STEP-POOL SYSTEM FOR EROSION CONTROL AND ECOLOGICAL RESTORATION

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Abstract

The ecological and hydraulic features of step-pool systems are studied by field investigation (sampling and analysis) and field experiment. Field investigations are done on five streams in China (the Jiuzhai and Shengou Creeks, the Jinsha River, Jiangjia and Xiaobaini Ravines). These steps and pools provide high diversity of habitat for the stream bio-community. The density of benthic macro-invertebrates in the streams with step-pool systems is 800 times higher than neighboring streams without step-pool systems. A new habitat diversity index is proposed considering the spatial distribution of various substrates, velocity, and water depth. A step-pool system develops in incised channels as a result of streambed erosion. A step-pool system maximizes the flow resistance and protects the bed sediment from erosion. Thus, the riverbed and bank slope are stabilized. The development degree of step-pools, *SP*, is proportional to the streambed slope. The study suggests that artificial step-pool systems can be used for training of mountain streams, which may stabilize the streambed and bank slope, restore healthy river ecology and high biodiversity, and promote a better aesthetic landscape as well. A field experiment using artificial step-pool system for aquatic ecology restoration was carried out on the Diaoga River, an incised mountain stream in Yunnan-Guizhou Plateau, Southwest China. Artificial step-pool system increases the flow resistance and controls channel incision effectively, and maintains a relatively stable stream habitat. Different substrate, flow velocity and water depth environment alternating upstream steps and in pools creates spatially diversified stream habitats, and enhances the development of the aquatic creatures. The benthic macro-invertebrates are used as indicator species to evaluate the ecology of the stream. The number density of individual benthic invertebrate and taxa richness (number of benthic invertebrate species) both rise with the increase of habitat diversity. The artificial step-pool system is an effective way for aquatic ecology restoration of incised mountain streams.

Key words: step-pool system, benthic macro-invertebrates, biodiversity, habitat diversity, artificial step-pool system, ecological restoration

1. INTRODUCTION

A step-pool system is a geomorphologic phenomenon occurring in high-gradient mountain streams (>3–5%) with alternating steps and pools having a stair-like appearance (Chin, 1999). The step-pool system develops usually on a bed of slope larger than 3% with bed materials consisting of particles with diameters differing by several orders of magnitude with the largest diameter on the same order as the water depth. Cobbles and boulders generally compose the steps, which alternate with finer sediments in pools to produce a repetitive, staircase–like longitudinal profile in the stream channel, as shown in Fig. 1. The tight interlocking of particles in steps gives them an inherent stability that only extreme floods are likely to disturb, which suggests that step-pools are a valid equilibrium form, especially when coupled with their apparent regularity and their role in satisfying the extreme condition of resistance maximization. step-pool systems develops in many mountain streams in China, such as the Pitiao River, a tributary of the Minjiang River and the Jiuzhai Creek in Sichuan Province, the Qingshui River in Guizhou Province, and the Shengou Ravine and Heishui River, tributaries of the Xiaojiang River in Yunnan Province.

There are many research results on the hydraulic features of regular step-pool systems. The step-pool system affects not only flow resistance but also sediment transport, which in flume experiments occurs as a series of waves linked to the underlying bed morphology (Whittaker, 1987; Rosport and Dittrich, 1995). Their role as energy dissipaters can be impaired when pools become filled with sediment (Whittaker and Jaeggi Martin, 1982), for then there is an increase in velocity and erosive capability, reactions that are opposite to original formation of the step-pool system. The bed adjustment in a step-pool system in Lainbach, Germany shows the function of increasing flow resistance (Ergenzinger, 1992). The large boulders in the steps act as a framework tightly interlocking the structure resulting in considerable stability. Given the need for one or more keystones, the development of step is strongly influenced by local supply and transport conditions. The pools between steps provide storage sites for finer bed material. Although steps composed of boulders are the most common type, they can also form in bedrock (Hayward, 1980; Wohl and Grodek, 1994) and through accumulation of large woody debris in heavily forested catchments (Keller and Swanson, 1979). Step-pool systems have been reported from a wide range of humid and arid environments (Chin, 2002), and analogous forms have even been observed in supraglacial streams (Knighton, 1984). They, thus, appear to be a fundamental element of steep fluvial systems.

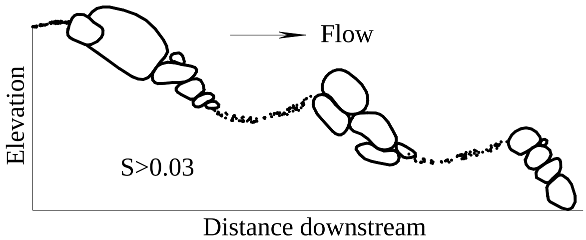


Fig. 1. Staircase-like longitudinal profile of the regular step-pool system in high gradient stream channels

Step-pool morphology can be characterized by two variables: step wavelength, L, and step height, H_s, so that H_s/L is an index of step steepness and bears a close relation to the loss of head per unit length of channel (Abrahams et al., 1995). Pool-pool or step crest-step crest spacing has an average of 2-4 stream widths in two Oregon streams and is also rather variable because of an uneven distribution of bedrock outcrops and boulder deposits along the channels (Grant *et al.*, 1990). Step structure appears to be better defined and more regular on steeper slopes (Judd and Peterson, 1969; Whittaker, 1987; Chin, 2002; Grant et al., 1990; Wohl and Grodek, 1994), which implies that, if step height is controlled by the largest particles an increase in the bed slope must be accommodated by more closely spaced steps.

Whittaker (1987) suggested that the length of a regular step-pool system, or the distance between two steps or two pools is inversely proportional to the average slope of the stream. Rosport (1997) reported that the length of a regular step-pool system increases with the average discharge. Abrahams et al. (1995) found that the ratio of the step height to the length is proportional to the average slope. The flow over the boulders forming each step is supercritical ($Fr>1$) and changes to sub-critical ($Fr<1$) in the pool, causing a considerable amount of energy dissipation through turbulent mixing (Hayward, 1980; Whittaker and Jaeggi Martin, 1982). In addition, energy is expended as a result of the form drag exerted by the large particles that make up the steps. Thus, step-pool systems have an important resistance role, which is of particular significance in mountain streams where alternative forms of energy dissipation, such as lateral adjustment, are inhibited by the narrowness of the valleys, and where the large amounts of potential energy generated by the steep slopes could otherwise lead to extreme erosion.

