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Regional ecosystem changes under different cascade hydropower dam construction scenarios in the LRGR

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Ecological effects of the cascade hydropower dam construction on ecosystems have acquired much concern from scientists with the expanding of dam development scales in the Longitudinal Range-Gorge Region. In the Lancang River region and Yuanjiang River-Red River region of the Longitudinal Range-Gorge Region (LRGR), an index system has been therefore established to assess the current ecological vulnerability and to predict the likely future ecological vulnerability of these two river regions after the dam constructions. Eight cascade hydropower dam construction scenarios have been established in this paper for forecast. Abrupt change characteristics of the ecosystem have been considered in the calculation. Economic benefits like current supply, navigation and tourisms of the dam construction have not been considered in the calculation. The results show that (1) the current ecological vulnerability values of Lancang River region and Yuanjiang River-Red River region are 0.34 and 0.43 respectively, which would rise to 0.90−0.91 and 0.86−0.89 respectively after the joint work of all the planned dams; (2) abrupt change would happen to both the Lancang River region and Yuanjiang River-Red River region in future; (3) interval construction with high human response is recommended for both the Lancang River region and Yuanjiang River-Red River region, after which their likely ecological vulnerability would rise to 0.56−0.62 and 0.42−0.43 respectively. These results provide a reasonable method and theoretical references to assess the ecological effects of dam construction, and also give prewarnings to other mainstreams of the Longitudinal Range-Gorge Region which are being planned to construct cascade hydropower dams.

scenario analysis, ecosystem change, ecological vulnerability value, cascade hydropower dam construction, Longitudinal Range-Gorge Region

For all we know, cascade hydropower dam construction brings about both economic benefits like current supply, navigation, tourisms, etc., and ecological problems like biodiversity loss, flow reduction, land use change, etc. Cascade hydropower dam construction is a large scale disturbance on rivers and is the most important factor to change the natural characteristics of rivers[1]. Therefore, whether to construct the cascade hydropower dams or not has brought about strong arguments and discussion worldwide[2−5]. The number of studies on ecological effects of the dam constructions around the world has increased with the increasing of the ecological problems induced by the dam constructions. Many methods like habitat simulation, contrastive analysis, etc., have been used in the studies. Studies in the past mainly focused on the biodiversity[6−10], sediment transport[11], hydrological characteristics[1,12,13], river channel morphology[14−16], land use types[17], etc. From the previous reviews, it can be seen that the ecological effects of dams differ greatly depending on location, operation time, environment, substrate, bank material, released water and sediment, etc. Also, it can be seen that earlier studies on the

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impacts of dams and reservoirs have mainly focused on single indicators. These results provided much important knowledge to the field of the dam construction effects. Ecological effects of the cascade hydropower dam constructions in Lancang River region of the Longitudinal Range-Gorge Region[18−20] have been studied by many scientists, which was mainly focused on the water quality[21], water temperature[22] and transboundary effects[13,23]. Few studies on theses subjects have been carried out about the Yuanjiang River-Red River region.

The interaction between the constructing and operating of cascade hydropower dams and regional ecosystems is extremely complex, because of not only the complexity of the ecosystem itself, but also the accumulation of the ecological effects between cascade dams. That is why it is not accurate enough to study the effects on single indicators or single ecosystem types. Therefore, to understand the ecological effects more clearly and forecast the ecosystem changes more correctly, an integrated study must be carried out at the regional ecosystem scale. The Red River region, an important part of the longitudinal range-gorge region, becomes more and more important because of the large scale cascade hydropower dams planning. A case study was conducted on Lancang River region and Red River region. In this work, we are trying to find the ecosystem changes under different cascade hydropower dam construction scenarios. It is hoped to supply some suggestions for the regional ecological security and give prewarnings to other mainstreams of the Longitudinal Range-Gorge Region where the cascade hydropower dams will be constructed.

