

Fluvial transportation and sedimentation of the Fu-shan small experimental catchments

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Abstract

The Fu-shan long-term ecological site is one of Taiwan's mid-altitude forest drainage basins. This study provides an estimation of the denudation rate for two small catchments within that site. Data upon which the estimation is based include topographic maps, site surveys, and measurements on bed, dissolved, and suspended loads over the period from 1998 to 2000. The result indicates that typhoons and storm rainfalls, as well as geomorphic and ancestral conditions, have major impacts on hydrological and sediment regimes of these drainage basins. The total sediment output measured at Weir No. 1 indicates a denudation rate of ~2.7 mm per year, which is 53% of the figure calculated from the data measured at Weir No. 2. Since the geological settings in these basins are similar, the result is a demonstration of the nonlinear relationship between basin areas and sediment production. In Basin No. 1, 90% of the total sediment output is dissolved load. However, this figure plunges to 42% in Basin No. 2, in contrast with the fact that the runoff per unit area in Basin No. 2 is 35% higher than that in Basin No. 1. The denudation rates of these two drainage basins are relatively high in comparison with those from other areas around the world.

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1. Introduction

The major source of sediment transported to oceans is from the rivers draining the continent. There are some geomorphological processes in operation within the system, including erosion transportation and deposition. There are two distinct methods in this research: one is to estimate the mass of riverine sediment entering the oceans or reservoirs by river transportation while the other one is to estimate the denudation rate of the continent or drainage basins. There are research efforts of different scales and methods, including world-wide sediment budget (Meybeck, 1988), world-wide river transportation (Milliman and Mead, 1983), regional erosion rate (Dadson et al., 2003; Li, 1976; Ahnert, 1970; Trimble, 1983), drainage basin scale river transportation (Garcia et al., 2000; Milliman and Syvitski, 1992; Corbel, 1959; Schumm, 1963; Young, 1969).

The quantification of the global sediment budget, and the relationship between it and its tectono-climatic drivers,

is a key issue in our understanding of global environmental change. Denudation rate, which may be described as the total load divided by the catchment area, is an indication of the nature and magnitude of the geomorphic processes occurring within a drainage basin. Sediment production in high mountain environments is a key part of this dynamic system, as denudation rates here are often high (Walling and Webb, 1996; Korup et al., 2004). However, mountain catchments are particularly problematic from a methodological perspective, because it has long been recognised that the determination of the production of sediment from mountain catchments is an important component to the understanding of earth surface processes in upland environments. This is a particularly challenging problem for two key reasons:

- the accurate measurement of sediment loads is difficult, especially where discharge is variable and subject to large events;
- sediment movement is probably highly variable in space and time, with short term measurements often seriously under-estimating the overall dynamics of the system.

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In steep mountain environments subjected to high intensity rainfall events the problems are particularly serious (Carson and Griffiths, 1987), as most movement of sediment probably occurs during short term precipitation events, and their associated flash floods, and a substantial (though poorly quantified) proportion of the sediment movement is probably through the mechanism of bed load transport. Where anthropogenic activity has had an impact then the sediment supply may be altered greatly (e.g. Alvera and García-Ruiz, 2000).

In consequence, many sediment production measurements follow one of two well-trodden paths. First, there is the approach that measures only the suspended fraction of sediment transported (e.g. Dadson et al., 2004). Although such an approach might be reasonable for lowland rivers, it probably leads to substantial errors for steep catchments. For example, different rating curve techniques used by Griffiths (1979) and Adams (1980) for the analysis of the same basic discharge and sediment concentration data for the Cleddau River in New Zealand produced calculated loads that differed by approximately two orders of magnitude. Second, there is the application of long-term sediment production rates derived from volumetric datasets such as lake or reservoir sediments. However, these results generally contain systematic or censoring-based errors (Goudie, 1995; Evans and Church, 2000; Schiefer et al., 2001). Whichever approach is used, it is well-established that measured sediment production per unit area is generally inversely proportional to catchment size (Milliman and Syvitski, 1992).

In Taiwan, these problems are particularly serious. The area of Taiwan represents just 0.024% of the Earth's subaerial surface, but it produces 1.9% of estimated global suspended sediment discharge, based upon suspended sediment data (Dadson et al., 2003). This is because it is a young, steep, weak, rapidly uplifting mountain chain that

is subject to both frequent high intensity and magnitude precipitation events in the form of typhoons, and a high incidence of tropical cyclone activity (Petley and Reid, 1999). In consequence, high rates of fluvial bedrock incision (Hartshorn et al., 2002), landslide activity (Hovius et al., 2000), and debris flow activity are recorded (Lin et al., 2004). Measurement of sediment production have tended to focus upon either small-scale measurements of actual production rates (e.g. Hartshorn et al., 2002) or suspended sediment data (Dadson et al., 2003), with the large errors associated with these techniques. As a result, estimates or real sediment yields, and their relationship with precipitation inputs, are somewhat speculative and general.