A step-pool system is the best-ecologically sound riverbed pattern in mountain streams. Large fishes may swim up through the steps and small fishes may swim up against low velocity in the gaps between the stones. The shallow and deep waters and high and low velocities of flows provide high diversity of habitat for a high diversity of species. The pools provide refuge for juvenile fishes and in dry years may preserve water and serve as oases for faunal species. To date there have been few studies on the ecological features of step-pool systems in China. This paper studies the ecological features of step-pool systems through field investigation, sampling, and analysis. Benthic macro-invertebrates are sampled from the streams and examined and the aquatic faunal community is analyzed for the stream ecology assessment. The paper also introduces the field experiment for ecological restoration for a debris-flow ravine using artificial step-pool system in South China.

2. FIELD INVESTIGATIONS

Field investigations were done on the Jiuzhai Creek, Shengou Creek, the Jiangjia Ravine, the Xiaobaini Ravine, and the Jinsha River in May 2005. Jiuzhai Creek is a tributary of the Bailong River in the upper Yangtze River basin, and represents a large scale step-pool system. Shengou Creek, the Jiangjia Ravine, and the Xiaobaini Ravine are tributaries of the Xiaojiang River on the Yunnan Plateau in southern China, which flows into the Jinsha River - a upstream reach of the Yangtze River. Shengou Creek is representative of a well-developed regular step-pool system.

A step-pool system develops in the process of channel incision, in cases of insufficient sediment supply from upstream. For instance, the step-pool system developed in Shengou Creek in the past 30 years after extensive erosion control and reforestation projects were implemented in the drainage area of the creek. Before 1976 debris flows frequently occurred in Shengou Creek, and there were no step-pool systems. Slope and gully erosion provided enough sediment to the stream and heavy sediment transportation and poor vegetation cover dominated the river basin. Riparian vegetation has developed and sediment transportation has sharply reduced in the past decades thanks to the efforts of erosion control and reforestation projects. Thus, sediment-starved flows have scoured the channel bed and step-pool systems have developed. As a comparison, the Jiangjia Ravine is also a tributary of the Xiaojiang River and is only 17 km from Shengou Creek. Erosion has not been controlled in the Jiangjia Ravine watershed and bed load is transported by the stream flow. The streambed is still silting up as a result of too much sediment load from upstream. Fig. 2 shows the streambed morphology of Shengou Creek and the Jiangjia Ravine.

Fig. 2.
a) Step-pool systems have developed in Shengou Creek, a tributary of the Xiaojiang River on the Yunnan Plateau;
b) Bed load transportation prohibits development of step-pools in the Jiangjia Ravine, which is only 17 km from Shengou Creek.

The Xiaobaini Ravine flows into the Xiaojiang River from the opposite side (left side) and is 8 km from Shengou Creek. Although it has the same climate and bed sediment composition as Shengou Creek, no step-pool system is present in the ravine. Bed load motion and suspended load transportation are present in the stream. Sampling was also performed in a back flow area in the Jinsha River. The bed sediment consists mainly of gravel and sand and there are no step-pools in the river.

Both large-scale step-pool and regular step-pool systems are associated with good stream ecology. The structures exhibit high resistance, and consequently control channel incision and stabilize the riverbed and banks. Riparian vegetation may develop well in the stream with the step-pool structure. Fine sediment, including silt and clay, may deposit in the pools where the flow velocity is very low. Different animals may find their habitats in the step sections and pool sections. Therefore, the biodiversity of streams with step-pool systems is high. To study the biodiversity of the streams with different structures, sampling of benthic macto-invertebrates was done in the Jiuzhai Creek, Shengou Creek, the Jiangjia Ravine, the Xiaobaini Ravine, and the Jinsha River. The ecology of the streams is assessed based on the examination and analysis of the samples.

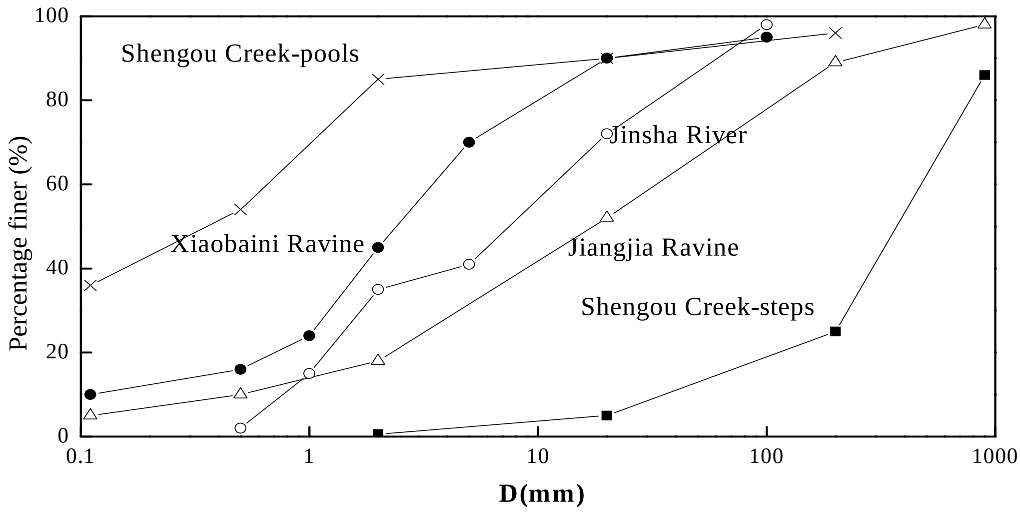


Fig. 3. Size distributions of bed sediment in the Jiangjia Ravine, Shengou Creek, the Xiaobaini Ravine, and the Jinsha River

Fig. 3 shows the size distributions of bed sediment in the Jiangjia Ravine, step section and pool section of Shengou Creek, the Xiaobaini Ravine, and the Jinsha River, in which *D* is diameter of sediment particles. The size distributions for the Xiaobaini Ravine and the Jinsha River are similar, and consist mainly of sand and gravel. The two streams are not good habitat for benthic macro-invertebrates because the sand and gravel mix together and sand fill the interstices of the gravel and the animals cannot move in the sediment. The size distribution of the Jiangjia Ravine is very wide, consisting of silt, fine and coarse sand, gravel, cobbles, and boulders. These bed materials mix together and provide poor habitat for benthic macro-invertebrates. The bed sediment in Shengou Creek was the same as the Jiangjia Ravine before 1976. The development of the step-pools in the past 30 years relocated the sediment with different sizes. Large particles, including cobbles and boulders, concentrate in the steps. The low flow and backwater in the pool sections trapped fine sediment, including silt and clay. The average size distribution of bed sediment becomes finer than before. Thus, the step-pool system provides high diversity of habitat for benthic macro-invertebrates.

