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ORIGINAL PAPER

Assessing ecological security at the watershed scale based on RS/GIS: a case study from the Hanjiang River Basin

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Abstract The purpose of this study is to develop an assessment framework of ecological security at the watershed scale to meet the need of watershed management, and to assess ecological security using this framework in the middle and lower reaches of Hanjiang River Basin (in Hubei Province, China). The states and their changes of ecological security in the study region are investigated with the support of ERDAS and ARC/INFO platform. The results show that the ecological security index (*P*) values in 1995 and 2000 were 0.685 and 0.699 respectively in the study region. While in 2005 and 2010, the *P* values were decreased to 0.657 and 0.624. In 1995, there were 5 counties with degree II state (the poor state) of ecological security, and 14 counties with degree III state (the common state). By 2000, the amount of counties with degree II decreased to 4 counties. And the number of counties with degree II is the same as 2000 in 2005. The result of 2010 shows there were 12 countries with degree III state as well as 7 counties with degree II state. The results of our case study of the Hanjiang River Basin reflect that the ES situation is very grim in the study area. The degree of ecological security developed in this study can be used as a useful tool for watershed managers and decision-makers.

Keywords Ecological security assessment · Indicator system · Degree of ecological security · Spatial analysis · Watershed management · Watershed scale

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1 Introduction

Ecological security (ES) is a concept with several meanings, and is defined as a comprehensive status of a human-ecological system. Its definition can be divided into the general definition and narrow definition. Taken broadly, ES is the status reflecting the threat to human living, human health, basic right, necessary resources, social orders, and the human's and environment's ability to respond to change; it includes natural, economic and social eco-security. In a narrow sense of the word, ES is the security of natural and semi-natural ecosystem, that is, the reflection of the ecosystem integrity and health. In this study, ES is defined as the level of threat posed by the economy, social development, and natural environment on human health. Eco-security emphasizes the environmental and ecological conditions to support sufficiently the ecosystems (Shi et al. 2006).

Ecological security assessment (ESA) focuses on the status of human-ecological systems. The cores of this assessment are system health, integrity and stability. In other words, the goal of ESA is to identify the stability of the ecosystem, and to distinguish the capacity of sustainable health and integrity under different kinds of risks. Its central content is the assessment of ecological risk and health, with the leading feature of human security (Wang et al. 2003; Yu et al. 2010b). Many indicator systems and assessment methods are used for this assessment (Liu et al. 2006; Zuo et al. 2002; Zhou et al. 2010). In the last decades, many basic ESA theories have gradually developed such as the theory of ecological health and environmental risk assessment, the national benefit theory of environmental (ecological) security, and the theory of ecological rights and their legal practices (Chen and Zhou 2005). According to the open system theory, ecosystem is of characteristics such as the order, the hierarchical structure, the in-reproducible feature, the self-adjust and control, and the self-organization (Muller 1997). Changes of these characteristics are of the ES meanings (Dale et al. 2004). Systematic methods are commonly adopted in the ESA. A series of assessment indicators are selected to constitute the assessing framework of indicators according to the diagnostic differences of goal systems, and this framework is used to assess synthetically the status of the system. In the selection of goal systems, a series of specific goal systems have been given much attention to form the specific object of ESA in past studies (Shi et al. 2006; Hui and Lin 2011; Liu et al. 2013). Many research reports focus on the studies of regional ES and watershed ES.

Regional ES studies should pay attention to the ES trends, the ES hidden dangers, and the ES spatial differences (Wang et al. 2007; Tian and Gang 2012). The well-knit theoretical basis is supported by landscape ecology, disturbance ecology, protect biology, restoration ecology, ecological economics, ecological ethnics, and the theory of complex ecosystems (Ma et al. 2004). Geographical zonality is the basic maxim of studies on regional ES, the original ecological values of landscape (land type) can be used as the objective tests of regional ES, and the degree of landscape degeneration can be used as the important marks (Zhang et al. 2005). Based on the concept system of the pressure–state–response (P–S–R) developed by the United Nations Environment Programme (UNEP), the regional ES mechanism can be defined as the state–danger–response system (Wang and Wu 2006; Pei et al. 2010; Li et al. 2010; Ye et al. 2011), and its course can be analyzed by the rheology-mutation (R-M) theory (Wang and Wu 2007). An integrative fuzzy set pair model for assessing the land ES was developed by integrating fuzzy assessment and set pair analysis (Su et al. 2010), and a catastrophe model for land ESA was developed in order to overcome the disadvantages in subjectivity and complexity of the currently used assessment methods (Su et al. 2011). For the health and development of human beings, the analysis of ecological footprint over a long period of time can also be used as the assessing basis of regional ES (Huang et al. 2007).

The watershed is a specific case of regions (Zhang et al. 2010). Because of the particularity of its inherent attributes, much attention is given to watershed ES studies. Watershed ES includes the structural security and functional security (Gao et al. 2007), and the highlights of research contents and methods are different in different watersheds (Guo et al. 2006; Yu et al. 2006a; Yang et al. 2003). The ES of the Yangtze River Basin directly influences the sustainable development of Chinese society and economics (Yu 2002), and this research is labeled as the State Key Basic Research and Development Plan of China (Zhao 2000). The Hanjiang River Basin is one of the branches of the Yangtze River Basin, and its ES status is indispensable.

The ES research methodologies and techniques are increasingly improving, and techniques of remote sensing (RS) and geographical information system (GIS) have been introduced to the ESA field (Wu et al. 2007). Dyer et al. (2000) utilized GIS to investigate large geographic areas using bottom-up and top-down approaches for assessing effects of multiple stressors (e.g. stream habitat, drainage area, cumulative effluent) on the index of biotic integrity (i.e. subbasin and basin level).