1 Study area and materials

1.1 Study area

Unprecedentedly, persistent and large scale disturbances have forced the special natural environments of the Longitudinal Range-Gorge Region to change fast, including biodiversity loss, biological invasions, ecological disasters, land use change and so on[18]. Large scale hydropower dam construction is one of the driving forces. Six dams have been planned on the upstream of the Lancang River, namely, Liutongjiang, Jiabi, Wunonglong, Tuoba, Huangdeng and Tiemenkan downstream, and eight dams have been planned on the middle and lower streams (Figure 1). The main purpose of the dam construction on the mainstream is electric power generation, and partially navigation and irrigation. The hydroenergy of Yuanjiang River and Red River was mainly concentrated on the tributaries. Only 15.7% of the total equipped capacitor and 19.4% of generating capacity were produced on the mainstream of the Red River region. Most of the dams on Yuanjiang River and Red River have been planned with small regulation capacity because of the unsuitable natural conditions. Five dams have been planned on the upstream, which are Sanjiangkou, Jiasa, Edehe, Mosha and Qiaotou. Four dams have been planned on the midstream, which are Luodie, Peijiao, Daheigong and Nansha. Three dams have been planned on the downstream, that is, Madushan, Xinjie and Dawan (Figure 1). Currently, Nansha Dam was finished in October of 2007.

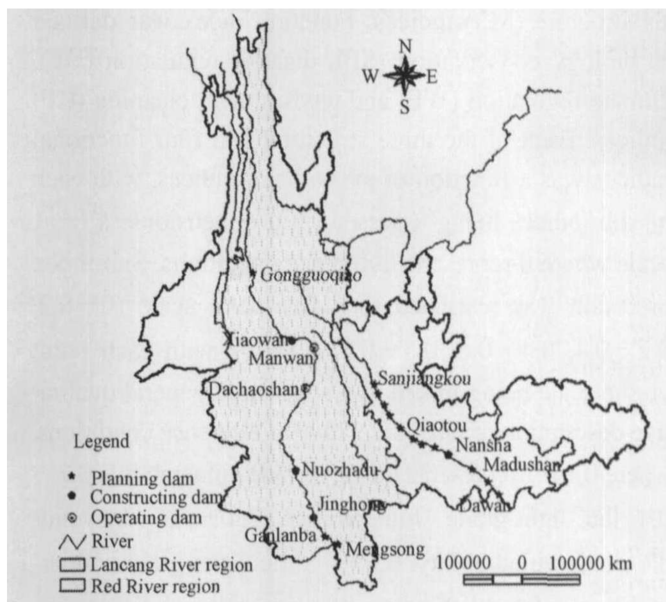

Figure 1 Cascade hydropower dam development along middle and lower reaches of Lancang River, Yuanjiang River and Red River in Longitudinal Range-Gorge Region.

1.2 Materials

The present research was based on the following materials: physical and chemical data about vegetations, soils and waters in the period of 2004−2006; remote sensing images, land use statistics and 1:50000 DEM images of the Longitudinal Range-Gorge Region for 1980 and 2001; weather data from the main cities of the study area in the period of 1950−2000; monthly flow data from the three mainstream hydrologic stations located at Jiuzhou, Gajiu, and Yunjinghong in Yunnan Province in the period of 1956−2001; water quality data of Lancang River, Yuanjiang River and Red River in the period of 2001−2005.

2 Methods

2.1 Index system

According to the principle of scientism, independence, sensibility and practicability, an index system including quality and quantity indicators was established to assess the current condition and to predict their likely future conditions of the ecological vulnerability in a range of cascade hydropower development scenarios. The selection and integration of the indicators were based on a great number of the corresponding results obtained by the scientists all over the world[24−39]. The index was defined as the lesser structure condition (SC) index and a function condition (FC) index. Structure condition was defined as the ecosystem components (ES) and morphosis structure (MS) indices. Function index was defined as biology conservation (SF), disaster regulation (DF), climate regulation (WF) and environment cleaning (CF) indices. Each of the three structural and four functional indices was a function of several sub-indices, with each of sub-indices being assessed on a dimensionless 0−1 scale where 0 represents reference conditions. Sub-index precision was restricted to a five-point scale (0−0.2, 0.2−0.4, 0.4−0.6, 0.6−0.8, 0.8−1), with each point on the scale being linked to a specific or general qualitative description of change relative to reference conditions, where 0−0.1 represents the tiny-grade vulnerability, 0.2−0.4 the light-grade vulnerability, 0.4 − 0.6 the middle-grade vulnerability, 0.6−0.8 the sever-grade vulnerability, and 0.8 − 1 the extreme-grade vulnerability.

Theoretical bases for weights determining and scales classification are as follows:

(1) Research findings about the related topics in the world showed that the natural morphology character of the river, hydrologic character, biodiversity and land use change are affected mostly by the dam construction[24−39].