For this reason, we have attempted to quantify the sediment production from two forested, undisturbed catchments in upland Taiwan using sediment traps to determine bed load and sampling to measure suspended and dissolved loads. Measurements are presented here for a 3 year period from 1998 to 2000.

2. Study area

The study area includes two experimental catchments situated within the Fu-shan nature reserves in Taiwan (Fig. 1). This is a mid-altitude (400–1400 m above sea level) densely forested drainage basin composed mainly of Oligocene slate and lightly metamorphosed sandstones. The geological structure consists of a NE–SW orientated, heavily faulted anticline (Lin and Lin, 1995) (Fig. 2). The vegetation in the catchment is primary forest that has received little human interference. Catchment No. 1 has a surface area of 35.55 hectares, whilst No. 2 has a surface area of 92.97 hectares. Both catchments drain into the Dan-Shui River, which flows into the Taipei basin. The study area is located in humid subtropics with annual

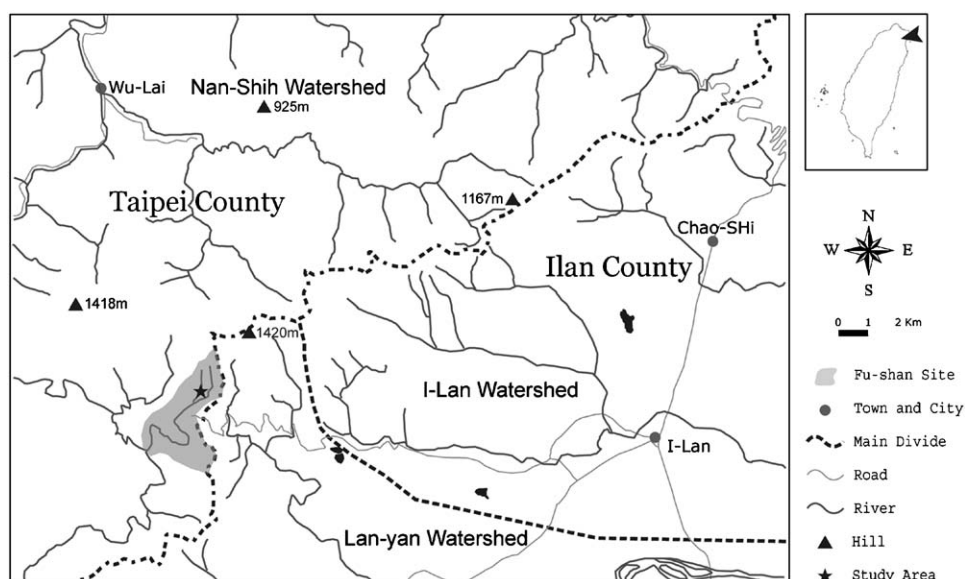


Fig. 1. Fu-shan natural reserve.