The aims of this paper are: (1) to develop an ES assessing system to investigate the ES state and evolvement in the middle and lower reaches of the Hanjiang River Basin (in Hubei Province, China), and (2) to discuss the relationships between the ESA and watershed management. Based on our earlier studies of land use change (Yu et al. 2008, 2010a) and landscape pattern evolvement (Yu et al. 2006b) in the Hanjiang River Basin, as a case study, the ES status and its evolvement in the middle and lower reaches of the Hanjiang River (in Hubei Province) are discussed using RS and GIS in this paper.

2 Study region

Most of the middle and lower reaches of the Hanjiang River Basin are located in Hubei Province, China, including the riverside region from the Danjiangkou Reservoir to the Longwangmiao in the Hankou district and the water-accepting region of the Hanjiang River. The Hanjiang River Basin has a subtropical monsoon climate, and its average precipitation is about 800–1,100 mm. The rainfall is focused in May through September, and is unevenly distributed in space and time. Flood and drought disasters take place frequently in this region. The amount of surface water resources is about 1.37×10^{10} m^3, and the amount of groundwater resources is about 5.58×10^9 m^3 in this region. Taking out double counting, the gross amount of water resources that come came from the basin itself is about 1.48×10^{10} m^3. The annual mean of entered water resources is about 4.04×10^{10} m^3, and the amount of water resources is on the low side with regards to both per capita and the unit area.

In the middle and lower reaches of the Hanjiang river Basin, agricultural natural resources are abundant and diverse. This region is the comprehensive base of ecological agriculture and diversified agricultural management in China, and also is the important base of food production, cotton production and edible oil production in China. Among the 100 counties of important food production in China, 9 counties are in the Hanjiang River Basin. Among the 100 counties of important cotton production in China, 15 counties are in this region. This region is also one of important production bases of fresh water aquaculture in

China, and is one of the centers of economic development in the Hubei Province, China.

3 The data sources and data processing

3.1 Data sources

(1) RS images: Three temporal LANDSAT TM images were acquired in 1995, 2000, 2005 and LANDSAT ETM + images were acquired in 2010 with the standard sheet-dividing map and the optimal effect of image radiation.
(2) Basic data: The basic data are taken from *The Atlas of the Yangtze River Basin* in scale of 1:1,000,000, such as the boundary of the study area, the administrative boundary, the distribution plan of water and soil loss, the topographical map of the study region, and so on.
(3) Statistical data: The statistical data are taken from *The Statistical Yearbooks* in 1996, 2001, 2006, 2011.

3.2 Data processing

(1) Data processing of RS: The processing platforms of RS data are ERDAS 9.2 and ARC/INFO software in this study. The approaches of image processing and interpretation are developed by Zeng et al. (2008), including projection transformation, image calibration, data fusion, image enhancement, and image interpretation.
(2) The conventional data processing: Map data are registered with geographic coordinates to digitize the information using ARC/INFO software. The average values of assessing indicators are used for the county level values that can't be abstracted directly from the statistical yearbooks, and the projections of increment speed are used for the indexes, whose values could be abstracted directly in 1996, 2006 and 2011 but not in 2001.

4 The degree of ecological security

4.1 The measure indexes of ecological security and their calculations

The regional ES is a macroscopic concept, and it should be translated as a quantizing definition. In this study, the index of ES (P) is defined as a measure index of regional ES. A calculated P value is developed with 11 measure indicators selected from 3 basic elements—the landscape threat (B_1), the landscape productivity (B_2), and the landscape stability (B_3). B_1 is calculated using the five indicators of the population density (C_{11}), the ratio of land cultivating (C_{12}), the cultivated area per capita (C_{13}), the percentage of vegetation coverage (C_{14}), and the index of water and soil erosion (C_{15}). B_2 is calculated using the three indicators of the annual output value of industry in the unit area (C_{21}), the annual output value of agriculture in the unit area (C_{22}), and the amount of biological Carbon storage in the unit area (C_{23}). B_3 is calculated using three indicators—namely, the index of landscape diversity (C_{31}), the area weighted mean patch fractal dimension (C_{32}), and the coefficient of patch area variation (C_{33}).

Most of the indicators are calculated by the corresponding conventional formulas, some of them are described here.

4.1.1 The index of water and soil erosion (C_{15})

Water and soil erosion is one of the characteristic values which can reflect the essential ES attributes. In this study, the index of water and soil erosion is calculated by the following equation:

$$C_{15} = \frac{\sum_{i=n}^{n} A_i W_i}{S_l} \tag{1}$$

where A_i is the ith degree of water and soil erosion in the study region, W_i is the area ratio of ith degree of water and soil erosion in the study region, and S_l is the total land area in the study region.

4.1.2 The index of landscape diversity (C_{31})

Ecological stability is the regional ES base. According to the diversity-stability theory, biodiversity is the basic guarantee for regional ES. Among the four basic levels of biodiversity, landscape diversity has the most direct impact on regional ES. In this study, the index of landscape diversity is calculated as follows:

$$C_{31} = -\sum_{k=1}^{n} P_k \ln(P_k) \tag{2}$$

where P_k is the arisen probability of a K-class patch in the landscape (that is, the ratio of the grid cell or pixel of a K-class patch to the total number of landscape grid cell or pixel), and n is the total number of patch class.

4.1.3 The area weighted mean patch fractal dimension (C_{32})

The area weighted mean patch fractal dimension is usually used to measure the complexity of landscape pattern, and it can be calculated as follow:

$$C_{32} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[\frac{2\ln(0.25P_{ij})}{In(a_{ij})}\right]}{N}\left(\frac{a_{ij}}{A}\right) \tag{3}$$

where P_{ij} is the side length of jth patch in ith patch class, a_{ij} is the area of jth patch in ith patch class, m is the total number of patch classes, n is the total number of ith patch class, and A is the area of the study region.