(2) Studies about the ecological structures and functions. There is a complex relationship between the ecosystem structures and the ecosystem functions. As both of them are important components of the ecosystem, the weights of them are assigned equal values in this paper.

(3) Studies on the special natural environments and large scale of human disturbances[13,18,19,23,40−48] in the Longitudinal Range-Gorge Region.

The index system for assessment, equations for calculation, weights for indices and detailed definitions of the sub-indices are given in Table 1.

2.2 Models

For assessing the cascade hydropower dam construction effects on regional ecosystems, a concept model was constructed based on the PESCR (press, effect, state, change, response) model (Figure 2). Two sub-systems were contained in the model: dam construction and regional ecosystem change. Cascade hydropower dam construction was considered as the main driving force of the ecosystem change. Ecosystem structures and functions were considered as the bases of the model system. The basic idea is to model and simulate the ecosystem changes influenced by different cascade hydropower dam construction scenarios at the regional scale.

The regulated rivers in the study area were divided into several reaches by the cascade dams. The ecological vulnerability value of the single index of each river reach u_i (eq. (1)) is not only related to the original value before the dam construction u_{i0}, but also related to some other indices, like the press coefficient induced by the dam P_i (P_i can be calculated using eqs. (2) and (3): H, height of dam; V, total reservoir cubage; E, electricity generated; Z, equipped capacitor; A, reservoir area; X_i is the above five indicators), regional special coefficient T_i (T_i means the regional particularity of the reach, e.g. there is a large tributary between two river reaches or the dam was constructed crossing over a natural protection area), cascade coefficient C_i (C_i means the interaction among the dams, e.g. sediment interception effect from the upper dams to the lower dams) and human response coefficient R_i (R_i means the protective and restoring measures in the construction and operation processes). The ecological vulnerability values of single index of all the river reaches were calculated using eq. (4), where l_i is the length of each river reach, L is the length of all the river reaches, u' is the index value of the rest river reaches, cs is the cumulative coefficient in space (cs was considered if the distance between the two adjacent dams is less than 100 m), and st is the cumulative coefficient in time (it was considered if the operation time between the two adjacent dams was less than 5 years). Use eq. (5) to calculate the integrated ecological vulnerability values of all the river reaches, where w_j is the weight of the index, and $g(u_j)$ is the standardized value of the index after grading. The hydropower dam constructions may have strong effects in a small scale but less effect in a larger scale. The ecological effects can be

Table 1 Index system for assessing the regional ecosystem change under cascade hydropower dam construction and the calculation formulae, weights and definitions for each index

