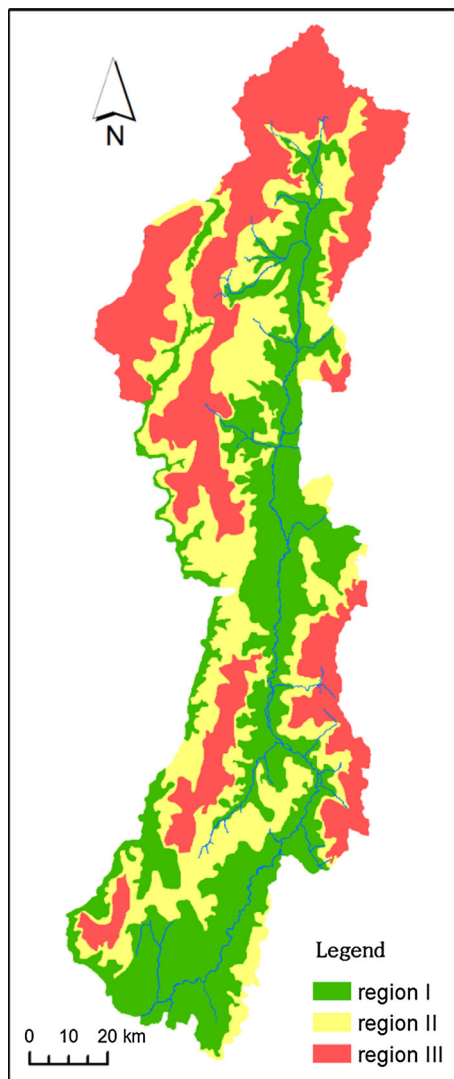


Fig. 5 Regionalization of eco-environmental vulnerability

1. Potential and slight vulnerable regions in the Anning River Valley as well as the middle and low valleys need comprehensive development. These regions are distributed in four counties with an approximate area of 4105.61 km², which accounts for 35.73 % of the whole study area. These regions are the central part of economic development in our study area, which has a dense population and considerable arable land. The topography of these regions is mainly plains and low mountains. The eco-system types are mainly low mountain shrubbery, low or middle mountain evergreen forest and grassland.
2. Light and middle vulnerable regions need more strict protection. These regions are also distributed in four counties with an approximate area of 4,555.11 km², which accounts for 39.64 % of the whole study area. The main human activities in the regions with low

population density are mining and reclamation on steep slopes. The terrain in the regions is mainly middle and high mountains. The ecosystem types are mainly alpine evergreen broad-leaved forests, grasslands, alpine bushes, and a small amount of alpine coniferous forests. The regions in our study area have the highest vegetation coverage rate and the most complex ecosystem.

3. The heavy regions need strictest protection. These regions with an approximate area of 2,830.48 km² are mainly distributed in Mianning County, northwest of Xichang City and the east of Dechang County. A portion of this region is distributed in Miyi, which accounts for 24.63 % of the whole study area. Population density is fewer than five persons per square kilometer, and the terrain is mainly high mountains. The ecosystem in the region is composed of alpine coniferous forests, alpine bushes and grasslands.

Discussions

Analysis of change driving forces

Through analysis of the change trend of the eco-environmental vulnerability of the study area, the driving forces that cause such change can be analyzed further. Factors such as elevation and slope change have been insignificant on eco-environmental vulnerability during the past 20 years. Temperature, precipitation, soil type, soil erosion and other factors also have limited effects on the change of eco-environment. By comparing the eco-environmental vulnerability classification maps of 1990, 2000 and 2010, we find the change trends in the distribution of vulnerable regions are basically in accordance with the change trends of woodland cover. Therefore, the main factors that caused eco-environmental changes were human activities and social and economic conditions, and the human factors caused changes in land use status and the eco-environment.

We can conclude that the eco-environmental situation in 1990 was better than that in 2000 (Fig. 3; Table 4). There are two reasons: One reason is that the excessive deforestation, construction of vegetation and industrial development caused soil erosion and eco-environmental deterioration. Another reason is that the heavy exploitation of mineral resources caused significant pollution and destruction that resulted in irreversible eco-environmental changes.

