ENVIRONMENTAL VULNERABILITY ASSESSMENT IN MIDDLE-UPPER REACHES OF DADU RIVER WATERSHED USING PROJECTION PURSUIT MODEL AND GIS

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Abstract: The middle-upper reaches of Dadu River Watershed are located in the transitional zone between Qinghai-Tibet Plateau and western hilly area of Sichuan Basin. This transitional zone is an important ecological barrier of the upper reaches of the Yangtze River. However, the innate vulnerability of the environment combined with the unreasonable development and utilization of hydropower, forestry, agriculture and grassland resources lead to prominent eco-environmental problems in this area. In order to analyze environmental problems in the study area, based on the selected environmental vulnerability indicators (including elevation, slope, vegetation coverage, land use, soil type, precipitation, temperature, Gross Domestic Product (GDP) and population), this paper integrates Projection Pursuit Model (PPM) and Geography Information System (GIS) to quantitatively evaluate the environmental vulnerability in the middle-upper reaches of Dadu River Watershed in both 2000 and 2010. According to the evaluation results, the environmental vulnerability of the study area is divided into five grades, namely, potential vulnerability, slight vulnerability, light vulnerability, moderate vulnerability, and high vulnerability. On the whole, the environmental vulnerability of the study area is at the moderate level, and exhibits obvious vertical distribution characteristics. Meanwhile, the environmental vulnerability changes show a trend of generally improved and partially deteriorated for the past 10 years (from 2000 to 2010) in the study area. Besides, the driving forces of the environmental vulnerability changes are discussed and analyzed. The general improvement of the study area environment mainly benefits from the carrying-out of the environmental protection policies such as "Natural Forests Protection" and "Grain-for-Green". And the primary reasons that cause local environment of the study area worse are over-exploitation of hydropower and mineral resources. At the end of this paper, according to the environmental vulnerability classification results, specific suggestions were proposed for regional environmental protection.

Key words: the middle-upper reaches of Dadu River Watershed; environmental vulnerability; Projection Pursuit Model; GIS

1. INTRODUCTION

The middle-upper reaches of Dadu River Watershed, which is located in the transitional zone between Qinghai-Tibet Plateau and western hilly area of Sichuan Basin, is an important ecological barrier in the upper reaches of Yangtze River and plays a significant role in the ecological security construction of Sichuan Province (12th Five-year Plan Outline for Sichuan Province). However, due to some severe problems of high elevation, natural condition, complicated structure, abrupt slope and deep valley, it is innately vulnerable. In addition, because of the unconscionable exploitation of hydropower, forestry, agriculture and grassland resources, the trend of environmental vulnerability in this area becomes severer. Therefore, this watershed couldn't serve as an ecological barrier effectively but instead became a deteriorated area with many environmental problems. It poses a threat to the ecological security of Sichuan province, and even the security of whole Yangtze River Basin.

Thus, it's highly significant to implement environmental protection and ecological construction in this area (Outline Planning of Vulnerable Areas Protection of China).

In order to achieve regional sustainable development and environmental protection, environmental vulnerability and its change trend in recent years should be assessed firstly and the assessment results are basic to construct a better regional eco-environment. In order to first construct a better eco-environment, many methods were used by different researchers to analyze regional environmental vulnerability, such as the analytic hierarchy process(Zheng et al., 2010a; Bottero et al., 2011), comprehensive evaluation method(Wang et al., 2012; Kong et al., 2013), fuzzy decision analysis(Ma & Wang, 2008; Navas et al., 2012), artificial neural network(Zhu et al., 2005; Kia et al., 2012; Castin et al., 2014), the P-S-R model (Bai & Tang, 2010; Pei et al., 2010), environmental sensitivity areas (ESA) approach(Löscher et al., 2008; Lavado et al., 2009; Ferrara et al., 2012), landscape ecology approach (Duo,2009), gray evaluation (Yang & Guo, 2001; Wang, 2004; Wang et al., 2009). Because qualitative information is obtained based on researcher's subjective judgment in these methods, there are obvious uncertainty and randomness in the result of these researches. For example, analytic hierarchy process utilizes expert scoring method to define weights on indicators, so it is not objective enough and the result will be greatly influenced by experts' knowledge (Schoenherr et al., 2008; Aryafar et al., 2013). As for artificial neural network, because it involves a process of selecting samples of environmental vulnerability manually, the accuracy of this method also depends on experts' knowledge. Moreover, in terms of principal component analysis method (Yang, 2005; Zhu et al., 2012; Doukas et al., 2012; Villegas et al., 2013; Shao, 2009), although it is a combination of qualitative analysis and quantitative analysis, part of the information is removed in the process of selecting principal components so that it affects the results of the evaluation. PPM (Friedman & Tukey, 1974; Wang & Li, 2006; Cao et al., 2011) is a new statistics method to process and analyze high dimensional data, whose main theory is projecting high dimensional data to lower dimension and studying data structure in low dimensional space. This method has many advantages of high robustness, high anti-interference, great veracity and great objectiveness. Updating the data of vulnerability indicators in time by using Remote Sensing (RS) technique, studying environmental vulnerability by using mathematic model and GIS,

monitoring vulnerable ecosystem timely and evaluating environment dynamically have gradually became the primary purpose of regional environmental vulnerability assessment. (Wilkinson, 1996; Mesev, 1997; Clarke & Gaydos, 1998; Guisan & Zimmermann, 2000; Demet & Oner, 2012.).

In recent years, some scholars applied PPM to evaluate regional environmental quality (Wang & Li, 2006). But it is rare to integrate PPM and GIS to assess regional environmental vulnerability until now. In this paper, the middle-upper reaches of Dadu River Watershed was selected as study area, the environmental vulnerability in both 2000 and 2010 were quantitatively evaluated and analyzed by applying PPM and GIS comprehensively, and reliable suggestions to environmental protection of the study area are proposed according to the results of assessment in the end.