First order index	Second order index	Third order index	Sub-index	Detailed definitions
Ecosystem change $IN=\frac{1}{n}\sum_{i=1}^{n} w_i in_i$	0.50 structure $S=\frac{1}{n}\sum_{i=1}^{n} w_i s_i$	0.43 ecosystem component structure $ES=\frac{1}{n}\sum_{i=1}^{n} w_i es_i$	0.33 diversity indices $H=-\sum_{i=1}^{n}(p_i)\log_2(p_i)$	It reflects the change of the proportion of each ecosystem type area and the type numbers. P_i is the proportion of each ecosystem type area, and n is the total numbers of the ecosystem types.
			0.33 dominance indices $D=H_{max}+\sum_{i=1}^{n}(p_i)\log_2(p_i)$ $H_{max}=\ln(n)$	It means the deflection degree of the ecosystem diversity to the maximum diversity or the control degree of minority ecosystem types to the whole ecosystem. H_{max} is the maximum ecosystem diversity index. The meanings of P_i and n are the same as above.
			0.33 degree of homogeneity $E=(H/H_{max})\times 100\%$ $H=-\log(\sum_{i=1}^{n} p_i^2)$ $H_{max}=\log(n)$	It describes the degree of homogeneous of the distribution of each ecosystem types. E is the homogeneous index, H is the modified Simpson index, and H_{max} is the maximum degree of homogenous under the given abundant degree T. The meanings of P_i and n are the same as above.
		0.14 morphosis structure $MS=\frac{1}{n}\sum_{i=1}^{n} w_i ms_i$	0.13 breadth depth ratio of river valley $P=W/D_{max}$	It describes the effects of the submergence on the river shape. W is the breadth depth ratio of river valley and D_{max} is the maximum depth of the river valley.
			0.33 river longitudinal continuity	The main function of the index is to judge the dam's block effects on the longitudinal continuity of the river.
			0.12 river channel morphology	It mainly describes the downstream flushing intensity induced by the released water.
			0.24 river channel curvature	It describes the change of the river channel curvature. The river channel will be much straighter after the reservoir filling.
			0.18 river bed shape	It describes the change of the river bed shape induced by the sediment accumulation.
	0.50 function $F=\frac{1}{n}\sum_{i=1}^{n} w_i f_i$	0.32 biodiversity conservation function $SF=\frac{1}{n}\sum_{i=1}^{n} w_i sf_i$	0.33 habitat continuity	The habitat continuity has important meanings to the animals and plant lives for their existence, communication and propagation.
			0.14 habitat diversity	High ecosystem biodiversity and edge effects has advantages to biology for their existence, hiding and avoidance.
			0.33 habitat value	It depends on the value, protective degree and rareness of the biology.
			0.20 habitat stability	Habitat stability here mainly focuses on the downstream stability, which may be induced by the water level change, aperiodic submergence and the element composition change in the drainage water.
		0.23 disaster regulation function $DF=\frac{1}{n}\sum_{i=1}^{n} w_i rf_i$	0.33 regulated reservoir capacity	The regulation capacity has important roles in flood control and drought resistant.
			0.33 earthquake inducted intensity	Dam construction will increase the probability, scales and intensity of the earthquakes. It mainly related to the geological conditions, dam numbers and densities.
			0.33 shore stability	It is mainly caused by the current scour induced by the flow regulation and the debris flows and landslides induced by the dams.
		0.17 climate regulation function $WF=\frac{1}{n}\sum_{i=1}^{n} w_i wf_i$	0.50 average temperature	The increase of the water surface area may change the climate regulation function, especially on temperature and relative moisture. Local climate may have an obviously change after the joint operation of the cascade dams.
			0.50 relative moisture	
		0.28 environment cleaning function $CF=\frac{1}{n}\sum_{i=1}^{n} w_i cf_i$	0.50 water quality	Water quality is a good indicator for reflecting the environment cleaning function.
			0.50 water runnability	The fast water runnability can accelerate the water cycle rate and increase the self-purification capacity.

