The ecological restoration potential (ERP) of river reaches after hydropower dam construction: a case study from the Lancang River, China

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Abstract: Ecological effects from cascade hydropower dams and the ecological restoration of rivers have attracted worldwide attention. The assessment of ERP, a method used to determine the natural restorable degree for damaged river ecosystem, would reduce the blindness of restoration projects, and further guide the implementation of river ecological management. In this paper, we selected four kinds of ecological elements to evaluate ERP, i.e. regional climate conditions (E_1), hydrological conditions (E_2), riparian conditions (E_3) and biological conditions (E_4), and then calculated the loss rate of ERP for the river reaches between Manwan and Dachaoshan hydropower dams in Lancang River, where Downstream, Upstream and Reservoir area of each dam were selected as monitoring sections during two periods of 1977-1986 and 1987-1997. The results showed ERP values of E_1 (ERP_1) changed insignificantly during two periods, indicating that E_1 was not the key factor for ecological restoration management of this area. The order of ERP_2 was reservoir > upstream > downstream section in the first period, when Manwan dam only existed; ERP_2 decreased highly in the second period after Dachaoshan dam construction, and E_2 of Upstream Section of Dachaoshan dam (USD) became the worst one in all the sections. ERP_3 in each reaches showed the same order in first and second periods, which was reservoir > upstream > downstream section, but ERP_3 in Manwan reaches increased in the second period because of artificial restoration and self-restoration. ERP_4 was bigger than ERP_2 and ERP_3, which illustrated that dam construction, had not brought the loss of endangered species and the damaged plant communities recovered quickly. Finally, all the loss rates of ERP showed that E_2 was most heavily damaged by cascade hydropower dam construction, and followed by E_3.

Key words: River ecosystem; Hydropower dams; Ecological restoration potential (ERP); Assessment; Lancang River

1 Introduction

Societal development needs for hydropower generation and water management, but these often have resulted in a significant departure from the natural processes of hydrologic regimes and material transport throughout most of the rivers flowing. It is well known that hydropower dams can disturb the fluxion of material and energy in a regional ecosystem violently, and destroy the dynamic equilibrium of the natural river ecosystem. Water quality (Joseph et al., 1999), sediment and flow are changed greatly by dam construction (Carling, 1988; Kummu, 2006; Morocco, 2002); the change of river way shape and construction of reservoir damage fishes in the stream and plant on the riparian (Brandt, 2000; Marks et al., 2006). Dam construction can also bring the changes of regional temperature and rainfall (He and Zhang, 2004; You and He, 2005). In addition, cascade hydropower dams can bring temporal and spatial cumulative effects and make against the natural process of ecological restoration, while much more damages to ecological characters(Chen and He, 2000; Ma and Chen, 2006; Zhai et al., 2007). If this kind of effects may go beyond systematic endurance, they can cause the succession of the whole damaged ecosystem (Gagnon and Chamberland, 1993; Morocco et al., 2002; Francis and Keith, 2005). Due to the long-term development and utilizing of the river, the river ecosystems suffered from a large amount of destruction in the past time, and have formed different types of degenerate ecosystems (Frutiger, 2004a; Frutiger, 2004b). It is a clear need to maintain sustainable ecological services and restore ecosystem function and habitat range.

How to restore or rebuild the self-sustaining and self-resilient system is also acknowledged as the management objective of the governments (Palmer et al., 2005; Elmqvist et al., 2003). With the development of the river restoration theory and study, engineering, biological and management measures have been carried into execution in many countries, such as river repair, revetment virescence and many kinds of measures for good water quality.(Jackson, 1995; Bernhardt, 2005; Richard, 2004; James, 2007). At the same time, ecological assessment is necessary for these projects before and after restoration projects, while it can help to improve our understanding of how ecosystems work(Bradshaw, 1993), and further guide the implementation of the ecological restoration projects and hydropower stations (Giller, 2005).