This study primarily achieved the following goals: (1) A regional environmental vulnerability assessment model was established by integrating GIS with PPM. (2) Environmental vulnerability results were classified by using clustering principle. (3) Spatial distribution and the change trends (from 2000 to 2010) of environmental vulnerability were analyzed and the driving forces were discussed. (4) Proposals for environmental protection and management of the study area were proposed.

2. METHODS

2.1. Study area

The study area, located in the middle-upper reaches of the Dadu River Watershed, encompasses an area (between latitude 29°08′26″N and 31°58′02″N and longitude 101°00′11″E and 102°58′55″E) of approximately 36884 km^2 spanning over parts of six counties: Maerkang, Jinchuan, Xiaojin, Danba, Kangding and Luding. The dominant landforms in the study area are medium-high Mountain with eroded structures, High Mountain with glacier, plain with aggradational river valley, and intermountain down-faulted basin. In the study area, the perpendicular band spectrum phenomenon of the climate is apparent. The alpine cold temperature zone is 4000 meters above sea level with an mean annual temperature below 0°C; The temperate mountain is 2500m-4000m above sea level with an average annual temperature below 8°C; The low mountain valley zone in northern subtropics is 1550m-2500m above sea level with mean annual temperature between 9°C and 15°C; The valley zone in the central Asian tropic is 1330m-1640m above sea level with mean annual temperature of 17.4°C. Plateau monsoon climate and

continental monsoon climate dominate local climate with average annual temperature of about 6℃, relative humidity of about 60%, average precipitation of approximately 715mm and evaporation of approximately 1300mm. The location and general situation of the study area are shown in figure 1.
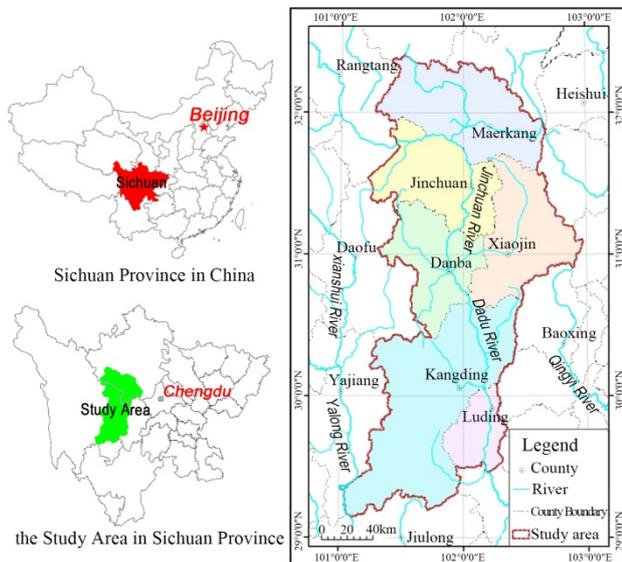

Figure 1. Location and general situation of the study area

2.2. 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). Spatial data include the following: (1) Enhanced Thematic Mapper Plus (ETM+) imagery of Landsat7 satellite with spatial resolution of 30m, obtained from the Geospatial Data Cloud, 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 spatial resolution of 90m obtained from the Geospatial Data Cloud; (3) Normalized Differential Vegetation Index (NDVI) data obtained from the Geospatial Data Cloud MODIS data products; (4) spatial data of soil types in the study area on the scale of 1:100 000, provided by the Sichuan Provincial Academy of Environmental Sciences. Attribute data include the following: (1) population and GDP data obtained from Ganzi Yearbook and Aba Yearbook; (2) temperature and precipitation data obtained from China Meteorological Data Sharing Service System.

Further processing the collected data mainly includes following steps: (1)Acquisition of thematic data: land use data were obtained by applying the method that combining unsupervised classification with visual interpretation to Landsat ETM+ images, a few SPOT5 images and a few RapidEye images. And

we verified the selected 200 fields and drew the conclusion that the accuracy of land use types is more than 90%. Elevation and slope data were obtained based on DEM data. Meanwhile, Population, GDP, temperature and precipitation data were converted into spatial data by Spatial Data Interpolation Tool in ArcMap; (2) Projection coordinate and other information: In order to ensure highly spatial veracity of different thematic data, equal area projection was used. The projection parameters is set as follows: initial longitude 110° E, initial latitude 0 °, double standard parallel 25°and 47°, 1954 Beijing geodetic datum and Krassovsky ellipsoid. (3) Conversion of raster data: raster data is favorable to spatial analysis in GIS. So, in order to perform algebraic and logical operations, all thematic data were converted into raster data with grid size of 250 m × 250 m.

2.3. Evaluation process

Environmental vulnerability of the study area was evaluated by three steps: (1) established an evaluation indicators system; (2) obtained optimal projection direction; (3) used mathematical model to calculate and analyze environmental vulnerability. Evaluation process is shown in figure 2.
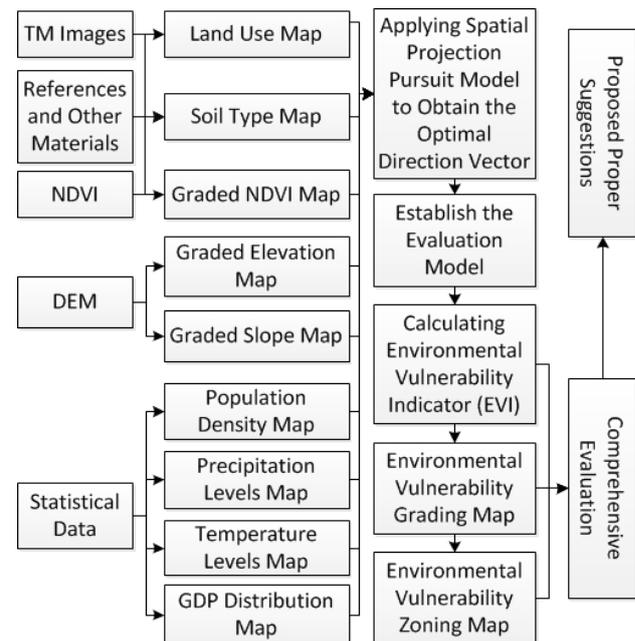

Figure 2. Schematic representation of environmental vulnerability evaluation.

