Journal of Arid Environments 72 (2008) 1929– 1939

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Regional assessment of environmental vulnerability in the Tibetan Plateau: Development and application of a new method

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ARTICLE INFO

Article history:
Received 25 November 2007
Received in revised form
10 April 2008
Accepted 9 June 2008
Available online 21 July 2008

Keywords:
Environmental assessment
Environmental vulnerability index
Geographic information system
Methodological development

ABSTRACT

Regional environmental evaluation often requires a large amount of spatial information. Remote sensing (RS) and geographic information systems (GIS) are capable of managing large amounts of spatially related datum, and providing the ability to integrate multiple layers and to derive additional information. A methodological reference framework, using RS, GIS, and AHP (the analytic hierarchy process), is developed for environmental vulnerability assessment. Using this proposed method, we carried out a case study in the Tibetan Plateau. An environmental vulnerability index (EVI) proposed incorporates 15 factors covering natural conditions, environmental issues, and human activities. According to the EVI values, the vulnerability was classified into five levels: slight ($EVI<2.2$), light ($2.2\leqslant EVI<2.7$), moderate ($2.7\leqslant EVI<3.0$), heavy ($3.0\leqslant EVI\leqslant 3.4$), and extreme vulnerability (>3.4). The case study showed that the majority of the area in the Tibetan Plateau is ecologically lightly (light level; 22% of the total area), moderately (moderate level; 27%), and heavily (heavy level; 30%) vulnerable. Except for a clearly horizontal distribution, the environmental vulnerability increased clearly with increasing elevation (vertical distribution). The case study verified the usefulness and feasibility of the methods developed, for the results gained reflect the reality of the Tibetan environment closely. Further use in other regions should pay attention to what factors seem to be important in determining the local environmental vulnerability, and how is the impact of each factor on the complex environment.

1. Introduction

Environmental evaluation was introduced in the 1960s as a tool to assess the environmental situation qualitatively and quantitatively. In recent years, it is recognized that subjective evaluation often overestimates or underestimates the environmental impacts (Basso et al., 2000). This, therefore, led to a new concept of environmental vulnerability focusing on vulnerability analyses (Aars, 1998; Weston, 2004). As a new branch of environment assessment, the trend evaluation of the environmental vulnerability has been fast developed in past years, and many methods have been proposed, such as the comprehensive evaluation method (Goda and Matsuoka, 1986), the fuzzy evaluation method (Adriaenssens and Baets, 2004; Enea and Salemi, 2001), the gray evaluation method along with the artificial neural-network evaluation method

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doi:10.1016/j.jaridenv.2008.06.005

(Dzeroski, 2001; Hao and Zhou, 2002; Park et al., 2004), the osculation value method (Xue et al., 2003), and the landscape evaluation method (Antonio et al., 2003; Kangas et al., 2000). The variables used in these models, however, are not always easy to be acquired and operated. For example, the neural-network method needs a number of historical data, which especially is a problem of using existing domain knowledge in the learning process (Li et al., 2006a, b). Moreover, the methods developed for a small spatial scale have been confronted with serious criticism when used at the regional level (DeAngelis et al., 1990; Suter, 1993), where information may be available on terrestrial and aquatic ecosystems, land-use changes, and a variety of simultaneous stressors (Tran et al., 2002). Hence, regional environmental vulnerability assessment still remains a great challenge (Boughton et al., 1999; Jones et al., 1997).

Remote sensing (RS) and geographic information system (GIS) provide a powerful tool for environment assessment on a macroscopical scale (Krivtsov, 2004; MacMillan et al., 2004; Store and Jokimäki, 2003). An important feature of RS and GIS is the ability to generate new information by integrating the existing diverse datasets sharing a compatible spatial referencing system (Goodchild, 1993). Although RS and GIS technology has already been widely used to assess regional ecological risk (Gaudet, 1994; Xu et al., 2004), environmental degradation (Bastin et al., 1995; Holm et al., 2003), and landscape changes (Gobster et al., 2000; Gustafson et al., 2005), studies addressing regional environmental vulnerability evaluation are limited. The presentation of vulnerability evaluation for regional environmental protection in the form of maps is ideal when using GIS, in which multiple layers' information can be integrated in different combinations. This can also overcome the existing difficulties in combining numerous spatial-related parameters involved in environmental vulnerability, and thereby provide a useful and effective tool.

RS-aid and GIS-aid were used for evaluating the environmental vulnerability for the whole Tibetan Plateau with an area of over 1.20 million km^2. This evaluation incorporates 15 factors covering natural conditions, environmental issues, and human activities. An assessment model is developed by integrating RS with GIS and AHP (analytic hierarchy process). Using the model proposed, the environmental vulnerability index (EVI) for the study area is computed. The EVI is then classified into five levels: slight, light, moderate, heavy, and extreme vulnerability by means of the cluster principle. A resultant map is performed to show the spatial distribution of the environmental vulnerability for the whole study area.