At present, less effective evaluation methods to dam specially can be used to explain these questions clearly. Besides, rivers in different regions have their own key elements because of their special backgrounds and dam conditions. To solve with the problem above, in this paper we report on a study designed to assess the possibility of ecological restoration of dammed river and the changes of typical ecological characteristics. We aim to establish the integrative fuzzy hierarchical assessment model of ERP, through combining qualitative analysis and quantitative assessment, overcoming the disadvantages of the previous analysis methods. In addition, functional characteristics of different ecological elements are discussed by comparing their ERP values in order to find the key elements of river restoration management and reduce the blindness of restoration projects.

2 Material and methods

2.1 Background

Lancang - Mekong River originates in the Qinghai-Tibet Plateau and flows through six countries, China, Myanmar, Laos, Thailand, Vietnam and Cambodia. The total length of its mainstream is 4,880 km, and the basin area is 79.5×10^4 km^2. It is known as the Lancang River (E 98°35′□102°19′, N 21°08′□29°16′) in the region of Yunnan province, China. Up to 2006, two dams have completed on the river; two dams are building; four dams have been planned, but not yet built. The study area is carried out in the reaches of two completed ones, from 2 km in the front of Manwan reservoir to 10 km at the back of Dachaoshan dam with 165 km in length (Fig.1). The basis data of two completed dams are shown on Table 1.