Population density increased rapidly in study area from 1.0658 million in 1990 to 1.483 million in 2010. Meanwhile, the area of arable land increased from 1715.75 km²

in 1990 to 1,783.27 km² in 2010, with a net increase of 67.52 km², in which the area of reclamation and cultivation on steep slopes reached 53.74 km² and accounted for 79.59 % of the increased area of arable land. Reclamation and cultivation on steep slopes caused the massively deforested of woodland, water and soil erosion and the deterioration of the eco-environment from 1990 to 2000 in study area.

From 1990 to 2010, industries developed rapidly in the study area. The industry focuses on mining and hydro-electric development in the study area. No large reservoir existed in this region in 1990, but three large reservoirs, i.e., Ertan, Jinping, and Mianning Bridge, existed in 2010 with an approximate area of 36.02 km². On the one hand, construction of reservoirs raised the groundwater level, expanded the erosion scope of the reservoir and caused climatic change in this region. On the other hand, much arable land and grassland were swamped. The area of swamped arable land is 21.32 km², the area of swamped grassland is 12.02 km² and other is 2.68 km². Mineral resources are rich in this region and there are mainly large open mines. Mine development area was 5.54 km² in 1990, 6.67 km² in 2000 and 13.41 km² in 2010. The influences of mine development on eco-environment in study area focus on the following aspects: (1) Destruction of land resources and damage of landscape: for example, iron mine in Pan-zhihua, Taihe iron mine in Xichang, and Niuping rare earth mine in Mianning and so on; mine development destroyed a large number of grassland, woodland and farmland. By 2010, due to mine development, the area of grassland, woodland and farmland decreased by 1.25 km², 4.68 km² and 1.56 km², respectively. (2) Mine geological hazard and hidden danger: according to result of the remote sensing survey, there were 17 points of mine geological hazard and hidden danger caused by mining, in which 1 point of landslide, 3 points of mud-rock flow and 13 points of hidden danger. The geological structure in study area is complicated, and the rock structure is unstable. The characters of terrain have the feature of high mountains, deep valleys, and steep slopes. In terms of climate, rainy is concentrated, and heavy rain and rainstorm are often formed. These special geological and geographical conditions and climate caused mining area's geological environment inherent vulnerability, and vanadium-titanium magnetite ore, rare earth ore, marble, silica and other mining activities and waste-rock pile was exacerbating the frequency and intensity of geological hazard. In mine area, there was no fixed spot to pile a lot of waste produced by the mining field, which was always piled up at the nearest ditch. Due to the loose of waste, steep slope was formed during the process of piling up. If there was rainy, especially heavy rain even rainstorm, it was easy to form mud-rock flow which causes big security hidden danger. (3) The

influence of water condition: The problem of water pollution was prominent, which was caused by the solid waste that generated by the mining of rare earth ore in Mianning rare earth mine area. On the one hand, wastewater that washed the ore directly discharged without treatment into the Nan River, the main branch of the Anning River. However, the wastewater that washed the rare earth ore is harmful to water quality, and constitute a threat to the safety of drinking water and crop irrigation. On the other hand, in rare earth mine area of Maoniuping and Sanchahe and the concentrating mill in the downstream, a lot of solid waste was piled up along the Nan River, which was harmful to water quality and affects the safety of drinking water and crop irrigation. Nan River, which polluted by waste water that wash rare earth ore and solid waste, as an important tributary of Anning River, flowed directly into the Anning River and affected the water quality directly. The lead zinc ore in Anbaoshan in study area is a famous large lead-zinc deposit in China. The mining of the lead zinc ore in Anbaoshan began from 1970, and almost 500 thousand tons of tails wastewater discharged into Mosuo River, another branch of the Anning River and flow into Anning River after 19-km-journey. The water polluted by lead zinc ore was used for irrigating the farmland and caused soil heavy metals pollution.

In contrast to the eco-environmental situation in 2000, the situation in 2010 has improved. The causes of the changes are mainly the national implementation of “Grain-for-Green” and “Natural Forest Protection” and other projects, which required those sloping arable lands with a slope that greater than 25° be converted to woodland. These projects not only play a vital role in maintaining the ecological security, but also promote regional sustainable development. Due to relevant policy, locals have begun to plant forests for eco-environmental reconstruction, which made the area of arable land decrease from 1,783.27 km² in 2000 to 1,299.79 km² in 2010, in which the area of reclamation and cultivation on steep slope reached 393.21 km² and accounted for 81.33 % of the decreased area of arable land. Thereby, the problem of water and soil erosion was curbed, while the eco-environmental conditions have been improved significantly.