2. Methods

2.1. Study area

The Tibetan Plateau is located in the western part of China. It spans from 78°25′ to 99°06′E and from 26°50′ to 30°53′N, and has a total area of over 1.20 million km^2 (Fig. 1). The population in the region was ~2.7 million in the year 2004. The mean annual temperature varies between −3.0 and 11.8 °C, according to different geographical locations and various

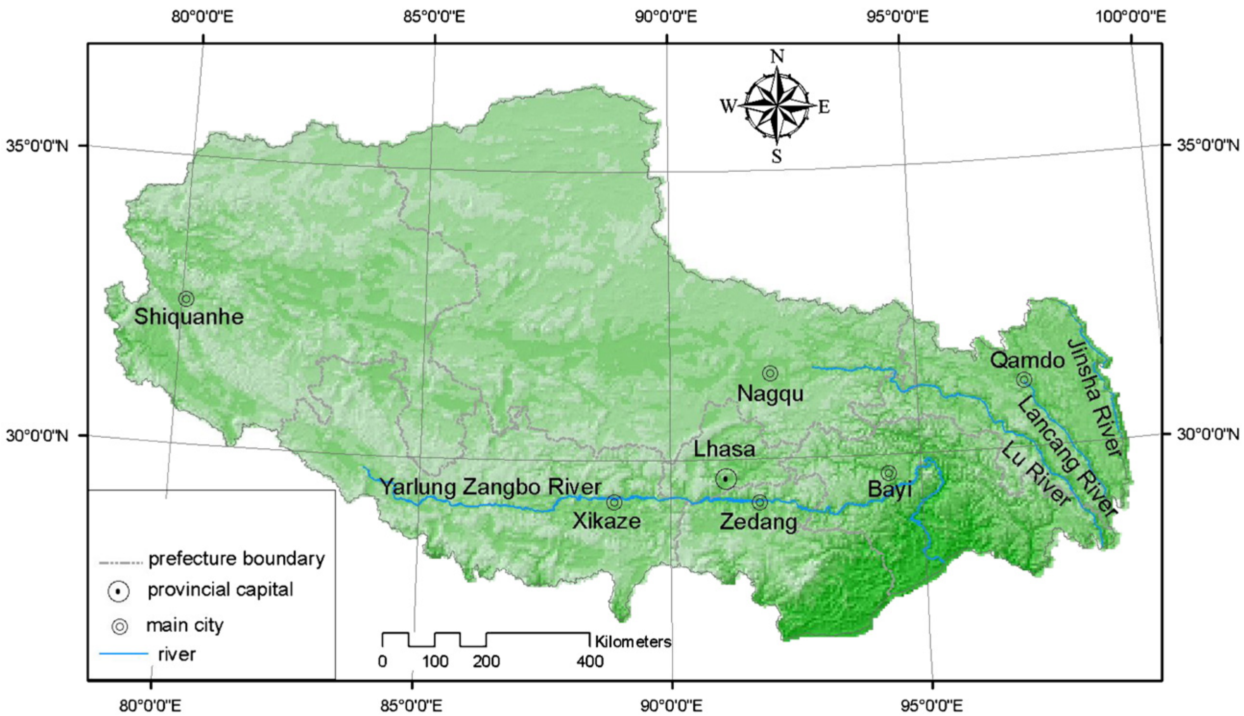

Fig. 1. Location of the study area.

topographical conditions, and the daily fluctuation in temperature often reaches around 15 °C. Such climate conditions can weather rocks very fast. As a result, this region is prone to soil erosion, land desertification, and mountain hazards. The southeastern part of the Tibetan Plateau has an annual precipitation of 600–800 mm, while the western part suffers from obvious drought with an annual precipitation of <200 mm, of which 80–90% occurs between May and August. Corresponding to the region-dependent differences in climatic conditions, geography, and topography, the Tibetan vegetation shows also an obvious vertical and horizontal distribution, following the order of tropical rain forest, mountain coniferous forest, shrub meadow, steppe, and desert steppe from the lower southeastern region to the higher northwestern region (Wang et al., 2005a).

As one of the most ecologically sensitive region on the earth, the Tibetan Plateau has a very unique and fragile environment which can be easily affected by global climate change and socio-economic activity. The state and development of the environmental vulnerability in the Tibetan Plateau influence both the regional sustainable development and further climate change.

2.2. Data collecting and processing

The basic data used in the present study include remote-sensed data from satellites or aircrafts, existing digitized data in form of GIS maps, and data published in statistics and reports. The common characteristic is that each type of data describes the attributes of recognizable point, linear, or areal geographical features. Details of the features are usually stored in either vector or raster formats.