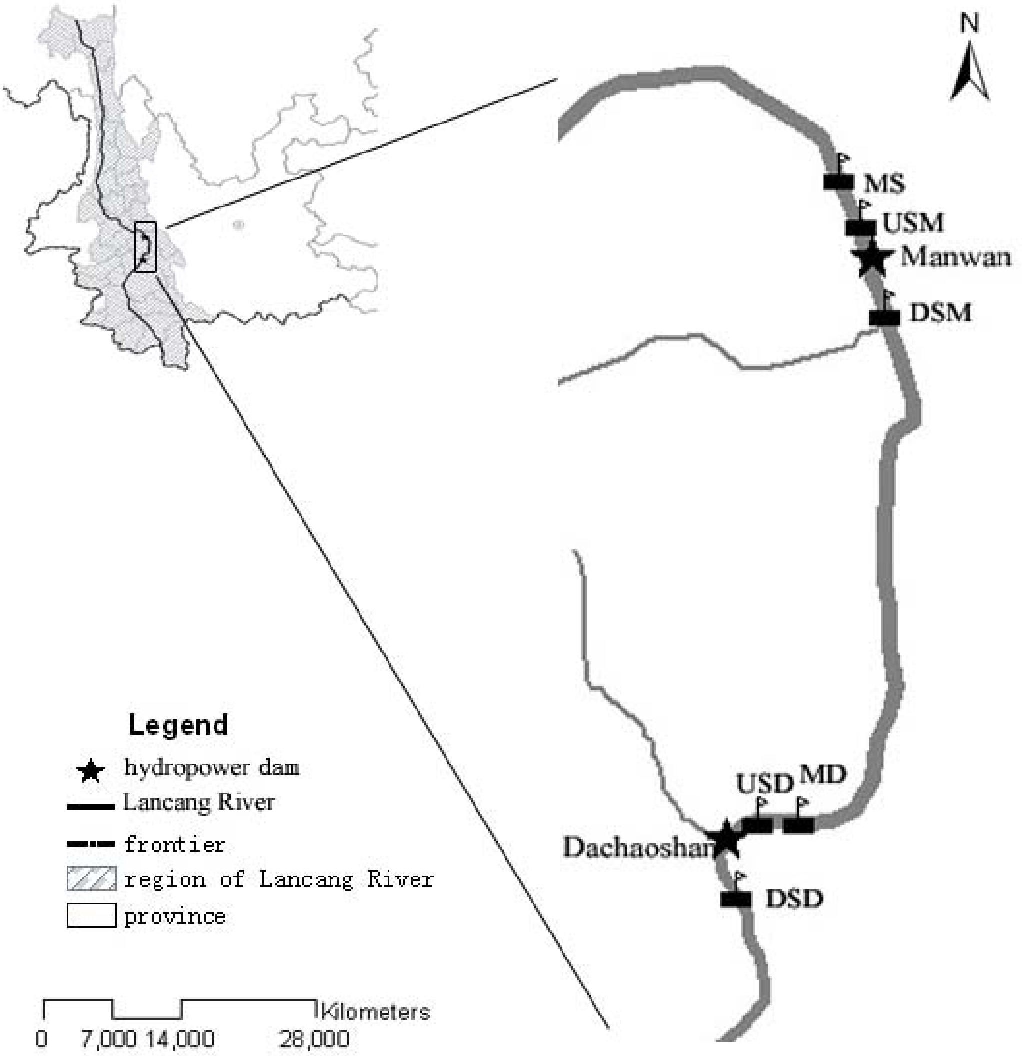

Fig. 1 Locations of the study area

The study area is located in the subtropical plateau monsoon climate zone, and the climate of this area changes vertically obviously because of the altitude discrepancy of the landform. Influenced by southwest wind in summer, there are more rain in summer and less rain in winter and spring. The average rainfall of each year is 1000~1150 millimeters, and average temperature is from 18□ to 20□. Climates and terrains bring on complex ecosystems, especially abundance species with a large number of rare ones, and in the natural circumstance, semi-humid evergreen broad-leaved forest, evergreen broad-leaved forest and Yunnan pine forest distribute widely. In this region, the contradictions between dam construction and ecological equilibrium become more conspicuous.

2.2 Date resources

Two date resources: (1) The current conditions. From October to November in 2006, we went field visits along all the study reaches, while six monitoring sections i.e. Downstream, Upstream and Reservoir section of each dam were chosen as samples (Fig.1, Table 2). Hydrologic and biological data were obtained by this field visits directly. After that, organic matter(OM), six kinds of heavy metals (P_b, A_s, C_r, Z_n, C_d, C_u) and pH value of soil were analyzed in the laboratory. The determination of OM adopts the potassium dichromate-volumetric method. The value of soil pH is measured with the instrument of Sour Degree (water: soil=5:1), and contents of heavy metals are determined with the instrument of Inductively Coupled Plasma Spectrum (France- -ICP2AES). (2) The historical conditions (reference conditions). Historic hydrologic and hydrobiology data during 1950-2005 were accessed from the regional hydrologic bureau.

Table 1 The basic data of Manwan and Dachaoshan hydropower dams (Yao et al., 2005; Yao et al., 2006)

Name of dam	Average water level(m)	Height of dam (m)	Installation capacity (MW)	Average flow (m^3/s)	Area of catchments (km^2)	About dam (year)	
						Build	Operate
Manwan	994	130	1500	1230	114500	1985	1993
Dachaoshan	895	110	1350	1340	121000	1997	2001

Table 2 The basic circumstances of selected monitoring sections

Monitoring sections	Longitude and Latitude	Altitude (m)	Distance from the nearest dam(km)
Manwan Reservoir (MR)	E100°21′50. 6″,N24°45′15. 5″	997	35
Upstream Section of Manwan dam (USM)	E100°26′44.1″, N24°37′30.0″	994	1
Downstream Section of Manwan dam (DSM)	E100°28′46.0″, N24°36′04.8″	900	8
Dachaoshan Reservoir (DR)	E100°30′56.3″, N24°33′20.8″	899	50
Upstream Section of Dachaoshan dam (USD)	E100°22′39.8″, N24°01′24.0″	897	1
Downstream Section of Dachaoshan dam (DSD)	E100°23′43.6″, N24°00′05.1″	788	10

2.3 Mathematics model and calculation

2.3.1 Indicators for assessment

Based on researches from former ecologist and circumstance of study area, the fuzzy hierarchical assessment model of ERP is established by considering three types of elements, which are Regional climate conditions (E_1), Hydrological conditions (E_2), Riparian conditions (E_3) and Biological conditions (E_4), and thirteen kinds of indexes. The weights of each element are determined by the means of Analytic Hierarchy Process (Zhao et al., 1986; Zhao and Yang, 2007). According to the above analysis, the river assessment indexes framework of ERP and their weights for Lancang River system is established in Table 3.

