ELSEVIER
Catena 25 (1995) 117–126
CATENA

Log-jam effects on bed-load mobility from experiments conducted in a small gravel-bed forest ditch

A.A. Assani, F. Petit

Department of Physical Geography, University of Liège, Belgium

Received 9 July 1993; accepted after revision 25 February 1994

Abstract

Bed-load transport experiments have been conducted in a steep gravel-bed open ditch. This initially straight ditch has been neglected for many years and looks at present like a second-order natural stream channel. The channel flows through a spruce forest and several log-jams have produced chutes and pools, creating supplementary roughness. The total shear stress has been evaluated using the slope–hydraulic radius product, and the ratio between grain and bed-form shear stresses has been calculated using different methods. The shear stress has also been evaluated from the shear velocities, and this gives a good evaluation of the grain shear stress. Additional experiments have been conducted with marked pebbles to estimate particle mobility and to improve the motion equations. Equations such as $\theta_c = a(D_i/D_{50})^b$, defined by Andrews, apply in these cases but the values of a and b are lower than those produced by this author. In a second stage of experimentation, we have destroyed the log-jams resulting in a diminution of the roughness and critical shear stress (when the total shear stress is used), an increase of the grain shear stress, and thus greater bed particle mobility for the same discharge. It emerges from these experiments that the log-jams contribute to the reduction of bed-load evacuation and explain the very weak bed-load discharge measured by a bed-load trap ($0.3\ \mathrm{t \cdot km^{-2}\ yr^{-1}}$).

---

1. Introduction

In order to improve soil drainage and to allow spruce plantations, a large number of open ditches were dug in the Ardenne at the end of the last century and the beginning of the present one. In some basins the drainage density was thus tripled, creating hydrological problems, mainly the response of discharge to precipitation (Mbuyu, 1989), but also, as shown elsewere, problems relating to erosion and the evacuation of sediments (Newson, 1980; Burt et al., 1984). Nowadays these ditches are poorly maintained; dead

SSDI 0341-8162(95)00004-6

branches, old tree stumps or small trees fall into the channel, developing dams. Dietrich and Dunne (1978) have shown the importance of such channel debris in humid temperate forest sediment budgets. Indeed, log steps allow the storage of sediment, Marston (1982) showing that the amount of sediment stored was more than 120% of the mean annual sediment discharge of the system. On the other hand, the signifiance of log steps is also important for the dissipation of energy (Graf, 1988). Log jams may dissipate more than half of the energy of log-step streams (Heedee, 1972), and Keller and Tally (1979) have reported that the amount of energy dissipation ranges from 20 to 60%, a similar result to those of Keller and Swanson (1979) (30–80%).

Log-jams perform an important role in the dynamics of channels and the mobility of particles. Thus, we have conducted experiments in a forest ditch, using marked pebbles, with the object of determining the size of the material set in motion, the level of discharge at which movement occurrs, as well as the frequency of transport. These experiments were also intended to refine the critical shear stress values for the pebble bed-load.

2. Characteristics of the site

The area under investigation lies in the Hautes-Fagnes close to ''Signal de Botrange'', the highest point in Belgium at an altitude slightly less than 700 m. The flow in the stream was measured by a rectangular thin plate weir and water-level recorder. This station has been working for four years.

The main characteristics of the basin and channel studied (the Rû des Waidâges) are in Table 1 (Mbuyu and Petit, 1990). Because of the geometry of the ditch, overbank discharge did not occur during the four year period. This discharge, calculated by Manning's formula, would be about 200 $l \cdot s^{-1}$. This corresponds to a flood occuring only once in several decades. The discharge with an annual return period ($Q_{1\ \mathrm{year}}$) is estimated to be 40 $l \cdot s^{-1}$ in the partial duration series. This value appears to be the theoretical bank-full discharge, because, translated in terms of specific bankfull discharge, it is close to values established for other small Ardenne rivers in which the recurrence of bankfull discharge is known to be of the order of 1 year (Petit and Daxhelet, 1989).