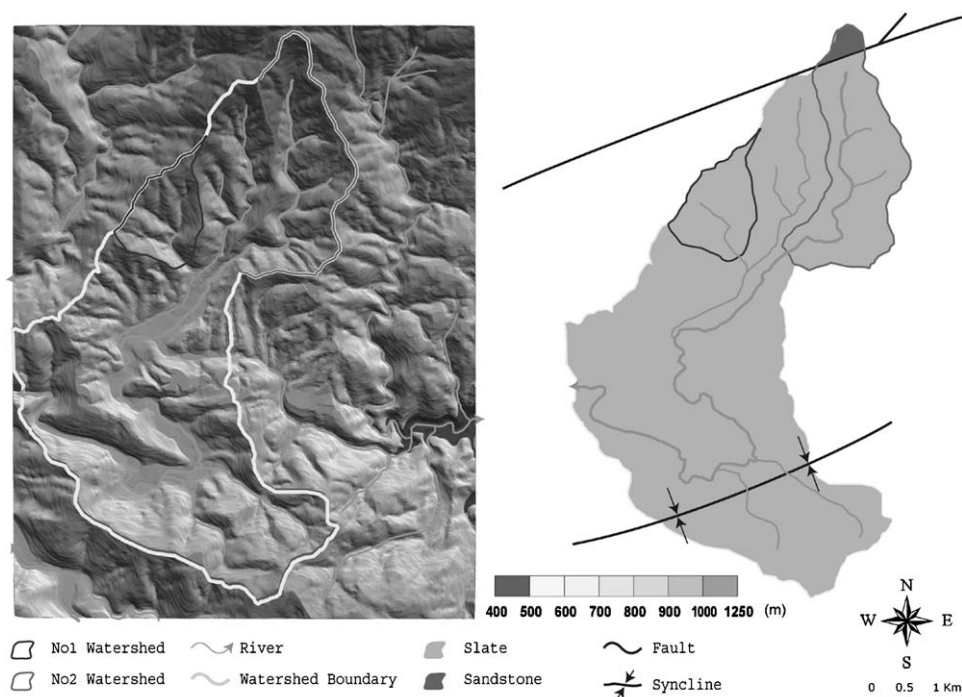


Fig. 2. Nos. 1 and 2 instrumented drainage basins

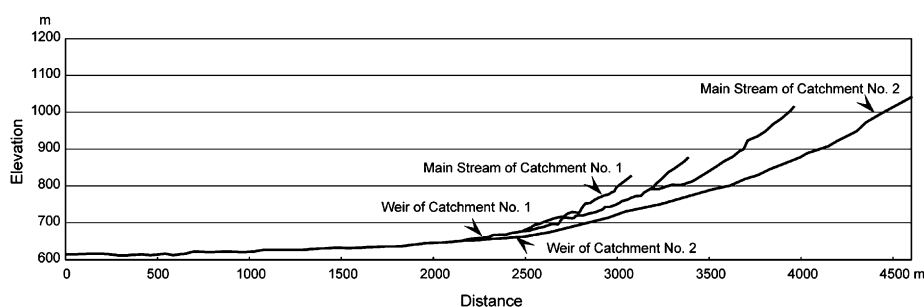


Fig. 3. The longitudinal profiles of rivers of the study area.

rainfall between 3000 and 5200 mm during 1998–2000. Typhoons are the main source of heavy rainfall, and also the cause of flushing floods in this region.

In morphological aspect, the longitudinal profiles of the rivers in Fu-shan are concave upward (Fig. 3). The river channel No. 1 is steeper than that of No. 2. Fig. 3 shows a knick point in river No. 1, but no knick point in river channel No. 2. The hypsometric curve shows a slight difference in basin morphology as a whole (Fig. 4). The difference between the hypsometric curves of these two basins has a covariance equal to 6.17%. It is significantly higher than the covariance of the frequency distributions (in percentage) of gradient of these two basins, which is only 2.58% (Fig. 5).

Well-established methods employed for measuring bed load include the continuous belt slot system (Leopold and Emmet, 1976), the Birkbeck-type slot sampler (Reid and Layman, 1980), the continuous pressure transmitter system (Garcia et al., 2000), the continuous measurement of magnetic particles (Ergenzinger and Conrady, 1982) and

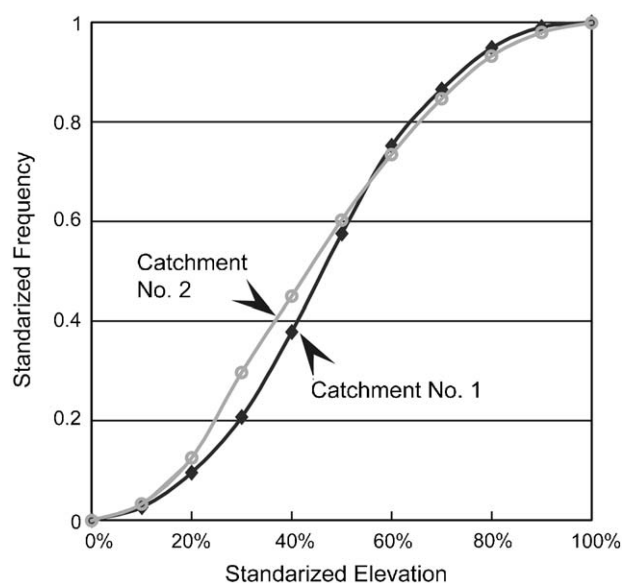


Fig. 4. The hypsometric curves of basin Nos. 1 and 2.

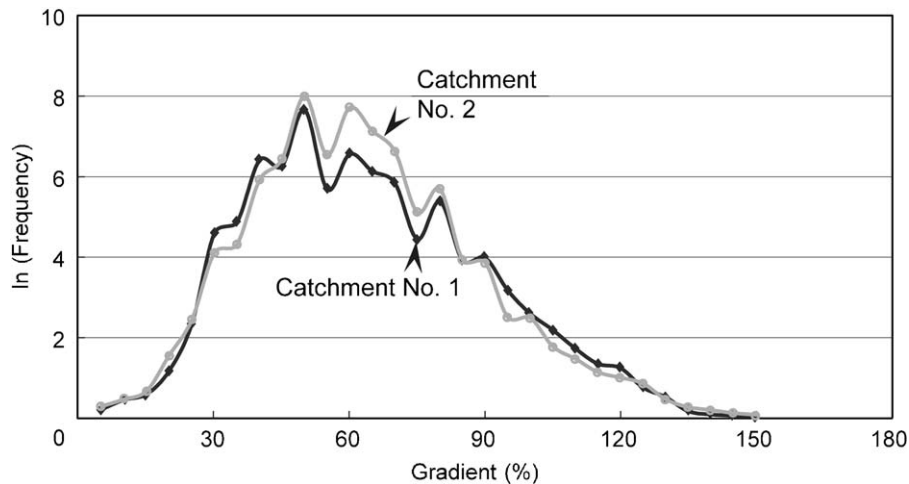


Fig. 5. The semi-log graph of gradient frequency distributions of two basins.

other bespoke designs (Lenzi et al., 1999). In this study we have used a V-notch weir and sediment sink to collect the bed load complemented by suspended sediment and dissolved load sampling. The weirs were installed by the Taiwan Forestry Research Institute, administrators of the nature reserve.