The selection of data source should be influenced by their accuracy and resolution, together with the nature of the problem to be investigated (Hiscock et al., 1995). The 1:100,000 topographical maps (40 m interval) covering the study area were purchased from local survey authority, and digitized manually using the PC Arc/Info GIS software. The method of triangulated irregular network (TIN) was applied to develop the regional digital elevation model (DEM) from the digitized contour lines. The slope and elevation maps were derived from this digital elevation model (DEM) data. Data for climate, soil, and vegetation were obtained from the Chinese Environmental Background Database. Data for soil erosion, mountain hazards, and land desertification were supplied by local water, land, and forest authority. The degree of vegetation degradation is derived by comparing the RS data for August of 1986 and August of 2000 with a user–computer interactive interpreting method (Li and Liu, 2003). Human activities including population density, traffic construction, pasturage disturbance, and cultivation disturbance were cited from Zhong et al. (2005). The above-mentioned base maps were complied at a scale of 1:100,000 for the study area.

The vector base maps were then transferred to the desktop ArcView GIS, and rasterized for subsequent analyses. The raster grid cell definition was selected as $500 \times 500\,m^2$ resolution, which permit a closer approximation of a spatially continuous description of the geomorphic features. In the ArcView software environment, several base raster maps are generated. Using the method of Kriging Interpolation calculation (Oliver and Webster, 1990; Mason et al., 1994), every unknown point is estimated by the weighted sum of the known points investigated directly in the field.

2.3. Factors influencing the eco-environment

The selection of evaluation criteria plays a key role in a regional environment assessment. The evaluation factors should be operational, indicative, and representative (Alewell and Manderscheid, 1998; Zhao, 1999). Various factors influencing the environmental vulnerability of the Tibetan Plateau are considered. But it should be noted that this selection of factors is not exhaustive, and only those salient factors for which information is of great significance were selected.

Based on some previous qualitative analyses of environmental features in the study area (e.g. Wang and Zhong, 2003; Wang et al., 2005b), we considered all possible environmental variables for the present assessment. All variables were submitted to principal component analysis (PCA) to reduce data dimensionality by performing a covariance analysis between factors (Gauch, 1982; Legendre, 1998). The 15 independent factors representing the principal trait of the environmental variability are selected to assess the environmental vulnerability for the study area. Fig. 2 shows an integrated evaluation criteria system. Natural conditions including topography, climate, soil, and vegetation cover form an important determinant of vulnerability evaluation (Li et al., 2006a, b; Tran et al., 2002). Soil erosion, vegetation degradation, mountain hazards, and land desertification are considered because the study area is severely suffering from these earth surface processes and environmental problems (Wang et al., 2005a; Zou et al., 2002). The regional environmental vulnerability is also strongly related to local socio-economic factors since human activities can greatly influence the evolution of numerous environmental characteristics (Basso et al., 2000). Population density, traffic construction, pasturage, and cultivation disturbances are therefore selected to evaluate the impacts of human activities.

2.4. Standardization of factor measurement

In the process of environmental vulnerability evaluation, a primary step is to ensure a standardized measurement system for all factors considered. Since most images hold cell values for the original map codes, they have to be standardized to a uniform rating scale—in this case between 1 and 5 for ease of analysis (Dai et al., 2001). Assigning values

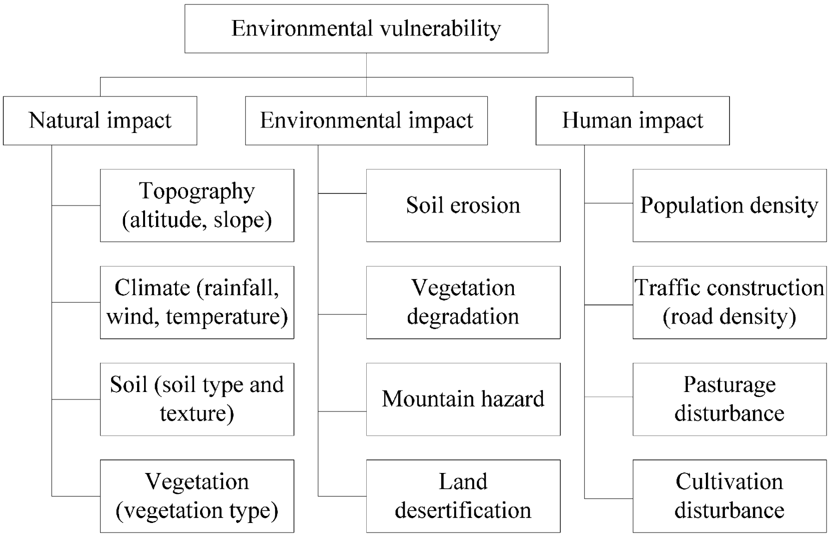

Fig. 2. Hierarchical structure of environmental vulnerability estimation.