Water samples were also taken for examination of the water quality. All the sampling sites are in mountain areas with low population density, there is little pollution in the areas, thus, the water quality in the streams is good. The suspended sediment concentration was zero in Jiuzhai Creek, Shengou Creek, and the Jiangjia Ravine, less than 0.1 kg·m^{-3} in the Jinsha River and 21.7 kg·m^{-3} in the Xiaobaini Ravine. No bed load motion is present in Jiuzhai Creek and Shengou Creek, visible bed load motion is present in the Jiangjia Ravine and the Xiaobaini Ravine.

Table 1. Number density and biomass of benthic macro-invertebrates from the five streams

Taxa	Jiuzhai Creek		Shengou Creek		Jiangjia Ravine		Jinsha River and Xiaobaini Ravine	
	Density ind/m^2	Biomass g/m^2	Density ind/m^2	Biomass g/m^2	Density ind/m^2	Biomass g/m^2	Density ind/m^2	Biomass g/m^2
Amphipoda		0.8001		1.1243				
Gammaridae	123		85					
Diptera		0.1130		0.1837		0.0048		
Chironomidae	66		138		0.08			
Tipulidae	9		2		0.25			
Ceratopogonidae			35					
Simuliidae			9					
Trichoptera		2.4541		0.0099				
Hydropsychidae	15		3					
Brachycentridae	147							
Rhyacophilidae	6							
Phryganeida	6							
Polycentropodidae	3							
Odonata		0.0189		3.3730				
Libellulidae								
Gomphidae	3		14					
Aeschnidae			2					
Cordulegasteridae			3					
Euphaeidae			3					
Ephemeroptera		3.0103		1.8117				
Ephemeridae			12					
Baetidae	39		9					
Siphlonuridae	6		4					
Heptageniidae	9							
Ephemerellidae	42							
Plecoptera	18	0.0282						
Coleoptera				0.0184		0.0006		
Dryopidae			2					
Elmididae								
Hydrophilidae					0.17			
Elmidae			27		0.17			
Acariformes	42	0.0010						
Gastropoda				4.1315	0.08	0.0026		
Planorbidae			2					
Hydrobiidae			32					
Physidae			2					
Oligochaeta			5	0.0062				
Hirudinea			3	0.2176	0.1	0.0007		
Tricladida	9	0.0395						
Unidentified	63	0.0006	76	0.0053				
Sum	534	6.3964	389	6.5029	0.75	0.0081	0	0.0000

The samples of benthic macro-invertebrates were taken from the five sites and analyzed. The sampling area is 1 m^2, but for the streams with low population density the sampling area is 10–12 m^2. Table 1 lists the number, density, and biomass of benthic macro-invertebrates per area from the five streams. The animals were examined under a microscope but some small invertebrates were not identified. The faunal communities are different for different streams. There are many species of Trichoptera in Jiuzhai Creek, which like clean and cold water. Shengou Creek has high biomass of Gastropoda and Odonata, which are associated with the fluid mud layer in the pool sections of the creek. The biomass per area of invertebrates in the Jiuzhai Creek and Shengou Creek is as high as 6.4–6.5 $g \cdot m^{-2}$, which is more than 800 times higher than that in the Jiangjia Ravine, because step-pool systems have developed in the former streams and no step-pools are present in the later one. The number density of the former streams also is 500–700 times higher than the later stream. Shengou Creek was also a debris flow gully like the Jiangjia Ravine before 1976, and they have the same climate and original bed compositions. The difference in biodiversity and richness of benthic macro-invertebrates are mainly due to development of the step-pool system in Shengou Creek.

3. HABITAT ASSESSMENT OF STREAMS WITH STEP-POOL SYSTEM

The streams provide habitat for benthic macro-invertebrates, and on the other hand, the stream habitat can be rapidly assessed with benthic macro-invertebrates. The intent of the benthic rapid bioassessment is to evaluate the overall biological condition, optimizing the use of the benthic community's capacity to reflect integrated environmental effects. Using benthic macro-invertebrates is advantageous for the following reasons: 1) they are good indicators of localized conditions; 2) they integrate the effects of short-term environmental variables; 3) degraded conditions are easily detected; 4) sampling is relatively easy; 5) they provide food for many fish of commercial or recreational importance; and 6) macro-invertebrates are generally abundant (Plafkin *et al.*, 1989). The biodiversity of the streams may be evaluated with the Shannon-Weaver Index, *H*, which is defined as follows (Krebs, 1978):

$$H = -\sum_{i=1}^{T} P_i \ln P_i \qquad (1)$$

where H represents the biodiversity; T is the number of species in the sample; P_i is the number ratio of the i-th species in the sample, $P_i = n_i/N$, in which n_i is the number of individuals of the i-th species, and N is the total number of individuals in the sample. For healthy ecosystems the Shannon-Weaver index is usually in the range of 1.5-3.5 with very few over 4.

The Shannon-Weaver Index (Krebs, 1978) represents the number of species and uniformity of distribution of species in the sample, but provides no information on the total abundance of the bio-community. For instance, samples from two sites have the same number of species, the distributions are also the same but the total number of individuals for site one is 100 and for the site two is 1000. Eq. (1) gives the same values of *H*. The difference in population density for the two cases is large, but it is not reflected by the values of *H*. Considering both the abundance and biodiversity, the following bio-community index was used:

$$B = H \lg N = -\lg N \sum_{i=1}^{T} P_i \ln P_i \qquad (2)$$

Table 2 lists the calculated values of bio-diversity, *H*, and the bio-community index, B, for the five streams. The bio-diversity of the streams with step-pool systems is much higher than those of streams without a step-pool system. The calculated B value for Jiuzhai and Shengou Creeks is about 4 times that of the Jiangjia Ravine. The development of a step-pool system remarkably improved the stream ecology and increased the bio-diversity and B value.

