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THE RELATIONSHIP BETWEEN SHEAR STRESS AND THE SHAPING OF THE BED OF A PEBBLE-LOADED RIVER LA RULLES—ARDENNE

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SUMMARY

Geomorphological modifications in the bed of a small pebble-loaded river were related to different parameters such as flow velocity and shear stress. Experiments carried out with marked pebbles of known diameter demonstrated that shear stress calculated from the energy grade line slope and the hydraulic radius is a reliable criterion in explaining erosion and transport of the pebble load. Increase in shear stress with discharge entrainment varies according to site. At times of low flow, shear stress is weak in the pools allowing transitory accumulation of fine deposits and pebbles; these originate mainly from erosion downstream of riffles where shear stress is already considerable. At times of discharge near bankfull stage, shear stress becomes considerable in the pools, so that pebbles deposited at lower discharge rates are then displaced. However, the coarser elements are halted on the counter slope of the pools and upstream of riffles, since shear stress there is then weaker than in the pools. Riffles thus appears as stopping-places with only small elements (1.5 cm diameter) able to cross them at times of high discharge. The size of these elements thus provides an estimate of the true competence of the river.

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RESUME

Les modifications géomorphologiques du lit d'une petite rivière à charge caillouteuse ont été mises en relation avec différents paramètres dynamiques tels que les vitesses du courant et les forces tractices. Des expériences faites avec des cailloux marqués de diamètre connu ont montré que la force tractice calculée à partir de la pente d'énergie et du rayon hydraulique était un critère fiable qui permettait d'expliquer l'érosion et le transport de la charge caillouteuse. L'augmentation des forces tractices avec le débit est différente suivant les sites. Lors de débits peu importants, les forces tractrices sont faibles dans les mouilles et permettent une accumulation transitoire de dépôts fins et de cailloux; ceux-ci proviennent notamment de l'érosion dans la partie aval des seuils où les forces tractrices sont déjà importantes. Lors de débits voisins du débit à pleins bords, les forces tractrices deviennent importantes dans les mouilles si bien que les cailloux déposés lors des plus faibles débits sont

alors remaniés. Toutefois, les éléments les plus grossiers sont stoppés dans la contre-pente des mouilles et dans la partie amont des seuils car les forces tractrices y sont alors plus faibles que dans les mouilles. Les seuils se présentent donc comme des lieux d'arrêt et seuls des éléments de petite taille (de l'ordre de 1.5 cm de diamètre) peuvent les franchir, lors de débits élevés. La taille de ces éléments donne ainsi une estimation de la compétence effective de la rivière.

1 INTRODUCTION

Geomorphological modifications of a gravel bed stream have been followed for five years in succession in seven 100 m sectors. A limnigraphic station was set up close to the sectors under investigation in order to identify the discharge engendering each type of modification and to determine the recurrence of these discharges. Thus, the rates of discharge of the annual flood and the quinquennial flood are respectively 3 m^3/sec and 5 m^3/s, whereas the bankfull discharge of 1.3 m^3/s is reached or exceeded on average 2.5 times per annum (DEGEE & PETIT 1981). As a result of these frequent floods, certain processes have been brought to the fore, which act in a specific manner on the outline of the bed. Thus, short-circuits taken by the flow in time of flooding allow surface hollows to be formed in the final loop of meanders, where there is runoff in the shape of a plunge-pool, as well as the cutting of channels, which ultimately lead to the creation of islets (PETIT 1984). Consequently, it is more particularly the modifications observed in the very heart of the minor bed, which are analysed below in relation to discharge velocity and shear stress. The results obtained from the study of one sector alone are submitted, since it is representative of the physical features of the river as a whole, and since more intensive investigation of this sector has been undertaken.

2 GEOMORPHOLOGICAL MODIFICATIONS IN THE MINOR BED

The river flows in its own distinct minor bed, incised into the compacted silt forming the alluvial plain. As a general rule, only rarely is the river in direct contact with the bedrock composed of quartzites and quartzpophyllades of the Siegenian. However, small pebbles lenses regularly come to the surface in the banks, or at their base, enabling the river to renew almost continually its pebble-load, the diameter of which is generally less than 5 cm. Conversely, when the river attacks the base of the slopes, it is then restocked with distinctly coarser material (10 cm diameter, sometimes greater).

The river forms a series of winding curves (index close to 2) which, in this sector forms two meanders the shape of which suggests an omega (fig.1) . Pools are associated with each of the loops of the meanders, while riffles comprising recent deposits of pebbles ("constructed riffles") are located at the inflexion points separating the loops (riffles cross-sectioned in profile G9/D11 and profile G25/D30 in fig.1).