Table 1
Standardized rates of evaluation factors

Factors	Rating				
	1	2	3	4	5
Altitude (m a.s.l.)	<3500	3500–4000	4000–4500	4500–5000	>5000
Slope (%)	<9	9–27	27–47	47–70	>70
Rainfall (mm/year)	<200	200–400	400–600	600–800	>800
Wind (days/year)	<50	50–75	75–100	100–125	>120
Accumulated temperature (⩾10 °C)	>120	90–120	60–90	30–60	<30
Soil type[a]	ADS	ASS, AMSS, ACDS, YS, PS, SSS	SMSS, RS, MS, BFS, YBS	BS, AMS, DBFS, SMS, CS	SAS
Vegetation cover (%)	>70	50–70	30–50	10–30	<10
Soil erosion	Potential	Light	Moderate	Heavy	Extreme
Vegetation degradation	Potential	Light	Moderate	Heavy	Extreme
Mountain hazards	Potential	Light	Moderate	Heavy	Extreme
Land desertification	Potential	Light	Moderate	Heavy	Extreme
Population density (person/km^2)	<1	1–6	6–12	12–25	>25
Road density (km/km^2)	<0.1	0.1–0.2	0.2–0.3	0.3–0.4	>0.4
Pasturage disturbance (sheep/10 hm^2)	<4	4–8	8–12	12–16	>16
Cultivation disturbance (farmland area/land area)	<0.2	0.2–0.6	0.6–1.2	1.2–2.6	>2.6

[a] Note soil types: SAS, saline-alkali soil; BS, boggy soil; AMS, alpine meadow soil; DBFS, deep brown forest soil; SMS, subalpine meadow soil; CS, cinnamon soil; SMSS, subalpine meadow-steppe soil; RS, red soil; MS, meadow soil; BFS, brown forest soil; YBS, yellow-brown soil; ASS, alpine steppe soil; AMSS, alpine meadow-steppe soil; ACDS, alpine cold desert soil; YS, yellow soil; PS, podzolic soil; SSS, subalpine steppe soil; ADS, alpine desert soil.

to specific factors requires specific decision rules in the shape of thresholds of each factor. Various statistical and empirical guidelines from the related national codes and literature were used to determine the boundary values. As a general guideline, a positive correlation between the value awarded and vulnerability is employed. The class boundaries and standardized measurements employed for each factor were shown in Table 1. The integer numbers ranging from 1 to 5 were assigned to slight, light, moderate, heavy, and extreme classes, respectively (Table 1).

2.5. *Weight of factors*

Another basic issue for the evaluation is to assign weights to each factor according to its relative effects of factors considered on the environmental vulnerability. The analytic hierarchy process, a theory dealing with complex technological, economical, and socio-political problems (Saaty, 1977; Saaty and Vargas, 1991), is an appropriate method for deriving the weight assigned to each factor. AHP gained wide application in environmental evaluation and regional sustainable management (e.g. Bantayan and Bishop, 1998; Carver, 1991). To apply this approach, it is necessary to break down a complex unstructured problem into its component factors. These factors are arranged in a hierarchic order.

Table 2
Scale of binary comparison (after Saaty and Vargas, 1991)

Degree of importance	Definition
1	Equal importance of two elements
3	Weak importance of an element in comparison to the other one
5	Strong importance of an element in comparison to the other one
7	Certified importance of an element in comparison to the other one
9	Absolute importance of an element in comparison to the other one
2, 4, 6, 8	Intermediate values between two appreciation
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Reciprocal values of the previous appreciation

Table 3
Relative weights of factors for eco-environmental vulnerability evaluation[a]

Factors	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	Weights
(1) Altitude	1															0.097
(2) Slope	1/3	1														0.082
(3) Rainfall	1/4	1/2	1													0.079
(4) Wind	1/5	1/3	2	1												0.059
(5) Accumulated temperature	1/7	1/5	1/4	1/6	1											0.047
(6) Soil type	1/4	1/3	3	2	5	1										0.083
(7) Vegetation cover	2	3	6	4	7	5	1									0.085
(8) Soil erosion	3	4	5	7	8	6	4	1								0.048
(9) Vegetation degradation	2	3	1/3	1/4	3	1/2	1/4	1/5	1							0.051
(10) Mountain hazard	1/3	2	4	1/2	5	1/4	1/5	1/3	1/2	1						0.058
(11) Land desertification	2	3	4	6	7	4	1/3	1/2	3	4	1					0.066
(12) Population density	1/4	1/2	1/3	1/4	3	1/5	1/6	1/5	1/3	1/4	1/4	1				0.069
(13) Road density	1/6	1/5	1/3	1/4	1/2	1/7	1/8	1/7	1/2	1/5	1/6	1	1			0.054
(14) Pasturage disturbance	1/4	1/2	1/2	1/3	3	1/4	1/6	4	1/3	3	4	2	5	1		0.076
(15) Cultivation disturbance	1/7	1/5	1/4	1/6	1/2	1/5	1/7	1/4	1/3	1/4	1/6	1	2	1/3	1	0.046
Consistency ratio: 0.03																

[a] The matrix is symmetrical, only the lower triangular half is filled, the remaining cells are simply the reciprocal of the lower triangular half.