Table 1
Physiographic characteristics of the ''Rû des Waidâges'' catchment

(1)	Annual precipitation	1300 mm
(2)	Area	0.26 km^2
(3)	Stream order (Strahler cl)	2
(4)	Channel gradient	0.046 $m \cdot m^{-1}$
(5)	Width	0.75 m
$Q_{1\ \mathrm{year}}$ (rec. interval)		40 $l \cdot s^{-1}$
Stream power ($Q_{1\ \mathrm{year}}$)		25 $W \cdot m^{-2}$
Bed material — D_{50}		22 mm

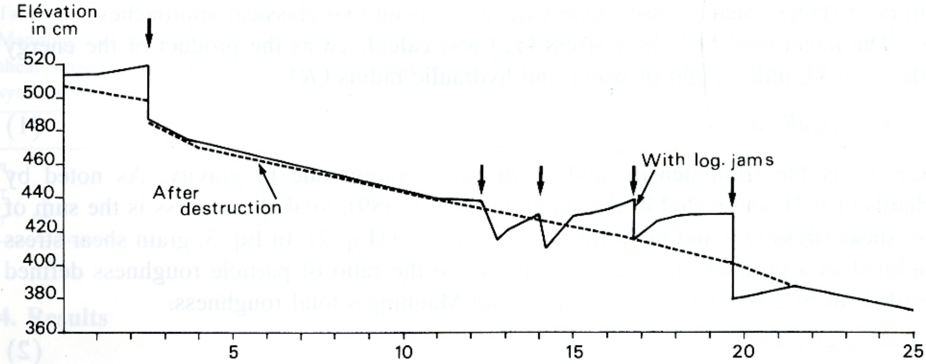

Fig. 1. Longitudinal profile of the reach studied in the Rû des Waidâges (exaggeration in elevation is 5-fold).

As Fig. 1 shows, the reach studied comprises five clearly defined log-jams. These completely dam the stream, which is narrow and does not flow in a V-shaped valley. The situation is very different from that shown by Nakamura and Swanson (1993) in first and second order streams. In the Rû des Waidâges, the dams cause overflows with plunge-pools downstream, as described by Robinson and Beschta (1990), and during low discharges, potential energy dissipated by log-jams amounts to more than 80%. This is comparable to the figures obtained by Keller and Swanson (1979) but greater than from reported by Marston (1982).

In the Rû des Waidâges, log-jam density is about 20 per 100 m on average. Such a density is not out of the ordinary in comparison with values quoted by Spencer et al. (1990) and Gregory et al. (1993) in recent reviews. Log-jam density varies as a function of stream-order, with a general decrease downstream: 20–40 dams per 100 m in first order streams, but only about 5–10 in third-order streams. However, as emphasized by Gregory et al. (1993), "stream order seems not be the best definition of channel size and may not give a consistent basis for comparison from one area to another". On the other hand, as shown by Trotter (in Gregory et al., 1993), log-jam density under coniferous forest is about ten times greater than, for example, in channels flowing in aspen woodlands.

The spacing of log-jams is usually about 2 or 3 times the stream width (Petts and Föster, 1985), which is much shorter than that for riffle sequences. Log-jam spacing in the Rû des Waidâges is 7 times the width, and fits well with the usual riffle spacing along channels (Richards, 1982).

3. Methodology and experimentation

Measurements and experiments were carried out in two distinct stages: firstly, when the log-jams were still in place in the ditch; and secondly after all the log-jams had been destroyed and the bed had been allowed to restablish.

In both stages shear stresses were calculated using two classical approaches:

(i) The mean total bed shear stress (τ_b) was calculated as the product of the energy grade line (S), unit weight of water and hydraulic radius (R):

$$\tau_b = \rho_f gR \cdot S \tag{1}$$

where ρ_f is the fluid density and g the acceleration due to gravity. As noted by Richards (1982), and tested in the flume by Petit (1989), total shear stress is the sum of grain shear stress (τ') and bedform shear stress (τ'') (Eq. 2). In Eq. 3, grain shear stress is defined as a product of total shear stress and the ratio of particle roughness defined according to Strickler's equation (Eq. 4) and Manning's total roughness.

$$\tau_b = \tau' + \tau'' \tag{2}$$

$$\tau' = \tau_b \left(\frac{n_o}{n_t} \right)^{3/2} \tag{3}$$

where

$$n_o = 0.048 D_{50}^{1/6} \tag{4}$$

and n_o = roughness due to particles, n_t = Manning's total roughness and D_{50} = median diameter of material forming the bed (expressed in m).

(ii) Shear stress was secondly calculated from the friction velocity (u^*):

$$\tau^* = u^{*2} \rho_f \tag{5}$$

The shear velocities (u^*) are estimated from the vertical distribution of flow velocities close to the river bed, represented by

$$\frac{u}{u^*} = 2.5 ln \frac{y}{y_o} \tag{6}$$

where u = velocity of the current measured at a distance y from the bed, y_o = roughness height, a function of the diameter of the particles forming the bed. In this case, the equation $y_o = 0.2 D_{50}$ (with D_{50} = median diameter) as proposed by Hammond et al. (1984), was employed.