4.1.4 *The coefficient of patch area variation (C_{33})*

The coefficient of the patch area variation can reflect the defensive interference ability of the regional ecosystem to resist exterior disturbances. Its value decreases with the increase of the defensive interference ability. The smaller the value, the more stable the regional ecosystem is. It can be calculated as follows:

$$C_{33} = \frac{\sqrt{\frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\left[a_{ij}-\left(\frac{A}{N}\right)\right]^2}{N}}}{\frac{A}{N}} \tag{4}$$

where a_{ij} is the area of jth patch in ith patch class, m is the total number of patch class, n is the total number of ith patch class, A is the total area of all the patches in the study region, N is the total number of patch.

4.2 Process of the dimensionless values

4.2.1 *Methods*

Different ES measure indicators are different in dimensions. To compare them with each other, their dimensions should be eliminated. In general, the normalizing method and the standard value method are usually used to eliminate the dimension. In this study, the standard value method is adopted.

The ES measure indicators can be grouped as the forward direction indicator (with the ES positive effect) and the reverse indicator (with the ES negative effect). The P value increases with values of the forward direction indicator, but decreases with values of the reverse indicator. In the process of dimensionless values, the forward and reverse direction indicators will be distinguished as follows.

Supposing that X_i is the actual value of the measure indicator, X' is the dimensionless value of X_i, and S_i is the standard value of this indicator.

For the forward direction indicator, when S_i is a safe value,

$$X' = \begin{cases} 1, & \text{if} \quad X_i \geq S_i \\ \frac{X_i}{S_i}, & \text{if} \quad X_i < S_i \end{cases}; \tag{5}$$

When S_i is an unsafe value,

$$X' = \begin{cases} 0, & \text{if} \quad X_i \leq S_i \\ \frac{S_i}{X_i}, & \text{if} \quad X_i > S_i \end{cases}. \tag{6}$$

For the reverse indicator, when S_i is a safe value,

$$X' = \begin{cases} 1, & \text{if} \quad X_i \leq S_i \\ \frac{S_i}{X_i}, & \text{if} \quad X_i > S_i \end{cases}; \tag{7}$$

When S_i is an unsafe value,

$$X' = \begin{cases} 0, & \text{if} \quad X_i \geq S_i \\ 1-\frac{X_i}{S_i}, & \text{if} \quad X_i < S_i \end{cases}. \tag{8}$$

4.2.2 *The standard value of indicators*

Selecting the reference conditions is a complex issue that involves choosing among the most critical processes, based upon the valuation of socio-economical criteria or ecological criteria or both (Aronson et al. 1993; Tapsell 1995; Lenders et al. 1998; Nienhuis and Leuven 2001). Reference conditions can be determined on the basis of historical data (palaeo-references), data derived from actual situations elsewhere (actuo-references), knowledge about system structure and functioning in general (system theoretical references), or a combination of these sources (Petts and Amoros 1996; Jungwirth et al. 2002). In this study, the standard value of measure indexes S_i is determined by the following criteria:

- The trade standard published by the national and regional managerial department.
- The safety standard recognized by the international organization or the national organization.
- The actual measurement value of the indicator in the field where this ecological factor is disturbed or less disturbed by human activities.
- The theoretical value of measure indicator.

In this study, the standard values are determined as in Table 1.

4.3 Weighting

In this study, the Delphi approach and the analytic hierarchy process (AHP) are used to determine the index weights of ES evaluation, and the results are shown in Table 2. The level of index system are processed by the AHP, and weighted by the Delphi approach. In Delphi approach, we ask 17 experts from institutes, universities and environmental management departments to score the index weights, and calculate their mean value.

For the criterion level, CR = 0.0016 < 0.1, and for the three element levels, CR are 0.0018, 0.0007 and 0.005 respectively. They are less than 0.1, and pass the consistency check.

Table 1 The safety standards and their basis of ecological security assessment

Indicator	Safety	Safety standard		Criterion
	Direction	Safe	Unsafe	
B1				
C11	−	310.51[a]/320.07[b]/324.42[c]/332.22[d]		Mean value in Hubei Province
C12	−		100	Theoretical value
C13	+	0.8		FAO definition
C14	+	100		Theoretical value
C15	−		4	Theoretical value
B2				
C21	+	0.55[a]/1.14[b]/1.33[c]/3.62[d]		Mean value in Hubei Province
C22	+	0.33[a]/0.36[b]/0.58[c]/1.15[d]		Mean value in Hubei Province
C23	+	19.3		Theoretical value
B3				
C31	+	1.79		Theoretical value
C32	−		2	Theoretical value
C33	−		19.36	Maximum value in the study region

[a] The safety value in 1995
[b] The safety value in 2000
[c] The safety value in 2005
[d] The safety value in 2010

Table 2 The index weight of ecological security assessment

Criterion level	Weight	Index level	Weight
B_1	0.3577	C_{11}	0.0789
		C_{12}	0.0687
		C_{13}	0.0705
		C_{14}	0.0730
		C_{15}	0.0666
B_2	0.3179	C_{21}	0.0981
		C_{22}	0.1041
		C_{23}	0.1157
B_3	0.3244	C_{31}	0.1071
		C_{32}	0.1092
		C_{33}	0.1081

4.4 Calculation and grading for the degree of ecological security (P)

The P value can be calculated as follows:

$$P_i = \sum_{i=1}^{n} W_i \mathrm{C_i} \quad (10)$$

where C_i is the dimensionless value of the ith indicator, and W_i is the weight of the ith indicator. As an ES degree, P value is classified into 5 degrees in this study, and the classification standard is shown in Table 3.

5 Results

By the Eq. (10), the P value is calculated for every county in the study region. The results are shown in Table 4.