2.3.1. Environmental vulnerability indicator system

Base on the principle of representative, holistic, scientific, and operational (Boruff et al., 2005; Yu et al., 2009; Xu et al., 2011), nine environmental indicators were selected (i.e.,

elevation, slope, vegetation, land use, soil type, GDP, temperature, precipitation and population) to evaluate environmental vulnerability of the study area take into account natural condition in the middle-upper reaches of Dadu River Watershed. Evaluation indicators are shown in table 1.

Table 1. Environmental vulnerability evaluation indicators

Indicator	Selecting principles	Obtaining time
Elevation and slope	Elevation and slope are basic geomorphic indicators with greatly influence on surficial runoff and land use. The altitude in middle-upper reaches of the Dadu River Watershed is between 976m and 7556m. Besides, the terrain is precipitous with high values of fragmentation depth. Thus, elevation and slope have crucial impacts on environment in the study area.	Obtained by calculating two digital elevation models with grid size of 90m×90m (in 2000 and 2010).
Vegetation coverage	Vegetation coverage is a vital indicator to assess the condition of surficial vegetation. The condition directly affects, and even determines the environmental functions and conditions such as the amount of primary biological production, ecological carrying capacity, soil erosion in eco-environment. This indicator has significant meaning in environmental vulnerability investigation. In this paper, normalized difference vegetation index (NDVI) serves as vegetation coverage indicator because it reveals vegetation coverage condition.	NDVI data obtained from MODIS data products (in July 2000 and July 2010).
Land use	Regional environmental problem in eco-system such as soil and water loss, forest vegetation decrease, land desertification, and soil salinization are closely related to land use. Before 2000, unreasonable exploitation, vegetation destruction and slope land reclamation contribute to soil and water loss. After 2000, the carrying-out of woods preservation and construction project in the upstream of Yangtze River facilitated the increase of vegetation coverage, the release of soil and water loss and the improvement of ecological environment. However, hydropower development contributed locally to vegetation tear down. Thus, land use is an important indicator to environmental vulnerability assessment.	Land use data from ETM+ images (in 2000 and 2010. orbit number: 131038, 131039, 131040, 130038, 130039, 130040).
Soil type	Soil is a vital prerequisite to protect ecological balance. Eroded soil scatter throughout the study area with different soil types and vulnerable soil may leads to vulnerable eco-system. The main soil types in middle and upper reaches of the Dadu River Watershed are rhodic ferralsols, ferric luvisols, plaggic anthrosols, calcaric cambisols. Common characters of these soils are weak water-retaining property, deficient anti-erosion ability, and deficient anti-deterioration ability. Thus, soil type is an important indicator to investigate environmental vulnerability.	Two periods of soil type data provided by Sichuan Academy of Environmental Protection Sciences, soil erosion data from the second (in 2000) and fourth (in 2010) soil erosion RS survey results of Sichuan Province.
Temperature and Precipitation	Climate factors (temperature and precipitation) are kinetic energy of all environmental factors and energy basis of ecosystem. If energy characteristics or transformation of climate factors disaccords with other environmental factors, ecological degradation will happen. As for the middle-upper reaches of Dadu River Watershed, on the one hand, the precipitation in the watershed is overly plentiful which leads to strong erosion and the strong erosion leads to a vulnerable ecosystem. On the other hand, precipitation changes a lot in different seasons and different period of time. Seasonal drought restraints plants from growing and results in vegetation degradation. This consequence is difficult to recovery. Thus, more serious seasonal drought is, more vulnerable regional environment will be. Hence, temperature and precipitation are indispensable in assessment.	Two periods of average precipitation and mean annual temperature (in 2000 and 2010) from observation data in meteorological stations.
Population and GDP	Population, education and human's cognition of nature are influencing factors to environmental vulnerability. Besides, the main factors of human activities that contribute to ecological degradation in the study area are slope land reclamation and excessive mining. Besides, primary financial activities in the study area are agriculture and animal husbandry with limited soil resource. Moreover, with the increase of population, vegetation destruction and slope land degradation were aggravated. Under this condition, plants were destroyed, water and soil loss was sharpened, and environmental vulnerability was aggravated. Therefore, population and GDP are crucial factors to environmental vulnerability assessment.	Two periods of population and GDP data from statistical data of Aba yearbook and Ganzi yearbook (in 2000 and 2010).

As for environmental vulnerability evaluation indicators, because the dimension of these indicators is not unified, comparability cannot be ensured. In order to define the environmental influence of every indicator, the influencing grade of each indicator was divided into five levels. There are two main dividing principles:

(1) Classification by referring to existing research results.

In terms of land use data, grading method is taken from the cited authors (Li, 1989; Liu et al., 2005; Tu et al., 2007). Grading for land use data is performed according to the relationship between land erosion type/intensity and land use type. The Levels of all land use types are shown in table 2.