3. Methodology

To quantify the denudation rate for a drainage basin requires measurement of the bed, suspended and dissolved loads in parallel with the discharge of the channel referenced to an appropriate time-base. The Taiwan Forestry Research Institute, administrators of the nature reserve have constructed V-notch weirs to measure the river discharge of Nos. 1 and 2 drainage basins. These weirs consist of two sections, an upper section, capable of detaining in excess of 250 m³ of bed load, and a lower section instrumented with an automatic water sampler for the determination of suspended and dissolved load concentrations and an ISCO stage recorder for discharge measurement. The upper section, after each cycle of stage rise and fall is emptied of all bed load material, and the instruments in the lower section are re-set and calibrated in preparation for the next event, while the dug out bed load is dried and weighted for further analysis.

Collated bed load samples, suspended and dissolved solid concentrations, discharge and rainfall results are integrated into the denudation model to estimate the annual denudation rates. Fig. 6 illustrates the denudation model adopted in this paper.

4. Results

Based upon hourly rainfall intensity measurements from two weather stations in this study area, Fig. 7 shows the frequency-magnitude distribution of hourly rainfall intensity. The frequency axial in Fig. 7 is logarithmic. The figure

shows that the frequency-magnitude relation of hourly rainfall intensity can be divided into two domains. At low hourly rainfall intensity, that relation is more or less a linear one in the semi-logarithmic graph. This pattern is similar to the exponential frequency-magnitude distribution of daily rainfall model suggested by Kirkby (1978). However, at high hourly rainfall intensity, the relation is more complicated and the gradient of its trend line is much lower. The implication of this division in the frequency-magnitude distribution of hourly rainfall intensity for hourly discharge and annual sediment transportation will be discussed later.

Fig. 8 shows the 3-year hourly discharge rates of these two basins. Fig. 9 gives the frequency-magnitude of hourly discharge rates (cms) at gauging stations for these two basins. They show similar patterns as those in Fig. 7. When the discharge is less than 0.5 cms in No. 1, the relationship between frequency and magnitude follows more or less an exponential function. In this basin, 0.5 cms implies 5.1 mm run off contribution per unit area across the whole drainage system. Similarly, when the discharge is less than 2 cms in No. 2, there is an exponential relation. 2 cms discharge in No. 2 implies 9.7 mm run off contribution per unit area across the whole drainage system.

It is suggested that 0.5 and 2 cms are the threshold discharge rates of Nos. 1 and 2, respectively. The threshold divides the frequency-magnitude of hourly discharge rate into two domains. Moreover, each domain has its own characteristics, which can affect the sediment production. Comparing the threshold discharge to the time series of hourly discharge data (see Fig. 8), there is no event having an hourly discharge rate over 0.5 cms in No. 1, in a year with no typhoons (1999). Using 2 cms as the threshold for hourly discharge rate in No. 2, there is one event over that threshold in 1999. To date, the chosen hourly threshold discharges are not yet linked to the sediment dynamics in these river channels. However, they must have

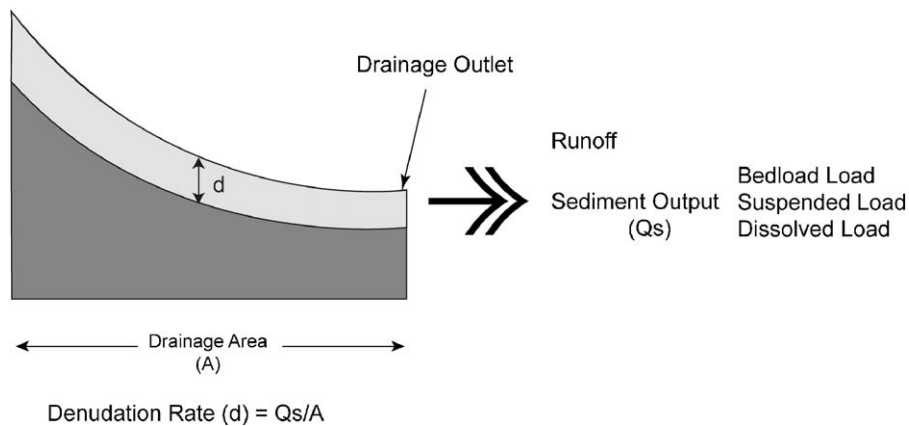


Fig. 6. Denudation model.

