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The effect of riverbed structure on bed load transport in mountain streams

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ABSTRACT: Bed load transport in mountain streams varies with the flow intensity, stream power, and the riverbed structure. The measured bed load transport rate varies in a range of 3-4 orders of magnitude in a mountain stream at the same place and the same flow discharge, with the presence or absence of a step-pool system. The relationship between bed load transport, stream power (product of discharge per width and the bed slope) and riverbed structure was studied in this paper experimentally in mountain streams. A parameter, S_p, is introduced, which is used to describe the development degree of a riverbed structure. A specially designed instrument was used to measure the development degree of a riverbed structure. A double-box bed load sampler was used to measure the rate of bed load transport in mountain streams. Field experiments on the bed load transport, riverbed structure and hydraulic features were conducted in 14 tributaries of the Xiaojiang River in the upper Yangtze River Basin in China. It was found that the rate of bed load transport was affected by both the stream power and the riverbed structure. In rivers or reaches with a similar unit stream power, a high riverbed structure was always accompanied with a low rate of bed load transport.

Keywords: Mountain streams, Riverbed structure, Bed load transport, Stream power, Step-pool system

1 INTRODUCTION

The study of bed load transport is an important part of sediment research. In the past half century, scientists and engineers have used semi-theoretical and semi-empirical methods to calculate bed load transport accurately in sand-bed rivers. However, the estimation of bed load transport in gravel-bed rivers is still extremely difficult and the results are imprecise (Gomez & Church, 1989; Wohl & Thompson, 2000; Apsley & Stansby, 2008; Papanicolaou et al., 2009). There are five main reasons for the difficulty to predict bed load transport in gravel-bed rivers: (1) Flow condition varies violently in the mountain streams; (2) The bed material size varies widely which is quite different from sand-rivers; (Simons & Simons, 1987; Cao et al., 2000; Singh et al. 2009); (3) Interaction of the particles, particle shape and orientation affect the sediment transport (Carling et al. 1992; Chin & Chiew, 1993); (4) The riverbed structure or bed roughness affect the flow condition and bed load transport (Davies & Sutherland, 1980; De Jong, 1992; Church et al., 1998; Oldmeadow & Church, 2006; Yu, et al., 2009a); (5) Field data is difficult to obtain in nature, and the bed load trap used at alluvial rivers is inaccurate when used at mountain rivers (Ryan & Troendle, 1996; Bunte et al., 2004; Luo, et al., 2008). Hence, estimation of the rate of bed load transport in mountain rivers is one of the most challenging aspects in sediment research.

Parker (2008) summarized the common bed load transport formulae which uses the concepts of hiding function, substrate relation, active layer, topographic variability, patchiness transport, partial transport, mobile armoring to elucidate the nature of bed load transport. More and more formulae have been used and these formulae have become more and more complex. But when estimating the rate of bed load transport in a given mountain stream, the bed load transport formula still needs to be regulated or some empirical methods need to be used. Consequently, the existing formulae to calculate the rate of bed load transport cannot be used in all mountain rivers. A method to accurately evaluate the rate of bed load transport based on a clarified theory still need to be explored.

Based on field experiments in the Diaoga River, a second-order tributary of the Yangtze River in China, Yu et al. (2009b) proposed the rate of bed load transport is most affected by the incoming sediment, flow conditions and the riverbed structure. In nature, bed load transport and riverbed structure are a couple of competing and mutually interacting aspects of flow energy dissipation (Wang et al. 2004; Liu & Wang, 2009). Nevertheless, how to determine the intensity of riverbed structure is a new challenge.

Riverbed structure is a structure of cobbles, boulders and gravel on the stream bed self-organized during fluvial process to reach the highest bed stability. Since step-pool systems are the most stable structures in gravel-bed rivers (Chin, 1989; Whittaker, 1987; Abrahams et al., 1995; Rosport, 1997; Wohl & Thompson, 2000), a parameter, S_p, was introduced to describe the development degree of a step-pool system (Wang et al., 2004). Furthermore, riverbed structure intensity (S_p) was suggested to estimate the bed roughness of a step-pool system (Wang et al., 2009). Figure 1 shows the definition of the parameter S_p, which is the ratio of the length of the curve ABCDEFG to the length of the straight line AG minus one, i.e.