(iii) Finally, when movement of bed material occurred, shear stress was evaluated by these two methods and then expressed in terms of dimensionless shear stress, using Shields' criterion (Eq. 7).

$$\theta_c = \frac{\tau_c}{(\rho_s - \rho_f) g \cdot D} \tag{7}$$

where θ_c = Shields' dimensionless criterion, τ_c = critical shear stress, ρ_s = density of the sediment and D = diameter of the material involved.

The experiments were conducted with pebbles marked in situ. Thus, there is no difference between the marked pebbles and the bed material, with regard to disposition, size, or shape (95% of the material with $C/B < 0.6$ and $B/A > 0.6$ according to the Zingg classification).

Table 2
Manning coefficient of total roughness (n_t), ratio of grain shear stress to total shear stress (τ'/τ_b) and ratio of shear stress from shear velocities to total shear stress (τ^*/τ_b) for the Q_1 annual recurrence discharge, in systems with and without log-jams. Average of values measured in six cross sections for each stage

	With log-jams	After log-jam destruction
n_t	0.350	0.055
τ'/τ_b	0.052	0.38 ($d/D_{50} \leq 4$)
τ^*/τ_b	0.47	0.72

4. Results

Table 2 provides a summary of results, showing (i) the values of Manning's coefficient of total roughness n_t (at the 1 year recurrence discharge); (ii) the ratio of grain shear stress (τ' from Eq. 3) to total shear stress (τ_b from Eq. 1); (iii) the ratio of shear stress from shear velocities (τ^* from Eq. 5) to total shear stress (τ_b from Eq. 1), for both stages (before and after removal of the log-jams).

It is immediately apparent that the roughness is significantly higher in the system with log-jams which suggests that the bed-form shear stress will be much higher. This emerges clearly from the ratio τ'/τ_b, which is very low here. However, this ratio remains relatively low (0.38), even after removal of the log-jams. This low ratio would appear to result from the low relative submergence which comes out clearly from the ratio d/D_{50} (where d is the depth and D_{50} the median diameter of the material forming the bed). As shown by various authors (Bathurst et al., 1981; Rauws, 1987; Petit, 1989), when relative submergence is below 4, supplementary roughness occurs. Indeed, a microrelief exists produced by the irregularities of the bed as a result of the arrangement of the particles, and this may act like a bed-form shear stress.

Furthermore, it can be seen that in both stages, the ratio between the shear stress calculated from shear velocities (τ^*) and total shear stress is higher. This fact has already been shown to be true for rivers (Petit, 1990). Similar measurements have been made over a range of discharges. It emerges that the ratios τ'/τ_b and τ^*/τ_b decrease both before and after the log-jams are removed as the discharge decreases.

Figs. 2 and 3 give the critical shear stresses — those necessary to initiate movement of particles — expressed in terms of Shields' dimensionless criterion θ_c.

4.1. θ_c calculated using τ_b

In Fig. 2 the shear stress used is total shear stress (Eq. 1), and values are plotted against the ratio D_i/D_{50} where D_i is the diameter of the particles moved and D_{50} the median of the particles forming the surface of the bed.

It is evident that the value of θ_c diminishes when the ratio D_i/D_{50} increases. Thus an equation of the type $\theta_c = a(D_i/D_{50})^b$ (Eq. 8), as proposed by Andrews (1983), seems applicable to these data. Moreover, close examination of these relationships indicates that critical shear stresses are significantly higher in the presence of log-jams, thus