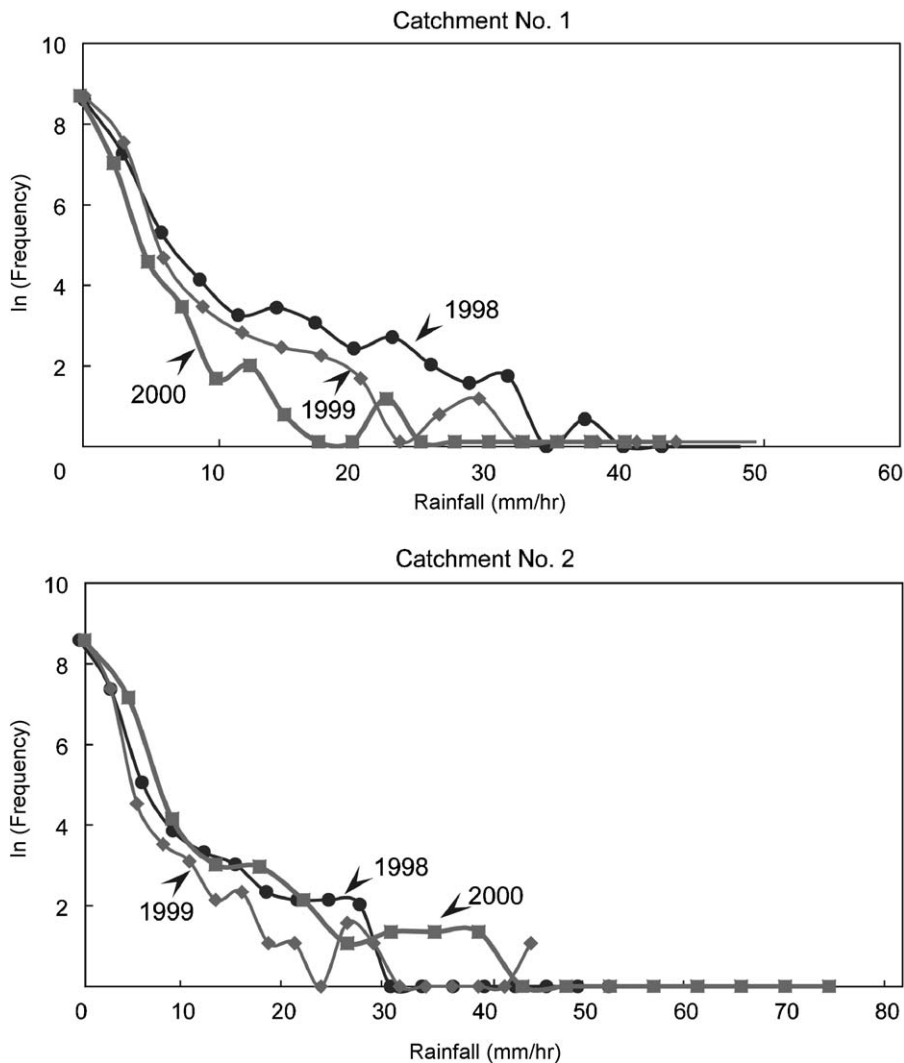


Fig. 7. The semi-log graph of hourly rainfall frequency-magnitude distributions of two basins.

significant implications for drainage hydrology and sediment transport.

The results of this 3-year study which commenced in January 1998 and terminated in December 2000 are

presented in [Tables 1 and 2](#). The variation in loads between the drainage basins may be attributed to the catchment area, topography and slope forming material. Aerial photo survey indicates that there were no landslides