Table 2. Gradation of Land use

Land Use Type	Erosion Type and Intensity	Level
Forest, shrub and marsh	High vegetation coverage, slight erosion	1
Low coverage forest, arable land and grassland	Slight water and wind erosion	2
River, lake and other water bodies	Slight/mild water erosion	3
Urban construction and digging	Slight/mild water and wind erosion	4
Glacier, bare rock, and bare land	Mild ice erosion, moderate/deep water and wind erosion	5

For soil type data, the influences of different soil types on environmental vulnerability are determined by soil erosion value (K) (Men et al., 2004; Zhang et al., 2009; Wu et al., 2010; Liang et al., 2013). Soil erosion value (K) is a vital indicator to indicate the possibility of soil erosion. It's an important factor of the Universal

Soil Loss Equation (USLE) and the Water Erosion Prediction Project (WEPP). The value of K can represent the vulnerability of soil in the study area. Soil erosion values (K) in the study area were gained and graded according to a published study (Deng et al., 2003). In order to ensure the comparability of all indicators, soil erosion intensity is divided into five levels, namely, unobvious erosion, which assigned 1; slight erosion, which assigned 2; mild erosion, which assigned 3; moderate erosion, which assigned 4; and deep erosion, which assigned 5. The present study directly uses these standards. The values (K) of typical soil types in the study area are shown in table 3.

Table 3. Soil erosion value (K)

Soil type	K	Soil type	K
Rhodic ferralsols	0.299	Cutanic luvisols	0.323
Plaggic anthrosols	0.302	Ferric luvisols	0.297
Skeletic cambisols	0.275	Ferralic cambisols	0.294
Gleyic cryosols	0.284	Histic gleysols	0.306
Haplic lixisols	0.278	Calcaric cambisols	0.330
Plaggic cambisols	0.268	Gleyic lixisols	0.291

(2) Classification by the principal of cluster analysis.

Elevation, population, GDP, slope, NDVI, precipitation and temperature were graded by natural breaks method classification method according to 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 (Shi & Qiao, 2009; Yan, 2010).

Table 4. Data and classified data of four indicators

Indicator / County		Population (10 thousand)		GDP (10 thousand yuan)		Temperature (°C)		Precipitation (mm)	
		2000	2010	2000	2010	2000	2010	2000	2010
Maerkang County	K	5.4	5.5	8824	17767	8.5	8.6	753	783
	Level	1	1	4	4	2	2	4	4
JinchuanCounty	K	6.8	7.4	3041	6149	12.8	13.1	616	587
	Level	2	2	1	2	3	3	2	1
Xiaojin County	K	7.4	8.1	3345	7151	12.2	13.2	613	615
	Level	3	3	2	1	3	3	2	2
Danba County	K	5.6	6	3267	9719	14.2	14.7	600	621
	Level	1	1	1	3	4	4	1	2
Kangding County	K	10.6	11.3	12455	22905	7.1	7.6	803	834
	Level	5	5	5	5	1	1	5	5
Luding County	K	7.6	8.5	4538	9321	15.5	15.7	664	681
	Level	4	4	3	3	5	5	3	3

Among these indicators, data and classified data of population, GDP, precipitation and temperature are shown in table 4. Data and classified data of elevation, slope, NDVI, soil type and land use are shown by spatial data in figure 3.
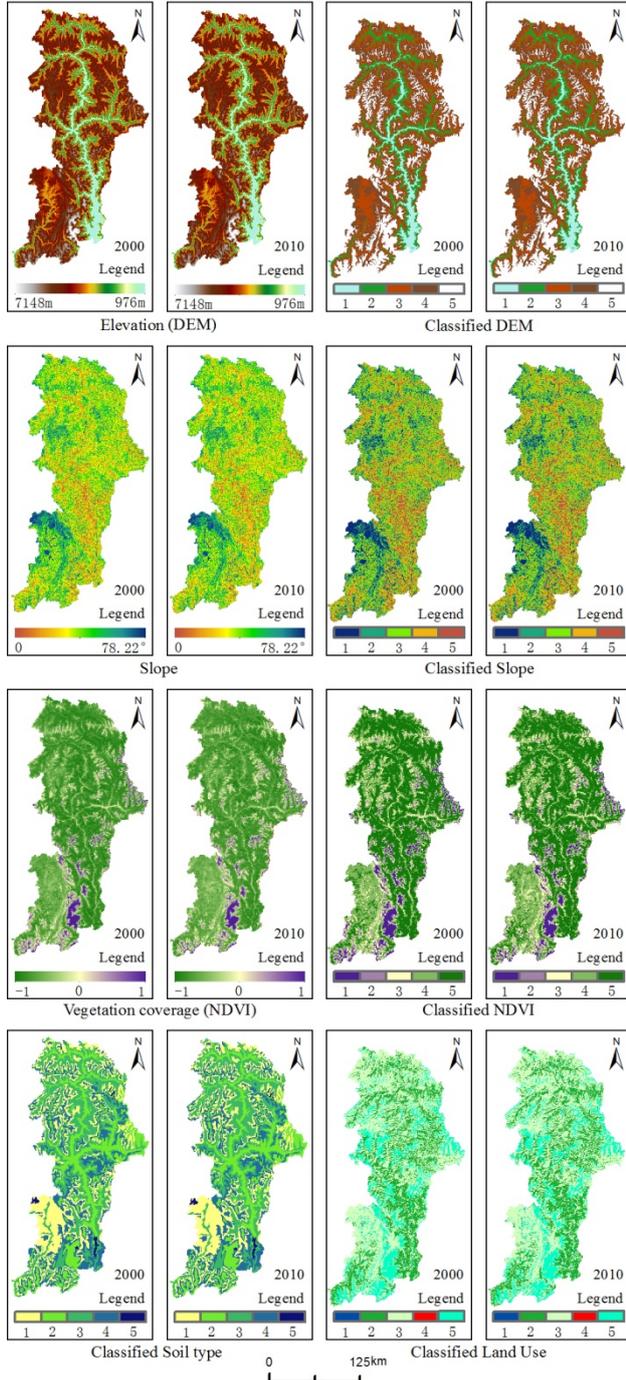

Figure 3. Data and classified data of five indicators

2.3.2. Evaluation model

The main purpose of environmental vulnerability assessment is using specific model to convert several characteristic indicators into a comprehensive evaluation indicator (Feng, 2003; Kim-Cohen et al., 2006; Zhao et al., 2008; Qiao et al.,