Numerical values are assigned to judge relative importance of each factor (Saaty and Vargas, 1991). In the construction of pair-wise comparison matrix, each factor is rated against every other factor by assigning a relative dominant value between 1 and 9 to the intersecting cell (Table 2). When the factor on the vertical axis is more important than the factor on the horizontal axis, this value varies between 1 and 9. Otherwise, the value varies between the reciprocals 1/2 and 1/9 (Table 2). The 15 factors selected for assessing the environmental vulnerability are compared with each other according to experts' judgments. The pair-wise comparison can be constructed as shown in Table 3, where the main diagonal is always equal to unity. It has been demonstrated that the eigenvector corresponding to the largest eigenvalue of the matrix provides the relative priorities of the factors (Saaty, 1977; Saaty and Vargas, 1991), i.e. if a factor is preferred to another, its eigenvector component is larger than that of the other. The components of the eigenvector sum to unity. Thus, we obtain a vector of weights which reflect the relative importance of various factors from the matrix of paired comparisons. In the present study, an external program was developed to implement the AHP algorithm described above. The weights for the selected factors are obtained from the matrix showed in Table 3.

Because the complete pair-wise comparison matrix contains many multiple paths by which the relative importance can be assessed, it is also possible to determine the degree of consistency that has been used in developing the judgments. In the construction of the matrix of paired comparison, the consistency of the judgments could be revealed because this matrix is a consistent matrix. For example, if factor 1 is preferred to factor 2 and factor 2 to factor 3, then factor 1 must be more preferred to factor 3. In AHP, an index of consistency, known as the consistency ratio (CR), is used to indicate the probability that the matrix judgments were randomly generated (Dai et al., 2001; Saaty, 1977):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}, \tag{1}$$

where RI is the average of the resulting consistency index depending on the order of the matrix given by Saaty (1977), and consistency index (CI) is defined as:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}, \tag{2}$$

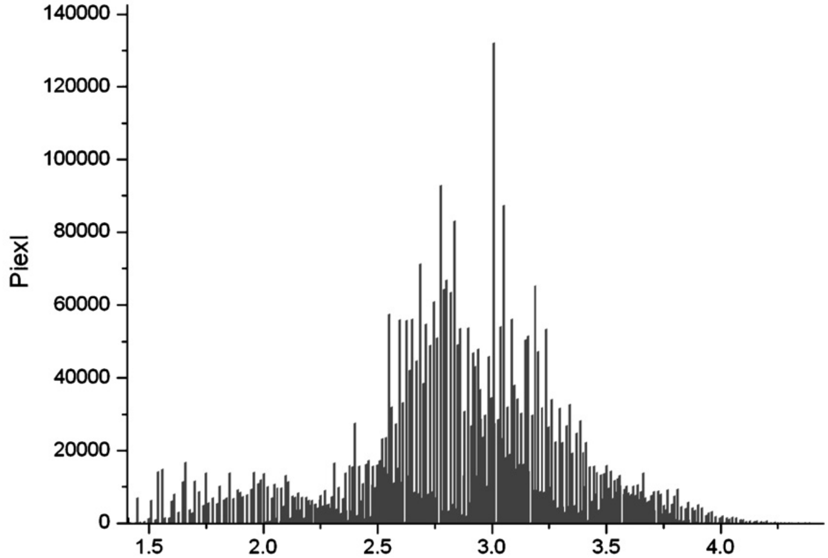

Fig. 3. Data distribution histogram of the integrated index of environmental vulnerability in the Tibetan Plateau.

where λ_{max} is the largest or principal eigenvalue of the matrix, and n is the order of the matrix. A CR of 0.10 or less is a reasonable level of consistency (Saaty, 1977). A CR above 0.10 requires revisions of the judgments in the matrix because of an inconsistent treatment of particular factor ratings. In the present study, the CR of 0.03 (Table 3) is then acceptable.

2.6. Environmental vulnerability index (EVI) calculation and mapping

Using the method of weighted linear combinations, the evaluation model is built to calculate the EVI (Eq. (3)). The factors evaluated were combined by applying a weight of each factor, followed by a summation of the results to yield a vulnerability index (Eastman et al., 1995), i.e.

$$\mathrm{EVI} = \sum_{i=1}^{15} w_i f_i, \tag{3}$$

where EVI is the environmental vulnerability index, w_i the weight of factor i, and f_i is the rating of factor i. The data layers of factors that influence the environmental vulnerability were reclassified so that they could be used as rating maps required in the evaluation process. The calculated weight values are then transferred to the ArcView GIS, and weighted linear combination is used repeatedly to create a vulnerability map with a value range per cell matching that of the standardized factor maps using a range of 1–5 in this case.

The EVI values gained from Eq. (3) are a series of continuous values, which should be classified into several levels representing different environmental vulnerabilities, to simplify the process of reading and understanding the estimated results, and to show the regional differences in the environmental vulnerability. Such a classification should be objective and logical. Histogram is a graphical tool to explore the statistical distribution of the classes and clusters in the attribute space (Apan, 1997). In the present study, we used the cluster principle to group the computed result through analyzing the histogram of index distribution, and to line out the dividing points between 'cluster' and 'cluster'. Then, the environmental vulnerability is divided into classes whose boundaries are set where there are relatively big jumps in the data values. Fig. 3 showed a polarized normal distribution of EVI values ranging from 1.4 to 4.5 with a mean value of 2.870 ($\pm$0.469 S.D.). The sharp breaks in the frequency distribution occur at the EVI value of 2.2, 2.7, 3.0, and 3.4 (Fig. 3) representing the five levels of the environmental vulnerability, namely slight (EVI$<$2.2), light (2.2$\leqslant$EVI$<$2.7), moderate (2.7$\leqslant$EVI$<$3.0), heavy (3.0$\leqslant$EVI$\leqslant$3.4), and extreme vulnerability ($>$3.4). Each vulnerability level is characterized by the typical features listed in Table 4. Fig. 4 displays the evaluation result of the environmental vulnerability for the Tibetan Plateau.