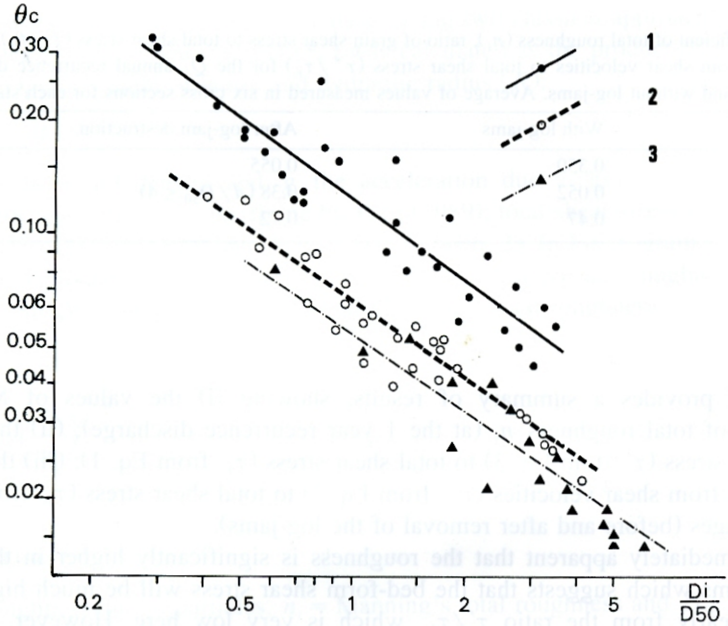

Fig. 2. θ_c (calculated with the total shear stress τ_b) versus the D_i / D_{50} ratio. (1) Motion of marked pebbles in the log-jam system. (2) motion of marked pebbles after log-jam destruction. (3) No motion of marked pebbles after log-jam destruction.

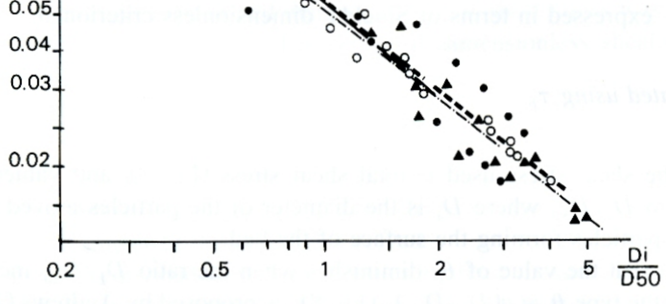

Fig. 3. θ_c (calculated with the shear stress from shear velocities $\tau *$) versus the D_i / D_{50} ratio. (1) Motion of marked pebbles in the log-jams system. (2) Motion of marked pebbles after log-jams destruction. (3) No motion of marked pebbles after log-jams destruction.

Table 3
Values of coefficients a and exponents b in the equation $\theta_c = a(D_i/D_{50})^b$ in systems with and without log-jams

	With log-jams	After destruction of log-jams	No movement
θ_c with τ_b	$a = 0.123$ $b = -0.70$	$a = 0.065$ $b = -0.69$	$a = 0.058$ $b = -0.69$
θ_c with τ^*	$a = 0.058$ $b = -0.80$	$a = 0.055$ $b = -0.78$	$a = 0.051$ $b = -0.78$

θ_c calculated using τ^*.

confirming the importance of bed-form shear stress (coefficient $a = 0.123$ as opposed to 0.065 in the absence of log-jams) (Table 3).

In order to test the validity of these relationships, we conducted a series of experiments involving systematic measurement of the shear stresses at which no movement of particles occurred despite high shear stress values. Confirmation was obtained that these values are lower than those at which movement does occur (a lower value of coefficient a in Eq. 8; 0.058 as opposed to 0.065).

4.2. θ_c calculated using τ^*

These same relationships are shown in Fig. 3, but this time with shear stresses calculated from shear velocities (Eqs. 5 and 6). The general tendency in the relationships persists (a decrease in θ_c when D_i/D_{50} increases), but contrary to Fig. 2, the relationships established with and without log-jams are very close. This strongly suggests that shear stresses calculated from shear velocities do not take into account effects of bed-form shear stress. Hence their application seems recommended in the evaluation of initiation of movement of bed particles. Moreover, the coefficients a are close to 0.055 and exponents b are close to -0.80. These values are lower than those suggested by Andrews (1983) (respectively $a = 0.083$ and $b = -0.87$) and approximate quite closely to those of Komar (1987) ($a = 0.045$ and $b = -0.7$), and those obtained in a gravel-bedded flume by Petit (1994).

Thus, as a result of the greater roughness and the higher degree of bed-form shear

Table 4
Discharge, frequency and duration for bed-load movement, before and after log-jams destruction

	With log-jams	After log-jams destruction
Q_{im}	$35\ l \cdot s^{-1}$	$25\ l \cdot s^{-1}$
Frequency of Q_{im}	1.7 times per year	4.7 times per year
Duration of Q_{im}	2 hours per event	10 hours per event
D_{50} (marked pebbles moved)	9.7 mm	12.5 mm
D_{90} (marked pebble moved)	32 mm	66 mm
Bed-load yield	$0.3\ t \cdot km^{-2} \cdot yr^{-1}$	

Q_{im} = discharge at initiation of bed load motion (about fifty percent of marked pebbles in motion, in both situations).

