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Suspended solids discharge from a small forested basin in the humid tropics

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Abstract:

Suspended solids (SS) discharge from a tropical rain forest was observed at the Bukit Tarek Experimental Watershed in Peninsular Malaysia in order to elucidate mechanisms of SS production and transport. Peaks of water discharge and electrical conductivity (EC) lagged further behind rainfall peaks than did dissolved oxygen (DO), indicating that the discharge in the early stage of a storm is mainly formed by rain water with high DO. Stream water showing a high value of EC originating from subsurface water formed the main storm flow and lagged behind the rainfall. SS concentrations rose to a peak quickly and, like DO, the peak preceded that of water discharge. A clockwise hysteresis loop in the relationship between SS and water discharge exists, and the magnitude of hysteresis loop is in proportion to storm size. The values of SS concentration correlate positively with the values of rainfall intensity on logarithmic axes. The time intervals between peaks of rainfall and SS concentrations are assumed to be a delivery term expressing distance from sediment source to measuring point. Immediate transport of SS from the source to the sampling site, the short time gap between the peaks of rainfall and SS concentrations, and the high rate of infiltration on the hillslope suggest that the sources of high SS concentrations are located close to the stream. The calculated source area is located at a gentler part of the stream, where wet riparian areas exist. The strong relationship between water discharge and SS concentration during the small storm proves that the source areas of SS and water were the same. In contrast, the source area of SS disappeared when rainfall ceased, whereas the source area of water discharge was still expanding in the larger storm. These phenomena may produce clockwise loops in the SS concentration–water discharge relationship.

KEY WORDS tropical rain forest; suspended sediment; source area estimation

INTRODUCTION

Rivers in tropical regions are characterized by high concentrations of suspended solids, especially downstream in denuded areas (Douglas, 1978). The high rainfall intensity in tropical regions (Abdul Rahim, 1983) plays a major role in the erosion process. Deforestation is the main cause of the sediment production that adversely affects tropical rain forest ecosystems. Based on earlier studies on the effect of deforestation on sediment yield, Lal (1993) concluded that conversion of forest to cultivated land may (i) increase sediment density and dissolved load in surface runoff and interflow, (ii) accentuate soil compaction and structural degradation, and (iii) decrease soil organic matter.

Surface erosion in tropical rainforests is generally low (Roose, 1977; Lal, 1983; Wiersum, 1984). However, the mechanism of suspended solids (SS) production and transport in natural forests is not fully understood.

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Evaluation of SS production in undisturbed tropical rainforests helps in comprehending SS effects on sequential forest–stream ecosystems. Cooperative research between the Forestry and Forest Products Research Institute, Japan and the Forest Research Institute Malaysia on hydrological processes, including SS production and transport, has been undertaken in a small forested second-order catchment at Bukit Tarek, Kering, Selangor, Malaysia, since 1992. The main observations were carried out during the rainy season in November 1992 and November 1993.

METHODS

Study site

Bukit Tarek Experimental Watershed is located in Selangor Darul Ehsan, Peninsular Malaysia (BT: latitude: 3°31′N; longitude: 101°35′E; altitude: 48–213 m; Figure 1). The Forest Research Institute Malaysia and Forest

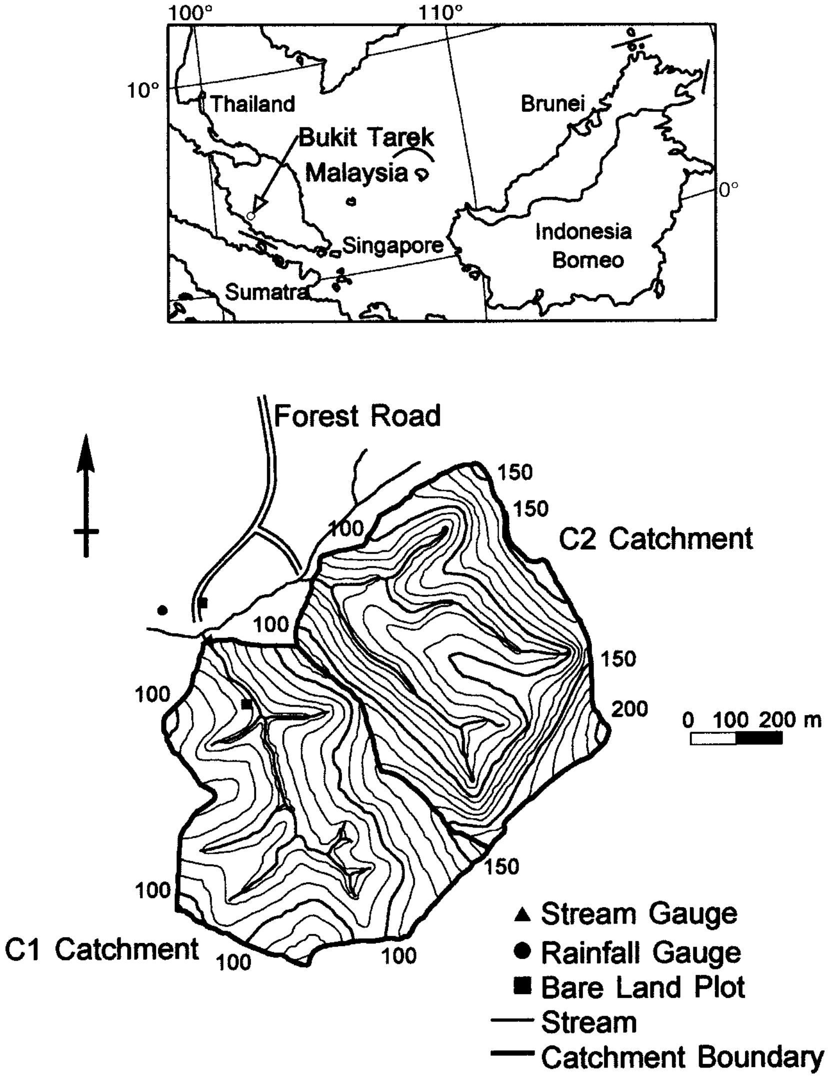

Figure 1. Bukit Tarek experiment watershed

Department established the Bukit Tarek Experimental Watershed to quantify the effects of forest managements on the hydrological aspects, including SS issues, in 1989. The study site is composed of two catchments: C1 (32·8 ha) and C2 (34·3 ha). The study in this paper was carried out in C1 catchment. The forest was logged selectively in the early 1960s and has now fully regenerated. The skid trails for logging at that time were also covered with regenerated trees, and there was no influence of forest roads on the SS generation. The vegetation is dominated by *Koompassia malaccencis*, *Eugenia* spp., and *Canarium* spp. The surface geology is metamorphic rocks consisting of quartzite, quartz mica schist, graphitic schist, and phyllite from the Arenaceous Series (Saifuddin *et al*., 1991).