Morphological changes were brought out by topographical cross-sections undertaken at time of minimal flow, but also at times of flooding and subsiding water levels. Furthermore, pebbles of known diameter were marked with paint in different locations and their entrainment was followed as a function of the

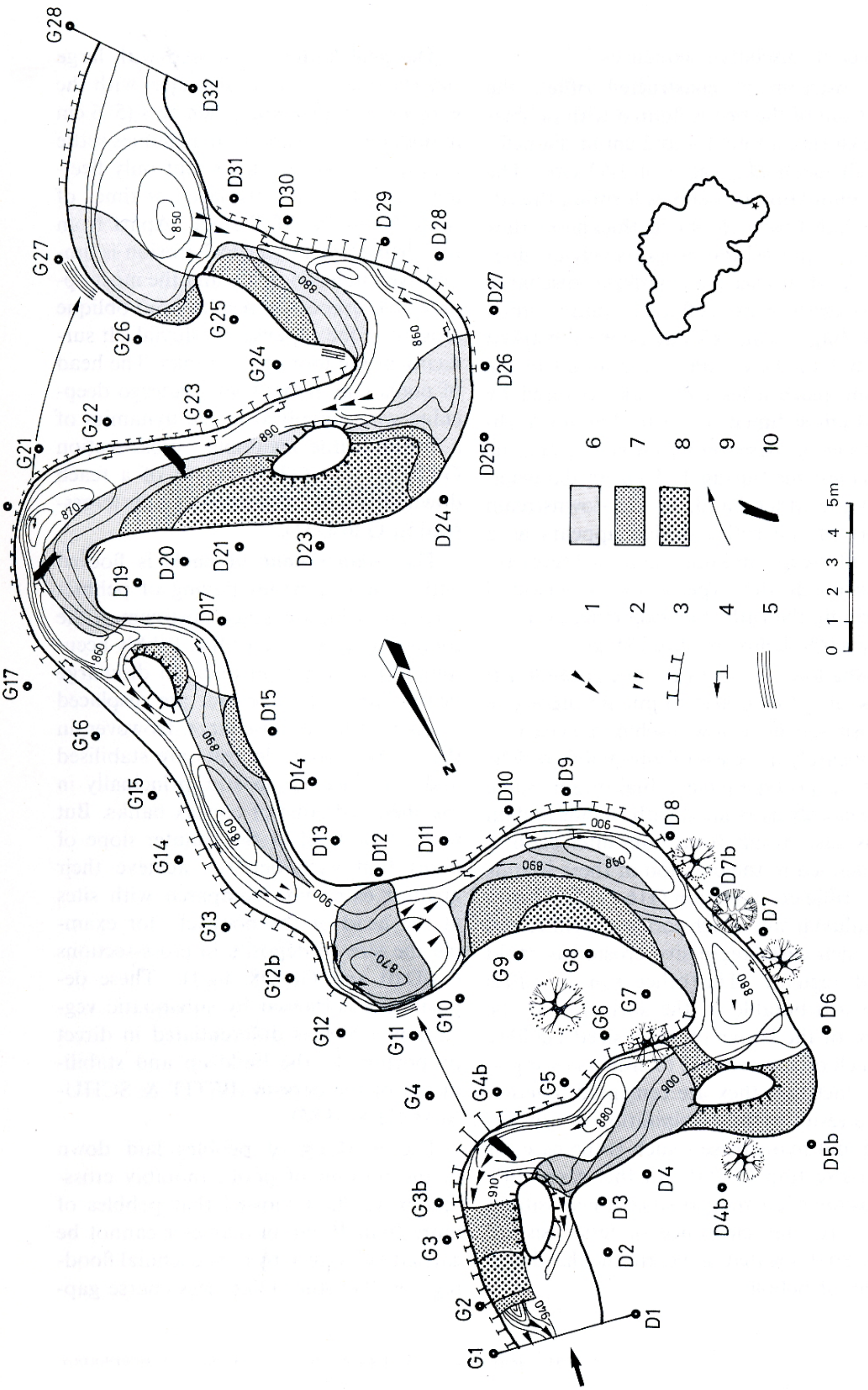

Figure 1: *Geomorphological changes observed during the period 1973–1978.*

1. regressive erosion; 2. Vertical erosion; 3. Lateral erosion. 4. Oblique erosion; 5. Erosion and toppling of clods following pour-off in period of flood; 6. Transitory deposits; 7. Stabilized accumulations (less than 20 cm thickness); 8. Stabilized accumulations (more than 20 cm thickness); 9. Short-circuit of discharge in time of flood; 10. Old tree-trunks set in the riverbank.

different discharge sequences.

Upstream of **constructed riffles**, the bottom of the bed is floored with pebbles measuring about 1.5 to 2 cm in diameter (with mean D_{50} value of 1.52 cm). The accumulation of pebbles forming the riffle may reach 25 cm in thickness; they are put in position progressively at times of flood in excess of bankfull discharge and resist heavier floods (quinquennial flooding). Thus eleven pebbles marked in one of these riffles were found in the same place after two years, covered by 3–4 cm sediment deposit. The mean diameter of these pebbles was 1.92 cm, the smallest measuring 1.35 cm in diameter. On the other hand, in the downstream part of the riffles, which appears as a small steep banking, there is regressive erosion at the expense of the material forming the riffle, this occurring even for discharge below bankfull stage.