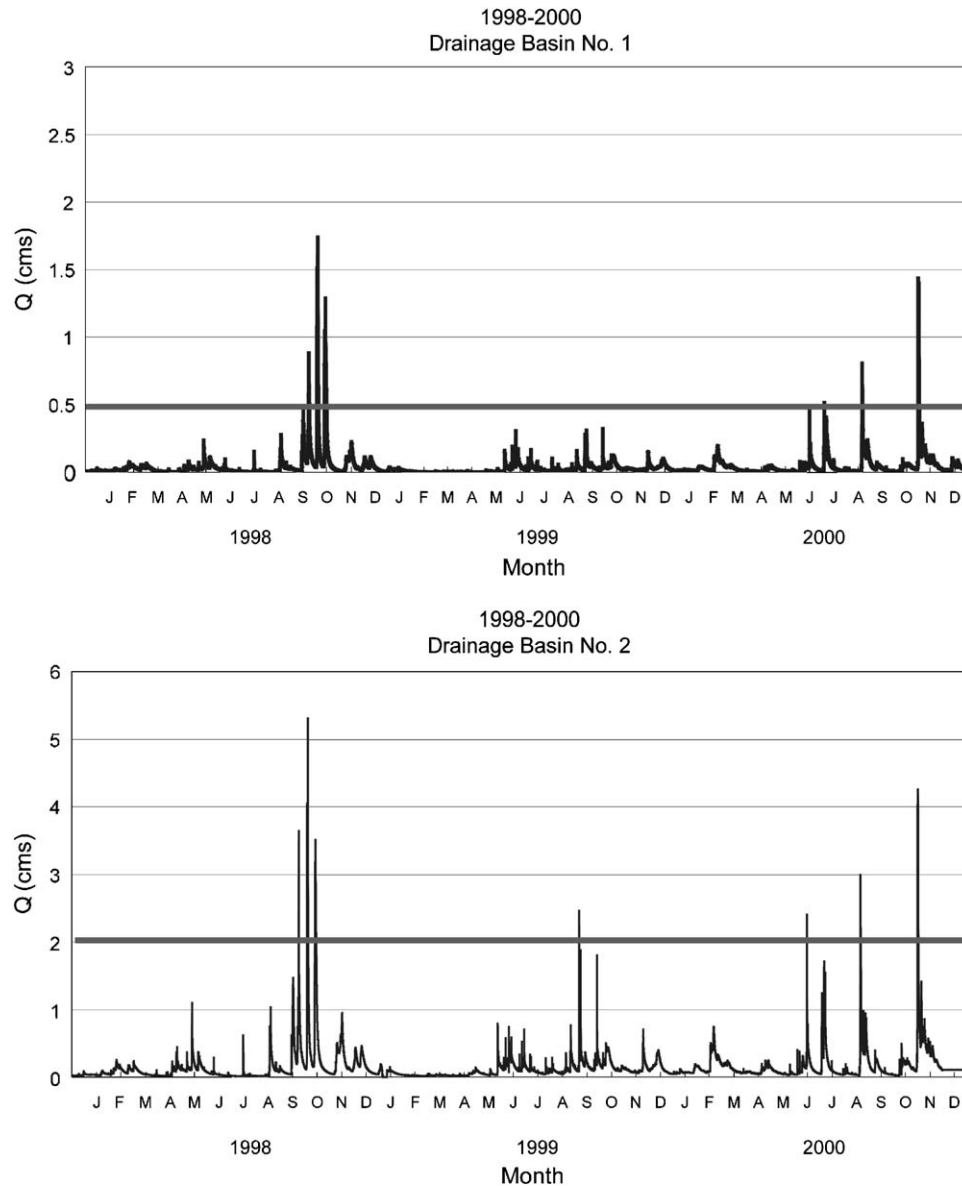


Fig. 8. The time series of hourly discharge rate of the two basins.

in these two drainage basins. This suggests that the significant variation of sediment discharge is due to the instability of river banks, channels and/or gullies under vegetation cover.

In river No. 1, bed load composes ~7% of the sediment, ~3% represents the suspended load, and the dissolved load consists of ~90% of the total load. This manifests the dominance of the weathered material in this watershed. In contrast, bed load, suspended and dissolved load for No. 2 are ~50%, ~1% and 49%, respectively. In this catchment, bed load and dissolved load are almost equivalent. It is clear that the sediment transportation patterns are different in these two drainage basins. In basin No. 1, dissolved load (weathering) is dominant, while in basin No. 2, bed load and dissolved load is dominant (erosion) according to Fig. 10.

The recorded discharge patterns for the two watersheds are similar, though the discharge of No. 2 is 3.45 times higher than that of No. 1 on average (Fig. 11). The hourly discharge rate per unit area of No. 2 is about 1.35 times of that of No. 1 on average. This manifests some inherent different hydrological response to similar rainfall events between the two watersheds. Similar rainfall produces more surface run off in drainage basin No. 2 than in No. 1. This could be a reason for the difference in sediment transportation pattern of the two watersheds. Higher discharge means higher stream power and thus more capacity for bed load transport. As a result, for any rainfall event, the chances of a raft of coarse particles being reworked are higher in No. 2, than in No. 1.

According to our observations, no landslides occurred in the study area during 1998–2000, and sediments