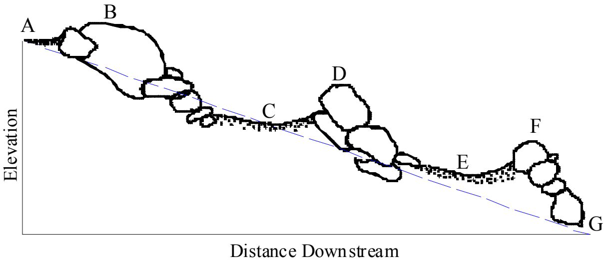


Figure 1. Definition of riverbed structure intensity (S_p)

$$S_p = \frac{\overline{ABC}+\overline{CDE}+\overline{EFG}}{\overline{AG}} - 1 \qquad (1)$$

The riverbed structure describes the resistance of bed surface, and also greatly influences bed load transport (Lamarre & Roy (2008). Based on field experiments, Yu (2008) found that even at the same reach of a river and in similar stream powers, the bed load transport rate (g_b) can still vary by several orders of magnitude with the presence or absence of riverbed structures. This research shows some new methods of estimating bed load transport in a mountain river. Thus, further field experiments were taken in the study to estimate the effect of riverbed structure intensity on the rate of bed load transport. Moreover, the relationship among the rate of bed load transport per width, riverbed structure intensity and the stream power per width is discussed.

1 STUDY AREA AND METHODS

1.1 *Study area*

Field experiments were conducted in the Diaoga River during the flood season of 2008, and six cross sections were used to measure the rate of bed load transport and flow intensity. Table 1 lists the locations of the field experiments sites.

Field experiments were further conducted in 14 mountain streams in the Xiaojiang River basin during the flood season of 2009. The field locations were shown in Fig. 2. The rate of bed load transport, stream power and the riverbed structure were measured at different times with different flow conditions.

Table 1. Measured site in Diaoga River

Section	Distance from the river mouth(km)	Altitude (m asl)	Average slope
Source	12.04	2608	0.115
C1	9.21	2284	0.139
C2	6.41	1895	0.059
C0	5.41	1836	0.052
C3	4.09	1768	0.081
C5	1.76	1580	0.052
C6	0.03	1490	0.033
Mouth	0.00	1489	