Ecological reconstruction in different regions

The study area takes the Anning River as the central axis. Mountainous region that gradually increases in height from the central south to northwest and northeast and many large mountains, contributing to the regional geographical and overall geographical vertical climate zone spectrum. This spectrum clearly and regularly reappear the forms of various climatic zones' replacing in the horizontal direction. According to the vulnerability, the study area is divided

into three regions for different degrees of ecological reconstruction.

Region 1 This region is mainly located in the Anning River Valley, and it is the major industrial base and grain production base of Sichuan Province. According to the front research results, the eco-environmental situation is stable, and it is predicted that under reasonable policy the eco-environment in the region will not experience further degradation. Therefore, the development of the region should be limited to a valid extent. Given that human activity is dominant in this region, the government should establish an effective and recycled eco-environmental compensation package that benefits the locals for a more comprehensive and effective development of the region. A feasible way is to establish a mixed ecosystem that is composed of multiple functional mixed ecological forests, agriculture mixed forests and so on in areas with low mountains or unsuitable for crop growth.

Region 2 This region with the widest distribution is not only a buffer of the Anning River Basin but also the most important region for protecting the Anning River Basin from soil erosion. The temperature, precipitation and elevation of this region are all conducive to the recovery of damaged ecosystem. The most important method for the recovery of the regional ecosystem is to cease the destruction of woodlands and prevent overgrazing, support the afforestation program, return farmlands to forest lands and grasslands, and establish a more reasonable protection scheme for the use of forest lands and grasslands.

Region 3 This region is mainly located in high altitude areas. Given the high altitude, the vegetation coverage in this region is rare with some areas covered in perennial snow all the years. So once the ecosystem is damaged, it is difficult to recover. The source of the Anning River is also located in this region, upstream river is the core area of environmental protection (Li et al. 2006). Once the upstream river is polluted, the midstream and downstream rivers and the valley will also be affected. In the upstream Anning River, strong tectonic movements, poor rock stability, loose soil, concentrated precipitation, and frequent torrential rains all make the eco-environment in this region particularly vulnerable. Therefore, the region should strictly control the logging industry and animal husbandry, and appropriate areas should be selected for afforestation. Eco-environmental protection should be strengthened while hastening eco-environmental restoration and development.

Conclusion

In support of RS and GIS, this paper mainly uses the spatial principal components analysis method to determine the

index and weight, and establishes an evaluation model to evaluate the eco-environmental vulnerability of the Anning River Basin. Based on our results, we can make the following conclusions:

The eco-environmental vulnerability of the Anning River Basin is primarily at the moderate level. The percentage of the slightly vulnerable region in the study area is the largest, followed by the lightly vulnerable region, whose percentage counted up surpasses 50 %, then followed by the moderately vulnerable region and the high vulnerable region. The percentage of the potentially vulnerable region is the smallest. Distributions of these levels have apparent vertical regional characteristics. Potentially vulnerable region and slightly vulnerable region mainly distributed near the middle of the valley, then a large scale distributed in Miyi. Lightly vulnerable region evenly distributed throughout the study area. Moderately vulnerable region mainly distributed in the western of Xichang County and the eastern and western of Dechang County, less distributed in Miyi and Mianning County. High vulnerable region mainly distributed in Mianning County, the northwest of Xichang City and the eastern of Dechang County, less distributed in Miyi County. In general, compared with the eco-environmental situation in 1990, the eco-environmental deterioration in 2000 was mainly caused by man-made activities such as reclamation and cultivation on steep slopes and over exploitation of mineral resources. Compared with the eco-environmental situation in 2000, the eco-environmental improvement in 2010 was caused by the “Natural Forest Protection” and “Grain-for-Green” policies. Under the influence of the policies, some measures of ecological rehabilitation such as afforestation and so on were putted into effect so that the eco-environmental situation was improved.

After the above studies, it is proved that the combination of RS, GIS and SPCA method is benefit for eco-environmental vulnerability evaluation, and further promotes the study of the eco-environmental vulnerability evaluation in Anning River Basin. Compared with conventional evaluation, the results with high geospatial resolution is better for reflecting the actual situation in the Anning River Basin on the whole. According to above study, relevant proposals are provided for the ecological development in the Anning River Basin, so as to provide a scientific basis for the ecological barrier construction of the upper reaches of the Yangtze River and the ecological protection and construction in the Anning River Basin, which could be more convincing and easy to be accepted for relevant policies making by the local government.

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