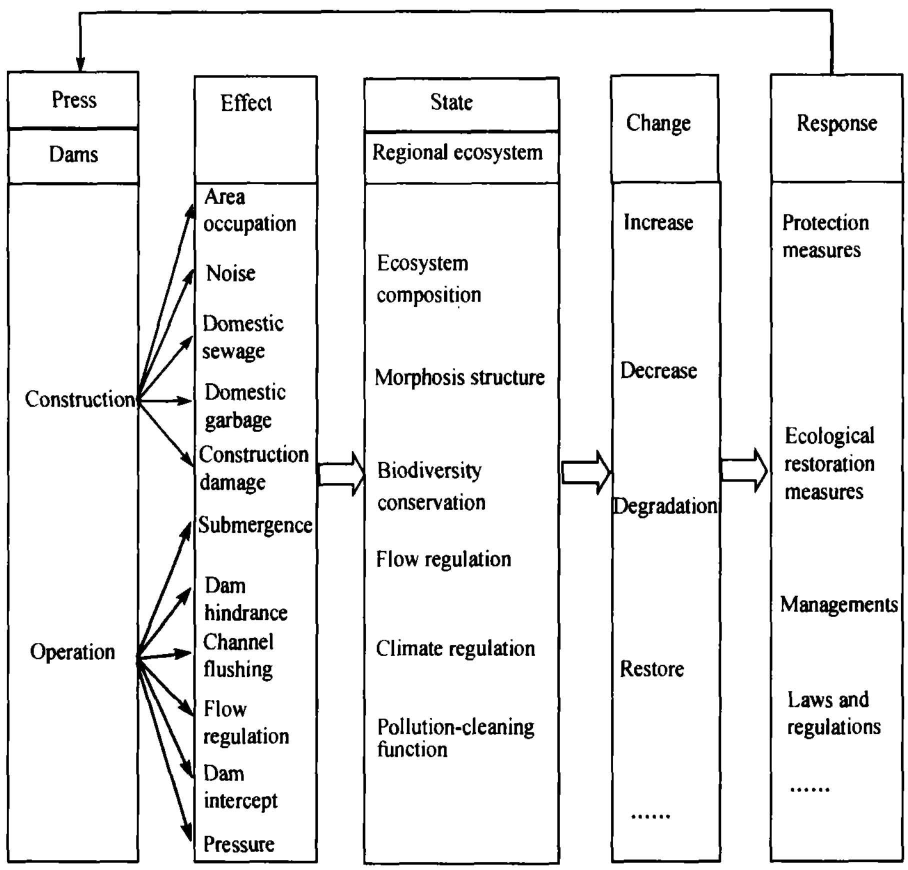

Figure 2 PESCR concept model of the interaction between cascade hydropower dams and regional ecosystem changes.

amplified or be reduced by the scale size. Therefore, in order to assess more accurately, the region was divided into three parts, namely, water area, riverside and terrestrial area, and the weights were assigned 0.45, 0.45 and 0.1 respectively by using the Delphi method. The riverside mentioned in this paper contains 3 km buffers from the river bank to the terrestrial area. The indices having regional characteristics were calculated using eq. (6), where F_s, F_g, F_l were water region, riverside and terrestrial area, respectively.

$$f(u_i) = f(u_{i0}, P_i, T_i, C_i, E_i), \quad (1)$$

$$P_i = (\bar{H}_i + \bar{V}_i + \bar{E}_i + \bar{Z}_i + \bar{A}_i)/5, \quad (2)$$

$$\bar{X}_i = \frac{1}{n} X_i / \sum_{i=1}^{n} X_i, \quad (3)$$

$$u = \frac{\sum_{i=1}^{n} u_i l_i + u'(L - \sum_{i=1}^{n} l_i)}{L} \times (cs + ct), \quad (4)$$

$$F = \sum_{j=1}^{n} g(u_j) \times w_j, \quad (5)$$

$$F = F_s w_s + F_g w_g + F_l w_l. \quad (6)$$

2.3 Determination of the abrupt change point for function

Ecosystem structures and functions will have big changes under the synergic effects and the antagonistic effects of the external pressure. Emergency chain reactions or magnifying effects may happen to the ecosystem and even an abrupt change such as the loss control of the partial ecosystem functions and the breakdown of the whole ecosystem will happen finally. Because of the existing complex relationships between all the ecological indices and external pressure, it is not accurate enough to determine the threshold value of the ecosystem change[49]. It must be determined against several indices. The abrupt change of ecosystem functions was stressed here. Several indices which may lead to the corresponding ecosystem functions change were selected (Table 2). The ecological vulnerability of the functions would be assigned a infinite value if more than 60% of all the index ecological vulnerability values of the corresponding functions are greater than 0.8.

3 Results and discussion

3.1 Scenario setting

Dam development order, development manner and human responses including protective and restoring measures are the three main driving forces of the ecosystem change and are the bases of the scenarios setting in this paper (Table 3). Two development orders from top to bottom and from bottom to top, two development manners, continuous development and interval development, and two human response levels, low and high responses, were contained in the scenarios setting. Twenty-two scenarios can be set according to the above three driving forces. Among them, 8 scenarios are selected for analysis according to the representation, practical meaning and the aim of this paper (Tables 4 and 5).

Table 2 Indices selected for the corresponding ecosystem functions to determine the threshold value of the ecosystem function change

Functions	Biodiversity conservation	Climate regulation	Environmental cleaning	Disaster regulation
Indicators	ecosystem diversity value	average temperature	river longitudinal continuity	regulated reservoir capacity
	habitat value	relative moisture	regulated reservoir capacity	river channel morphology
	habitat continuity		water quality	river channel curvature
	habitat stability		water runnability	soil erosion degree
	river longitudinal continuity			shore stability
	habitat diversity			earthquake inducted intensity
	water runnability			

Table 3 Parameters for the dam construction scenarios setting

Parameters choices	Development order	Development manner	Human response
First choice	top-down	continuous development	low response—response coefficient 0.8
Second choice	down-top	interval development	high response—response coefficient 0.4

Table 4 Cascade hydropower dams development scenarios of the Lancang River [a)]

Dams	Scenarios							
	Low human response				High human response			
	1	2	3	4	5	6	7	8
Liutongjiang	5	10	5		5	10	5	
Jiabi	6	9		5	6	9		5
Wunonglong	7	8	6		7	8	6	
Tuoba	8	7		6	8	7		6
Huangdeng	9	6	7		9	6	7	
Tiemenkan	10	5		7	10	5		7
Gongguoqiao	4	4	4	4	4	4	4	4
Existing	1	1	1	1	1	1	1	1
Ganlanba	2	2	2	2	2	2	2	2
Mengsong	3	3	3	3	3	3	3	3

a) The numbers stand for the development orders. The void spaces stand for the non-construction dams. "Existing" is the constructing and operating dams on the Lancang River: Xiaowan, Manwan, Dachaoshan, Nuozhadu and Jinghong.