From Table 4, it is observed that the average P value of the study region is degree III in the four study periods, meaning this region belongs to the common ES state, and obvious changes did not take place in general in this region. ES Degrees in every county of this region were between degree II (the poor ES state) and degree III (the common ES state). In 1995, there were 5 counties with degree II and 14 counties with degree III. In 2000, counties with degree II decreased from 5 counties to 4 counties. An increase in the ES degree indicates that the ES state improved. In 2005, counties with degree II is the same as 2000, but some of these counties are different from 2000, such as the ES degree of Xiangfan is degree III in 2000 while it was with degree II in 2005. In 2010, the number of counties with degree II was 7 and the ES state was weakened than before.

To investigate the spatial ES variation in the interior of the study region, the maps of ES degree are mapped in the interval 0.1 degree of ES with the support of software Arc/Info (Fig. 1).

From 1995 to 2000, the P value in the study region is increased from 0.685 to 0.699, meaning that the ES state is improved in this region. Analyzing on the ES state changes, 11 counties decreased in the P value, 7 counties increased in the P value, and one county did not change in the P value. From 2000 to 2005, the P value in the study region is decreased from 0.699 to 0.657, meaning that the ES state is no better than before. Meanwhile, 9 counties decreased in the P value, 10 counties increased in the P value. From 2005 to 2010, the P value in the study region is decreased from 0.657 to 0.624, which indicates a declining trend in resent 5 years. The analysis on the ES state changes shows that 14 counties decreased in the

Table 3 The P value classification of regional ecosystem in the study region

Grade	P_i	Representation state	Characteristic description
I	<0.4	Very poor	The function of ecosystem service is lost, and the ecological process is difficult to reverse. Environment is destroyed seriously, the ecosystem structure is mutilated, and ecological function is lost. Ecological restoration is difficult. Ecological environment issues are serious, and ecological disasters take place frequently
II	0.4–0.6	Poor	The function of ecosystem service is degenerated seriously, and environmental destruction is relatively serious. Ecosystem structural damage is relatively serious, and function is degenerated and lacks integrity. It is difficult to restore to the exterior disturbance. Ecological problems are relatively serious, and ecological disasters are relatively serious
III	0.6–0.8	Common	The function of ecosystem service has started to degenerate, and environment is destroyed partly. Ecosystem structure changes partly, but the ecosystem fundamental functions are still tenable. Environment is susceptible to the exterior disturbance. Ecological problems come out, and the ecological disasters take place infrequently
IV	0.8–0.9	Good	The function of ecosystem service is relatively perfect, and environment has minimal destruction. Ecosystem structure has relative integrity, and function is good. It is restorable to the common disturbance. Ecological problems are unobvious
V	≥0.9	Excellent	The function of ecosystem service is perfect, and environment is disturbed rarely. Ecosystem structure has integrity, and function is strong. System restoring ability is strong. Ecological problems are unobvious

P value, 4 counties increased in the P value and one county did not change in the P value.

6 Discussion

6.1 Change of ecological security and the changed range of P value

Statistical analysis of the P value shows that P values of every county in the study region are centered ranged from 0.45 and 0.75 between 1995 and 2010, and their changed values from 1995 to 2000 ranged between −0.03 and 0.06, from 2000 to 2005 ranged between −0.17 and 0.13, and ranged between −0.15 and 0.12 from 2005 to 2010. (Fig. 2).

6.1.1 Cause analysis on the spatial variation of P value

6.1.1.1 Landform is the key control factor of spatial variation Landforms in the middle and lower reaches of the Hanjiang River Basin can be classified as plain, hill and mountains. High P values exit in the plains, low P values exit in the hills, and the P values in the mountains are between them. In the hill region, landforms translate from the plain to mountain, and the P values are high. In this region, the landscape diversity and biodiversity are plentiful, the intensity of human activities is low, and economic development is underway. In the mountain region, the P value is low. In this region, the landscape is uniform, the ecosystem is vulnerable, resources of arable land are rare, and the economy has developed slowly. In the plain region, the P values are lowest. In spite of economic growth in these regions, the intensity of land use is high, the impacts of human activities are strong, the population pressure is high, and natural disasters take place frequently. The control action of landform presented here is similar to other μ-basins reported by Yates and Bailey (2006).

6.1.1.2 Economics is the dominant factor of regional differentiation in the interior of landform type The spatial pattern of the P values is controlled by landform type in the study region, and the internal diversity is driven by economic factors in the landform unit. For example, Wuhan City, Xiangfan County are all of the same landform type, the plain region, but the status of ES in Wuhan City is better than Xiangfan. Because the economic condition of Wuhan City is better than that of Xiangfan County.

6.1.2 Cause analysis on the change of P value

6.1.2.1 The P value is correlated with the land use intensity index in different stages Human activities are one of the key forces causing ES change. Of the many human activities, land use influences the regional ES most directly. The P value is, thus, correlated closely to the intensity of land use. (a) In 1995, the correlation coefficient between the intensity index of land use and the P value was −0.438 with a confidence level of 0.1. In other words, they are correlated but this correlation is unapparent, and the probability of reverse correlation is only 90 %. (b) In 2000, the correlation coefficient between the intensity index of land use and the P value was −0.459 with the confidence level up to 0.05, meaning that the probability of negative correlation is