2008). The present paper utilized Projection Pursuit model combined with GIS technology to conduct environmental vulnerability assessment. In support of GIS software, selected indicators were calculated and converted into optimal projection direction by using Raster Calculator in ARC/INFO. Then, the final comprehensive vulnerability indicator which is needed to establish the PPM was obtained. This method was performed by the following steps:

(1) Normalization of original data

Original data were normalized as follows:

$$a_{xy} = \frac{b_{xy} - b_{x,\min}}{b_{x,\max} - b_{x,\min}} \qquad (1)$$

Where, a_{xy} is normalized value (in the range of 0 to 1) of pixel y of indicator x; b_{xy} is true value of pixel y of indicator x; $b_{x,max}$ is maximal pixel value of indicator x. $b_{x,min}$ is minimal pixel value of indicator x. In this step, matrix is shown in the form of raster image and pixel is an element of the matrix.

(2) Establishment of projection pursuit model

W_{nm} is the indicator m of sample n(n = 1 ,2 , ···,s ; m = 1 ,2 , ···, t. s is the quantity of samples and t is the quantity of indicators)

1) Linear projection

$\vec{u}$ is unit projection direction in t-dimensional space. V_n is the projection eigenvalue of W_{nm} in one-dimensional linear space, which can be quantified as follows:

$$V_n = \sum_{m=1}^{t} u_m W_{nm} (m=1,2,3......t) \qquad (2)$$

2) Projection index

Because comprehensive assessment on regional environmental vulnerability which bases on indicator system is a specific classification or ranking of evaluation samples, Projection index can be established according to classified indicators. Moreover, the purpose of classification is achieving the maximal distribution structure in between-class distance $E(\vec{u})$ and inner-class density $G(\vec{u})$ in one-dimensional space. Thus, projection index H was defined as:

$$H = E(\vec{u}) \times G(\vec{u}) \qquad (3)$$

Between-class distance can be calculated by variance of projection eigenvalue in sample sequence. It can be formulated as follows:

$$E(\vec{u}) = [\sum_{n=1}^{s} (\alpha_n - \bar{\alpha})/s]^{1/2} \qquad (4)$$

Where, $\bar{\alpha}$ is average projection eigenvalue.

A larger $E(\vec{u})$ represents a more dispersive between-class distance.

Inner-class density could be defined as distance between two projection eigenvalue $T_{nl}=|a_n-a_l|$ $(n,l=1,2,3...s)$. Inner-class density $G(\vec{u})$ can be calculated as follows:

$$G(\vec{u}) = \sum_{n=1}^{s}\sum_{l=1}^{s}(Q-T_{nl})\times f(Q-T_{nl}) \quad (5)$$

Where, Q is an indicator to estimate density of partial scattered points which relates to data characteristics. The range of value of Q has been calculated in many researches, which is: $\max(T_{nl})+t/2\leq Q\leq 2t$. And the value of Q always be assigned as: $Q=t$. $f(Q-T_{nl})$ is a step function. While $Q>T_{nl}$, $f(Q-T_{nl})=1$, or it will be assigned zero. Besides, Cluster phenomenon will be more apparent with the increase of $G(\vec{u})$.

3) Optimization of projection direction

Projection direction is optimized base on projection index H. So, while the maximum value of H is gained, optimal projection direction is gained. Hence, projection direction optimization is converted into nonlinear optimization as follows:

$$\begin{cases} \max \ H \\ u = 1 \end{cases} \quad (6)$$

(3) Comprehensive assessment

According to optimal projection direction $\vec{u}$, comprehensive information which reflects characteristics of indicators can be calculated and environmental vulnerability can be assess according to the difference of comprehensive information. The present paper mainly utilized Environmental Vulnerability Index (EVI) to represent environmental vulnerability level. EVI was defined as the weighted sum of several characteristic indicators and every optimal direction vector of characteristic indicator serves as weight. The formula is present as follows:

$$EVI = \sum_{i=1}^{n} X_i Y_i = X_1 Y_1 + X_2 Y_2 + X_3 Y_3 ......X_n Y_n \quad (7)$$

Where, Y_n is the first principal component. X_n is the contribution of Y_n and also the value of optimal direction.

Every characteristic indicator and the weight were algebraically calculated to get a comprehensive evaluation indicator which represents the regional environmental vulnerability condition. Small EVI value follows serious vulnerable environment.

PPM is established according to indicator of

grading criterion of environmental quality. In this PPM, s=3, t=9. Then, optimal projection direction A was obtained as follows: A = (DEM, LUCC, GDP, Precipitation, NDVI, Slope, Temperature, Population, Soil type).

Because optimal projection direction is a continuous data, the maximum of every partial direction vector of optimal projection direction should be chosen as the weight. Weight of every characteristic indicator is shown in table 5.

Table 5. Weight of every characteristic indicator

Characteristic indicator	2000	2010
DEM	-0.009016311	-0.001081841
LUCC	0.394396757	0.447046248
GDP	-0.001486429	-0.000000767
Precipitation	0.341568439	0.392118299
NDVI	0.422751639	0.544094552
Slope	-0.029324536	-0.038807434
Temperature	0.335845612	0.411020876
Population	-0.000000098	-0.00000211
Soil type	0.362331943	0.424156414

Linear formula to calculate EVI in this study is shown as follows:

EVI_{2000}=-0.009016311$\times Y_1$+0.394396757$\times Y_2$-0.001486429$\times Y_3$+0.341568439$\times Y_4$+0.422751639$\times Y_5$-0.029324536$\times Y_6$+0.335845612$\times Y_7$-0.000000098$\times Y_8$+0.362331943$\times Y_9$ (8)

EVI_{2010}=-0.001081841$\times Y_1$+0.447046248$\times Y_2$-0.000000767$\times Y_3$+0.392118299$\times Y_4$+0.544094552$\times Y_5$-0.038807434$\times Y_6$+0.411020876$\times Y_7$-0.00000211$\times Y_8$+0.424156414$\times Y_9$ (9)

Where, EVI is environmental vulnerability indicator; Y_1-Y_9 are nine variables, namely, DEM, LUCC, GDP, Precipitation, NDVI, Slope, Temperature, Population, Soil type in two period of time.