Table 3 Assessment indexes framework of ERP for damaged river

Element (E)	Index (I)	Weight (q_i)
Regional climate conditions (E_1)	Annual average air temperature (I_1)/□	0.500
	Annual rainfall (I_2)/mm	0.500
Hydrological conditions (E_2)	Annual average water flow (I_3)/(m^3/s)	0.048
	Surface water temperature (I_4)/□	0.048
	Average sediment concentration (I_5)/□kg/m^3)	0.048
	Water quality condition /(I_6)	0.429
	Degree of river channelization(I_7)	0.429
Riparian soil conditions (E_3)	Soil organic matter (I_8)g/kg	0.485
	Soil heavy metal (C_d) (I_9)mg/kg	0.485
	Soil pH (I_{10})	0.054
Biological conditions (E_4)	Total coverage of plant(I_{11})	0.091
	Plant diversity(I_{12})	0.091
	The integrity of hydrobiology species (I_{13})	0.818

2.3.2 Grading, standardization and quantification of ERP indexes

There is not a uniform reference values and grading standard to assessment river ecosystem at present (Karr J R, 1999). The common methods to determine river assessment standard include reference to historical information, investigation to the field, comparison method, utilization of national standards and relevant research results for reference, public participation, and expert judgments (Jungwirth M, 2000; Zhao and Yang, 2007; Jeffrey et al., 2008). In this paper, the natural value represents the best state of river ecosystem through artificial restoration or self-restoration, while the reference values are the foundation of all the grading standards. We choose the ecological status of 1977□1984 as the best conditions of ecological restoration, that is the natural value. Overall, average value of every index from 1977 to 1984 would be chosen as the reference value. In addition, Environmental Quality Standards for Surface Water of China" (GB3838-2002), and the Background Values of Chinese Soil (1990) are selected as the reference values and grading standards. Quantificational indexes: I_1, I_2, I_3, I_4, I_5, I_8, I_9, I_{11}, I_{12} are calculated their membership degree by the formula (1) (Cui and Zhai, 2006; Zhao and Yang, 2007). Non-quantificational indexes: I_6, I_7, I_{10}, I_{13} are divided into five grades□i.e. <1, 1–2, 2–3, 3–4 and 4–5, rated by the expert judgment based on scope and extent of ecological effects from environmental stress they can bring (Chen and He, 2000; Francis and Keith, 2005), The value of element layer and goal layer can be calculated by the formula (2).

$$S_j = \begin{cases} I_j / I_{j1} & (I_j<I_{j1}) \\ (I_j - I_{j1})/(I_{j2} - I_{j1}) + 1.0 & (I_{j1}<I_j<I_{j2}) \\ (I_j - I_{j2})/(I_{j3} - I_{j2}) + 2.0 & (I_{j2}<I_j<I_{j3}) \\ (I_j - I_{ij3})/(I_{j4} - I_{j3}) + 3.0 & (I_{j3}<I_j<I_{j4}) \\ (I_j - I_{j4})/(I_r - I_{j4}) + 4.0 & (I_{j4}<I_j<I_r) \end{cases} \quad (1)$$

$$E_i = \sum_{j=1}^{n=13} q_j S_j \quad (2)$$

Where S_j refers to the membership degree of index layer; I_j refers to value of every index; I_{j1}□ I_{j2} □I_{j3} □I_{j4} refer to the every grading standards of indexes, respectively; I_r refers to reference value of indexes;   j=1,2,3……13; i=1,2,3,4.

2.3.3 Calculation of the loss rate of ERP

Manwan and Dachaoshan dam began to build in 1985 and 1997, respectively, where the study time is divided into two periods. The first period is from 1985 to 1996, when Manwan dam was built, and then operated, and no Danchaoshan dam; the second period is from 1997 to 2006, when both dams exist. In order to compare ecological loss by dams construction conveniently, the loss rate of ERP value of four elements are calculated by the formula (3). The natural value represents the best state of river ecosystem through artificial restoration or self-restoration.

$$\text{The loss rate of ERP of every element} = \frac{\text{Assessment value - Natural value}}{\text{Natural value}} \times 100\% \quad (3)$$