Table 2. Bio-diversity, bio-community index and habitat diversity of the five streams

Stream	Development of step-pools	$\sum_i \alpha_i$	Habitat diversity H_D	Number density (ind/m^2)	Biomass per area (g/m^2)	Taxa richness T	Bio-community index, β
Jiuzhai Creek	Large scale step- pool system	14	84	534	6.3964	24	35.07
Sengou Creek	Regular step-pool system	15	60	389	6.5029	23	33.18
Jiangjia Ravine	No step-pools	3	12	0.75	0.0081	6	8.55
Xiaobaini Ravine	No step-pools	0	0	0	0	0	0
Jinsha River	No step-pools	0	0	0	0	0	0

The physical conditions of stream habitat are mainly 1) the substrate; 2) water depth, and 3) flow velocity (Gorman and Karr, 1978). Different physical conditions support different bio-communities and diversified physical conditions may support diversified bio-communities. A habitat diversity index, H_D, is proposed as follows：

$$H_D = N_h N_v \sum_i \alpha_i \tag{3}$$

where N_h and N_v are numbers for water depth diversity and velocity diversity, and α is the substrate diversity, which is different for different substrates. Wang et al. (2006) introduced the method to determine the value of N_h, N_v and α. If a stream has three water areas: 1) shallow water, in which the water depth is in the range of 0~0.1m; 2) mid depth water, in which the water depth is in the range of 0.1~1m; and 3) deep water, in which water depth is larger than 1 m, and each of the three areas is larger than 10% of stream water, N_h=3. If a stream has only shallow water and mid depth water, and each of them is larger than 10% of stream water, N_h=2. The value of N_h for other cases can be analogously obtained. If a stream has three water areas: 1) lentic area, in which the flow velocity is smaller than 0.3 m/s; 2) mid velocity area, in which the flow velocity is in the range of 0.3~1m/s; and 3) lotic area, in which the velocity is larger than 1 m/s, and each of the three areas is larger than 10% of stream water, N_v=3. If a stream has only lentic and mid-velocity areas, and each of them is larger than 10% of stream water, N_v=2. The value of N_v for other cases can be analogously obtained.

If the streambed consists of cobbles and boulders, water flows over the bed and also through the interstices, which provides the benthic macro-invertebrates diversified living spaces. Therefore, cobbles and boulders are associated with high habitat diversity. Stream flow over aquatic grasses has high velocity but the aquatic grasses generate a low velocity canopy, moreover, the aquatic grasses themselves are also habitat for some species. Thus, streams with aquatic grasses exhibit high habitat diversity. Some species may move and live within the fluid mud layer and consume the organic materials in the mud layer. The interstices in gravel and fine gravel bed are small but sufficient for some species. A sand bed is compact and the interstices between sand particles are too small for benthic macro-invertebrates to move and live within them. Moreover, sand particles are liable to be removed and the sand bed is not stable. Therefore, a sand bed is worst habitat for benthic macro-invertebrates. Based on the previous discussion and field investigations of 16 streams, the α-values for various substrates are listed in Table 3.

If a part of the streambed consists of one substrate and another part consists of the another substrate and both parts have areas larger than one tenth of the stream surface, the two α-values for the two kinds of substrates should be summed. If sand or silt fills the interstices of gravel the α-value should be taken as for the substrate of sand or silt. Only if different substrates cover different parts of the streambed, the α-values for different substrates should be summed. If a streambed has three parts with different substrates: boulders and cobbles, aquatic grasses, and fluid clay mud, and each of the three parts is larger than one tenth of the total stream area, the sum of the α -values for the stream is $\sum \alpha_i = 6 + 5 + 4 = 15$. If the streambed is covered by sand or all interstices of gravel are filled with sand, the α-value is zero, or $\sum_i \alpha_i = 0$.

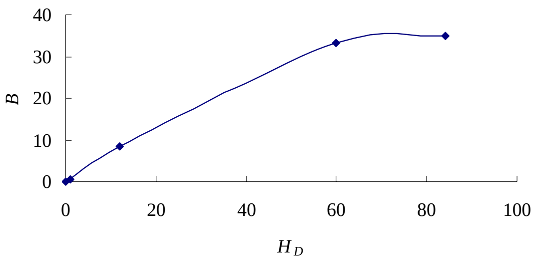
Table 3 Substrate diversity, α, values for different substrates

Substrate	Boulders and cobbles (D>200 mm)	Aquatic grass	Clay mud (D<0.02mm)	Cause gravel (20-200 mm)	Fine gravel (2~20mm)	Silt (0.02 -0.2 mm)	Sand (0.2 -2 mm)
α	6	5	4	3	2	1	0

Gorman and Karr (1978) also developed a Habitat Diversity Index combining the effects of substrate, velocity, and depth. They showed that fish species diversity and richness were strongly related to a combination of the effects of substrate, velocity, and depth. Their substrate classification is similar to that proposed here with the main differences being in the divisions of sediment sizes into the various classes, but a similar ordinal ranking is applied to the substrate material. They also developed class ranges for velocity and depth throughout a reach determined by a weighting of point measurements. The index applied here takes a simpler approach to considering the diversity of velocity and depth.

Of course, the biodiversity of streams depends not only on the physical conditions but also is affected by water quality. General speaking, water pollution reduces the biodiversity but may not reduce the number density of pollution-tolerant species. Water temperature also is an important factor for stream ecology. However, the temperature does not vary much in a reach of a stream unless a thermal discharge is present and it is not necessary to consider it in analysis of local habitat diversity. Only when habitat across different zones with great temperature differences is studied, temperature difference has to be considered in the analysis of habitat diversity.

Table 2 lists the habitat diversity of the five streams, which is calculated with Eq. (3). The streams with step-pool systems have much larger habitat diversity, because the steps and pools create high and low velocities, shallow and mid depth waters, and different substrates at different places. The habitat diversity index is zero for the Xiaobaini Ravine and the Jinsha River, because the streambeds are covered with the mixture of gravel and sand, in which all the interstices between gravel are filled with sand. Fig. 4 shows the relation between the habitat diversity and bio-community index, *B*, and the relation between the habitat diversity and the taxa richness (number of benthic invertebrate species). The higher is the habitat diversity, the higher is the bio-community index, *B*. The bio-community index, *B*, increases with habitat diversity, H_D, almost linearly until high values of H_D. The relationship between taxa richness and habitat diversity is similar to that of bio-community index and .habitat diversity. The step-pool system creates high habitat diversity, and, therefore, has the best stream ecology.



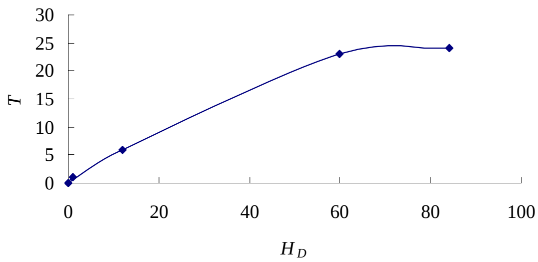


Fig. 4. Habitat diversity H and the bio-community index, *B*, as functions of the habitat diversity index, HD, for the five study sites in China

The results demonstrate that streams with step-pool systems are ecologically-sound and provide good habitat for various animals. Engineers have used artificial step-pool systems for stream ecology restoration (FISRWG, 1998). Nevertheless, natural and artificial step-pool systems experience a hydraulic and morphological process before they become mature and stable. The development and stability of a regular step-pool system is studied experimentally in the following section.