2.4. Gradation of vulnerability

Because the results obtained by applying the PPM to the nine indicators are continuous, a specific grading method was used to define environmental vulnerability levels according to these results on the purpose of showing the whole regional environmental vulnerability condition. An objective grading method is crucial to evaluate the environment of study area (Su & Su, 2007) and it is an objective method that classification according to

data histogram (Zhong et al., 2005). Thus, natural breaks classification method was used to conduct cluster classification to the histogram of the environmental vulnerability evaluation results. Natural breaks classification is a popular data classification method in which classification intervals was defined by using statistic method with the process of searching relatively highly-different neighbor elements. Accuracy of this classification can be known in statistic way by calculating the sum of variances in all classes and optimal classification result (which does not have to be unique) can be obtained by finding the minimal sum of variances. This is the principle of natural breaks classification method. By observing data histogram, it could be easily found that the faulted point coincide with the breakpoint (threshold) calculated by Natural Breaks method. Therefore, natural breaks classification method is indeed a "natural" classification method with obvious difference between classes, yet little difference within each class, and a distinct breakpoint between two classes. So, in this research, we used natural breaks classification method to analyze environmental vulnerability result to get breakpoints between different classes and ranked vulnerability levels of the whole study area.

According to the result graded by natural breaks classification method, environmental situation in the study area was divided into five levels: potential vulnerability, slight vulnerability, light vulnerability, moderate vulnerability and high vulnerability. (Fischer et al., 2002; Guan & Su, 2006; Li et al., 2009). Each level is shown with its typical characters in table 6.

2.5. Analysis of overall vulnerability change trend

In order to quantificationally analyze the overall change trend of environmental vulnerability, an integrated index which reflects the whole regional vulnerability condition should be defined. The way to calculate integrated index E was formulated as follows:

$$E = \sum_{i=1}^{n} \frac{A_i}{SA_j} \times P_i \qquad (10)$$

Where, i is vulnerability level; n is the number of all vulnerability levels; j is the evaluation unit; A_i is the area of level i in the evaluation unit j; SA_j is the area of j; P_i is the score of i. According to the vulnerability levels, each level is scored: the potential vulnerability is assigned one, slight vulnerability is assigned two, light vulnerability is

assigned three, moderate vulnerability is assigned four and high vulnerability is assigned five. A bigger integrated environmental vulnerability index E represents a more vulnerable environment.

Table 6. Environmental vulnerability classification in the study area

Vulnerability Level	EVI	Character Description
High vulnerability	<0.41	The ecological system is extremely unstable with weak erosion resistance, relatively high altitude, barren soil and sparse vegetation coverage which are mainly hardy plants
Moderate vulnerability	0.41-0.60	The ecological system is unstable with weak erosion resistance, poor soil and few vegetation types.
Light vulnerability	0.60-0.73	The ecological system is relatively unstable with a relatively weak erosion resistance, poor soil, and relatively diverse vegetation types.
Slight vulnerability	0.73-0.82	The ecological system is relatively stable with erosion resistance, fertile soil, relatively low altitude, and fine vegetation coverage.
Potential vulnerability	>0.82	The ecological system is stable with a relatively strong erosion resistance, fertile soil, relatively low altitude, and good vegetation coverage.

Table 7. Percentage of different environmental vulnerability in the study area

Vulnerability degree	2000		2010	
	Grid number	Percentage	Grid number	Percentage
Potential	62803	9.42%	69613	10.44%
Slight	309183	46.38%	318813	47.82%
Light	160248	24.04%	142749	21.41%
Medial	75408	11.31%	83545	12.53%
Heavy	58983	8.84%	51905	7.79%

3. RESULTS

3.1. Distribution of vulnerability levels

According to environmental vulnerability assessment method in this paper, the proportions of areas at different environmental vulnerability levels are shown in table 7. The result of the environmental vulnerability gradation of the study area in different
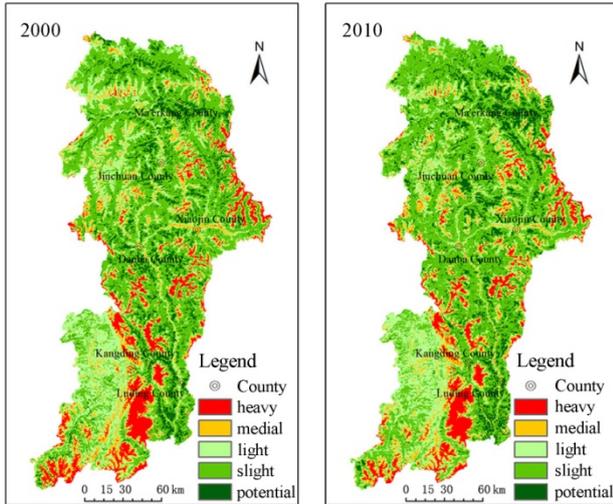
years is shown in figure 4.

Figure 4. Distribution map of the environmental vulnerability in the study area

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, it was found that the percentage of the slightly vulnerable regions in the study area is the largest, followed by the lightly vulnerable regions, the moderately vulnerable regions and the potentially vulnerable regions. The percentage of high vulnerable regions is the smallest. For example, in 2010, the slightly vulnerable regions occupy the largest proportion of the whole study area which is 47.82%. Meanwhile, the proportion of lightly vulnerable regions is at 21.41%, the proportion of moderately vulnerable regions is at 12.53%, and the proportion of potentially vulnerable regions is at 10.44% and the smallest is the high vulnerable regions which occupy the percentage of 7.79%. Moreover, the total percentage of the slightly vulnerable regions, the lightly vulnerable regions and moderately vulnerable regions exceed 80%. Thus, we can draw the conclusion that environmental condition in the study area is in moderate vulnerability in 2010. Likewise, the study area is in moderate vulnerability in 2000.