In the 3 year period from 1992 to 1994, the air temperature ranged from 19·1 to 34·9 °C and the average annual precipitation was 2654 mm. The monthly precipitation has two major peaks in May and November, because of both southwest and northeast monsoons. There is a distinct diurnal cycle in precipitation, with 62% of the rainfall occurring between 13 : 00 and 19 : 00 Malaysia Standard (MST). The rainfall at Bukit Tarek is characterized by short-duration and high-intensity storms. About 55% of rain events fell within 1 h. The highest and mean amounts of rainfall were 94·0 and 14·3 mm in the same period. We compared the rainfall characteristics at Bukit Tarek with Hitachi Ohta, which is located in a temperate area (latitude: 36°34′N; longitude: 140°35′E), and concluded that the amount rainfall in each rain event at Bukit Tarek and Hitachi Ohta were almost the same (14 mm), but Bukit Tarek had a lower maximum value (<100 mm). This rainfall characteristic of Bukit Tarek is based on the daily meteorological turbulence, not frontal storms, which is peculiar to the tropics (Noguchi *et al*., 1996, 1997a).

The saturated hydraulic conductivity K_s decreased as the soil depth increased. The K_s values range from 169 mm h^{-1} at the 80 cm depth to 1466 mm h^{-1} at the 10 cm depth. These K_s values are higher than the prevailing rainfall intensity at this site (Noguchi *et al*., 1997b) and higher than those of other tropical soils at most depths. Soil water retention curves of the B and C horizons show high volumetric water content values for saturated conditions (θ_s : 0·5 to 0·6), and also show a large difference (0·1 to 0·2) between saturation (θ_s) and residual suction (θ_r) values of volumetric water content (Noguchi *et al*., 1997b), implying high potential for rainwater storage. These soil and rainfall properties may play an important role in surface runoff and SS production processes.

Measurement method

Rainfall in the Bukit Tarek Experimental Watershed is characterized by high-intensity and short-duration storms. To record rainfall and discharge response in detail, a sensitive rainfall intensity recorder (0·0083 mm per pulse) and a digital water-level sensor with high resolution were added to the hydrological monitoring system at the weir of C1 at Bukit Tarek; records were collected at 5 min intervals. The electrical conductivity (EC) and dissolved oxygen (DO) of stream water were also measured in C1 at 5 min intervals. EC and DO are useful tracers that can be obtained almost maintenance free during short-term field experiments. EC is an indicator of total ionic strength, which is mainly comprised of solutes from the soil water. DO shows high values in the stream water compared with the soil water, due to aeration. The phase difference between EC and DO indicates the source of flowing water in the stream, and it is useful in estimating the source area of suspended solids in the catchment.

The peak of SS concentration during a storm event usually precedes the peak of water discharge in small catchments (Heidel, 1956). The high-intensity and short-duration rainfall in Bukit Tarek requires temporal changes of SS concentrations to be measured over short time intervals in order to assess fully the sediment discharge and water quality response. A combination of two water sampling systems was installed at weir C1. One was triggered by a rainfall-intensity sensor and collected samples at 5 min intervals, and the other sampled stream water at 2 h intervals. SS concentration was determined by the gravimetric method. Water samples were vacuum filtered through a 0·45 μm membrane filter and residues were oven dried at 103–110 °C for 1–3 h. The dried residues were then ignited in muffle furnace at 550–700 °C. The further loss of weight due to combustion of organic matter provided the loss on ignition expressed as a percentage.

Hydraulic experiment of surface runoff

In addition to the observations at the C1 weir, artificial surface runoff experiments on forested hillslopes and a forest road (refer to Figure 1) were conducted to measure Manning's roughness coefficient and sediment discharge rate by the surface flow (see Kitahara *et al.* (1993)). The surfaces of the experimental slope were partitioned into 1·0 m long (longitudinal direction) by 0·2 m wide plots by inserting a pair of thin steel plates to control flowing water. Water was supplied from a reservoir tank located upslope of the test site. The water discharge was regulated by a needle bulb and monitored by a flow meter upslope of the outlet. The regulated water was fed into a rectifying tank and water discharged from a 0·2 m wide rectangular notch on the downslope side of the tank onto the plot surface to establish uniform surface flow.

At the bottom of the partitioned slope, the overland flow and sediments were collected in a trough. The overland flow volume was also measured and compared with the flow meter upslope; the difference is the infiltration into the soil. Suspended sediment concentrations were also determined by the gravimetric method as stated earlier. The velocity of flowing water on the slope was estimated by the travel time of coloured water over a fixed distance. The inclination of test slopes was also measured. All these values were used to calculate Manning's coefficient of roughness for the slope.

Especially on the forest road site, temporal sediment and water discharges during the natural storm #4 were obtained in order to elucidate the sediment production during the storm. The comparison between these natural storm data and runoff plot experiment data will suggest the mechanisms of SS generation.

RESULTS AND DISCUSSIONS

During the observation periods in November 1992 and in November 1993, there were several storm events. We sampled four complete storms for discharge and water quality (#1 to #4). The characteristics of storms are summarized in Table I and in Figures 2 to 5. All four of the rainstorms started in the afternoon and ended in the evening. There is a large time lag between rain and water discharge. The rainfall peaks preceded the discharge peaks in all storms.

Response of water discharge to rainfall

Storm #2 was the largest during the observation period. The amount of rainfall reached 84 mm, and the highest 5 min rainfall intensity was 11·38 mm, which is equal to 136·6 mm h^{-1}, at 14:25–14:30 MST. The peak of water discharge (330 l s^{-1} or 3·5 mm h^{-1}) appears at 19:04 MST. Flood discharge increased rapidly but converged to the base flow within 24 h even in the largest storm of #2; this is typical in small watersheds.

Storms #1 and #4 were of moderate scale in Bukit Tarek Experiment Watershed. The amounts of rainfall were 32 mm and 63 mm respectively. However, these storms generated substantial SS in stream flow (150 to 180 mg l^{-1}), because the maximum 5 min rainfall intensities were 5·32 mm and 7·62 mm, equal to 63·8 mm h^{-1} and 91·4 mm h^{-1} respectively.

Storm #3 is the smallest among the four storms. Total rainfall was 13 mm, which is almost equal to the average rainstorm volume in Bukit Tarek. However, the maximum 5 min rainfall intensity was high (3·52 mm,

Table I. Storm data for Bukit Tarek watershed obtained in November 1992 and 1993

Storm	Date	Total rain (mm)	R_{max} (mm 5 min^{-1})	Time (MST)	Q_{max} (l s^{-1})	Time (MST)	SS_{max} (mg l^{-1})	Time (MST)
1	14–15 November 1992	32	5·32	18:00–05	153·8	18:20	182·2	18:27
2	21–22 November 1992	84	11·38	14:25–30	315·4	19:04	341·7	14:44
3	11–12 November 1993	13	3·52	14:55–00	99·6	15:35	29·7	15:09
4	16–17 November 1993	63	7·62	15:45–50	204·6	17:15	155·5	15:21