4. STABILITY OF STREAMS WITH A STEP-POOL SYSTEM

A step-pool system stabilizes the streambed because the steps increase the flow resistance, consume the flow energy and protect the streambed from erosion. The results of flume experiments have extended this role in suggesting that step-pool systems not only increase flow resistance but also maximize it (Whittaker and Jaeggi, 1982; Abrahams *et al*., 1995). Their innovative experiments and field observations led Abrahams et al. (1995) to conclude that step-pool structures evolve toward a state of maximum resistance because that implies maximum stability. Thus, an explanation of why step-pool systems develop and why they have a particular morphology can be couched in terms of their effect on energy dissipation. In the experiments the resistance and the bed roughness increased in the process of bed erosion. Finally, the step-pool system developed, which maximized the resistance. Then the bed became stable. In the mountain streams in the Cascades of Washington state, the resistance caused by the step-pool systems composes more than 90%, and the grain resistance and channel form drag make up less than 10% of the total (Curran and Wohl, 2003). Because the resistance caused by step-pool systems makes up the main resistance of the flow the Manning's roughness coefficient, *n*, is a function of the development degree of the step-pool system. Fig. 5 shows the results of the experiments. The resistance increases linearly with the development degree of the step-pool system.

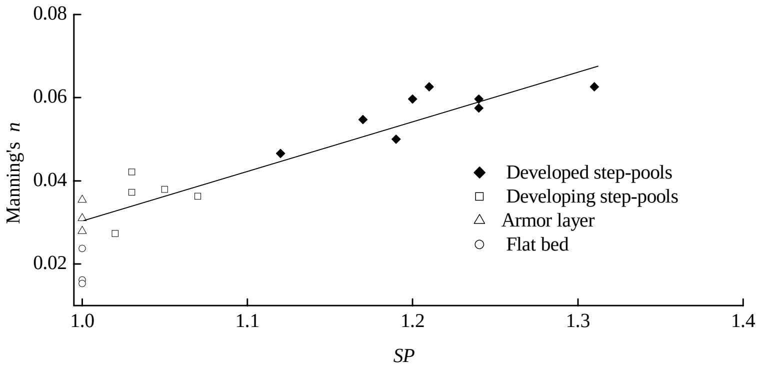


Fig. 5. Manning's roughness coefficient, n, as a function of the development degree of the step-pool system, SP

In Shengou Creek and Jiuzhai Creek, the slope and water depth are large but the flow cannot scour sediment from the bed because the step-pool system protects the bed sediment from erosion. In other words, the scour rate is zero for almost all flow conditions. Only if an extreame flood event occurs, the keystones in the steps may be removed and the sediment may be scoured from the bed. For most cases the scour rate is zero, therefore, the riverbed inertia is infinite. Shengou Creek had the same bed material and even has larger slope (s = 0.105) and larger water depth than the Jiangjia Ravine. The development of a step-pool system has increased the riverbed inertia to infinity, and, thus, maximizes the channel bed stability.

5. ECOLOGICAL RESTORATION WITH ARTIFICIAL STEP-POOL SYSTEM

A field experiment using an artificial step-pool system for ecological restoration was carried out on the Diaoga River, a debris-flow ravine on the Yunnan-Guizhou Plateau of Southwest China.

The Diaoga River, in which the field experiment was carried out, is a small stream with a length of 11.6km and a drainage area of 54.3 km^2. Fig. 6 shows the sketch of the Diaoga River watershed, which is located upstream of Xiaojiang River (an upstream tributary of the Yangtze River). The Diaoga River originates from Huangcaoling Mountain (latitude 25°56.078', longitude 103°19.741', elevation 2708m), Yunnan-Guizhou Plateau in Southwest China, and confluences to Xiaojiang River at latitude 25°54.075', longitude 103°15.057' (elevation 1490m), the average gradient of the river channel is about 9.6%.

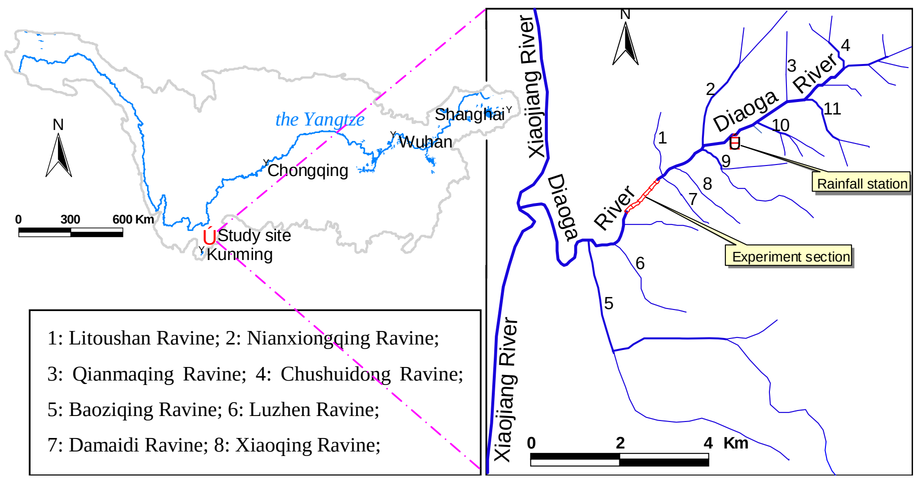


Fig. 6. The sketch of the Yangtze River basin and the Diaoga River watershed

The Diaoga River is a seriously incised stream. The relative elevation difference in the small mountain watershed is over 1500 m due to long-term channel incision. The environmental impacts of channel incision are extensive and range from damages to human structures to impacts on aquatic and riparian ecosystems. The incision causes serious bank erosion and landslide, debris flow and hyper-concentrated flow. There are several large sliding masses along the river; many houses built on these masses have shocking cracks on the walls and floors. The strong incision also makes the bridges across the river on the edge of collapse. Moreover, the stream ecology of the river is impaired because the habitat is often destroyed by incision-induced hazards. Therefore, the incision of channel must be controlled to reduce or avoid these above-mentioned hazards and restore the aquatic eco-system.

Some researchers have tried to apply artificial step-pool system in bed stabilization in steep mountain stream (Lenzi, 2002; Todd and Mike, 2003). In Germany, South Korea and Taiwan, people constructed artificial step-pools for streambed stabilization, stream ecology restoration or human recreation.

No step-pool system develops under natural condition in the Diaoga River. The stream habitat is rather monotonous. An field experiment was performed by constructing artificial step-pool system which mimics the natural step-pool morphology features. The field experiment aims to solve following three problems: (1) to increase the resistance and thus control the channel incision; (2) to create the stream habitat, thus restore the stream ecology; (3) to create beautiful landscape. The following part introduces mainly the results of stream ecology restoration.