Table 4 The degree of ecological security in the study region

Region	Time	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	P_i
Wuhan	1995	0.030	0.021	0.071	0.003	0.050	0.098	0.104	0.063	0.067	0.092	0.065	0.664
	2000	0.026	0.021	0.071	0.003	0.050	0.098	0.104	0.063	0.067	0.092	0.066	0.661
	2005	0.007	0.027	0.033	0.000	0.050	0.098	0.104	0.055	0.107	0.044	0.093	0.619
	2010	0.013	0.018	0.016	0.004	0.034	0.098	0.104	0.052	0.106	0.042	0.100	0.586
Xiangfan	1995	0.013	0.030	0.021	0.013	0.038	0.098	0.104	0.058	0.082	0.098	0.094	0.649
	2000	0.010	0.030	0.014	0.013	0.038	0.098	0.104	0.057	0.082	0.098	0.093	0.637
	2005	0.001	0.037	0.003	0.000	0.038	0.098	0.104	0.048	0.107	0.043	0.097	0.576
	2010	0.001	0.018	0.002	0.009	0.050	0.098	0.101	0.038	0.107	0.045	0.107	0.576
Xiangyang	1995	0.063	0.010	0.071	0.006	0.037	0.026	0.104	0.062	0.041	0.090	0.013	0.523
	2000	0.063	0.010	0.071	0.006	0.037	0.059	0.104	0.062	0.041	0.090	0.012	0.555
	2005	0.079	0.000	0.071	0.001	0.037	0.085	0.104	0.060	0.107	0.042	0.050	0.636
	2010	0.079	0.012	0.071	0.010	0.039	0.065	0.104	0.047	0.107	0.042	0.103	0.679
Yicheng	1995	0.079	0.027	0.071	0.025	0.029	0.069	0.104	0.072	0.057	0.093	0.057	0.683
	2000	0.079	0.027	0.071	0.025	0.029	0.042	0.104	0.072	0.057	0.093	0.057	0.656
	2005	0.054	0.040	0.071	0.001	0.029	0.098	0.104	0.065	0.107	0.044	0.070	0.684
	2010	0.079	0.011	0.071	0.009	0.014	0.068	0.104	0.047	0.107	0.042	0.103	0.656
Nanzhang	1995	0.079	0.050	0.071	0.052	0.024	0.026	0.104	0.083	0.043	0.092	0.065	0.689
	2000	0.079	0.050	0.071	0.052	0.024	0.059	0.104	0.083	0.043	0.092	0.065	0.722
	2005	0.079	0.041	0.071	0.002	0.024	0.022	0.064	0.077	0.107	0.039	0.036	0.561
	2010	0.079	0.055	0.071	0.057	0.024	0.022	0.058	0.013	0.107	0.040	0.099	0.623
Gucheng	1995	0.079	0.056	0.071	0.058	0.018	0.026	0.104	0.086	0.043	0.091	0.057	0.689
	2000	0.079	0.056	0.071	0.058	0.018	0.059	0.104	0.086	0.043	0.091	0.057	0.722
	2005	0.079	0.049	0.071	0.004	0.018	0.034	0.074	0.080	0.107	0.037	0.000	0.552
	2010	0.079	0.052	0.071	0.054	0.035	0.069	0.060	0.014	0.107	0.037	0.092	0.669
Baokang	1995	0.079	0.064	0.071	0.068	0.014	0.026	0.104	0.089	0.026	0.093	0.075	0.709
	2000	0.079	0.064	0.071	0.068	0.014	0.059	0.104	0.089	0.026	0.093	0.075	0.742
	2005	0.079	0.055	0.071	0.004	0.014	0.008	0.028	0.088	0.107	0.041	0.074	0.568
	2010	0.079	0.065	0.047	0.069	0.037	0.012	0.030	0.003	0.055	0.036	0.075	0.508
Laohekou	1995	0.052	0.016	0.071	0.010	0.038	0.098	0.104	0.062	0.060	0.091	0.027	0.629
	2000	0.052	0.015	0.071	0.009	0.038	0.098	0.104	0.062	0.059	0.091	0.027	0.626
	2005	0.042	0.038	0.071	0.008	0.038	0.095	0.104	0.065	0.107	0.044	0.088	0.700
	2010	0.048	0.008	0.071	0.002	0.032	0.098	0.104	0.052	0.068	0.039	0.084	0.606
Zaoyang	1995	0.076	0.021	0.071	0.019	0.034	0.098	0.104	0.068	0.055	0.090	0.001	0.637
	2000	0.079	0.021	0.071	0.019	0.034	0.069	0.104	0.068	0.055	0.090	0.000	0.610
	2005	0.072	0.045	0.071	0.009	0.034	0.028	0.104	0.074	0.107	0.045	0.055	0.644
	2010	0.080	0.009	0.071	0.007	0.046	0.076	0.104	0.050	0.107	0.042	0.105	0.697
Jingmen	1995	0.079	0.030	0.071	0.029	0.044	0.098	0.104	0.072	0.059	0.090	0.012	0.688
	2000	0.079	0.030	0.071	0.029	0.044	0.098	0.104	0.072	0.059	0.090	0.012	0.688
	2005	0.014	0.023	0.071	0.015	0.044	0.098	0.104	0.066	0.107	0.043	0.088	0.673
	2010	0.039	0.014	0.049	0.014	0.030	0.098	0.104	0.042	0.107	0.041	0.096	0.635
Hanchuan	1995	0.041	0.010	0.071	0.000	0.050	0.098	0.104	0.058	0.046	0.093	0.050	0.621
	2000	0.040	0.010	0.071	0.000	0.050	0.098	0.104	0.058	0.047	0.093	0.035	0.606
	2005	0.038	0.039	0.071	0.017	0.050	0.098	0.104	0.057	0.107	0.041	0.068	0.689
	2010	0.041	0.008	0.071	0.002	0.050	0.098	0.104	0.058	0.065	0.039	0.082	0.618
Yingcheng	1995	0.044	0.009	0.071	0.003	0.046	0.098	0.049	0.060	0.046	0.091	0.050	0.567
	2000	0.045	0.009	0.071	0.003	0.046	0.098	0.104	0.060	0.046	0.091	0.049	0.622
	2005	0.043	0.037	0.071	0.017	0.046	0.098	0.104	0.062	0.107	0.042	0.061	0.687
	2010	0.050	0.006	0.071	0.003	0.038	0.098	0.104	0.055	0.067	0.038	0.104	0.634