3 Results

Table 4 The assessment results of ERP for Manwan and Dachaoshan reaches in Lancang River

Time	Location	E_1	E_2	E_3	E_4

Natural river □1977-1984□	Total river reaches (The natural reach)	5.000	4.548	3.908	5.000
The first period □1985-1996□	Manwan reservoir-□ (MR-□)	5.000	3.431	3.638	4.936
	Upstream section of Manwan dam-□(USM-□)	5.000	3.140	2.857	4.482
	Downstream section of Manwan dam-□ (DSM-□)	5.000	3.066	2.571	4.909
The second period □1997-2006□	Manwan reservoir-□(MR-□)	5.000	3.265	3.638	4.991
	Upstream section of Manwan dam-□(USM-□)	5.000	3.169	3.175	4.573
	Downstream section of Manwan dam-□ (DSM-□)	5.000	2.410	2.784	4.982
	Dachaoshan reservoir (DR)	5.000	2.828	3.083	4.909
	Upstream section of Dachaoshan dam (USD)	5.000	2.265	1.951	4.500
	Downstream section of Dachaoshan dam (DSD)	5.000	3.051	1.040	4.909

3.1 Spatial distribution of ERP

In Fig.2, the whole trends of ERP_1 curve are like a level line, so constructions of Manwan and Dachaoshan dams have not resulted in the change of climate conditions. The order of ERP_2 is shown as DSM<USM<MR in the first period, and ERP_2 of USD is the least in the second period. While Fig.3 shows loss rates of E_2 change much bigger in DSW-□and DR. It is found that all indexes of E_2 have some deterioration in the second period, especially in USD. E_2 from downstream of the first dam to upstream of the second dam loses heavily. In the whole periods, the order of ERP_3 in all river reaches is reservoir > upstream of dam > downstream of dam. While ERP_3 in DSD is the worst in the second period, some ERP_3 in Manwan reaches in the second period are better than that the first period. As shown in Fig.2&3, ERP_4 values of two upstream sections lose more, but reservoirs and downstream sections lose less. The lowest position of ERP_4 is USD, 4.482.

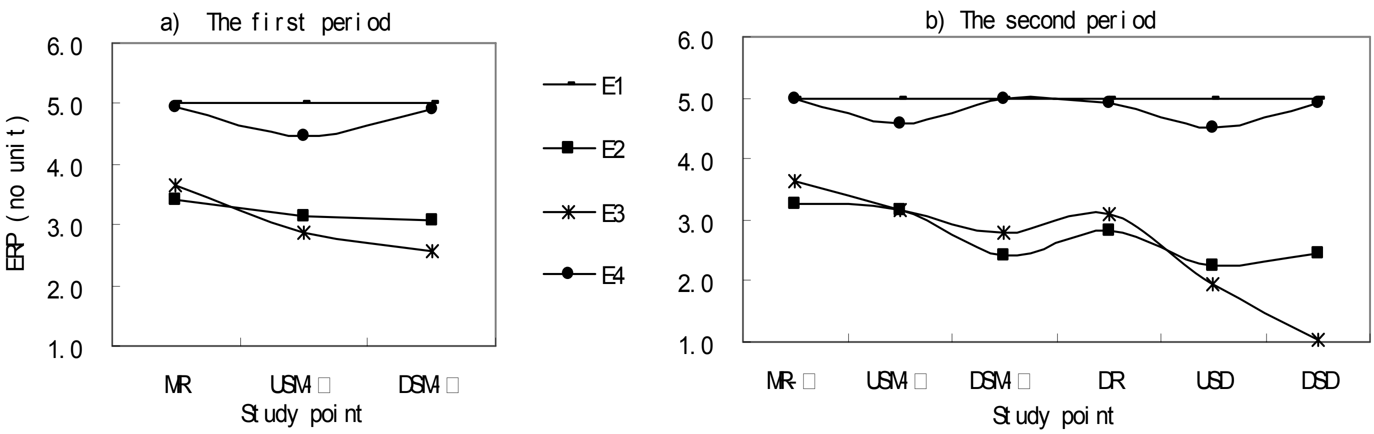

Fig. 2 Four kinds of ERP in the first and second period in Manwan and Dachaoshan reaches