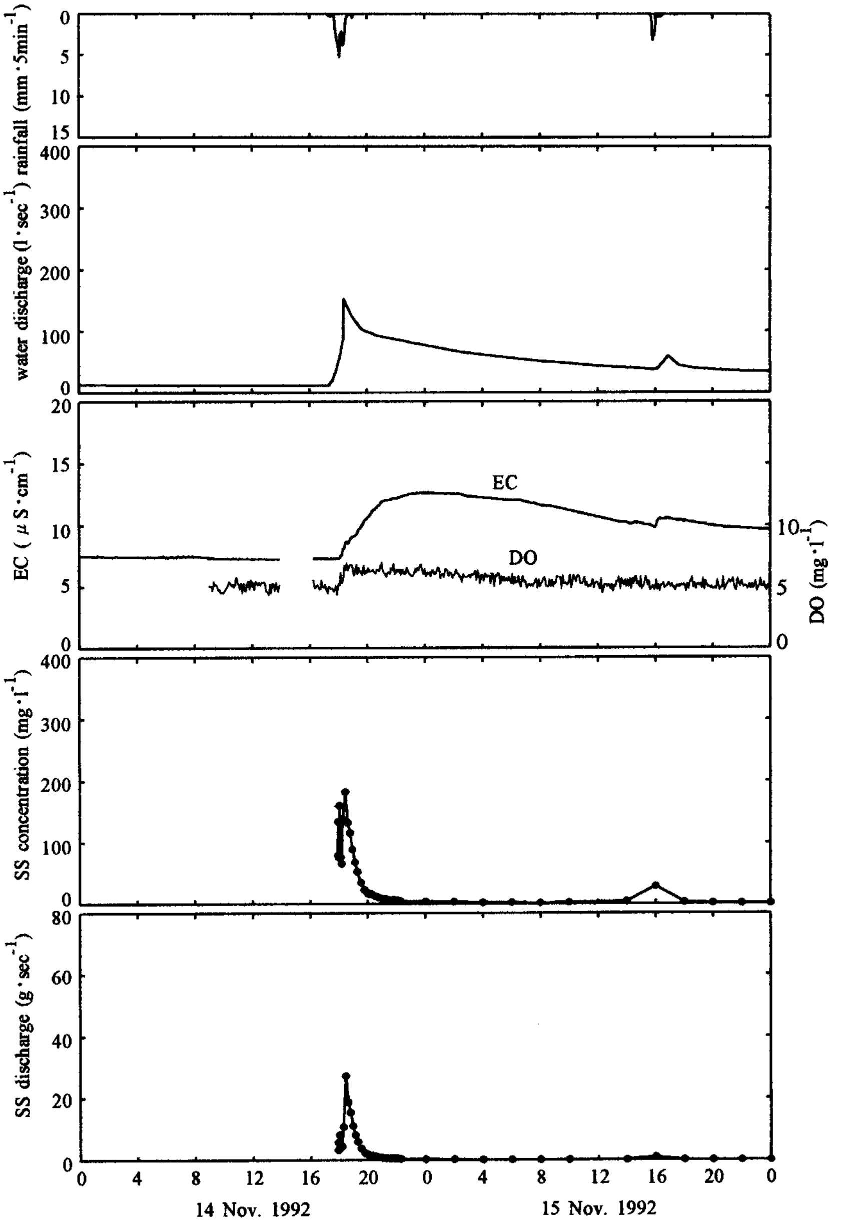

Figure 2. Observed fluctuation of rainfall intensity, water discharge, EC, DO, SS concentration and SS discharge of storm #1

equal to 42·2 mm h^{-1}). The time lag between rainfall and discharge was relatively small compared with the other three storms.

Response of DO and EC to rainfall

Peaks of water discharge and EC show larger time gaps with respect to rainfall peaks than does the DO (Figures 2–5). The response of DO coincided with rainfall. There are two reasons why the value of DO increases quickly with rainfall. Firstly, rain drops contain high amounts of dissolved oxygen; secondly, rain

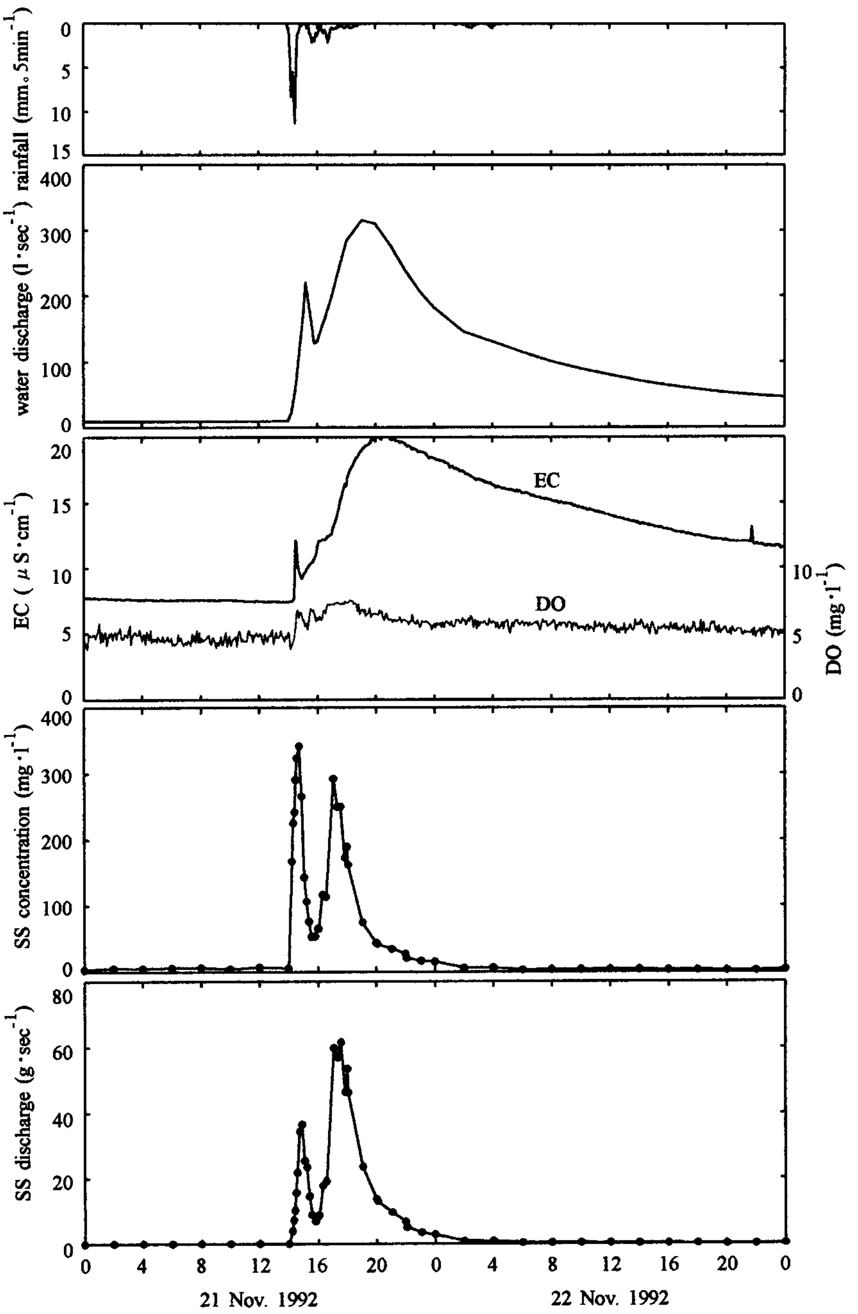

Figure 3. Observed fluctuation of rainfall intensity, water discharge, EC, DO, SS concentration and SS discharge of storm #2

drops entrain air as they collide with stream water. For the case of inclusion of oxygen by collision, the DO value of stream water should decrease within a few hours after rainfall stops. However, delivery delay from upstream to the measuring point is taken into consideration in such a small catchment as Bukit Tarek, because the velocity of stream water is fast enough to arrive from upstream to the weir site and thus flush out