Table 4 continued

Region	Time	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{21}	C_{22}	C_{23}	C_{31}	C_{32}	C_{33}	P_i
Xiantao	1995	0.041	0.009	0.071	0.000	0.050	0.098	0.104	0.057	0.044	0.090	0.003	0.567
	2000	0.043	0.010	0.071	0.000	0.050	0.098	0.104	0.058	0.047	0.090	0.008	0.579
	2005	0.043	0.040	0.071	0.033	0.050	0.098	0.104	0.065	0.107	0.040	0.061	0.712
	2010	0.056	0.014	0.071	0.005	0.038	0.098	0.104	0.054	0.087	0.041	0.078	0.645
Tianmen	1995	0.038	0.006	0.071	0.001	0.048	0.098	0.104	0.056	0.041	0.090	0.009	0.562
	2000	0.040	0.006	0.071	0.001	0.048	0.098	0.104	0.056	0.042	0.090	0.009	0.565
	2005	0.042	0.037	0.071	0.037	0.048	0.089	0.104	0.059	0.107	0.039	0.000	0.633
	2010	0.117	0.004	0.071	0.002	0.018	0.085	0.104	0.056	0.058	0.037	0.000	0.552
Qianjiang	1995	0.050	0.009	0.071	0.001	0.050	0.098	0.104	0.055	0.050	0.093	0.075	0.656
	2000	0.049	0.009	0.071	0.001	0.050	0.098	0.104	0.055	0.051	0.093	0.075	0.656
	2005	0.011	0.014	0.071	0.038	0.050	0.098	0.104	0.057	0.107	0.040	0.066	0.655
	2010	0.054	0.003	0.051	0.002	0.044	0.098	0.104	0.054	0.057	0.036	0.090	0.594
Zhongxiang	1995	0.079	0.029	0.071	0.025	0.039	0.098	0.104	0.071	0.063	0.092	0.060	0.731
	2000	0.079	0.029	0.071	0.025	0.039	0.071	0.104	0.071	0.063	0.092	0.061	0.705
	2005	0.079	0.040	0.071	0.044	0.039	0.040	0.099	0.065	0.107	0.043	0.067	0.694
	2010	0.079	0.017	0.071	0.015	0.050	0.054	0.090	0.044	0.107	0.042	0.103	0.673
Jingshan	1995	0.079	0.036	0.071	0.036	0.034	0.037	0.043	0.077	0.053	0.093	0.058	0.617
	2000	0.079	0.036	0.071	0.036	0.035	0.026	0.043	0.077	0.053	0.093	0.058	0.607
	2005	0.079	0.047	0.071	0.061	0.035	0.036	0.100	0.076	0.107	0.043	0.065	0.719
	2010	0.079	0.029	0.071	0.030	0.050	0.059	0.095	0.034	0.107	0.041	0.101	0.694
Fangxian	1995	0.079	0.063	0.071	0.067	0.031	0.055	0.039	0.089	0.024	0.093	0.062	0.673
	2000	0.079	0.058	0.071	0.061	0.032	0.033	0.031	0.087	0.036	0.092	0.060	0.640
	2005	0.079	0.052	0.071	0.062	0.032	0.004	0.017	0.088	0.107	0.040	0.050	0.603
	2010	0.079	0.062	0.071	0.066	0.029	0.005	0.024	0.006	0.059	0.037	0.083	0.520
Shennongjia	1995	0.079	0.067	0.071	0.071	0.030	0.003	0.005	0.088	0.028	0.090	0.036	0.568
	2000	0.079	0.066	0.071	0.071	0.030	0.002	0.005	0.088	0.028	0.090	0.035	0.565
	2005	0.079	0.055	0.071	0.064	0.030	0.003	0.005	0.087	0.107	0.040	0.076	0.618
	2010	0.079	0.068	0.035	0.072	0.048	0.003	0.004	0.002	0.051	0.036	0.068	0.467
Total	1995	0.073	0.030	0.071	0.028	0.036	0.074	0.104	0.071	0.065	0.091	0.042	0.685
	2000	0.064	0.030	0.071	0.027	0.036	0.098	0.104	0.071	0.066	0.091	0.041	0.699
	2005	0.047	0.028	0.071	0.024	0.036	0.098	0.104	0.070	0.107	0.041	0.031	0.657
	2010	0.050	0.026	0.071	0.024	0.036	0.098	0.104	0.037	0.107	0.040	0.031	0.624

95 %. In general, correlation coefficients between the P value and the intensity index of land use in 2000 were more than that in 1995, meaning that the correlation between them trended to increase with time. (c) In 2005, however, the correlation coefficient between the intensity index of land use and the P value is 0.366, lower than previous period. That is, the correlation between them is unapparent. (d) In 2010, the correlation coefficient between the intensity index of land use and the P value was 0.492 and the confidence level is same as 2000, which indicates that the probability of positive correlation is 95 %.

6.1.2.2 The P value is significantly correlated with the changing index of land use intensity as well as the rate of interconversion of land use types Land use change is one of the driving forces of the state change of regional ES. Land use change can be represented as the change of land use intensity as well as the transition of land use types. The P value changed not only with the land use intensity, but also with the transition of land use types. The change of land use intensity can be defined as the changed index of land use intensity, and the transition of land use types can be defined as the rate of conversion of land use types. The results of correlation analysis show that, the correlation coefficient between the changed index of land use intensity and the change in the P value is 0.672 with a confidence level of 0.01, meaning that the correlation probability is 99 %, and the correlation coefficient between the rate of the conversion of land use types and the changed P value is 0.723 with a confidence level of 0.001, meaning that the correlation probability is 99.9 %.