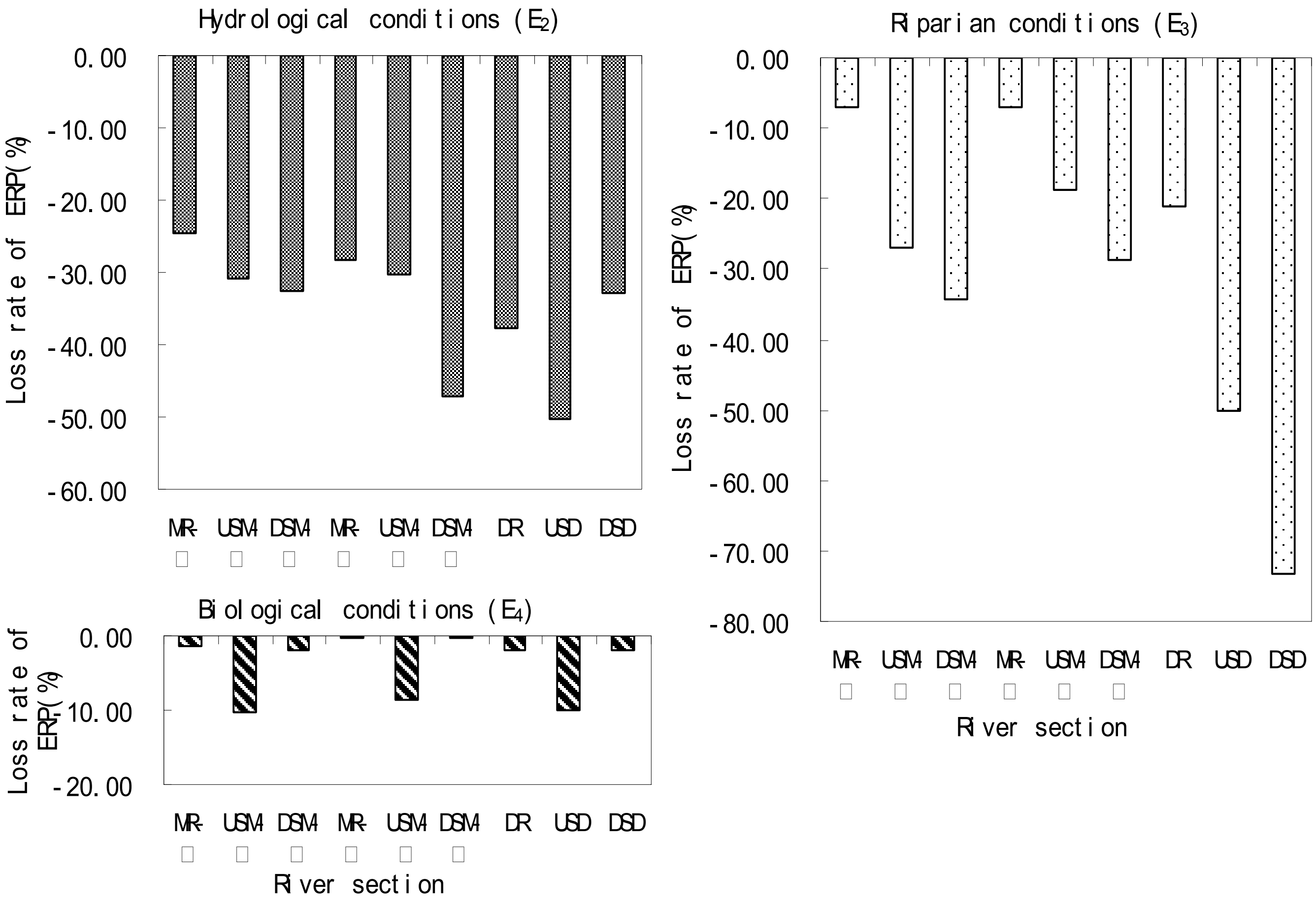

Fig. 3 Comparison of the loss rates of ERP in the first and second period in Manwan and Dachaoshan reaches

(To E_1, the difference of loss rate between the assessment value and the natural value is less than 0.5 , so it need not be shown on Fig.3.)