Table 5
Annual bed-load discharge and some physiographic characteristics for two small Ardenne streams

	Area (km^2)	Gradient ($m \cdot m^{-1}$)	Bed-load discharge ($t \cdot km^{-2} \cdot yr^{-1}$)	D_{50} (mm) [a]	D_{90} (mm) [a]	
Ruisseau de la Mer	1.36	0.071	0.56	19.5	56	Mercenier (1973)
Ruisseau de Wavelinse	4.33	0.024	0.36	9.8	34	Dave (1975)

[a] In sediment traps.

stress, the total shear stress required to initiate movement of the bed load is higher in the system with log-jams. These higher shear stresses are reached only in higher discharges of ca. $35 \ l \cdot s^{-1}$, as compared with the $25 \ l \cdot s^{-1}$ required to initiate bed-load movement after destruction of the log-jams (Table 4). Such higher levels are obviously less frequent: on average twice a year as opposed to five times a year for $25 \ l \cdot s^{-1}$. Additionally the duration of this discharge also differs. A $35 \ l \cdot s^{-1}$ flow lasts two or three hours per event whereas the $25 \ l \cdot s^{-1}$ discharge lasts on average more than ten hours.

These differences are also apparent in the size of particles eroded and transported: the D_{50} of the bed load is only 9.7 mm in the system with log-jams as opposed to 12.5 mm after removal of the log-jams. This difference in competence is even more evident when considering D_{90} (32 and 66 mm respectively).

These results clearly show that development of log-jams inhibits initiation of movement and transport of bed material and thus tends to reduce the amount of material transported. Confirmation on this point was obtained by determining the bed load transported, by means of a sediment trap. This was only $0.3 \ t \cdot km^{-2} \cdot yr^{-1}$, which correlates quite well with values obtained in other small Ardenne rivers flowing through forest cover, and in which log-jams are also well developed (Table 5).

These values are significantly lower than those obtained by Reynolds (1986), of 8 $t \cdot km^{-2} \cdot yr^{-1}$, in a small moorland catchment basin in Wales. Moreover, Newson (1980) reported rates of bed-load transport this high in small, steep catchments in moorland Wales subject to artificial drainage, stressing the risk of sedimentation in reservoirs situated downstream.

On the other hand, the volume of sediments stored behind log-jams in the Rû des Waidâges amounts to three times the annual bed-load discharge on average. This value is higher than those produced by Marston (1982), of about 120% of the total sediment discharge including the suspension load. However, in the Rû des Waidâges, log-jams may cause a local increase in erosion in the plunge-pools, which results in greater storage of material in the next log-jam.

5. Conclusion

These results allow two types of conclusion to be drawn.

Firstly, from a methodological viewpoint: (1) grain shear stress (τ') evaluated on the basis of the roughness ratio (Eq. 3) seems to be underestimated in this type of channel;

(2) shear stress values obtained from shear velocities (Eqs. 5 and 6) are adequate for determining the critical condition and the transport of material; and (3) as proposed by Andrews (1983), dimensionless critical shear stress (Shields' θ_c) diminishes when the D_i/D_{50} increases, but the values of the coefficient a and exponent b are lower.

Secondly, from a practical standpoint, the effect of log-jams increases roughness considerably; the total shear stress necessary to initiate movement of material is thus much higher and requires higher discharges, these being naturally rarer and of shorter duration. Hence log-jams do reduce the mobility of particles, the bed-load discharge and, finally, erosion and denudation of hydrographic basins.

Acknowledgements

The authors thank Prof. K. Richards (Cambridge University) and Prof. A. Abrahams (University at Buffalo) for suggestions and corrections to our draft.

References

Andrews, E.D., 1983. Entrainment of gravel from naturally sorted river bed material. Geol. Soc. Am. Bull., 94: 1225–1231.

Bathurst, J.C., Li, R.M. and Simon, D.B., 1981. Resistance equation for large scale roughness. J. Hydraul. Div. ASCE, 107: 1593–1613.

Burt, T.B., Donohoe, M.A. and Vann, R.A., 1984. Changes in the yield of sediment from a small upland catchment following open ditching for forestry drainage. Catena Suppl., 5: 63–74.

Dave, C., 1975. Etude de la dynamique fluviale d'un petit ruisseau de type torrentiel. Le ruisseau du fond de Wavelinse. Mem. Lic. Sc. Géog., Univ. Liège, 147 pp.

Dietrich, W.E. and Dunne, T., 1978. Sediment budget for a small catchment in mountainous terrain. Z. Geomorphol. Suppl., 29: 191–206.