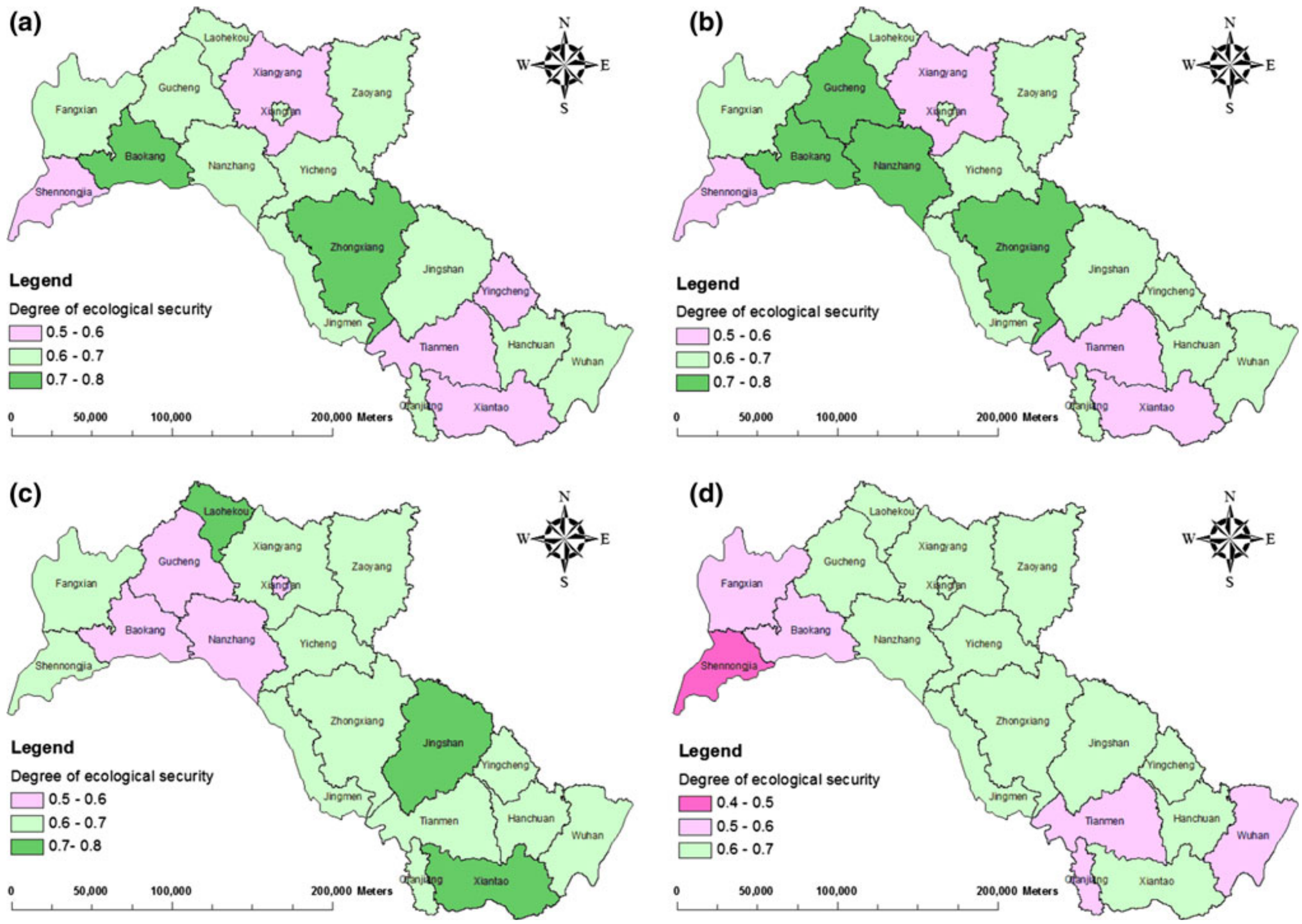

Fig. 1 ES Degree in the study region: **a** In 1995, **b** in 2000, **c** in 2005, **d** in 2010

6.2 ES and ESA

ES is the cornerstone of regional sustainable development (Cui et al. 2005), and it is related to different spatial scales (Peng et al. 2004). Existing research, both the basic research on ES mechanisms and information service systems, is still primitive in its abilities to resolve eco-security problems (Shi et al. 2006). ES requires the maintenance of both human and ecological system stability. One way to assess this stability is most often addressed with a set of indicators that can provide multiple lines of information on the holistic driver–pressure–state–impact–response (DPSIR) of the human-ecological system. Another way is focused on ecosystem variables on the ecosystem level of integration that can reflect the ecosystem integrity and health, especially in the structures and functions of the ecosystem. Based on this thinking, we selected three basic elements—the landscape threat, the landscape productivity, and the landscape stability—to meet the needs of assessment in this study.

The assessing ES key is identification and selection of suitable indicators. Because many key response variables are difficult to measure directly, a series of relative indicators and drawing analogies with the assessment of test results are considered as surrogates (Murtaugh 1996). In some researches, the indicators themselves seem to be the responses or endpoints of interest, and the identification of useful indicators then depends largely on expert judgement (Murtaugh and Pooler 2006). An ecological indicator can be defined as “a measure, an index of measures, or a model that characterizes an ecosystem or one of its critical components” (Jackson et al. 2000). In other researches, investigators seek variables that reflect ecosystem health or integrity (e.g., see Bryce et al. 2002; Hughes et al. 2004).