3.2 Average loss rates of ERP

As shown in Fig.4, by comparison of the average loss rate of Manwan reaches between the first and second period, E_2 continues to be damaged, but E_3 and E_4 are recovering on the whole. Although Dachaoshan dam construction has a negative impact to all kinds of environment conditions of the Manwan reaches, but Manwan Dam was built in 1985, twenty three years to now, so soil and biological conditions have restored in a way. By comparison of the average loss rate of total river reaches between the first and second period, two kinds of loss rates in the first period are less than that in the second period, and all the loss rates of ERP of Dachaoshan dam is higher than that of Manwan dam in the second period, except E_4. The loss rates of ERP_2 and ERP_3 increase 10% or so, but the loss rate of ERP_4 decreases in the second period. Although the sizes of two hydropower dams are similar and the second dam began to build after twelve years of the first dam construction, the loss rates of ERP would still become bigger after the second dam construction.

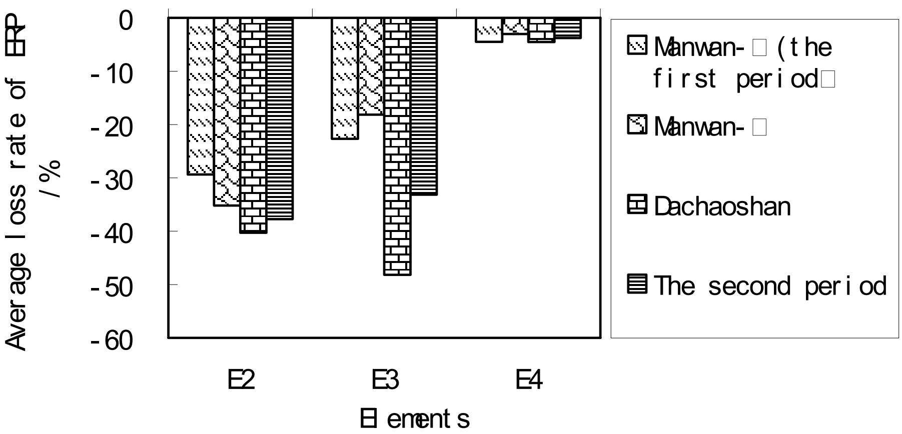

Fig.4 Comparison of the average loss rate of ERP in Manwan and Dachaoshan reaches

4. Discussion

4.1 The natural value and reference value

The natural value of E_1 is full mark (5 marks). All the changes of annual average temperature (I_1) are within ± 0.5□ before and after construction of hydropower dam, and annual rainfall (I_2) is found few changes in all the study areas, so the evaluation value of E_1 nears to 5 marks. The natural value of E_2 is 4.548 marks, no full mark, To its indexes, average sediment concentration (I_5) of Lancang River was 1.07kg\m^3 in 1960s, but increased to 1.36 kg\m^3 in 1980s, because industrial and agricultural activities have intensified in the past twenty years. If the average value of sediment concentration from 1977 to 1986 was chosen as the reference value, the reference value would be affected by human activities, so it is appropriate to choose 1.07kg\m^3 as the reference value, and then the score of E_2 from 1977 to 1986 in total river reaches is 4.548. The reference values of E_3 choose the cadmium background values of Yunnan soil. The average measured value of soil organic matter is chosen as the reference value of I_8. By analysis of six kinds of heavy metals, cadmium is the maximum of exceeding its background values of Yunnan soil, so cadmium is chosen as the representative of soil contamination, and the cadmium background values of Yunnan soil is chosen as the reference value of I_9. We found the content of cadmium in natural soil had already exceeded the background value in some sections and there is the phenomenon of cadmium pollution. Therefore, ERP_3 of the natural soil is scored 3.908. Natural river reaches have lost some ERP because of urbanization and artificial pollution before hydropower dams were built.