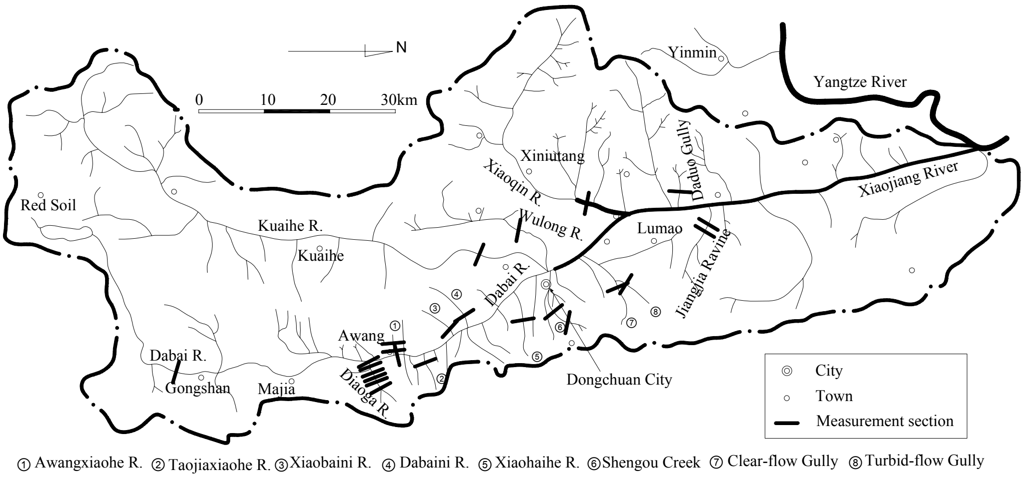


Figure 2. The main measuring spots in Xiaojiang River basin

1.2 *Field measurements of bed load transport*

The rate of bed load transport varies dramatically in mountain rivers, and accurately measuring the rate of bed load transport is difficult (Bunte et al., 2004). Samplers installed into the riverbed of a channel may be the most accurate method to measure the rate of bed load transport. However, samplers are not used widely because of their high cost and awkward operation. Pit or trough samplers usually are used in some small streams where they can be easily installed (Kuhnle, 2008). In order to obtain more reliable data from field experiments, a double-box bed load transport sampler was used to measure the rate of bed load transport (Fig. 3). The outer box was installed into the stream bed with its top edges even with the local bed surface. The size of the inner box was 0.5m×0.25m×0.05m. A steel-wire mesh with a diameter of 0.4 mm was used at the bottom of the box to drain the water rapidly when the box was lifted out of the river. Wet weight of collected bed load sediment was measured and the rate of bed load transport was calculated. The bed load samples were mainly taken in flood season of 2008 and 2009, and samples at different sections had been taken one after the other. All the samples were taken during from two hours to four hours varying with different rate of bed load transport, the larger the rate of bed load sediment transport was, the less duration of sampling time was. Each sample had been taken two or three times till the rate of bed load transport being relatively balanced.

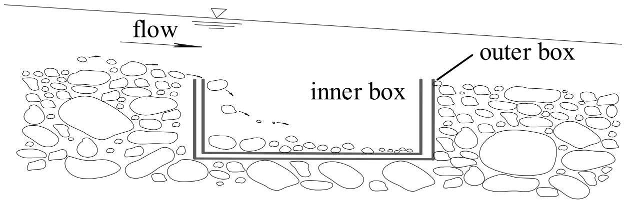


Figure 3. Double-box bed load sampler

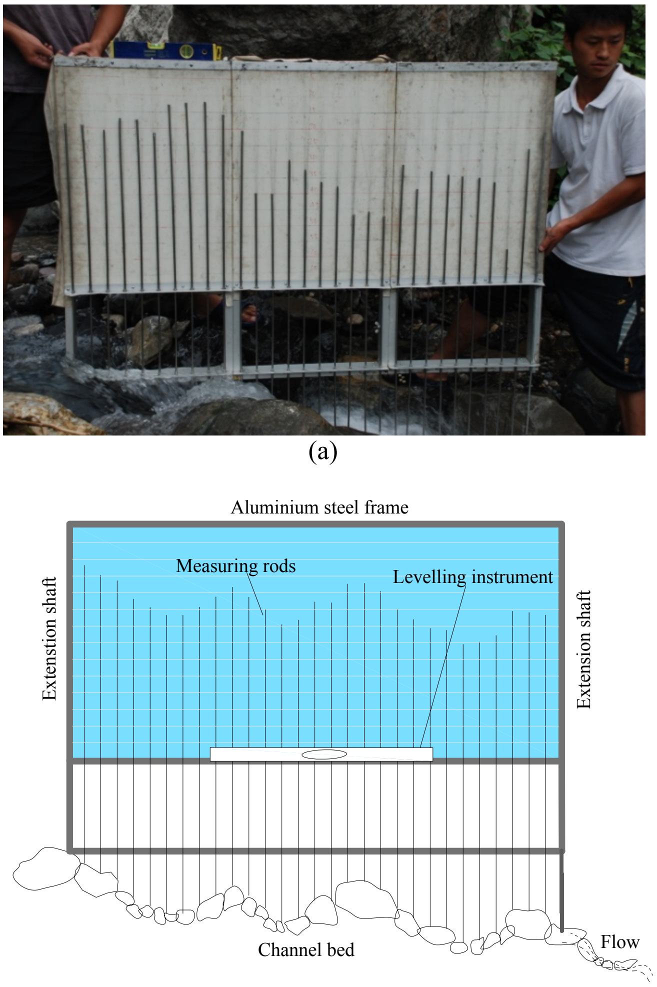
1.3 *Field measurement of riverbed structure intensity*

Riverbed structure intensity was obtained by a dimensionless parameter, S_p, which was measured by a special instrument as shown in Fig. 4. The instrument, aimed at measuring the index of S_p, was similar to the mini-Tausendfussler (De Jong, 1992) but with more flexibility and portability. The instrument was made of thirty steel measuring rods spaced 5 cm apart placed horizontally on an aluminum steel frame. These rods were able to slide down onto the bed surface. The upper ends of the rods described the bed profile in front of a screen. The frame was moved along the thalweg of the stream 10 times and each time a picture was taken. The S_p value was then calculated by using the following formula (Wang et al., 2009):

$$S_P = \frac{\sum_{i=1}^{m}\sqrt{(R_{i+1}-R_i)^2+5^2}}{\sqrt{[5(m-1)]^2+(R_m-R_1)^2}} - 1 \tag{2}$$

in which R_i is the reading of the upper end of the measuring rods on the screen (in cm), and m is the total number of readings (=300). In field investigations, the S_p value for all the mountain streams was measured by this instrument.