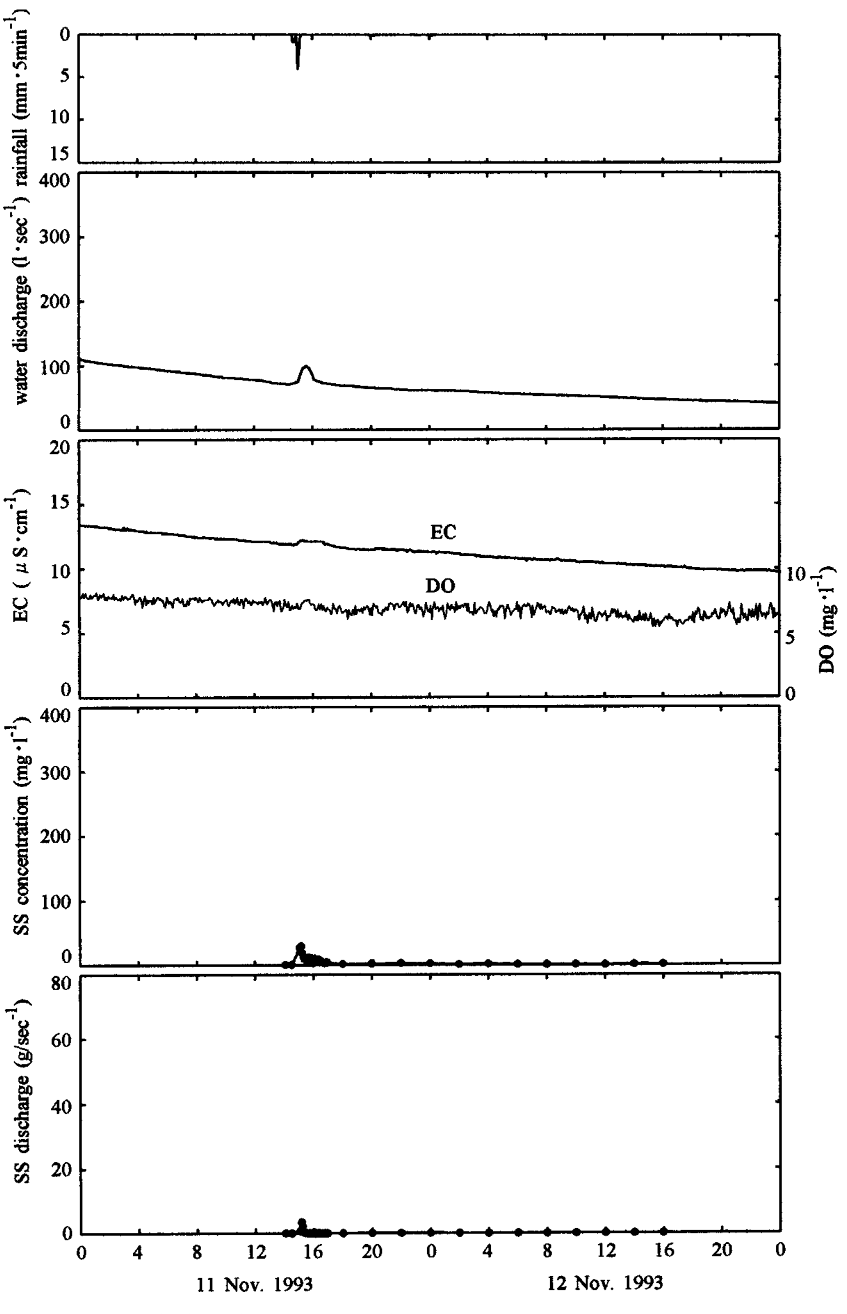

Figure 4. Observed fluctuation of rainfall intensity, water discharge, EC, DO, SS concentration and SS discharge of storm #3

the surface stream water containing high DO. However, the fluctuations of DO values during the moderate storms (#1 and #4) continued for a half a day (Figures 2 and 5).

The DO value in storm #2 indicated near saturation during the rainstorm and the DO levels decreased after the rainfall stopped; however, these post-storm values were still high compared with the values preceding the rainstorm (Figure 3). As a result, the rapid response of DO to rainfall is believed to have occurred because the

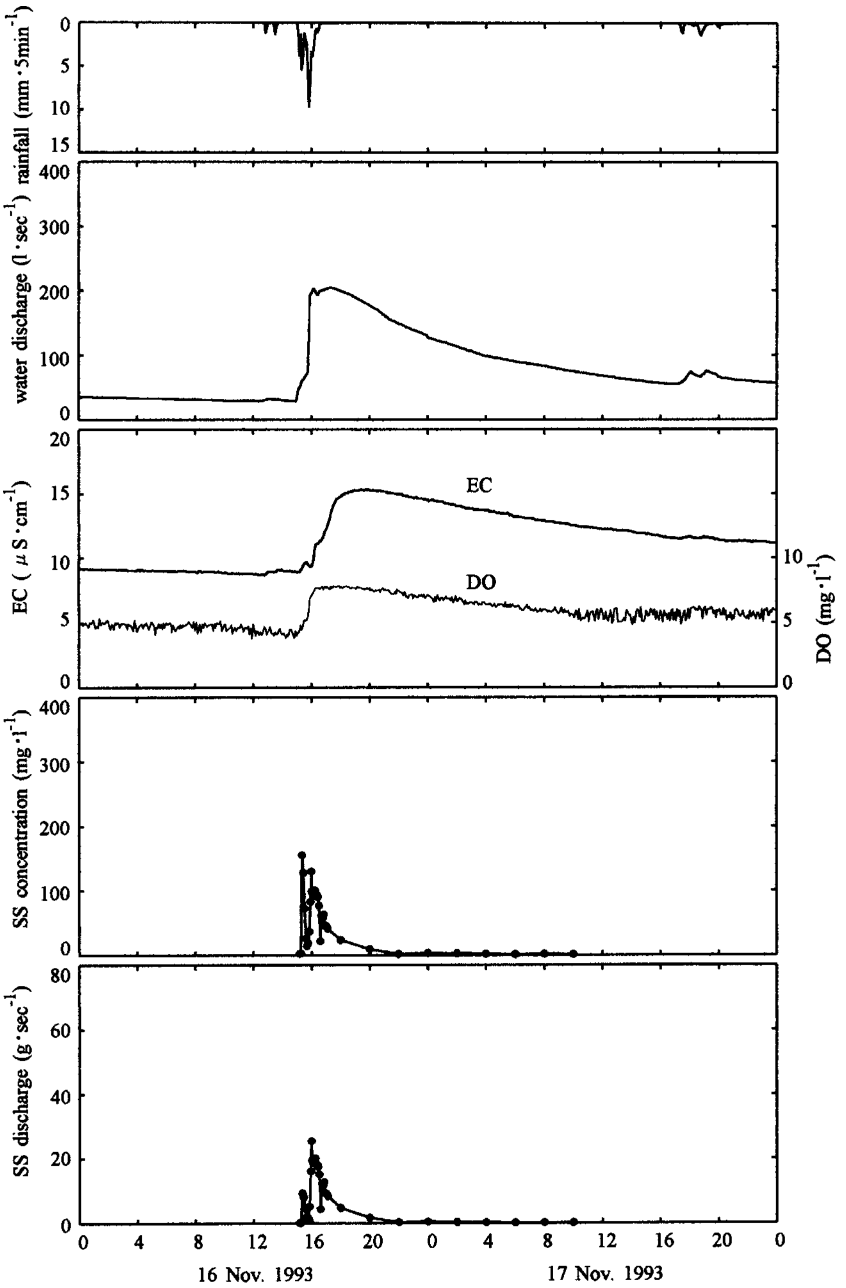

Figure 5. Observed fluctuation of rainfall intensity, water discharge, EC, DO, SS concentration and SS discharge of storm #4

discharge in the early stage of the storm was mainly derived directly from rain water. In contrast, the stream water had high values of EC, indicating that it originated from subsurface water. This subsurface flow formed the main or later storm flow following a lag after the rainfall due to the relatively longer flow pathway in the top soil. The value of EC was relatively small during base flow, indicating low levels of dissolved ions in Bukit Tarek Experimental Watershed. The maximum value (20 μS cm^{-1}) of EC emerged in the largest storm #2. The magnitude of the storm also affected the EC of stream water.