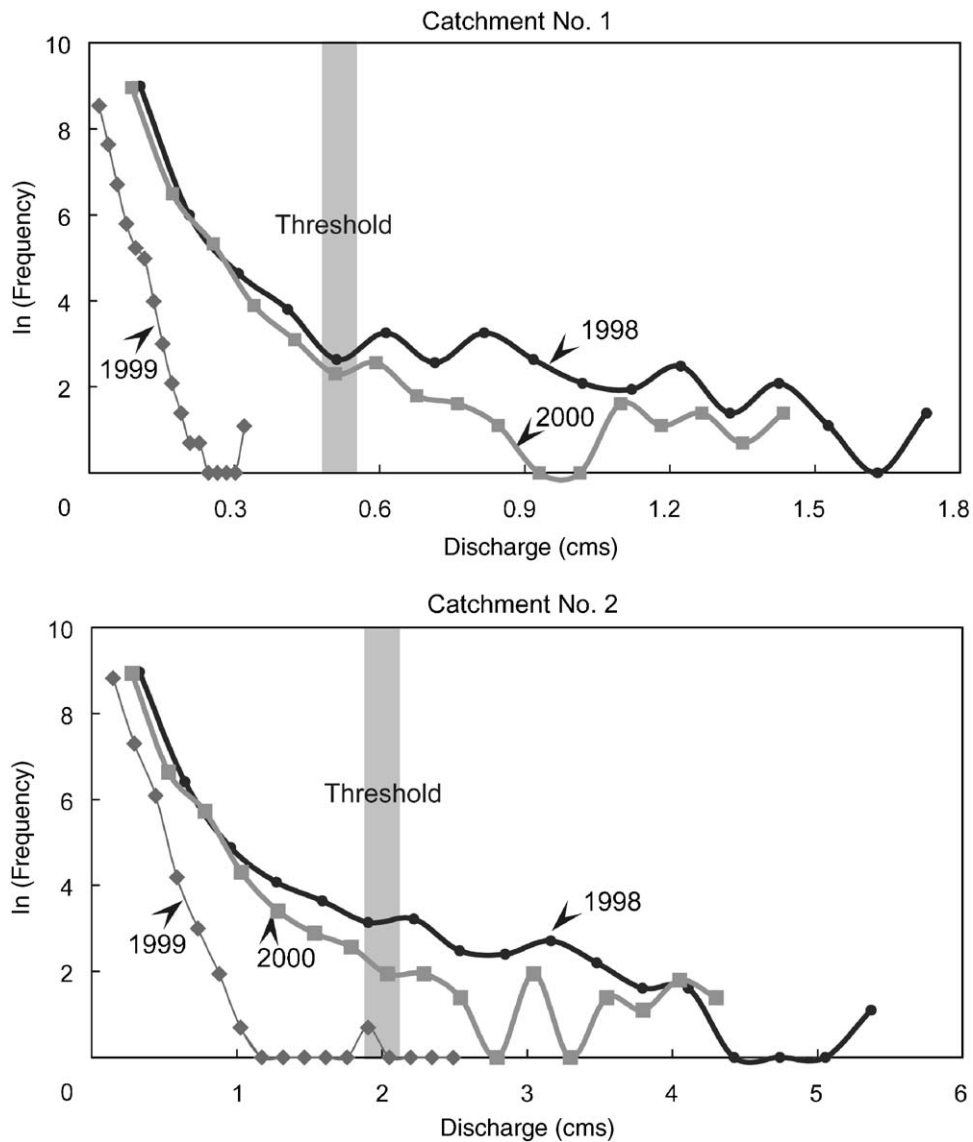


Fig. 9. The semi-log graph of hourly discharge frequency-magnitude distributions of two basins.

Table 1
Bed load recovered from study area from 1998 to 2000

Time	Catchment Drainage Basin No. 1 (kg, Area 35.55 ha)	Time	Catchment Drainage Basin No. 2 (kg, Area 92.97 ha)
1 January 1998–15 July 1998	239	1998–1999	1 097 200
15 July 1998–1999	49 973	2000	1 411 800
2000	99	Total	2 509 000
Total	50 311		

derived from previous slope movements were deposited in channels and along banks. During typhoon and storm periods, water level rises and the flow speed increases accordingly. When frictional force is overcome, the sediment deposited on the riverbank, channel, and hillslope will be eroded. As a result, the sediments are removed and

transported as pulses in consort with the rise and fall of the water level.

Between 1998 and 2000, the total sediment load reached ~ 738 t in drainage No. 1 and 4372 t in No. 2. Thus, the calculated denudation rate is 2.7 and 5.1 mm a^{-1} , respectively if a specific weight of 2.6 is assumed. Although

different types of sediment sources, including landslides, river bed erosion and soil erosion, have to be considered in more detail to obtain a realistic picture of the landscape development, the estimated denudation rates above show rather high values, compared with $455 \text{ mg cm}^{-2} \text{ a}^{-1}$, or 0.182 mm a^{-1} , values proposed by Li (1976). According to Dadson et al. (2003), the erosion rate is about $3\text{--}4 \text{ mm a}^{-1}$ in this area. The results of Li (1976) are mainly estimated from suspended and dissolved load. The results of Dadson

et al. (2003) are mainly based on suspended load. Both studies used data collected and compiled by the Commission of Water Resource Control of Taiwan but at different periods. As bed load consists of a significant portion of the total sediment, particularly in basin No. 2, negligence of this important transportation mode results in the disparities between the different results.

The recorded concentrations of dissolved ions exceed the actual dissolved material contributed from within the watershed, as ions in the river water could come from various exterior sources, such as chemical weathering, atmospheric CO_2 , oceanic aerosols contribution and anthropogenic inputs (Li, 1976; Meybeck, 1988). Therefore, overestimation of dissolved load in this study is expected. Taking account of the estimated contribution of exterior sources derived from the New Zealand data (Meybeck, 1988), $8.6 \text{ t km}^{-2} \text{ a}^{-1}$ is deducted from the dissolved load calculation. The amounts of dissolved load for basin Nos. 1 and 2 become 9172 and 23 986 kg, respectively, and the denudation rates become 2.67 and 5.07 mm a^{-1} for the two respective watersheds. Further study is required to derive more concrete conclusions.