5.1 Field experiment with artificial step-pool system

Fifteen artificial steps were constructed on a stretch of about 120m in the middle-reach of the Diaoga River. The artificial steps were designed to mimic the natural step-pools developing in a neighboring stream, Shengou Ravine, which is about 30 km away from the Diaoga River. The Shengou Ravine also is a tributary of the Xiaojiang River, before 1976 debris flows frequently occurred here and there was no step-pool system developed. Slope and gully erosion provided enough sediment to the stream and heavy sediment transportation and poor vegetation cover dominated the river basin. After extensive erosion control and reforestation projects were implemented in the drainage area of the creek in the past 25 years, step-pool system has developed in the Ravine.

Before the flood season in June, 2006, a stretch reach of about 150 m was chosen on the middle Diaoga River for field experiment (Fig. 6), and 15 artificial steps were constructed. The construction of artificial steps mimics the natural steps which developed in mountain streams. The height of and distance between the steps was roughly determined according to the empirical equation (7), and the height of artificial steps in general is about 1m, the space between them is about 5–12m.

$$\overline{H/L} = 1.5S \quad \text{(Abrahams, 1995)} \tag{7}$$

where H is the step height (m), L is the distance between the steps (m) and S is gradient of streambed.

The steps was composed of large stones (0.2–1m) overlapping with each other (Fig. 7). The large boulders act as a framework tightly interlocking the structure with considerable stability. Several flood events occurred during the flood season of 2006, almost all these steps survived, only two most downstream steps are partly destroyed.

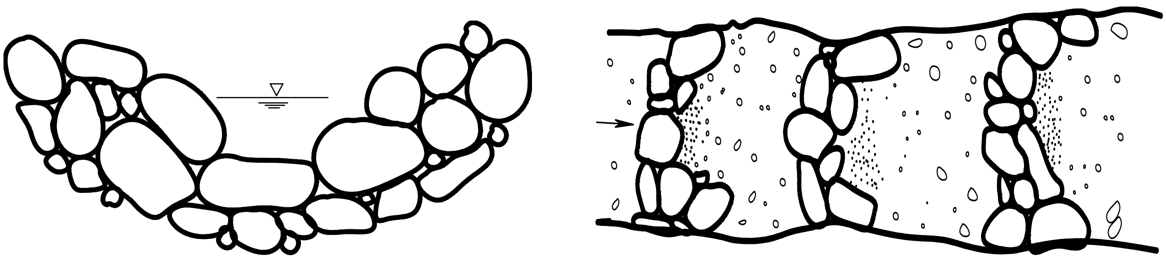


Fig. 7. Large stones overlapping with each other to form a tight interlocking structure

Heavily bed load transportation and debris flow may causes sedimentation in the pool section, to preserve the pools for habitat restoration, the pools are designed to separate into too parts: the right part serves as a path of bed load transportation, which is shallow and with high velocity, and the left part is deep and with low velocity. There is a gravel bar separate the two parts and control bed load particles to move into the left part.

Artificial step-pool system effectively increases the water surface area, compared to the channel without step-pool system, as shown in Fig. 8. After the artificial step-pools finished, water surface area increased from 310 m^2 to 450 m^2 (almost 50% up), which made the aquatic habitat area have a big rise. Under different discharge conditions, the water surface area of the reach with the artificial step-pool system is larger than that without artificial step-pool system, especially in low discharge conditions (0.2–0.5 $m^3 \cdot s^{-1}$).

The artificial step-pool system increases the flow resistance and controls channel incision effectively. Fig. 9 shows that, the previous channel cross-section between artificial step seven and step eight was incised for about 0.7m in just three year (from June in 2003 to June in

2006), which threatened the base of a highway. With the artificial step-pool system constructed on the channel, the incision was effectively controlled; some sediment even silted up on the channel, so the elevation of the cross-section rose.

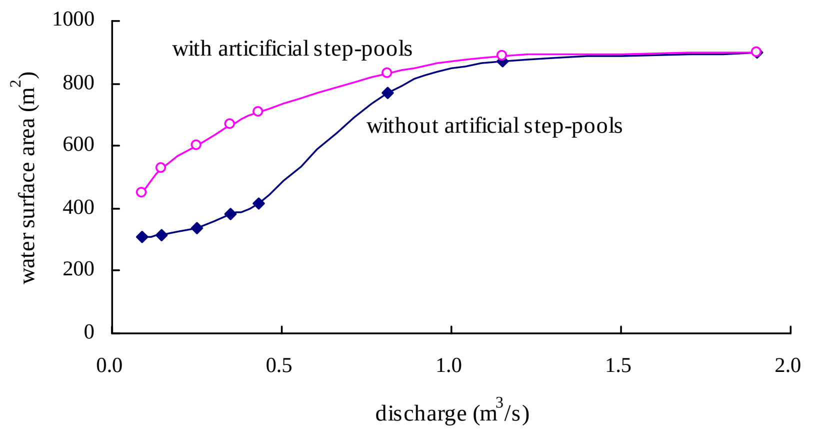


Fig. 8. Water surface area as a function of discharge before and after the artificial step-pools

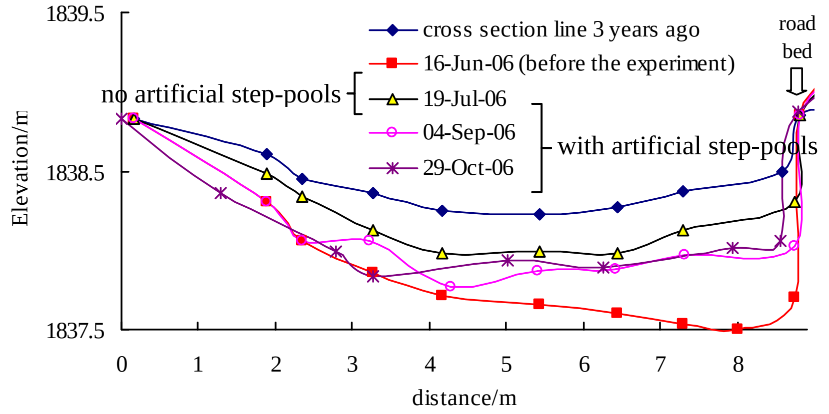


Fig. 9. The elevation variation of a cross section between step seven and step eight

5.2 Ecological restoration

The artificial step-pools increases the water depth, the maximum water depth increases from 0.3 m to 0.8–1.1 m, and the average water depth increased from 0.08 m to 0.4 m. Thus water depth diversity has a big improvement.