These characteristics of DO and EC fluctuations are based on the origin of the water that composed the earlier and later portions of the direct runoff. And the analysis between these parameters and SS will infer a useful hypothesis concerning the mechanism of SS generation and source area estimation.

Response of SS concentration

SS concentration rose quickly, with the peak of SS preceding that of stream water discharge, similar to the temporal DO response. The maximum value of SS concentration of each storm emerged on the rising limb of the hydrographs while it was still raining. This result strongly suggests that the main cause of SS is not the stream flow. In Table I and Figures 2–5, we can see a shorter lag between rainfall and SS concentration than the lag between peak of discharge and peak of SS concentration. Analysis of the relationship among water discharge, rainfall intensity and SS concentration is useful for determining the SS production mechanisms and sediment sources.

A clockwise hysteresis loop (Williams, 1989) for the relationship between SS and water discharge exists for all storms (Figures 6–9). The magnitude of hysteresis is proportional to storm size. Williams (1989), in

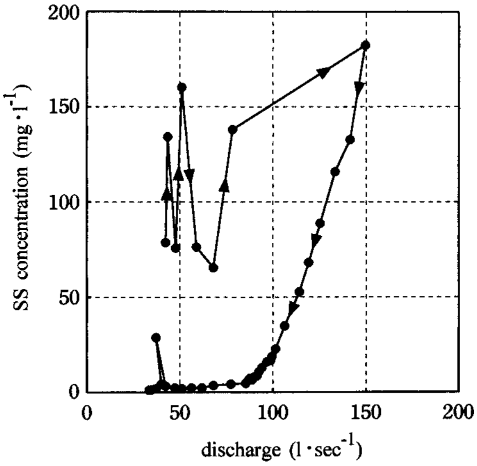

Figure 6. Relationship between discharge and SS concentration of storm #1

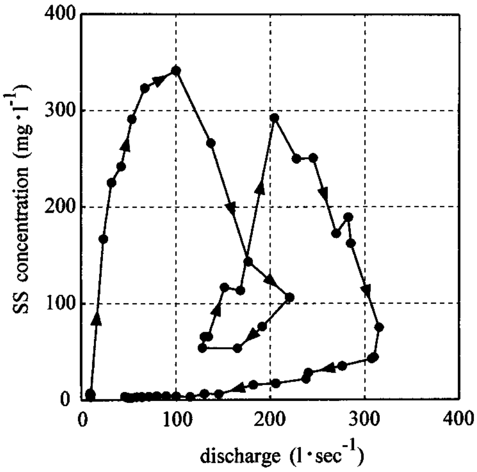

Figure 7. Relationship between discharge and SS concentration of storm #2

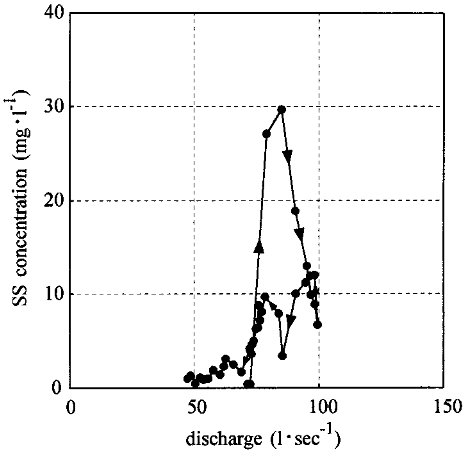

Figure 8. Relationship between discharge and SS concentration of storm #3

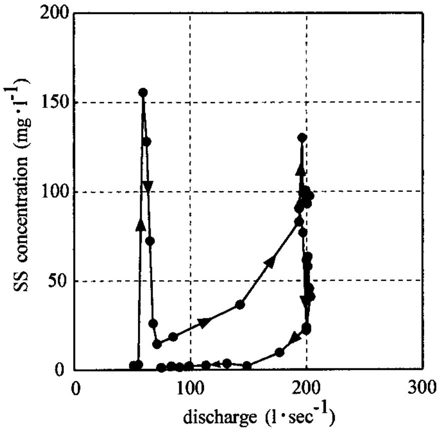

Figure 9. Relationship between discharge and SS concentration of storm #4

summarizing previous studies, attributed clockwise hysteresis to two major causes. The first is a depletion of available sediment before the peak of water discharge. The second is the effect of an armoured layer formation before the discharge peak. In Bukit Tarek, two significant hyetograph peaks were recognized in storms #2 and #4, and the SS concentrations fluctuating with the hyetograph also produced two major peaks (Figures 3 and 5). The two causes, however, do not explain the phenomenon in Bukit Tarek, since SS concentration rose again during the second rainfall peak. Furthermore, during the rising stage of SS concentration, water discharge was quite low and stream power was also low in relation to the low discharge. The main reason that the sediment response in Bukit Tarek cannot be explained by these hypotheses of hysteresis and SS sources is because of the relatively low tractive flow power in the Bukit Tarek stream. The clockwise hysteresis can be regarded as evidence of temporal and spatial differences between SS production and water discharge generation if the catchment and stream power are relatively small, such as at Bukit Tarek Experiment Watershed.

It is important to evaluate shorter, but not negligible, time gaps between the peaks of rainfall and SS concentration when we consider the production and delivery mechanisms of SS because rainfall intensity fluctuates in the short term. We observed that the flow rate was quite small but sedimentation rose quicker in the early stage of storms.

Here, we assume that SS act as a tracer which runs from the source to the measuring point for the distance. Discharge Q is described as follows:

$$Q = vlh \tag{1}$$

where v is mean velocity of stream flow, l is the width of the stream, h is the depth of stream water when the cross section shape of the stream is rectangular, and v is flow velocity calculated by Manning's formula:

$$v = \frac{1}{n} i^{1/2} h^{2/3} \tag{2}$$

where n is the roughness coefficient and i is gradient of stream bed. Combining Equations (1) and (2), we obtain

$$Q = \frac{1}{n} l i^{1/2} h^{5/3} \tag{3}$$

and h can be estimated as

$$h = \left(\frac{nQ}{l}\right)^{0\cdot 6} i^{-0\cdot 3} \tag{4}$$

The flow discharge Q (l s^{-1}) and velocity v from the start of rainfall to the first appearance of SS is assumed to be constant. The travel time ΔT (Min) from the source to the measuring point is obtained by

$$\Delta T = \frac{L}{v} = \frac{Llh}{Q} = (Ll^{0\cdot 4} n^{0\cdot 6} i^{-0\cdot 3}) Q^{-0\cdot 4} = aQ^b \tag{5}$$

Parameters a and b are 45·3 and −0·337 derived by the least-squares method using the values of Q and ΔT for the four storms. Variable b is affected by the cross-sectional shape of the stream; theoretically it is −0·4 when the channel cross-section is rectangular. The optimized value of b is close to the theoretical value for a rectangular shape. The relationship between initial discharge Q_{in} for a given storm and the time gap between the first peak of suspended solids concentration and the first peak of rainfall is shown in Figure 10.