3. Results and discussion

3.1. Area distribution of EVI levels

According to the resultant map (Fig. 4), the area distribution of different EVI levels for the whole Tibetan Plateau was calculated, using the grid numbers of each EVI level multiplied by the grid size of $500 \times 500\,\mathrm{m}^2$ (Table 5). An area of $36.27 \times 10^4\,\mathrm{km}^2$, accounting for 30.10% of the total area of the Tibetan Plateau, belongs to the heavy vulnerable zone, and

Table 4
Classification of the environmental vulnerability index in the Tibetan Plateau

Evaluation level	Environmental vulnerability index	Feature description
Slight	<2.2	Stable ecosystem, great anti-interference ability, rich soil, and relatively low altitude
Light	2.2–2.7	Relatively stable ecosystem and anti-interference ability, rich soil, and relatively low altitude
Moderate	2.7–3.0	Relatively unstable ecosystem and poor anti-interference ability, bad-quality soil, complex vegetation distribution type, and strong human disturbance
Heavy	3.0–3.4	Unstable ecosystem, poor anti-interference ability, deteriorated soil, arid climate dominated by alpine steppe vegetation, and apparent eco-environmental problems
Extreme	>3.4	Extremely unstable ecosystem and poor anti-interference ability, deteriorated soil, very arid climate, and sparse steppe meadow dominated by extreme-coldness plants, and serious eco-environmental problems

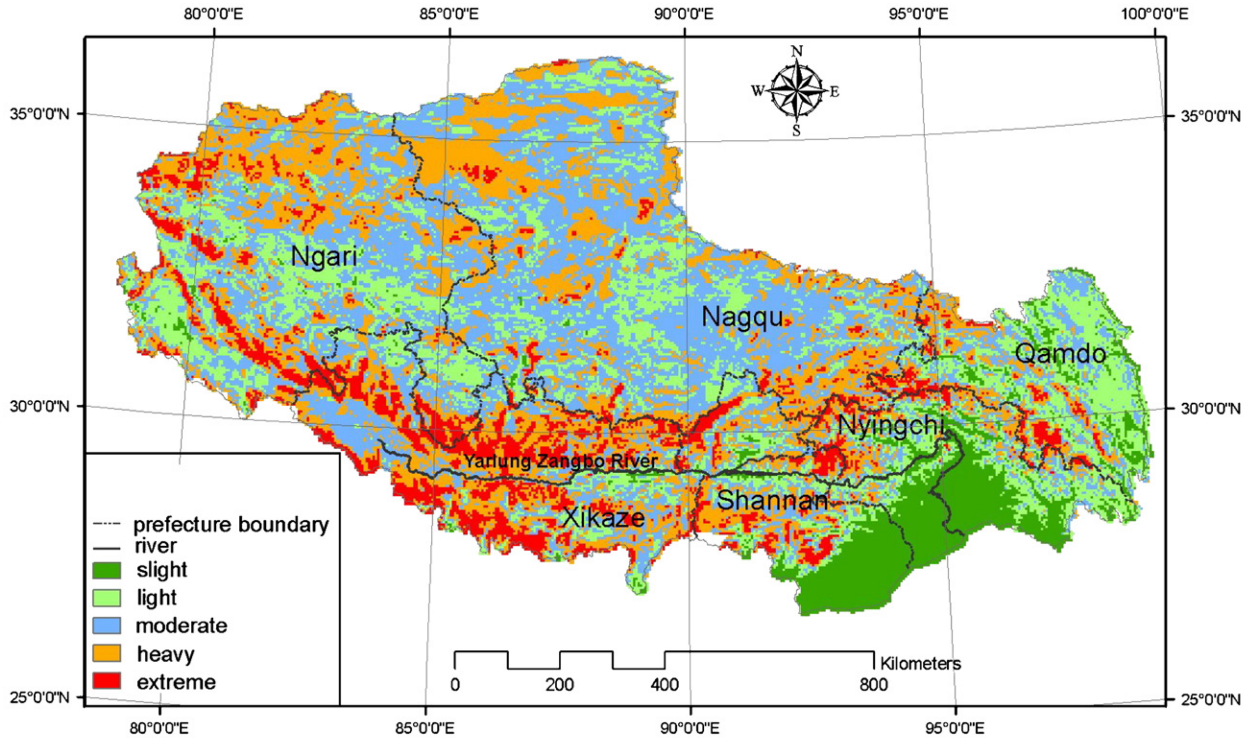

Fig. 4. Distribution of the environmental vulnerability in the Tibetan Plateau.