The value of S_p is always greater than 0. The greater the value is, the stronger the riverbed structure intensity is, reflecting that more step-pool systems have developed. If the bed surface is smooth it means that there is no riverbed structure, and the S_p value will be 0. However, this condition does not exist in nature.



(a)

(b)

Figure 4. (a) Instrument for measuring the riverbed structure intensity, S_p; (b)Measurement of the S_p value on the Shengou Creek

1.4 *Stream power per unit width*

The definition of stream power is described as:

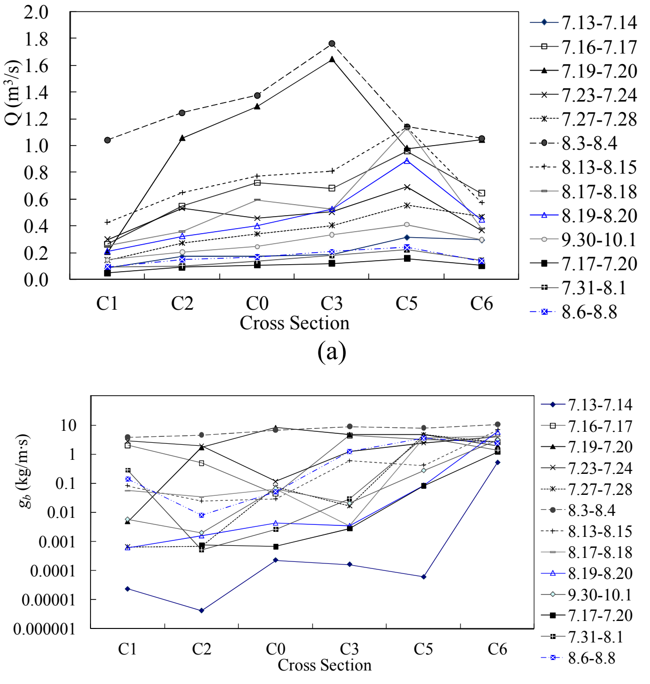
$$p=\gamma qJ \tag{3}$$

in which p is stream power per unit width (kg/m·s); γ is specific weight of water (kg/m^3); q is discharge per unit width (m^2/s); J is local water surface slope (m/m).

2 DATA ANALYSIS

2.1 *The rate of bed load transport in Diaoga River*

Figure 5 shows the variation of discharge and rate of bed load transport in the measured sections of the Diaoga River. Similar to Yu et al. (2009(b)), the measured rate of bed load transport varied 3-6 orders of magnitude in the Diaoga River in 2008 (Fig. 5(b)). The rate of bed load transport in Aug. 13-Aug. 15 was 1 000 000 times greater compared with the values in July 13- July 14 at the same section of C2, however, the discharge during the two different time varied by less than one order of magnitude (Fig. 5(a)). The results show that the rate of bed load transport changes drastically with small changes in discharge. Hence, researchers proposed a simple power function of discharge to describe the bed load transport (Whitting et al., 1999; Barry et al., 2004). Certainly, the relationship of discharge and rate of bed load transport changes in different sections. Figure 5(b) shows the rate of bed load transport quickly increased when flow discharge was increasing. This result was similar to Barry et al. (2004).



(a)