Figure 11 shows the relationships between rainfall intensity and SS concentration for the four storms taking into consideration the time gap ΔT. The log-transformed value of SS concentration correlates positively with the log of rainfall intensity (Figure 11), and the following linear relationship could be applied in all four storms:

$$\mathrm{SS}(T) = c[R(T - \Delta T)]^d \tag{6}$$

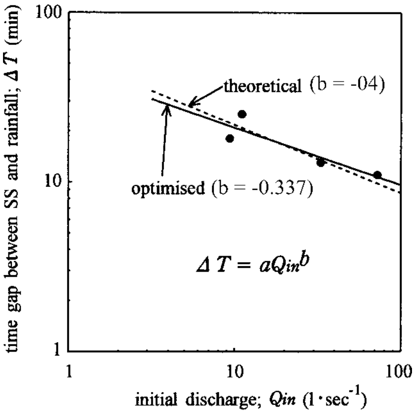

Figure 10. Initial discharge Q_{in} versus time gap ΔT between SS concentration and rainfall of four storms

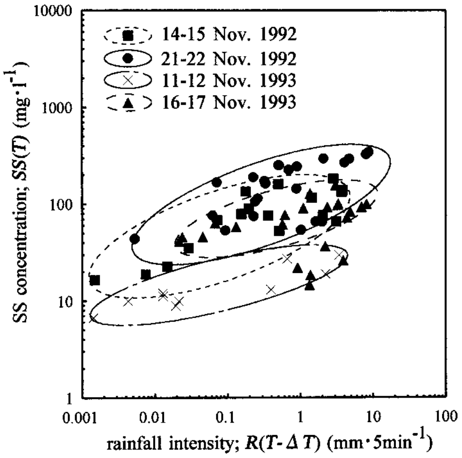

Figure 11. Relationship rainfall intensity; $R(T - \Delta T)$ and SS concentration $\mathrm{SS}(T)$

where $\mathrm{SS}(T)$ is the SS concentration at time T, $R(T - \Delta T)$ is rainfall intensity at time $T - \Delta T$, and c and d are the parameters that vary with storm events and are described as

$$c = 1258 Q_{\mathrm{in}}^{-0\cdot909} \tag{7}$$

$$d = 5\cdot513 Q_{\mathrm{in}}^{-0\cdot280} \tag{8}$$

Parameters c and d also depend on the initial discharge Q_{in} (Figure 12).

Soil detachment by raindrop impact contributes significantly to sediment production with surface sheet flow (Ellison, 1947; Meyer and Monke, 1965). Fukada (1993) reported that flow depths greater than 3·2 to 3·5 times the raindrop diameter do not affect soil detachment from the surface. Hudson (1971) investigated the relationship between raindrop diameters and rainfall intensities, and concluded that the mean diameter of raindrops shows a gentle convex curve against the rainfall intensity, and comes to 2·7 mm, when rainfall intensity exceeds 0·5 mm min^{-1}. The effective flow depth for SS generation is assumed to be less than 1 cm, based on the reports of both Fukada (1993) and Hudson (1971). Consequently, flow deeper than 1 cm protects against soil detachment by raindrop energy.

Hortonian overland flow will not occur on the hillslope in Bukit Tarek because the saturated hydraulic conductivities of the top soils are high (Noguchi *et al.*, 1997b) compared with the highest rainfall intensities.

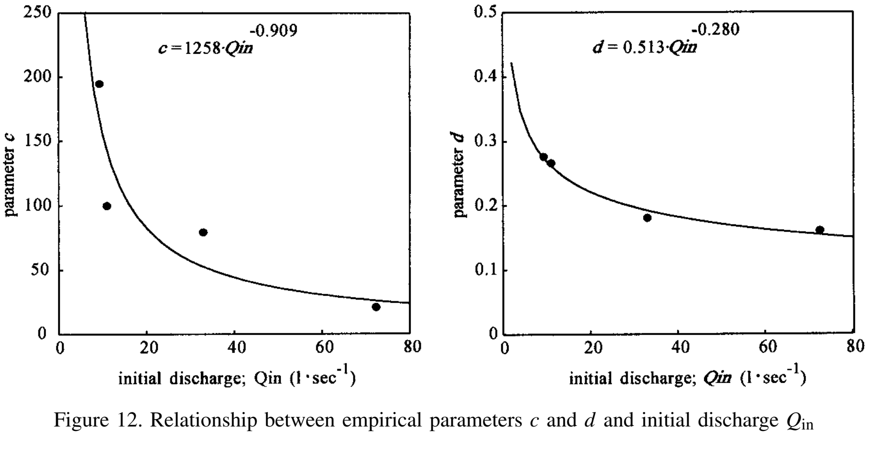

Figure 12. Relationship between empirical parameters c and d and initial discharge Q_{in}

The negative correlation between the empirical parameters *c* and *d* and the initial water discharge Q_{in} indicates that the source area of SS in Bukit Tarek is dependent on the stream flow. The following hypothesis of source area of SS explains these parameter relationships. The source area is already covered and protected with surface water from rainfall detachment when the value of Q_{in} is relatively large. In contrast, this source area is exposed to rainfall detachment when the value of Q_{in} is low. The relationship between SS concentrations observed and values calculated from Equation (6) is strong ($R^2 = 0{\cdot}66$; Figure 13).

Relationship between ignition loss and SS concentration

The percentage of SS mass lost after ignition indicates the relative mass of organic material in the SS. At low SS concentrations, organic matter comprised a large proportion of SS (Figure 14), as observed in other studies (e.g. Sidle and Campbell, 1985). The ignition loss converges at the 30–40% level, indicating relatively high organic matter content in SS even at higher SS levels, although the general relationship of organic matter

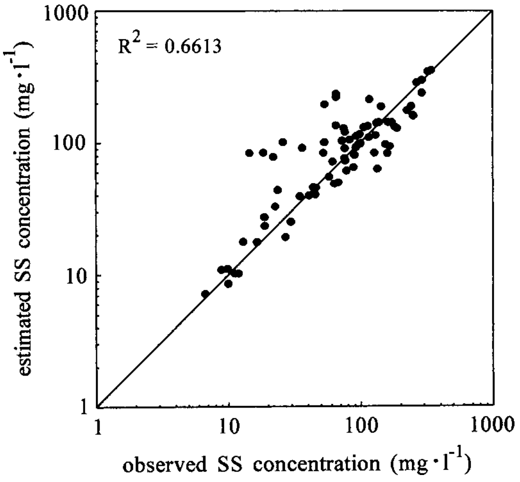

Figure 13. Observed and estimated SS concentration

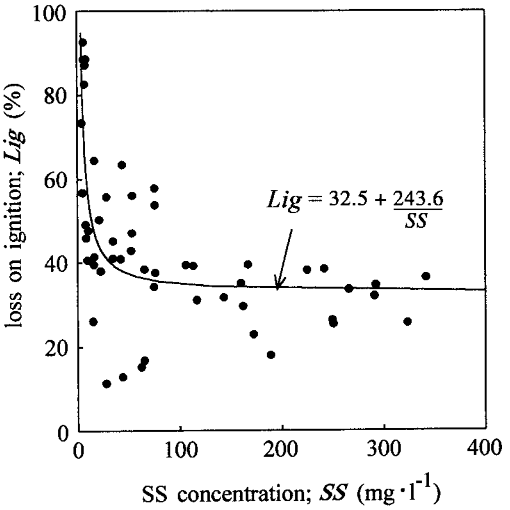

Figure 14. Relationship between SS concentration and loss on ignition L_{ig}

percentage with the SS concentration is inverse. This means that the source of high SS concentration differs from that of low SS concentration. The source of SS in Bukit Tarek at the peak is not confined to the stream gravels, because the minimum loss on ignition exceeds 30%, indicating a relatively high organic content compared with bedload gravels.