Table 5
Area and proportion of each environmental vulnerability levels in the Tibetan Plateau

Environmental vulnerability level	EVI	Grid number	Area (10^4 km^2)	Percentage (%)
Slight	1.4–2.2	436462	10.91	9.06
Light	2.2–2.7	1061570	26.54	22.02
Moderate	2.7–3.0	1314184	32.85	27.27
Heavy	3.0–3.4	1450866	36.27	30.10
Extreme	3.4–4.5	556918	13.92	11.55

13.92×10^4 km^2 (11.55%) to the extreme vulnerable zone in the Tibetan Plateau. This means that nearly half (~42%) of the total area of the Tibetan Plateau is very vulnerable. The moderate and the light vulnerable zone accounted for 27.27% (32.85×10^4 km^2) and 22.02% (26.54×10^4 km^2), respectively, whereas the slight vulnerable zone has only a small proportion of 9.06% (10.91×10^4 km^2) (Table 5). The profile of the Tibetan environmental vulnerability showed an asymmetry normal distribution but the center of the profile lean to the 'heavy' level (Fig. 5).

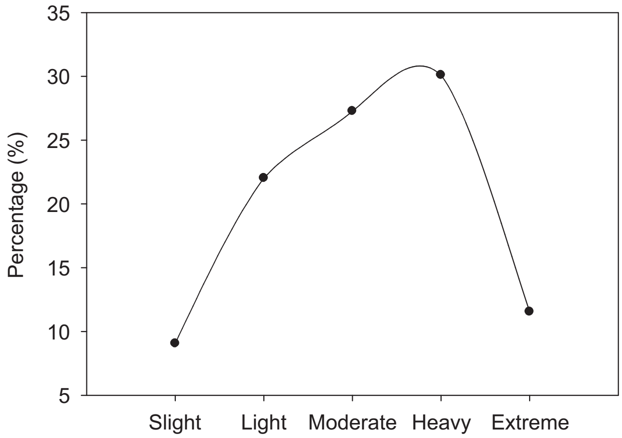

Fig. 5. Environmental vulnerability index profile which shows an asymmetry normal distribution.

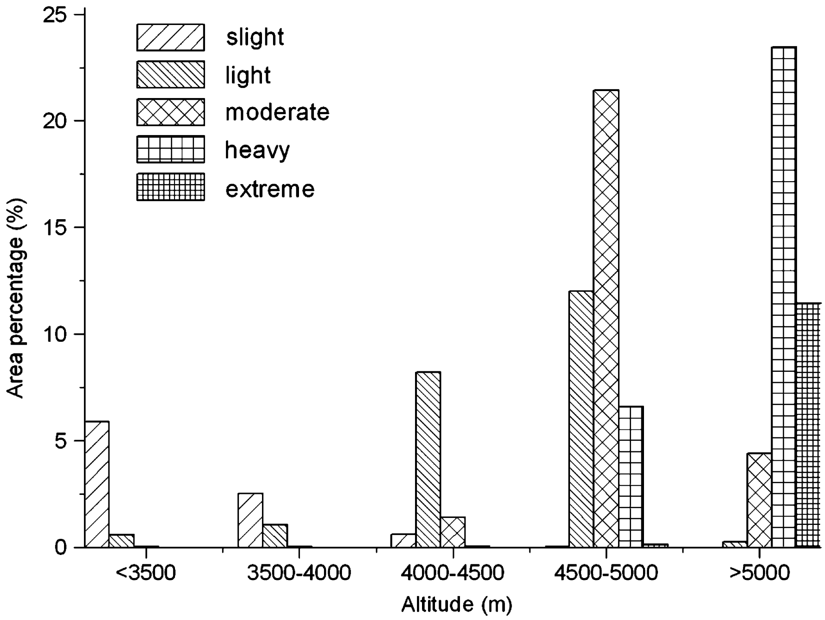

Fig. 6. Distribution of environmental vulnerability levels in relation to elevation in the Tibetan Plateau.

3.2. Spatial distribution pattern of different EVI levels

The environmental vulnerability showed a clearly horizontal distribution (Fig. 4). The extreme or heavy level of EVI occurred more in northwest and south extending to east, whereas the slight level concentrated in the southeastern part of the Shannan prefecture and in the southern Nyingchi prefecture (Fig. 4). Areas with lower to moderate vulnerability were scattered distributed in the whole Tibetan Plateau (Fig. 4). In general, the vulnerability is relatively light in the eastern part and heavy in the western part (Fig. 4). These findings were confirmed by our field investigation and are consistent with the actual environmental situation.