The artificial step-pool system also expands the range of flow velocity. The flow velocity of the experimental stream reach is somehow uniform before the construction of artificial step-pools. After the completion of the artificial step-pools, flow in different zone has a relatively big difference. Upstream the steps is sluggish water zone, the surface flow velocity is low (0–0.1 $m \cdot s^{-1}$), while near the crest of the steps, the flow velocity is 0.5–1.0 $m \cdot s^{-1}$ or even higher, and in the pools is violent fluctuating flow, the water body mixes much air bubble, thus increased the concentration of dissolved oxygen. Around the pools are large boulders and cobbles which are very hard to be moved by flow, the spiral flow scour the base of these large stones to form cavity, which is relatively dead water zone since almost no flow velocity here except very weak flow fluctuation. Thus artificial step-pool system makes the diversity of flow velocity increased markedly, benthic animals like different flow conditions, such as sluggish water, flowing water, spiral current or torrent all can find velocity zone suitable for them to grow and inhabit.

Table 4. variation of habitat diversity and benthic invertebrates sampling results in the Diaoga River experimental reach

	Sampling date	Dominant substrate	Water depth (m)	Flow velocity (m/s)	H_D	Number density (ind/m^2)
Natural channel	6-13	boulders and cobbles, coarse and fine gravel	0.15-0.30	0.4-1.0	11	61.5
with Artificial step-pools	6-28	boulders and cobbles, coarse and fine gravel	0.10-0.80	0-0.50	22	987.0
	7-4	sand, coarse gravel	0.10-0.35	0.2-0.55	6	31.5
	7-24	sand, fine gravel	0.10-0.35	0.3-0.90	2	2.3
	8-6	sand, coarse gravel	0.10-0.35	0-0.55	3	19.3
	8-25	sand, fine gravel	0.20-0.40	0-0.50	4	59.3
	9-11	boulders and cobbles, coarse gravel, coarse and fine sand	0.10-0.50	0-0.50	12	612.8
	10-31	boulders and cobbles, coarse gravel, sand, silt	0.10-0.30	0-0.50	18	534.7
	11-12	boulders, coarse and fine gravel, silt, clay, and organic debris	0.10-0.40	0-0.20	30	1087.5

With the change of water depth and flow velocity, the streambed substrate also diversified, except previous boulders, cobbles and gravels, other substrates such as silt, mud layer and even organic debris appeared on the streambed, which creates a favourable environment for aquatic organisms. After the artificial step-pool system, the aquatic habitat tends to be diversified, and habitat diversity index, H_D, which is calculated with equation (3) rises obviously (Table 4), for the natural channel (for instance, June 13th), H_D =11, and H_D increased to 22 (June 28th) after the artificial step-pool system.

5.3 Ecological evaluation

The improvement of habitat creates a favourable aquatic environment, thus promotes the development and growth of benthic macro-invertebrates, which is used as indicator to evaluate the stream ecology of the River. The results of benthic invertebrates sampling and evaluation show that, diversified habitat helps to develop diversified species and increase the number density of benthic invertebrates and bio-community diversity index, B. As shown in Table 5, the taxa richness (number of benthic invertebrates species) and number density of individual invertebrates are markedly improved after the artificial step-pool system.

Table 5. Variation of taxa richness and diversity before and after artificial step-pool system

	Sampling date	Taxa richness	Number density (ind/m^2)	Dominant species (number density of the individual invertebrate per m^2)
Natural channel	13-Jun	17	61.5	Hydropsychidae (17); Baetidae (9); Haliplidae, Haliplus sp (7)
With artificial step-pools	28-Jun	39	881.5	Baetidae (492); Simuliidae (150); Tipulidae, Antocha (65)
	11-Sep	28	612.8	Baetidae, Baetis (330); Baetidae, Baetiella sp (70); Chironomidae sp 1 (57); Chironomidae sp 2 (48)
	12-Nov	35	1087.5	Baetidae, Baetis (445); Baetidae, Baetiella sp (257); Heptageniidae, Iron sp. (139); Hydropsychidae, Ceratopsyche sp. (66);

The number density of individual invertebrates and taxa richness increases with the rising of the habitat diversity index, H_D (Fig. 10).

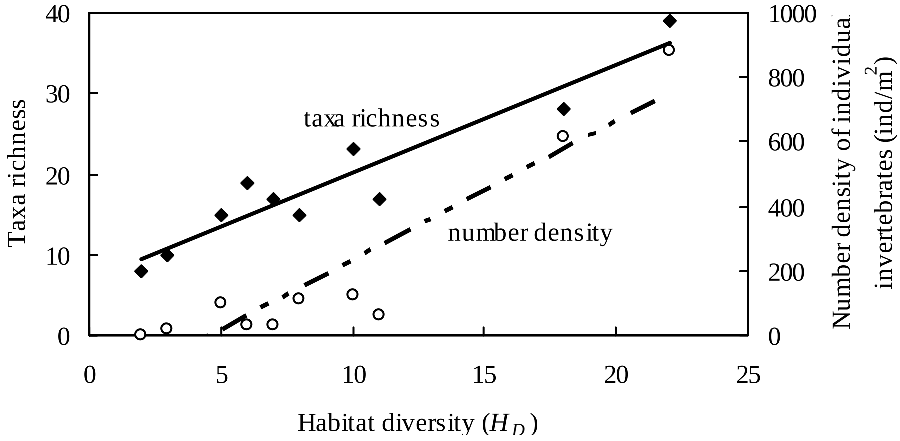


Fig. 10. Relations between the habitat diversity and taxa richness & number density of individual invertebrates

Fig. 11 shows that the bio-community diversity index B also increase with the rising of the habitat diversity index, H_D, which means the bio-diversity of the Diaoga River is improved after the artificial step-pool system.

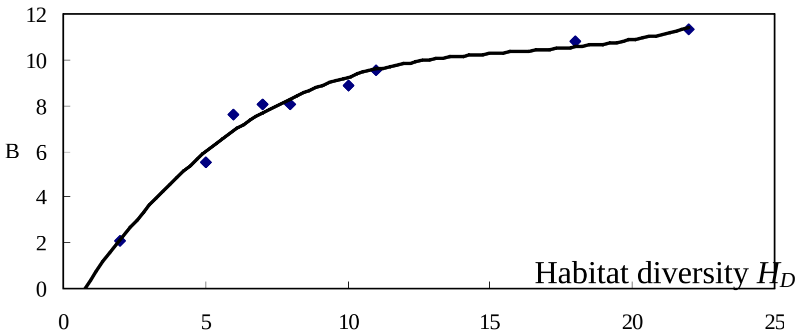


Fig. 11. Relation between the habitat diversity, HD, and bio-community diversity, B

Before the artificial step-pool system, the main species of benthic invertebrates sampled in Diaoga River were Hydropsychidae, Baetidae, Haliplidae, and so on; after the artificial step-pool system, many species which were never found in the stream before have being attracted to colonize the habitat (Fig. 12 and 13).