Hydraulic experiment of surface runoff

The experiment results are summarized in Table II. The roughness values obtained from the forested slopes with humus are about one-tenth of the values for the slopes without humus. Inflow during the runoff experiments on forested hillslopes from a reservoir tank was set at the maximum 5 l min^{-1} rate on the 0·2 m by 0·5 m slope because of the extremely high infiltration rate (almost 3000 mm h^{-1}). Therefore, Hortonian overland flow would not occur on the forested hillslope under normal storm conditions.

On the other hand, infiltration rates on the forest road were quite low and produce significant amounts of overland flow. However, surface flow on the forest road did not produce the SS. The maximum SS

Table II. Results of runoff experiment on forested hillslope and forest road

Plot	Surface condition	Velocity v (cm s^{-1})	Hydraulic radius h (cm)	Slope gradient i (sin θ)	Roughness n (m$^{-0.333}$ s^{-1})	SS (mg l^{-1})
1	Humus	6·395	0·2450	0·2867	0·032 79	8·8
	Bare	21·053	0·1146	0·2867	0·006 00	—
2	Humus	5·618	0·1113	0·4040	0·026 17	4·7
	Bare	29·520	0·0982	0·4040	0·004 58	24·9
3	Road	7·475	0·1236	0·1405	0·012 45	4·3
		10·602	0·1685	0·1405	0·010 79	7·4
		13·564	0·1981	0·1405	0·009 39	15·3
		16·181	0·2409	0·1405	0·008 97	—
		18·684	0·2336	0·1405	0·007 61	—

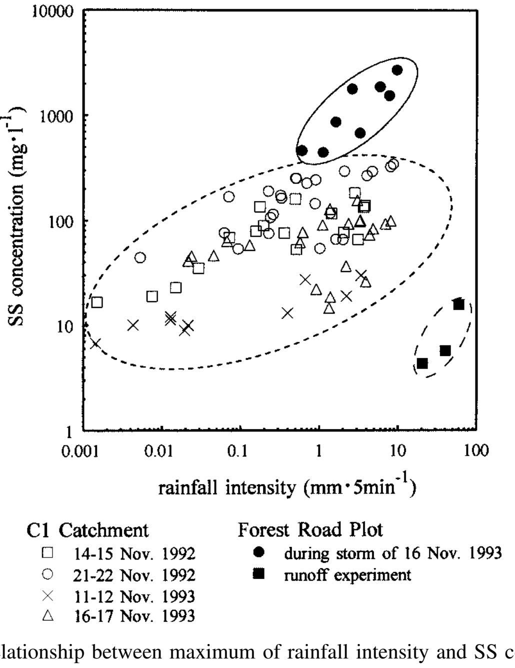

Figure 15. Relationship between maximum of rainfall intensity and SS concentration

concentration is only 15·3 mg l^{-1} (Table II) without rain. The sediment concentration during a storm event on the forest road plot was about two to three orders of magnitude higher than that of the sheet flow of the artificial experiments (Figure 15). These differences are due to the raindrop impact exerted during the natural storm compared with no chance of capturing raindrop impact in the artificial runoff experiments.

Flowing water was sampled from the side ditch of the forest road during the storm peak of 21 November 1992. The SS concentration was 14 096 mg l^{-1}, 41 times higher than the SS level in stream water of the forested basin at that time. This value is close to the data obtained from the surface runoff plot on the forest road during the storm event (Figure 15). Surface sheet flow with raindrop splash produces high levels of SS.

Source area and production mechanism of SS in the Bukit Tarek Experimental Watershed

The observed results, i.e. clockwise hysteresis, positive correlation between rainfall intensity and SS concentration, inverse correlation between c and d parameters and initial discharge Q_{in}, and negative relationship between loss on ignition and SS, provide important information for interpreting the SS production mechanisms at Bukit Tarek.

The source of high SS concentration must have been located close to or in the stream. This is because of the immediate transport of SS from the source to sampling site inferred from the short time gap between the peaks of rainfall intensity and SS concentration (Figure 3), as well as the high rate of infiltration on hillslopes. Furthermore, sheet flow as saturation overland flow, which does not appear on the hillslope, must have easily occurred in the SS source area during storm events for the rapid mobilization of SS to the stream. As riparian areas and deposits in the stream satisfy these requirements, such areas are likely sources of SS. The wet riparian zones and the stream deposits are exposed to raindrop impact when discharge is low (Figure 16). When stream discharge is high, these areas are covered by flowing water that protects soils and sediments from the kinetic energy of raindrops (Figure 16). This conceptual hypothesis also satisfies the inverse relation

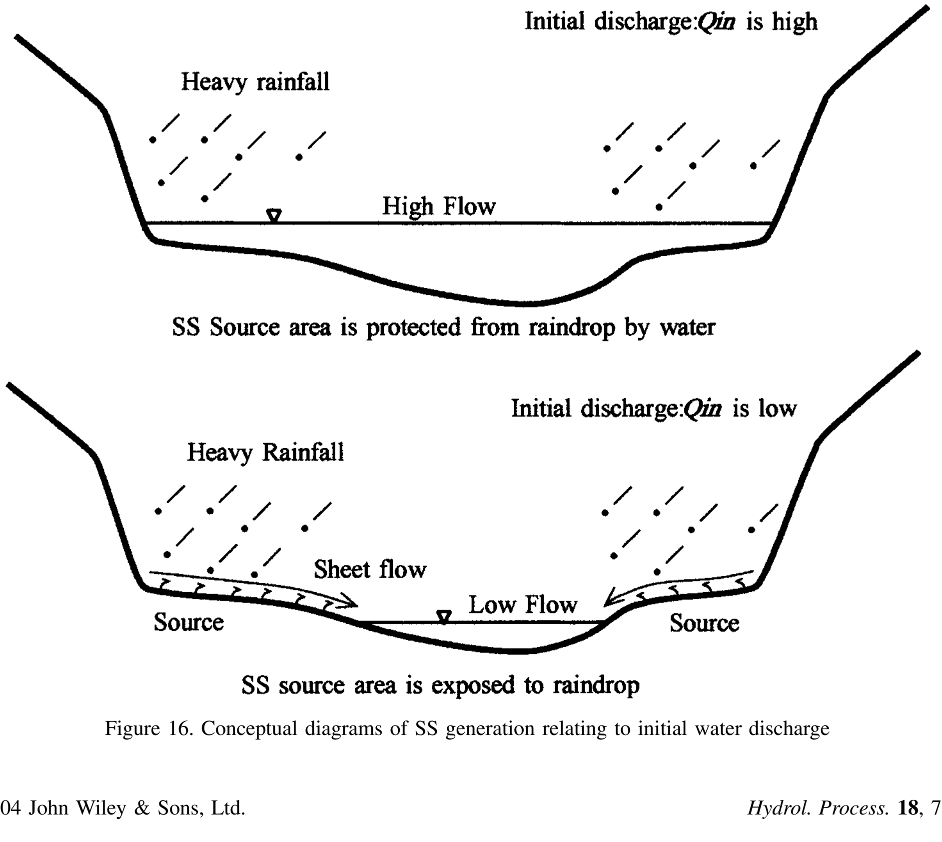

Figure 16. Conceptual diagrams of SS generation relating to initial water discharge