The environmental vulnerability is also closely correlated with altitude. The EVI levels showed a distinct vertical-belt distribution in the Tibetan Plateau (Fig. 6). The moderate and heavy levels of EVI are mostly distributed in the areas with an elevation above 4500 m. The extreme level is entirely distributed above the elevation of 5000 m, whereas the slight level is distributed below the elevation of 4000 m, and the light level occurred in an elevational belt between 2500 and 4500 m (Fig. 6). This finding indicated that the environmental vulnerability increases with increasing elevation, which could reflect the harsh environmental conditions at the higher elevations. Similar results were also published by Li et al. (2006a, b).

3.3. Reviewing the method proposed

Zhang et al. (1999) discussed the relationships between natural environment factors and environmental quality at a valley scale on the middle reaches of the Yarlung Zangbo River in the Tibetan Plateau. A relevant contribution of the present study is that we added some socio-economic factors influencing the environmental vulnerability to the estimation model. Moreover, the use of RS and GIS technology proposed can provide more accurate results for assessing environmental vulnerability on regional or national scales, and easily create visible graphics to display spatial distribution of complex environmental characteristics. Our case study demonstrated that the proposed method is an effective approach which can be used for assessing the environmental vulnerability in other regions also.

The accuracy and reliability of the evaluation results depends on a multitude of factors including the quality of the database, weight of factors and weighting method applied, analysis of GIS, and processing of RS data (Dai et al., 2001; Merwe, 1997). Sensitivity analysis shows that the modeling results from the proposed method are highly sensitive to the weights applied (data not shown). Altering the weights assigned to the various factors will have significant effects on the results. The determination of weights for the various factors is one of the most important challenges, as frequently encountered in conventional evaluation (e.g. Dai et al., 2001; Merwe, 1997). In additional, although the developed method has a strong ability for dynamic estimation of environmental vulnerability, the present case study is limited in the current situation of the Tibetan environmental vulnerability without a trend analysis, due to the lack of local historic data.

3.4. Suggestion for local environmental management

The environmental situation in the Tibetan Plateau poses a major challenge for those scientists, conservation planners, policy makers, and local people concerned with sustainable ecological–economic development. Current global climate change, in combination with other changing global factors, will result in changes in natural and man-made disturbance regimens affecting the environmental systems (Li et al., 2006a, b). An important goal of environmental evaluation is to provide assistance to policy makers and practitioners in the environmental protection. The ecologically more sensitive and/or vulnerable systems/areas should be protected over all others. Our study indicates that the local government and authorities should pay more attention to the high-elevational areas with high EVI values (extreme, heavy, and moderate vulnerability; Figs. 4 and 6). To protect and maintain the ecological environment in those areas, a population-control policy might be needed, and some regulations and laws (e.g. 'Environmental Protection Act', 'Land Act', 'Forestry Act', 'Grassland Act', etc.) could be established and implemented. Moreover, to reduce the environmental vulnerability, soil erosion control, the prevention and control of mountain hazards should be emphasized in Nyingchi and Qamdo prefectures (Fig. 4) due to heavy rainfall, steep slope, and fragmentized stratum. Lhasa, Xikaze, and Shannan prefectures (Fig. 4) are important base for the socio-economic development of the whole Tibetan Plateau, but most areas of these prefectures along the Yarlung Zangbo River have been highly threatened by land desertification. In areas (e.g. valleys) where some water is available for irrigation, trees (e.g. *Populus* spp., *Betula* spp., and some conifers planted in the Lhasa River Valley) and shrubs as fences or small plots, or grass belts should be planted to reduce the rate of desertification and regain lost land. This vegetation decreases the wind velocity near the base of the dune and prevents much of the sand from moving. It can also protect farmland, conserve water and soils, and provide fuelwood. For Ngari and Nagqu prefectures, it is difficult to restore the degraded land due to the arid climate and high elevation. In these areas, it is crucial to reduce and limit the number of livestock to prevent further degradation from overgrazing.

4. Conclusions

We proposed a method considering multiple factors for assessing the regional environmental vulnerability, using RS, GIS, and AHP. Compared to other traditional estimation methods, these techniques allow us to integrate various spatial information. However, regardless of methods used, all regional vulnerability estimations have similar basic principles, although the assessment framework, selection of factors and their weights may vary from region to region due to varying local conditions.

Using the method proposed, we carried out a case study in the Tibetan Plateau. The results showed that the majority of the Tibetan Plateau is ecologically lightly (light level; 22% of the total area), moderately (moderate level; 27%), and heavily (heavy level; 30%) vulnerable (Table 5; Fig. 5). The environmental vulnerability has a clearly vertical (Fig. 6) and horizontal distribution pattern (Fig. 4). The environmental vulnerability increased with increasing elevation (Fig. 6). Our case study verified the usefulness and feasibility of the methods developed, for the results gained reflect the reality of the Tibetan environment closely. However, this method still needs further improvement to reduce the subjectiveness of judgments. Further use in other regions should pay attention to what factors seem to be important in determining the local environmental vulnerability, and how is the impact of each factor on the complex environment.

Acknowledgments

This study was supported by the projects funded by National Basic Research program of China (Grant no. 2005CB422005) and the 'West Talent Plan' Program of Chinese Academy of Sciences.

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