Table 5 Cascade hydropower dams development scenarios of the Yuanjiang River and Red River [a)]

Dams	Scenarios							
	Low human response				High human response			
	1	2	3	4	5	6	7	8
Sanjiangkou	5	12	5		5	12	5	
Jiasa	6	11		5	6	11		5
Edehe	7	10	6		7	10	6	
Mosha	8	9		6	8	9		6
Qiaotou	9	8	7		9	8	7	
Luodie	10	7		7	10	7		7
Peijiao	11	6	8		11	6	8	
Daheigong	12	5		8	12	5		8
Nansha	1	1	1	1	1	1	1	1
Madushan	2	2	2	2	2	2	2	2
Xinjie	3	3	3	3	3	3	3	3
Dawan	4	4	4	4	4	4	4	4

a) The numbers stand for the development orders. The void spaces stand for the non-construction dams.

3.2 Analysis and discussion

The current ecological vulnerability value is 0.34 for Lancang River region and 0.43 for Yuanjiang River-Red River region. Both of them belong to the light-middle vulnerability state. The severe self-topographical features and formidable self-climate conditions of the Yuanjiang River-Red River region determine the high ecological vulnerability value and the weak resistivity to the external disturbances. From Figure 3(a), we can see that the way of scenario 8 was found to be the best selection for Lancang River with the lowest ecological effects, followed by scenario 7, scenario 5, scenario 6, scenario 4, scenario 3, scenario 1 and scenario 2. Scenario 8 was found to be the best selection for Yuanjiang River and Red River with the lowest ecological effects, followed by scenario 7, scenario 4, scenario 3, scenario 6, scenario 5, scenario 2 and scenario 1 (Figure 3(b)). From the above results, we can see that generally, the hydropower dam construction with high human responses brings about the least ecological effects on ecosystems, and the interval development brings about less ecological effects than continuous development while different development orders bring about approximately equal ecological effects. Downstream degradation (channel morphology) and sediment accumulation (river bed shape) may be affected mostly by the development orders. Top-to-bottom development may have more effects on downstream degradation while bottom-to-top development may have more effects on sediment accumulation (Figure 4).

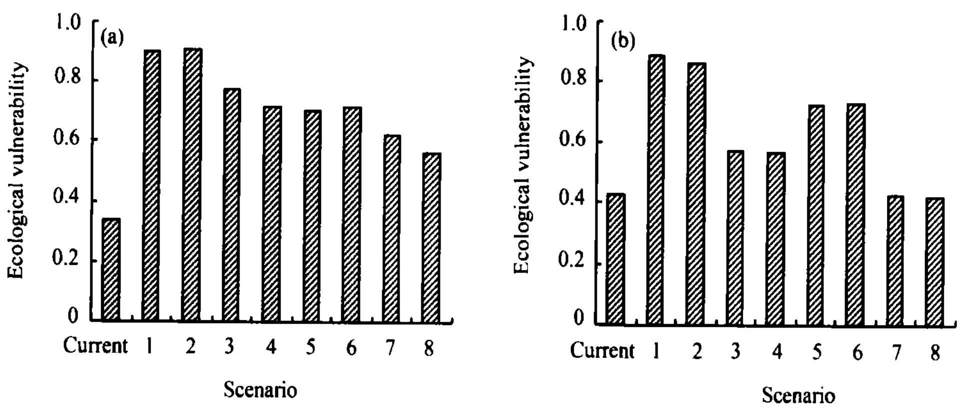

Figure 3 The ecological vulnerability of Lancang River region (a) and Yuanjiang River-Red River region (b) in different scenarios (not considering the ecosystem abrupt change characteristic).