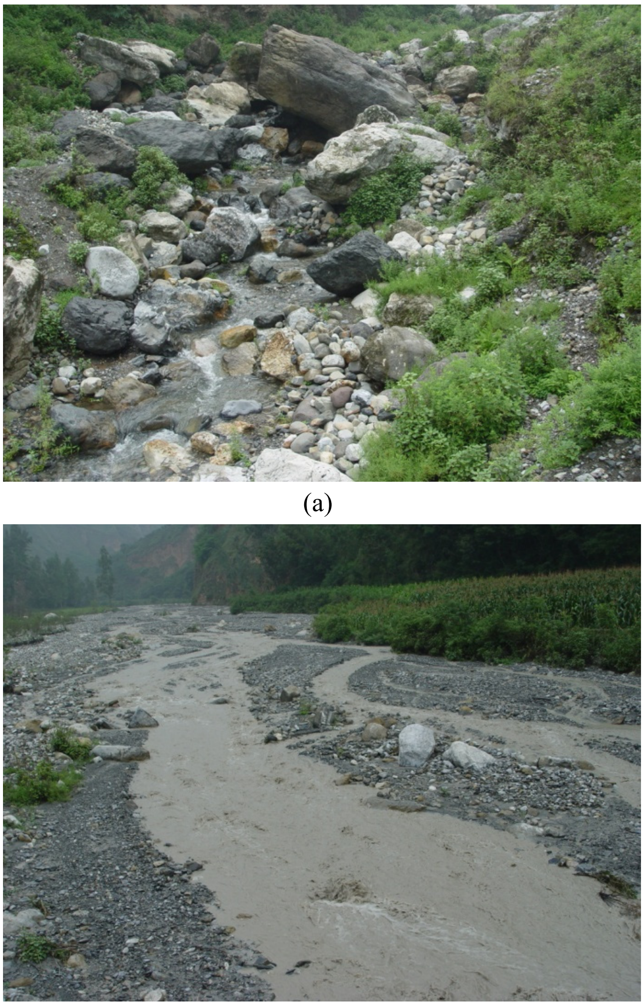
(b)

Figure 5. (a) Flow discharge variation in measured sections in the Diaoga River; (b) Rate of bed load transport per unit width variation in different sections in Diaoga Rive

On the other hand, the rate of bed load transport varies intensively at the same time in different reaches of the Diaoga River (Fig. 5(b),). The rate of bed load transport increased from upstream to downstream (Fig. 5(a)). To some extent, the increased bed load transport was affected by the increased flow discharge. However, the rate of bed load transport per unit width fluctuated 1-4 orders of magnitude in similar flow discharges. For example, flow discharges measured during July 13-July 14 in all sections were low (0.1 m^3/s-0.3 m^3/s) and fluctuated 2-4 times (Fig. 5(a)). Conversely, the rate of bed load transport per unit width changed 120 000 times (C6/C2). However, when the flow discharge was high (1.0m^3/s-1.8m^3/s) in Aug.13-Aug.15, the rate of bed load transport per unit width varied by only 2.7 times at most (C6/C1). Hence, the flow discharge is not a single reason to determine the rate of bed load transport, and there are some other reasons causing the fluctuation of the rate of bed load transport.

2.2 *Effect of riverbed structure on bed load transport*

Although the flow discharge fluctuated slightly in different sites or different times, the bed surface was quite different. Riverbed structure intensity, S_p, varied from 0.02 to 0.06 in C6, and at the same time S_p varied from 0.09 to 0.15 in C2. Thus the bed surface in C6 was much smoother than the surface of C2, consequently the rate of bed load transport per unit width was always intensive in C6 with low or great flow discharge. However, the riverbed structure varied by orders of magnitude in C2, and the rate of bed load transport per unit width also fluctuated dramatically.



(a)

(b)

Figure 6. (a) Step-pool system develops in clear-flow gully, a tributary of Daqiaohe River; (b) Heavy bed load transport with little riverbed structure in turbid-flow gully, another tributary of Daqiaohe River, 500 m from the clear-flow gully

In mountain rivers, the rate of bed load transport will be quite different even in adjacent tributaries. For example, the rates of bed load transport per unit width in clear-flow gully and turbid-flow gully, 2nd-order tributary of Xiaojiang River, are completely different as shown in Fig. 6. The rate of bed load transport per unit width was up to 9 kg/m·s in turbid-flow gully, and 0 in clear-flow gully. Whereas, the distance between the two field experiment sites in turbid-flow gully and clear-flow gully was less than 500 m and the