4.2 Analysis of key restoration elements

Water temperature and flow change greatly in the downstream of dam when the first dam had been built and no other dams, but the river reaches between two dams formed channelization when the second dam had also been built, and Manwan and Dachaoshan dams almost connected head and tail, so ERP_2 from downstream of the first dam to upstream of the second dam loses heavily. By comparing of the loss rates of ERP_2 between the first and second period in Manwan reaches, which are due to the increasing channelization and sediment the Manwan and Dachaoshan river reaches after the Dachaoshan dam construction (Sear, 1995; Phillips et al, 2005). If riparian shape was destructed, it would be difficult to restore them to the natural state. The change of loss rate of ERP_3 shows heavy metals pollution and soil erosion become more and more serious from upstream to downstream (Kondolf and Swanson, 1993; Kondolf, 1997). Besides, the second dam construction made soil erosion in the Dachaoshan reaches aggravated even more. But ERP_3 in Manwan reaches in the second period are better than that the first period, so this kind of phenomenon shows soil organic matter was recovering naturally in the past twenty years, and the effect of recovery in Manwan reaches exceeded the damage. Dam construction brings the bigger effects on riparian soil conditions, but the restoration capacity of the riparian soil itself is also stronger.

All the loss rates of ERP_4 are less than that of ERP_2 and ERP_3. It is found that three ecological zones formed in the upstream sections after the reservoir, which were adjacent, but different. The first ecological zone is deep and lenitic flow zone in the front of dam; the second one is glide flow zone at the end of the reservoir; the third one is the slow flow zone between two above zones. But the ecological environment in the first zone is far away from that of the natural ecosystem, so it is not suited to indigenous fish (Wang and Zhang, 2000). Although, there are some differences between other two zones and the natural ecosystem, some indigenous fish also exist (Wang and Zhang, 2000). After dam construction, the distribution and number of fish must change, and it has a greater impact on the fish in the surroundings of flow water. They have moved to the end of reservoir or branches, where the original characteristics of river ecosystem are still retained. Besides, some plant has been submerged by dam construction in this area. So, biodiversity decreased significantly in the upstream zone. Through investigation and analysis, the Manwan and Dachaoshan Hydropower Dam does not affect on distribution of the state's key animals and Nature Reserve, for example Wuliang Mountain Nature Reserve. Fortunately, construction of hydropower dam has not caused the loss of endangered species. Besides, the riverbed is raised with the forming of two dams, and valley areas are flooded, which can damage the riparian habitat. But increasing of water temperature makes aquatic habitats change, a great deal of aquatic plant and animal propagate (Wang, 1999; Wang and Zhang, 2000; IREP, 2006). So plant restores quickly on both riparian land, and plant diversity is increased. Lancang River is located in subtropical rainfall, plentiful rainfall, and the growth rate of plant is faster than that of the drought area, so the natural value of E_4 is full mark and average loss rate of E_4 is less than 10%.

In the study area, hydrological conditions are damaged the most heavily by cascade hydropower dam, and riparian soil conditions in the next place, and they can be as key restoration elements. Sediment and river channelization are representatives of ecological disturbance from the cascade hydropower projects. However, it is easier to recover biological conditions in study area. These results provide a reasonable method and theoretical references to evaluate the ecological conditions of dam construction, and further guide the implementation of the ecological restoration projects. Although it is inevitable that hydropower dam construction disturbed river ecosystem in the region of Lancang River, artificial restoration and protection to the ecological environment will bring different results. If cascade dams of the Lancang River are analyzed from the perspective of ecological restoration, we should notice pollution and accumulation of heavy metals in the soil and water, and should change riparian shape as little as possible in the period of dam construction. The best solution might be to restore hydrological conditions first and mostly to the river management in the period of dam operation. In this paper, the focal point is how to restore and monitor the eco-environments after the dam construction, but economic benefits like current supply, navigation and tourisms of the dam construction are not considered in the calculation. Owing to the increase of cascade hydropower dams, it will be the main point for us to study the ERP of river ecosystem influenced by more than two dams in future.

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