Graf, W.L., 1988. Fluvial Processes in Dryland Rivers. Springer-Verlag, 346 pp.

Gregory, K.J., Davis, R.J. and Tooth, S., 1993. Spatial distribution of coarse woody debris dams in the Lymington Basin, Hampshire, UK. Geomorphology, 6: 207–224.

Hammond, F.D.C., Heathershaw, A.D. and Langhorne, D.N., 1984. A comparison between Shield threshold and the movement of loosely packed gravel in a tidal channel. Sedimentology, 31: 51–62.

Heedee, B.H., 1972. Influences of a forest on the hydraulic geometry of two mountain streams. Water Resour. Bull., 8: 523–530.

Keller, E.A. and Tally, T., 1979. Effects of large organic debris on channel form and fluvial processes in the coastal redwood environment. In: D.D. Rhodes and G.P. Williams (Editors), Adjustments of the Fluvial System. Kendall-Hunt, Dubuque, IA, pp. 169–197.

Keller, E.A. and Swanson, F.J., 1979 Effects of large organic debris on channel form and fluvial process. Earth Surf. Process., 4(4): 361–380.

Komar, P.D., 1987. Selective grain entrainment by a current from a bed mixed sizes: a reanalysis. J. Sed. Petrol., 57: 203–211.

Marston, R., 1982. The geomorphic signifiance of log stress in forest streams. Ann. Assoc. Am. Geogr., 72(1): 99–108.

Mbuyu, N., 1989. Etude des paramètres influençant les relations pluie-débit. Modèle de prévision des crues. Application aux bassins alimentant le lac d'Eupen: Helle, Getz et Vesdre. Thèse doctorat, Sc. Géog., Univ. Liège, 302 pp.

Mbuyu, N. and Petit, F., 1990. Comportement hydrologique de deux bassins versants se différenciant par leur couvert végétal et leur épaisseur de tourbe. Bull. Soc. Belg. Etudes Géogr., 59(2): 261–274.

Mercenier, J., 1973. Dynamique fluviale dans un petit bassin du rebord méridional du plateau des Tailles (le bassin du ruisseau de Belleva). Mém. Lic. Sc. Géog., Univ. Liège, 145 pp.

Nakamura, F. and Swanson, F.J., 1993. Effects of coarse woody debris on morphology and sediment storage of a mountains stream system in western Oregon, Earth Surf. Process. Landforms, 18: 43–61.

Newson, M., 1980. The erosion of drainage ditches and its effects on bed load yields in Mid-Wales: reconnaissance case studies. Earth Surf Process., 5: 275–290.

Petit, F., 1989. The evaluation of grain shear stress from experiments in a pebble-bedded flume. Earth. Surf. Process. Landforms, 14: 499–508.

Petit, F., 1990. Evaluation of grain shear stresses required to initiate movement of particles in natural rivers. Earth Surf. Process. Landforms, 15: 135–148.

Petit, F., 1994. Dimensionless critical shear stress evaluation from flume experiments using different gravel beds. Earth Surf. Process. Landforms, 19: 565–576.

Petit, F. and Daxhelet, C., 1989. Détermination du débit à pleins bords et de sa récurrence dans différentes rivières de moyenne et haute Belgique. Bull. Soc. Géogr. Liège, 25: 69–84.

Petts, G. and Föster, I., 1985. Rivers and Landscape. Edward Arnold, Sevenoaks, 274 pp.

Rauws, G., 1987. The initiation of rills on plane beds of non-cohesive sediments. Catena Suppl., 8: 107–118.

Reynolds, B., 1986. A comparison of element outputs in solution, suspended sediments and bedload for a small upland catchment. Earth Surf. Process. Landforms, 11: 217–221.

Richards, K., 1982. Rivers Form and Process in Alluvial Channels. Methuen, London, 358 pp.

Robinson, G.E. and Beschta, R.L., 1990. Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska (USA). Earth Surf. Process. Lanforms, 15: 149–156.

Spencer, T., Douglas, I., Greer, T. and Sinun, W., 1990. Vegetation and fluvial geomorphic processes in South-East Asian Tropical Rainforest. In: J.B. Thornes (Editor), Vegetation and Erosion; Processes and Environments. Wiley, pp. 451–469.

Reprinted from

CATENA

Catena 25 (1995) 117–126

Log-jam effects on bed-load mobility from experiments conducted in a small gravel-bed forest ditch

A.A. Assani, F. Petit

Department of Physical Geography, University of Liège, Belgium

ELSEVIER