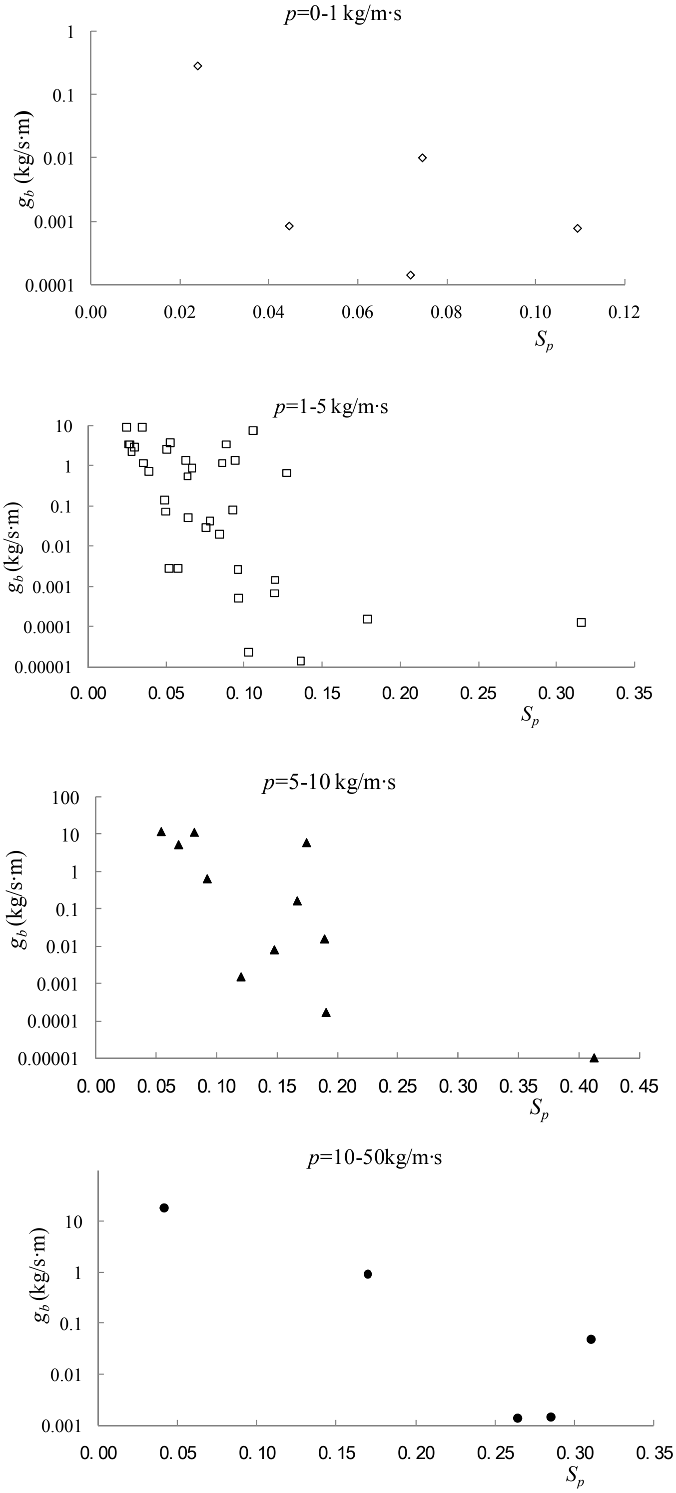


Figure 7. Relationship between riverbed structure and rate of bed load transport per unit width under condition of given stream power per unit width

flow discharge difference was only 0.3 m3/s (the flow discharge per unit width in turbid-flow gully was less than double of that in clear-flow gully). Moreover, the riverbed structure intensity, Sp, was also quite different in clear-flow gully and turbid-flow gully. The measured Sp was 0.02 in turbid-flow gully and 0.41 in clear-flow gully, however, the geomorphologic form and landscape was quite different in the two gullies.

In order to further study the effects of riverbed structure on bed load transport, 14 tributaries of Xiaojiang were measured in the flood season of 2009. Figure 7 shows the relationship between riverbed structure and rate of bed load transport per unit width under steady stream power per unit width.

Figure7 shows under the similar stream power per unit width in mountain streams, the higher the riverbed structure intensity was, the lower the bed load transport per unit width was. Moreover, bed load transport intensity fluctuated strongly with small changes in the riverbed structure. The rate of bed load transport decreased with a *log*-descending trend accompanying with ascending of riverbed structure intensity. The rate of bed load transport could decrease 10 to 1 000 000 times when the riverbed structure intensity increased by less than 10 times. Furthermore, based on the field experiments, it was found that there was no bed load transport in the river when S_p was greater than 0.4 and p less than 50 kg/m·s.

3 RESULT AND DISCUSSION

Bed load transport is affected by both the stream power and riverbed intensity. Scientists found that the resistance on the bed surface would decrease the rate of bed load transport (Parker and Klingeman, 1982; Bathurst, 2007). The research concentrated on the variation of coarse layer or the bed roughness and analyzed the coarse layer as a bed form (Carling et al., 1992). In fact, riverbed structure like step-pool systems usually consists of large boulders and cobbles acting as a framework tightly interlocking the structure with considerable stability. Because flow is deflected and dropped violently when flowing onto the step-pool system, the step-pool system disperses flow energy efficiently and resists riverbed erosion. Thus, a step-pool system is much more stable than boulders and cobbles arranged on the bed surface irregularly in decreasing bed load transport intensity.