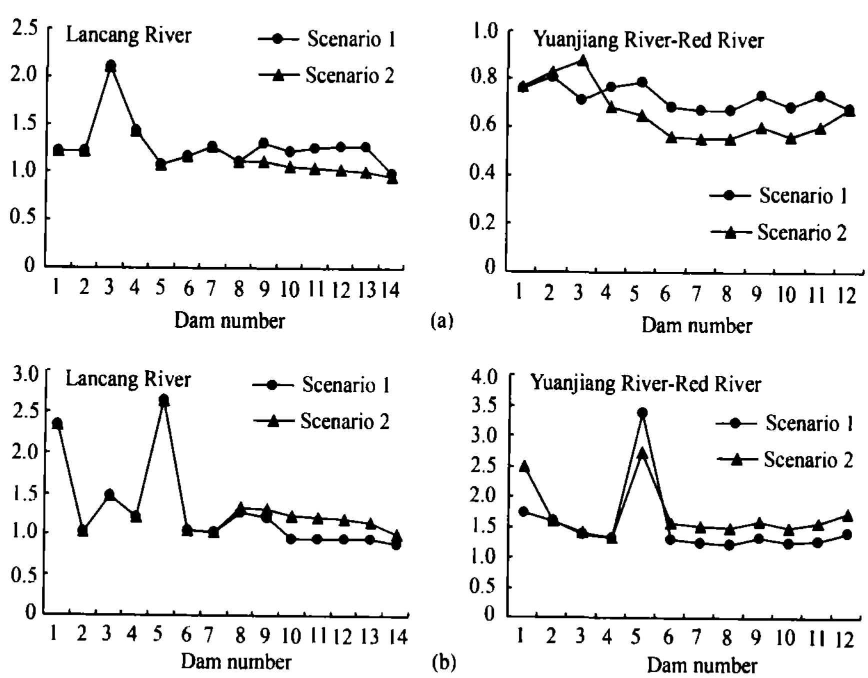

Figure 4 Changes for river channel morphology (a) and river bed shape (b) in different hydropower dam development orders. Horizontal ordinate is the number of dams. The development order is the same as scenarios 1 and 2 (Tables 3 and 4). The development orders of the existing dams in this paper are Manwan, Dachaoshan, Xiaowan, Jinghong and Nuozhadu. The longitudinal coordinate is the index values in the calculating process.

If we do not consider the ecosystem abrupt change characteristic, the ecological vulnerability of Lancang River region would rise to 0.90 or 0.91 after the continuous development with low human response. At these development levels, breakdown will happen to the regional ecosystem if the abrupt change characteristic was considered. After finishing the development scenarios 3, 4, 5 and 6, the ecological vulnerability values of Lancang River region would rise to 0.78, 0.72, 0.70 and 0.71, respectively. Therefore, even the interval development with low human response or continuous development with high human response would bring the regional ecosystem to a severe vulnerability state. Therefore, in order to maintain the regional ecological security, interval development with high human response was recommended for the upstream of Lancang River.

On the mainstreams of Yuanjiang River and Red River, the hydropower dams were planned with small equipped capacitors but large number. Therefore, the ecological effects of dam construction in Yuanjiang River-Red River region which has high ecological vulnerability value cannot be ignored. The results showed that in continuous development with low human response level, the ecological vulnerability value of Yuanjiang River-Red River region would rise to about 0.89 or 0.86, even leading to an ecosystem abrupt change. The ecological vulnerability values would rise to 0.58, 0.57, 0.73 and 0.73 at scenarios 3, 4, 5 and 6 levels respectively. The ecological effects of the interval development with low human response are higher than continuous development with high human response. Therefore, interval development of the cascade dam construction is a better choice for Yuanjiang River and Red River from the angle of the environment protection.

4 Conclusions

Economic benefits like current supply, navigation and tourisms of the dam construction were not considered in the calculation. Both advantages and disadvantages exist in the hydropower dam construction and operating processes. The focal point is how to protect the eco-environments in the constructing process and how to restore and monitor the eco-environments after the dam construction. If the protective and restoring measures are not effective enough, a serious change will happen to the regional ecosystem after the joint operation of the cascade dams. Since Lancang River, Yuanjiang River and Red River are the important international rivers, the transboundary effects of the cascade hydropower dam constructions are very important, critical and sensitive. The transboundary ecological security and control will be the main points for us to study in future. Also, the ecological effects of cascade hydropower dam constructions on Nujiang River, Salween River and Irrawaddy River will be the focal point.

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