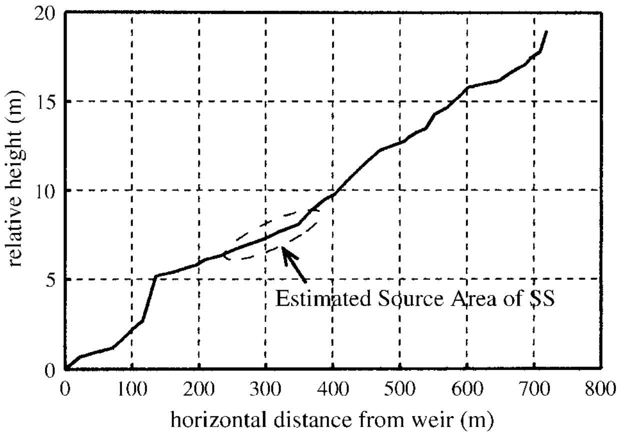

Figure 17. A longitudinal channel profile of C1 experiment watershed in Bukit Tarek

between the empirical parameters c and d and the initial discharge Q_{in}. In Bukit Tarek, such wet riparian zones are observed along the main stream over variable lateral extents.

The distance between the source area that generated the first peak of SS and the measuring point (defined as L) was calculated as 309·7 m by rearranging Equation (5) as

$$L = al^{-0\cdot4}n^{-0\cdot6}i^{0\cdot3} \tag{9}$$

where a, i, l and n are 205·8, 0·026 81 and 0·04 respectively. Figure 17 shows a longitudinal profile along the thalweg of the steambed within catchment C1. The source of SS is believed to be at a gentler stream gradient, where the wet riparian area exists.

The wet riparian areas correspond with the so-called contributing area (Betson, 1964) of water discharge, and the weak hysteresis of small storms (e.g. storm #3 Figure 8) verifies this hypothesis. However, the variable source-area concept (Tsukamoto, 1961; Ragan, 1967) of water discharge, which is extended from the partial area concept based on the contributing area, cannot be applied to SS production because the source area of SS production disappears when rainfall stops, whereas the source area of water discharge is still expanding (Figure 18). The SS source that is strongly related to rainfall generates a clockwise loop of SS concentration and water discharge. Heidel (1956) reported that the peak of sediment concentration usually occurs prior to that of water discharge in small catchments, a hypothesis that seems to apply in general to small catchments of humid regions in the world.

CONCLUSIONS

Intensive observations of rainfall, SS concentrations and simple surface runoff experiments were conducted on both forested hillslopes and a forest road in a small forested watershed in Bukit Tarek, Peninsular Malaysia. A clockwise hysteresis loop was found in the relationship between SS concentration and water discharge, and SS concentration was positively correlated with rainfall intensity. The concentration of SS during a storm was three orders of magnitude higher than that during an artificial overland sheet flow experiment without raindrop impact at the forest road site. These results strongly indicate that the SS source exists near the stream, and is likely concentrated along the wet riparian zone that corresponds to the so-called contributing area of water discharge. The hypothesis that a wet riparian zone close to the stream in a small catchment is a contributing area of SS requires extensive field observations to verify. However, there have been few examinations of the hysteresis phenomenon and source area of SS that consider both catchment scale and

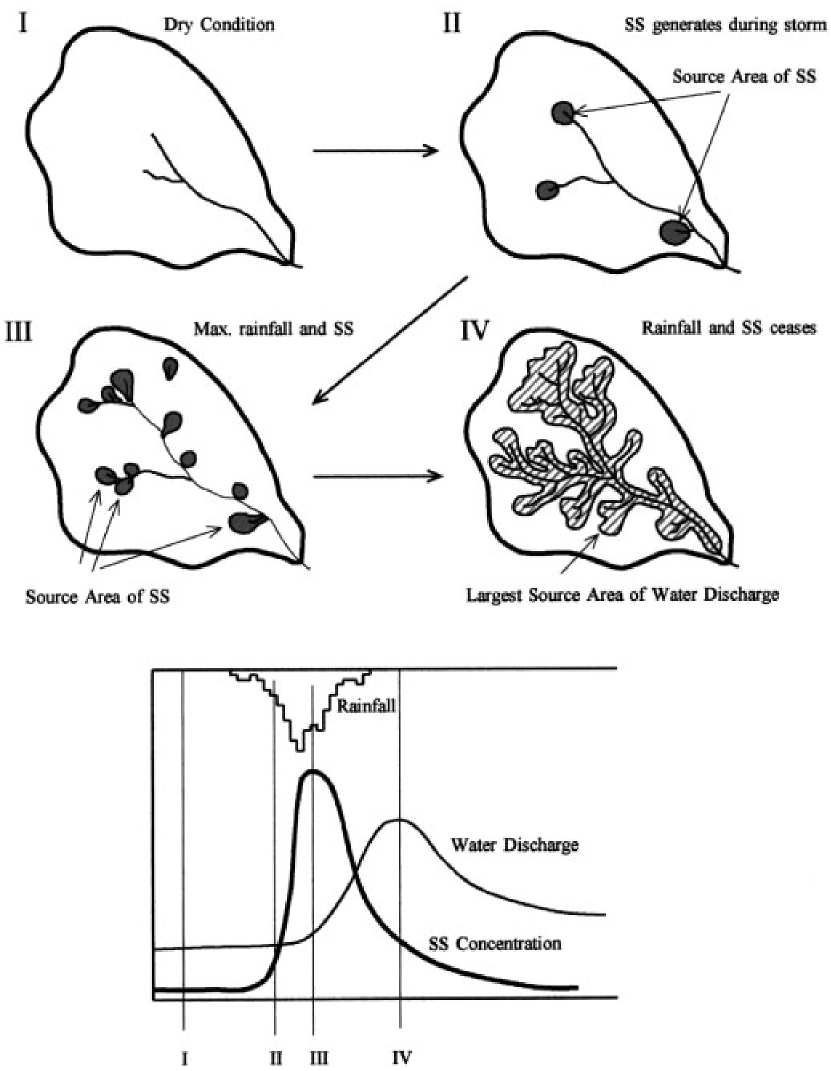

Figure 18. Conceptual diagram of source areas of SS and water discharge

stream power. Investigations that balance tractive stream power and raindrop energy related to catchment scales will be necessary to examine the SS issue more closely.

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