Riverbed structures usually form in high flow (Whittaker & Jaeggi, 1982; Grant et al., 1990). After formation the low flow removes fine sediment, and the riverbed structure is exposed on the bed surface. The measured riverbed structure intensity, S_p, reflects an equilibrium stage among flow condition, incoming sediment and bed load transport. Once there is no incoming sediment from upstream, riverbed structure is affected by flow condition and bed load transport. However, since the present step-pool systems are formed in previous high flow, and once the present flow intensity is less than the previous high flow intensity, the riverbed structure cannot be destroyed. Accordingly, the rate of bed load transport decreases gradually until there is no bed load transport. On the other hand, once the measured riverbed structure intensity, S_p, is lower than the riverbed structure formed in previous extreme high flow, the riverbed structure is unstable and there will be an increase in bed load transport to adjust the riverbed structure intensity until the riverbed structure intensity reaches a maximum. In Shengou Creek and clear-flow gully, where step-pool system have been developed, the S_p is larger than 0.35, consequently there was no bed load transport at all. As measured in Shengou Creek and clear-flow gully in 2009, where the step-pool system cannot be destroyed because of the stability of the riverbed structure, there was little bed load transport even as the flow intensity increased. However, in the mountain rivers with heavy sediment transport intensity, such as the Dabaini River, the Xiaobaini River, and the Jiangjia Ravine, where there is low riverbed structure with S_p less than 0.1, the measured g_b was always large than 3 kg/m·s in flood season. Moreover, debris flow often broke out in these three gullies, causing damage to the riverbed structure.

As shown in Fig. 7, the rate of bed load transport per unit width has the same dimensions as stream power per unit width, thus a relationship between riverbed structure intensity, S_p, and a defining dimensionless parameter $R= g_b /p$ can be made as shown in Fig. 8.

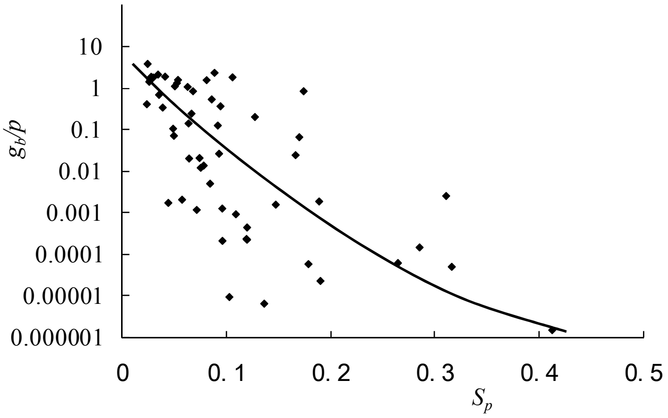


Figure 8. Relationship between riverbed structure and dimensionless ratio parameter of bed load transport rate per unit width and stream power per unit width

Figure 8 shows that R and S_p have an inverse trend in semi-logarithm coordinates. However, there are still dramatic errors by several orders of magnitudes in Fig. 8. Hence the bed load transport intensity is unstable in mountain rivers, which has stochastic characteristic in this fluctuation. Since flow discharge is quite different in flood season, especially in mountain rivers, the factor of stream power per unit width varies all the time. Moreover, the stream power per unit width was affected by fluvial process, such as riverbed incision and channel wandering.. On the other hand, according to the influence of incoming sediment from upstream and the variation of the flow intensity, the riverbed structure intensity also varies. Nevertheless, bed load transport rate changes greatly with small changes to S_p and p, consequently the bed load transport rate varies violently. However, the adjusting process of riverbed structure and stream power needs further studying.

4 CONCLUSION

According to field experiments in 14 mountain streams on the rate of bed load transport, it was found that the rate of bed load transport per unit width greatly varies with changes to the riverbed structure intensity and stream power per unit width. The rate of bed load transport increased dramatically when the stream power per unit width increased. In similar stream power per unit width, the more developed the riverbed structure was, the lower the bed load transport rate in the river or reach was. Conversely, the less developed the riverbed structure was, the more intensive the bed load transport was.

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