3.2. Change trend of environmental vulnerability

Compared with the pixel number of each vulnerability levels of the study area in 2000, during the ten years, the percentage of pixel numbers of potentially vulnerable regions increased by 1.02%; the percentage of grid number in slightly vulnerable regions increased by 1.44%; the percentage of grid number in lightly vulnerable regions decreased by

2.63%; the percentage of grid number in moderately vulnerable regions increased by 1.22%; the percentage of grid numbers in high vulnerable regions decreased by 1.06%.

In figure 5, the change tendency of vulnerability is clearly presented. Only the percentages of the high vulnerable regions and moderately vulnerable regions were decreased during ten years. Meanwhile, the percentages of other regions were increased.
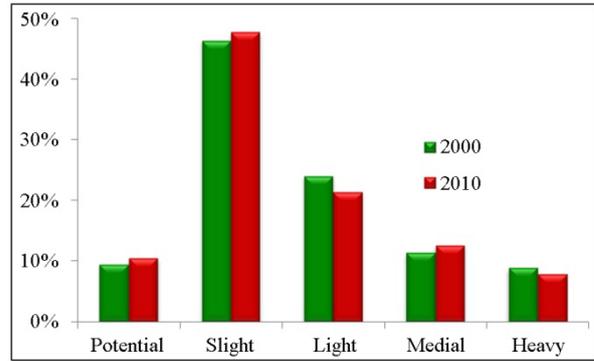

Figure 5. Proportion of environmental vulnerability levels

According to formula (8), the integrated *EVI* of the whole study area can be calculated. The integrated *EVI* of the study area in 2000 and 2010 are 2.64 and 2.59, respectively. This result shows that the whole environmental situation in 2010 is slightly better than it was in 2000.

3.3. Regionalization of environmental vulnerability

Referring to existing study methods, further analysis was conducted by making evaluations on environmental vulnerability degree of each subarea (Luers et al., 2003; Szlafsztein & Sterr, 2007; Zheng et al., 2010b; Xu et al., 2011), whose boundary should overlap with the geological boundary defined by natural environmental condition (Yang et al., 2007). In this paper, according to regional characters and requirements of ecological reconstruction, regionalization was conducted with the help of *EVI* in the middle and upper reaches of Dadu River Watershed. Regionalization of environmental vulnerability is shown in figure 6. In the figure, the study area was divided into three subareas according to environmental vulnerability condition on the purpose of providing guiding information to local ecological reconstruction so as to help reconstruction be sufficient carried through in the order of importance and urgency.

(1) Potential and slightly vulnerable regions such as river valley and other low terrains should be integrated developed. These regions are primarily

located in the north of Dadu River Valley to Kangding County covering an area of approximately 17957.83 km^2, which is 50.14% of the total study area. These regions are the central part of economic development in our study area, which has a dense population. The main topography there are river valley and mountain land with thick vegetation coverage. The main eco-system types are shrub woods, alpine coniferous forests, alpine evergreen forests and grasslands.
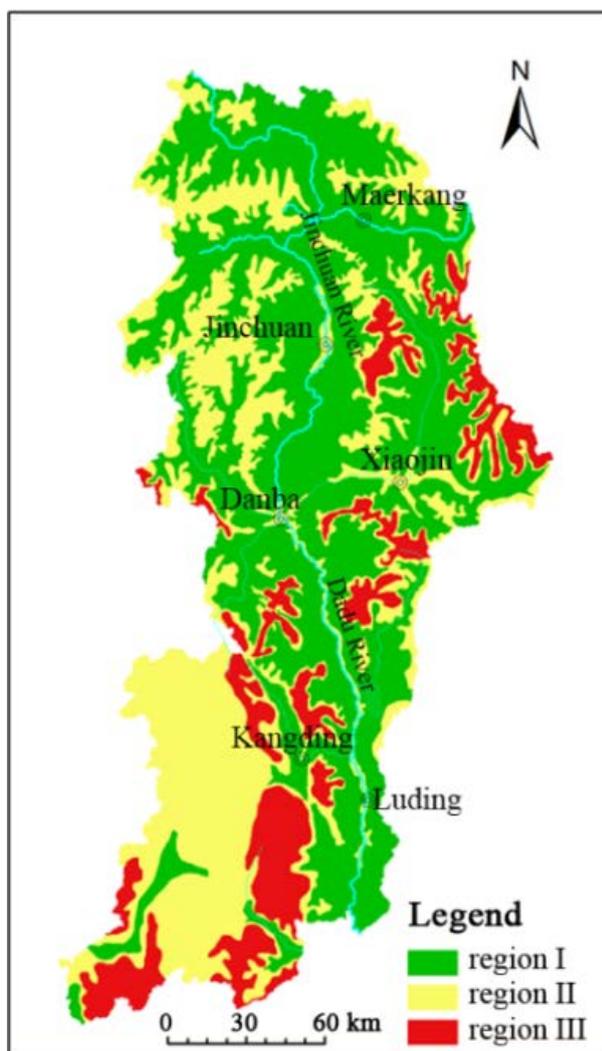

Figure 6. Regionalization of Vulnerability in the study area

(2) Light and middle vulnerable regions should be more strict protected. These regions are mainly located in the southeast of the study area where altitude is high or in river valley with many hydropower stations. These regions span over an area of approximately 13213.69 km^2, which account for 36.9% of the whole study area. There are sparsely populated areas whose main human activities are grazing, lumbering and hydroelectric construction. The main eco-system types are grasslands, alpine shrub jungles and alpine coniferous forest.