Although many environmental crises should have shown the significance of indirect, chronic and delocalized effects, this knowledge has not been adopted in indicator development to a satisfying degree (Muller and Lenz 2006). There is a lack of basic rules, methods and principles of indicator derivation and application. In too many cases indicator sets are developed without a satisfying scientific fundament. For the ESA, the theory of sustainable development is commonly used as the theoretical basis of selecting evaluation indicators, and the principal component analysis, the AHP and the Delphi method are the basic methods of selecting and

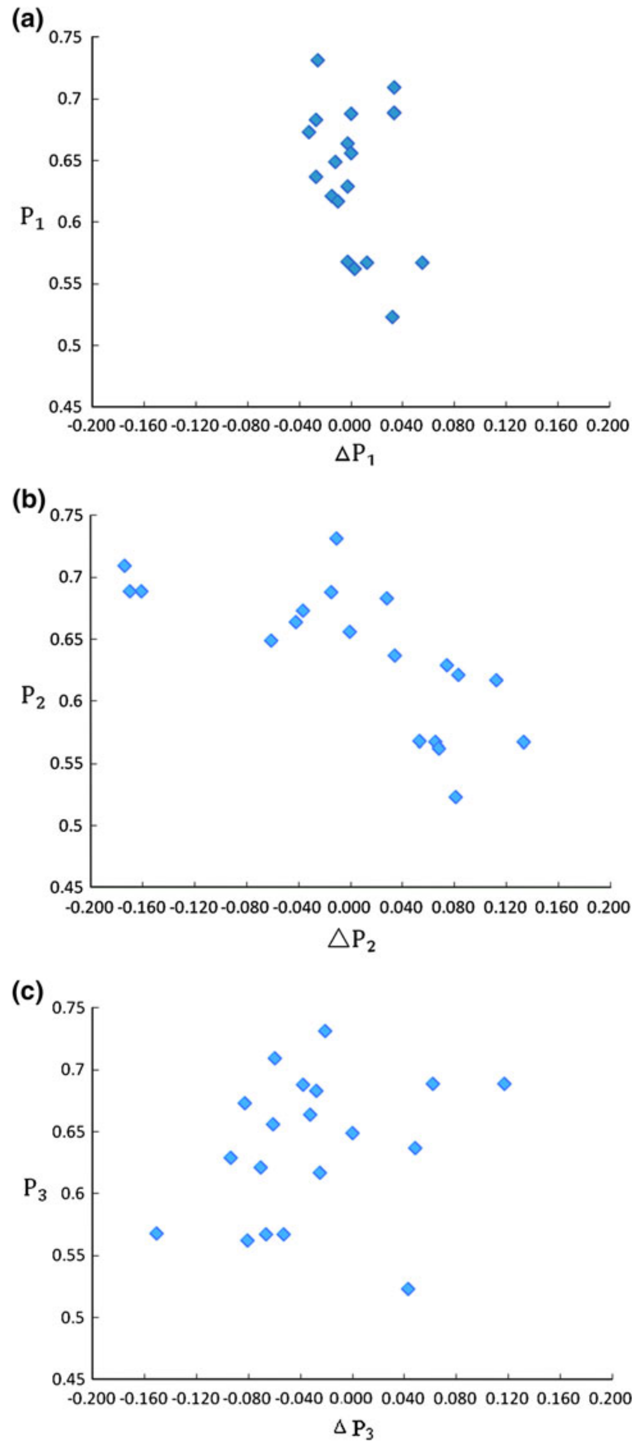

Fig. 2 Change of ES degree in the study region. P_i is the ES degree, ΔP is the value changed: **a** From 1995 to 2000, **b** from 2000 to 2005, and **c** from 2005 to 2010

weighting evaluation indicators. In this study, the indicator system of assessing ES is developed under the holistic DPSIR framework, and indicators are selected and weighted by the AHP and Delphi method. Considering the conflicts between simplicity and accuracy, and between complex indicator sets and a small number of understandable indicators, 11 indicators were selected in our study to calculate the *P* value to reflect the system states at the watershed scale on a suitable scientific level. Combining a suite of indicators into a single value is overviewed by Andreasen et al. (2001). The method is the simplest available (Walker et al. 2006), and is used successfully for a biological integrity index (Karr et al. 1986) and in the US-EMAP program (Jones et al. 1997). It has also been used by Walker et al. (2002) who tested the scores against independent biophysical data for catchments in the Canberra region and Liu et al. (2002) who applied the method to part of the loess plateau in China.

6.3 ES and watershed management

Integrated watershed management requires the integrated assessment of the ecological environment in different views of ecological researches, and ESA is just one of these assessments. To meet the need of watershed management, a lot of theories and methodologies are introduced to this field. But the integrity of the theoretical basis and methodological system in these assessments still needs to be discussed.

Watershed management represents a complex problem and therefore requires fully integrated approaches (Karageorgis et al. 2005). The DPSIR sequence is increasingly used to address integrated management issues in the marine environment (Turner et al. 1998; Elliot 2002). Karageorgis et al. (2005) have analyzed the Axios catchment—coastal area according to the DPSIR framework, and the results of the DPSIR analysis will offer policy makers a list of applicable measures, with sound socio-economic and environmentally friendly background toward an integrated and sustainable watershed-coastal zone management. Based on the DPSIR framework, we suggest that the ES degree can be used as a target of watershed management. As mentioned in the discussion above, given that the ES is correlated highly with the intensity of land use and the rate of interconversion of land use types, the sustainable watershed management should focus on land use change, especially the transition of land use types.

7 Conclusions

For the sustainable watershed management, two challenges are posed for the scientific community: estimating broad scale ecosystem conditions from highly disparate data, often observed at different spatial scales, and interpreting these conditions relative to goals such as sustainability (Quigley et al. 2001). In this study, we develop an assessing framework of watershed ES as one of the targets of watershed management. Combined with the support of

RS and GIS, the results of our case study of the Hanjiang River Basin reflect that the ES situation is very grim in the study area. The ES degree developed in this study can be used as a useful tool for watershed managers and decision-makers.

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