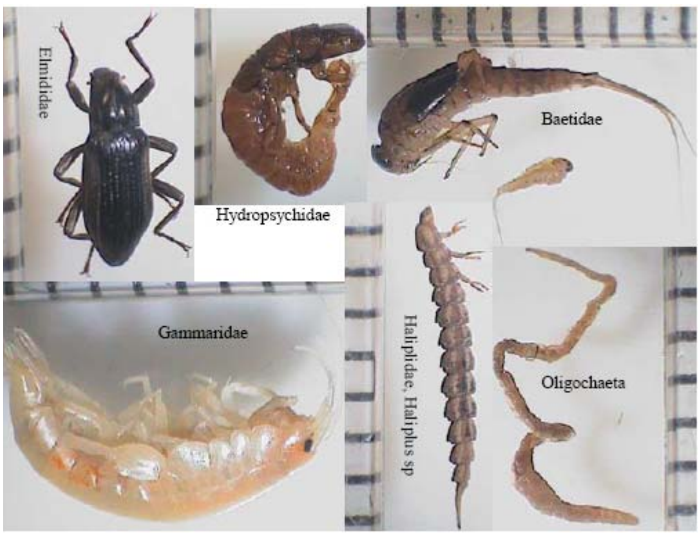


Fig. 12. Main species before the artificial step-pools system

Two debris flows occurred in the upstream branch ravines of the Diaoga River watershed, which carried great amount of sediment downstream, but the debris flows weakened to hyper-concentrated flows when passing through the experiment section due to great hydraulic resistance of artificial step-pool system, so the hazard was dramatically mitigated. The streambed incision of the experiment section is controlled, sediment even silted up in upstream of steps and pools, which made the habitats partly lost and the habitat diversity reduced, but after the flood season getting over, the habitat and aquatic bio-diversity is recovered again, as shown in Table 4 and 5.

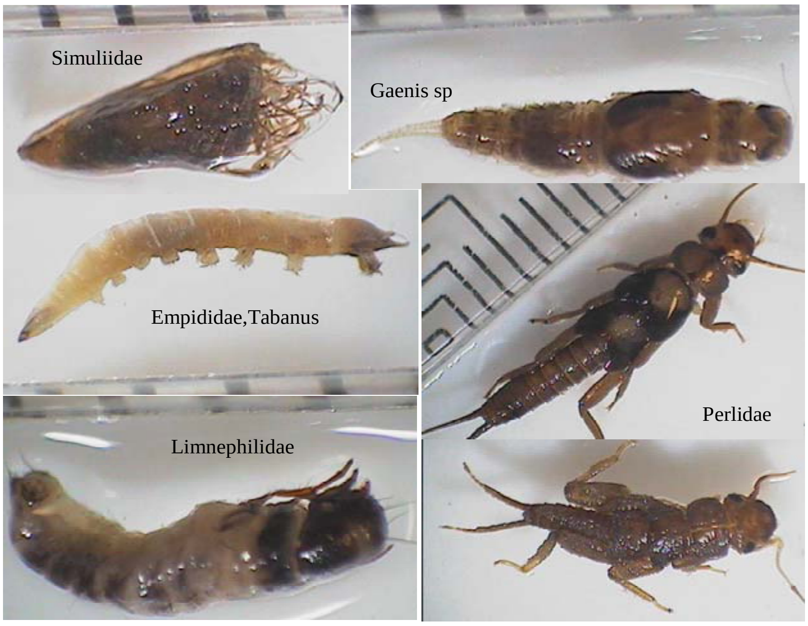


Fig. 13. Newly appeared species after the artificial step-pool system

Fifteen artificial steps, which were designed to mimic the natural step-pools developing in a neighboring ravine, were constructed on a stretch of about 120m in the middle-reach of the Diaoga River. Stones were laid out one overlapping another to ensure the stability of the step structure. The artificial step-pool system increases the flow resistance, controls channel incision effectively, debris flows reduces to hyper-concentrated flows when passing through the experiment section, and the hazards were mitigated greatly. The artificial step-pool system increases the water surface area, expands the range of water depth and flow velocity, thus shapes diversified habitat. The improvement of habitat creates a favourable aquatic environment, thus promotes the development and growth of benthic invertebrates. The number density of individual invertebrates, taxa richness (number of benthic invertebrates species) and bio-community diversity all rise with the increase of habitat, thus the aquatic ecology in the experimental reach is improved markedly. The artificial step-pool system can be used an effective strategy in aquatic ecology restoration of debris-flow stream.

6. CONCLUSIONS

Step-pool systems develop in the process of streambed incision with bed material consisting of boulders, cobbles, gravel, and sand. Boulders and cobbles form the steps having an inherent stability, which only extreme floods are likely to disturb. Sand, silt, and clay deposit in the pools behind the steps. These steps and pools provide high diversity of habitats for the stream bio-community. For the 5 streams studied in China, the density of benthic macro-invertebrates in streams with step-pool systems is 800 times higher than neighboring streams without step-pool systems. The paper proposes a Habitat Diversity Index, H_D, calculated considering the spatial distribution of various substrates, velocity, and water depth. Experimental studies show that step-pool systems maximize the flow resistance and protect the bed sediment from erosion. Thus the riverbed and bank slope are stabilized. The development degree of step-pools, *SP*, is proportional to the streambed slope. The experiments also show that the Manning's roughness coefficient, *n*, is proportional to the development degree of the step-pool system. A step-pool system does not only stabilize the streambed but also provides ecologically sound habitats for the aquatic bio-community. Fifteen artificial steps, which were designed to mimic the natural step-pools developing in a neighboring ravine, were constructed on a stretch of about 150m in the middle-reach of the Diaoga River. Stones were laid out one overlapping another to ensure the stability of the step structure. The artificial step-pool system increases the flow resistance, controls channel incision effectively, debris flows reduces to hyper-concentrated flows when passing through the experiment section, and the hazards were mitigated greatly. A relatively stable stream habitat is gradually formed in the experimental reach, different substrate, flow velocity and water depth environment alternating upstream steps and in pools creates spatially diversified stream habitats, and enhances the development of the aquatic creatures. The improvement of habitat creates a favorable aquatic environment, thus promotes the development and growth of benthic invertebrates. The number density of individual invertebrates, taxa richness (number of benthic invertebrates species) and bio-community diversity all rise with the increase of habitat, thus the aquatic ecology in the experimental reach is improved markedly. The artificial step-pool system can be used an effective way in aquatic ecology restoration of debris-flow stream.

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