(3) Preservation must be reinforced in heavy vulnerable regions. These regions are located in Kangding, Luding and northeastern Xiaojin covering an area of approximately 4640.22 km^2 which is 12.96% of the whole study area. Population density is fewer than 2 people per kilometer^2 in these regions. Main terrains there are high mountains and extremely high mountains. The main eco-system types are sparse grasslands and thin shrub woods.

4. DISCUSSIONS

4.1. Analysis of change driving forces

After analyzing the change trends of environmental vulnerability in the middle and upper reaches of the Dadu River Watershed, we should further understand the driving forces behind these changes. By comparing the distribution map of the environmental vulnerability in 2000 and 2010, we find the change trends in the distribution of vulnerable regions is basically in accordance with the change trends of woodland cover. Therefore, the main factor that cause some area become extremely vulnerable is elevation and the primary driving force that contributes to vulnerability change is human activities. Under the influence of human activities, land use type and the proportion of these types are changing. Sequentially, environmental condition is changing.

From figure 3 and table 4, it can be seen that environment generally became better during 10 years. There were two main reasons contribute to these changes: First, many environmental protection policies were carried out. It released the pressure of excessive felling and over grazing, and lead to an increase of forest land and grassland. According to the information that obtained from remote sensing, the area of vegetation coverage was increasing during the 10 years; the area of forest area was 15906km^2 in 2000 while it increased to 18466km^2 in 2010, which is an increase of 2560km^2; the proportion of vegetation coverage in the whole study area reached 51.57%; The proportion of grassland was also increasing from 17647km^2 in 2000 to 17779km^2 in 2010, which increased by 132km^2. The increasing of vegetation coverage stimulates the improvement of environmental condition. Second, Global Warming affects the temperature to become warmer in alpine region which leads to the effect that Glaciers melting provides sufficient water for plants to grow. Thus, environmental condition in alpine region gets great progress under this

circumstance.

During the study period, some regions deteriorated. There are two reasons: Firstly, hydroelectric resource was exploited in this period of time. During ten years, the Bala Hydropower Station, the Dawei Hydropower Station, the Pugousi Hydropower Station and other fourteen hydropower stations were planned and built in the study area. On one hand, the construction of hydropower stations risen the groundwater level, broadened the erodent places and changed the climate. On the other hand, serious submersion of plough and woodland destroyed local environment. In 2010, damaged area had reached 2.4637 km^2. Secondly, financial development: GDP of the study area had greatly increased from 356 million in 2000 to 730 million in 2010. The big growth mainly thanks to the quick development of secondary industry and the main representation is the development and utilization of mineral resources.

4.2. Ecological reconstruction in different regions

According to the spatial distribution of different eco-environment, the study area was divided into three subareas to provide different reconstruct suggestions.

Subarea 1: this zone mainly consists of rich vegetation coverage area around the Dadu River Valley which is the main place requiring ecological governance and conservation. With the help of forcible administration and loud appealing to environmental protection, environmental condition had been definitely improved. However, the construction of hydropower stations threatens the environment in this zone. So, government and hydropower development companies should establish an appropriate and favorable environmental protection strategy to promote local development. Practical measures are proposed as follows: Firstly, multifunctional ecological forests, financial agricultural forests, presentable pastures and many other mixed ecosystems should be established. Secondly, in the places with hydropower stations, managements should be strengthened to prevent landslide, debris flow and other geological disasters.

Subarea 2: this zone is located in the transitional place between river valleys and extremely high mountains. It's a crucial area to prevent water and soil loss and protect the whole environment of the study area. In order to protect the environment, first, illegal deforestation and over gazing should be rigorous supervised. Second, afforestation and seeding with protection of existing forest and grassland should be advocated. Third, government should set up a law to protect the forest and grassland.

Subarea 3: this zone is mainly located in extremely high mountains. Because of high elevation, vegetation coverage is low and some places are covered with snow all through the year. Thus, ecosystem is hard to restore after it was destroyed. To prevent this area from getting larger, government should control the quantity of lumbering and grazing, chose proper regions and plants to afforest according to environmental and soil condition. Only in this way, environmental resilience of this subarea can be promoted.

5. CONCLUSION

In support of GIS and RS, we established spatial PPM to define optimal direction and the weight of every indicator and establish an assessment model to evaluate environmental vulnerability in the middle-upper reaches of Dadu River Watershed. Through comprehensive investigation on environmental vulnerability, we draw the following conclusions:

Environmental vulnerability condition in the study area is medium. The proportion of slightly vulnerable regions is the biggest, with the lightly vulnerable regions following behind, and the combined area of these two regions composes more than 50% of the whole study area. And then follows moderately and potentially vulnerable regions, while high vulnerable regions cover the smallest area respectively. Potentially vulnerable regions are mainly located in Maerkang County and southeastern Luding County. Slightly vulnerable regions are scattered throughout counties. Lightly vulnerable regions are mainly in Kangding county and Jinchuan county. Moderately vulnerable regions distribute along Dadu River and some transitional places between high vulnerable region and lightly vulnerable region. High vulnerable regions are mainly in Kangding county, Luding county and northeastern Xiaojin county. Generally, environmental condition in the study area has been improved. The trend was formed primary under the influence of natural forest protection policy, plowland forestation policy, over grazing limitation policy, afforestation policy and many other measures relating to ecological reconstruction. Throughout comprehensive discussion, it was proved that the approach integrates GIS and PPM is very effective, and greatly promotes the study of vulnerability assessment in the middle-upper reaches of Dadu River Watershed. Compared with conventional

approaches, applying Projection Pursuit model to conduct regional environmental assessment has less jamming and its process is simpler. Thus, the result is more objective and it reflects the real condition and vulnerability change trend of the whole study area more accurately. Finally, according to this research, convincing suggestions for relevant policies making to ecological and economic development were proposed and scientific basis for regional environmental construction was provided.

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