Table 2
Mass of sediment transported within the study area from 1998 to 2000

Material transported	Catchment	
	Drainage Basin No. 1 (Area 35.55 ha)	Drainage Basin No. 2 (Area 92.97 ha)
Bed load (kg)	50 311	2 509 000
Suspended load (kg)	22 178	37 258
Dissolved load (kg)	665 343	182 568
Total (kg)	737 823	4 371 916

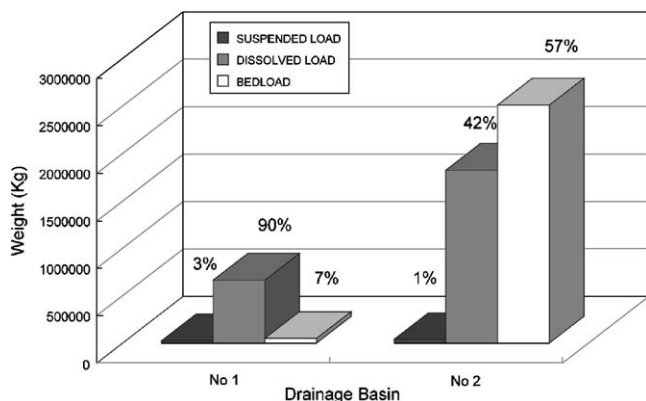


Fig. 10. The sediment weight and percentage in drainage Nos. 1 and 2 from 1998 to 2000.

5. Discussion and conclusions

The observation of sedimentation of two drainage basins in northeastern Taiwan during 1998–2000 shows that a significant amount of sediment has been evacuated from the fluvial system, although the watershed is well vegetated and not disturbed by human activity. As no landslides were observed in aerial photos of this study area during 1998–2000, the sediment accumulation in channel systems is the main source of sediment production at the drainage outlets.

The fluvial processes of the river and the wash processes on hillslopes transport the sediment through repeated and episodic erosion and deposition. By assuming that erosion

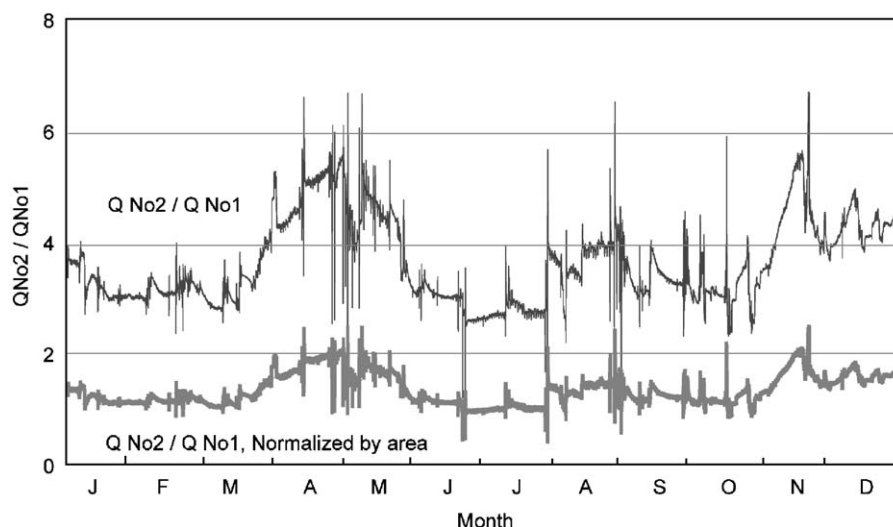


Fig. 11. The discharge ratio of drainage Nos. 1 and 2 in year 1998.

only takes place in a small riparian area, including channel and riverbank, local denudation rates along channel networks could be very high.

The two catchments behave very differently in terms of hydrological and sedimentological responses. Dissolved load dominates basin No. 1, while dissolved and bed load are of equivalent weight in basin No. 2. This is mainly due to the significantly different transportation capacity, indicated by the different hydrographic composition of the two drainage basins. On average, the discharge of No. 2 is 3.45 times higher than that of No. 1. Trimble (1997) also found some similar phenomena in other catchments influenced by urbanization, and attributed the variations to channel transport efficiency, soil texture, basin morphology and channel or bank erosion. The main causes for the different sediment transportation characteristics for our study area may result from the differences in channel or riverbank erosion, especially transported bed load. From field observations, there are two main factors contributing to significant bed load transport: elevated water level and abundant deposits available along the channel. This result is significantly different from the general relationships derived between drainage basin area and sediment yield (Milliman and Syvitski, 1992; Meybeck, 1988). According to these calculations, the average denudation rate in the larger catchment (No. 2) is higher than the smaller one (No. 1). However, when examining the basins within greater spatial and regional spectra, the data from these two drainage basins actually fall within the same category and thus the calculated denudation rates are not beyond reason.

The suspended load in both watersheds is not important, in contrast to the importance of the coarse material and the dissolved ions. During typhoon and storm periods, the river reworks a large amount of coarse sediment. In contrast, the river's main output is dissolved load when the water level is low. Thus, the watersheds in the headwater area tend to remove their sediment by bimodal transportation modes, which are manifested well by the character of frequency-magnitude distribution of hourly discharge rates.

The denudation rates of the two densely forested mountainous drainage basins calculated by this study are relatively high in comparison with the data provided by Li (1976). The steep terrain of the two watersheds which results in great stream power for transportation is likely to contribute to the high denudation rates calculated in this study. However, direct measurement of bed load could be the most important reason for the disparity, and may further indicate the pitfall of neglecting direct bed load in sediment budgets.

Acknowledgements

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