Shallows of another type, **run-off riffles**, are also subject to intense regressive erosion, even at low discharge, occasionally barely in excess of minimal flow. Riffles of this type have a dual origin. Some are closely associated with islands and, in this case, result from mini-intersections, which led to the creation of these islands (ex. riffle cross-section G16-D17). Then it is alluvial silt, which forms the riffle, and in such cases regressive erosion is rapid and regular. The other run-off riffles are attributable to the surfacing at the foot of the banks of grain sized pebbles, which offer resistance to erosion owing to the fact that they are cemented together as a result of the precipitation of iron oxide and manganese—such is the case for cross-section G1-D1. In this case, riffle erosion is less regular since it necessitates the previous clearance of less resistant material located beneath the hardened level of pebbles.

The pool bottom is floored with large size slabs (8–10 cm in diameter) with the gaps filled with smaller elements (5–6 cm in diameter). Layers of small stones settle on top of these elements, but only fleeting, since they are displaced at times of spate below bankfull stage. Apart from this displacement, vertical erosion is limited even in heavy spate and the most appreciable deepening results from oblique erosion at the expense of alluvial silt surfacing at the foot of the banks. The head of pools may nonetheless undergo deepening when involved in the dynamics of a run-off riffle (example: cross-section G17/D19 and G24/D24), or of a reach downstream of a constructed riffle (cross-section G26/D31).

The counter-slope of pools is floored with a homogeneous paving of pebbles foreshadowing the reach upstream of the following constructed riffle. Pebbly accumulations are put in place in discharge below bankfull stage, but are displaced at times of higher discharge. However, in the loops, certain deposits are stabilised and may increase in size, principally in the sheltered zone of convex banks. But it is at the level of the counter-slope of pools that such deposits achieve their greatest extension, compared with sites at the head of the pool (cf. for example the size of deposits in cross-sections G8/D10 and G8/D8, fig.1). These deposits are colonised by subaquatic vegetation, which is differentiated in direct proportion to the build-up and stabilisation of the deposit (PETIT & SCHUMACKER 1985).

The marking of pebbles laid down in the bottom of pools, (notably cross-section G5/D4) showed that pebbles of more than 10 cm in diameter cannot be carried away even by quinquennial flooding. On the other hand, less coarse gapfilling elements (6 cm) can be eroded, but leave the pool only to be blocked immediately in the following counter-slope (G6/D4B).

Moreover, pebbles painted in position at the level of the ridge of a constructed riffle (cross-section G3B/D3) were able to be moved following regressive erosion of the riffle, and thus pass through the pool located just downstream, and also its counterslope, thus occurring under the effect of small spates the heaviest of which remained below annual flood level. The larger elements (2 cm) were blocked in the upstream part of the next riffle (cross-section G7/D5B) and were, moreover, covered over subsequently by 2 to 3 cm of pebbly material. Only elements below 1.5 cm were able to pass over the riffle and even, in certain cases, other riffles further downstream, thus moving several dozen metres in a single flood.

The marking of pebble grains surfacing in the river banks showed that quite large pebbles (5 cm) set in finer material sufficiently high in the riverbank, when falling into the bed after the erosion of the surrounding material, could travel several metres in pseudo-suspension before settling on the bottom of the bed.

These observations indicate that upstream of riffles, accumulation sites are durable. In the counterslopes of pools, however, these accumulations are transitory, apart from shelter zones coinciding with the convex bank, where they are stabilized.

The part downstream of riffles and the bottom of pools appear as erosion sites, although in the case of the latter, the large boulders found in the bottom of pools cannot be moved and thus seem to hinder deepening. However, when the finer infill is displaced, undermining at the base of the boulders might lead to vertical erosion, but such erosion would, however, be less than in the absence of these boulders.

Measurement of current velocities was carried out in some fifteen sites for discharges ranging from minimal flow to heavy flood. However, as will be seen below, current velocities are not sufficient to explain all the geomorphological changes; that is why, subsequently, another criterion was taken into account, namely shear stress.

3 VELOCITY AND ORIENTATION OF CURRENT

Velocity was measured with an OTT current meter, the different blades of which were 3 cm or 5 cm in diameter. The meter was orientated along the line of highest current velocity. Besides, in test campaigns, instantaneous current velocities were measured with a MARSH McBIRNEY electromagnetic sounding device. This enabled a check to be made that differences between instantaneous velocities and velocities integrated over a certain time lapse, that is to say under measurement conditions identical to those carried out with an OTT meter, remained below $\pm 15\%$.

Moreover, the orientation of the current was estimated at different depths at each of the sites by means of a small vane.

The current organises itself into a succession of zones of confluence and of diffluence. The former are localised on the counter-slope of pools and in the upstream reaches of riffles, where there is appreciable narrowing of the section; the latter downstream of riffles and in the pools (fig.2). However, in the pool as-

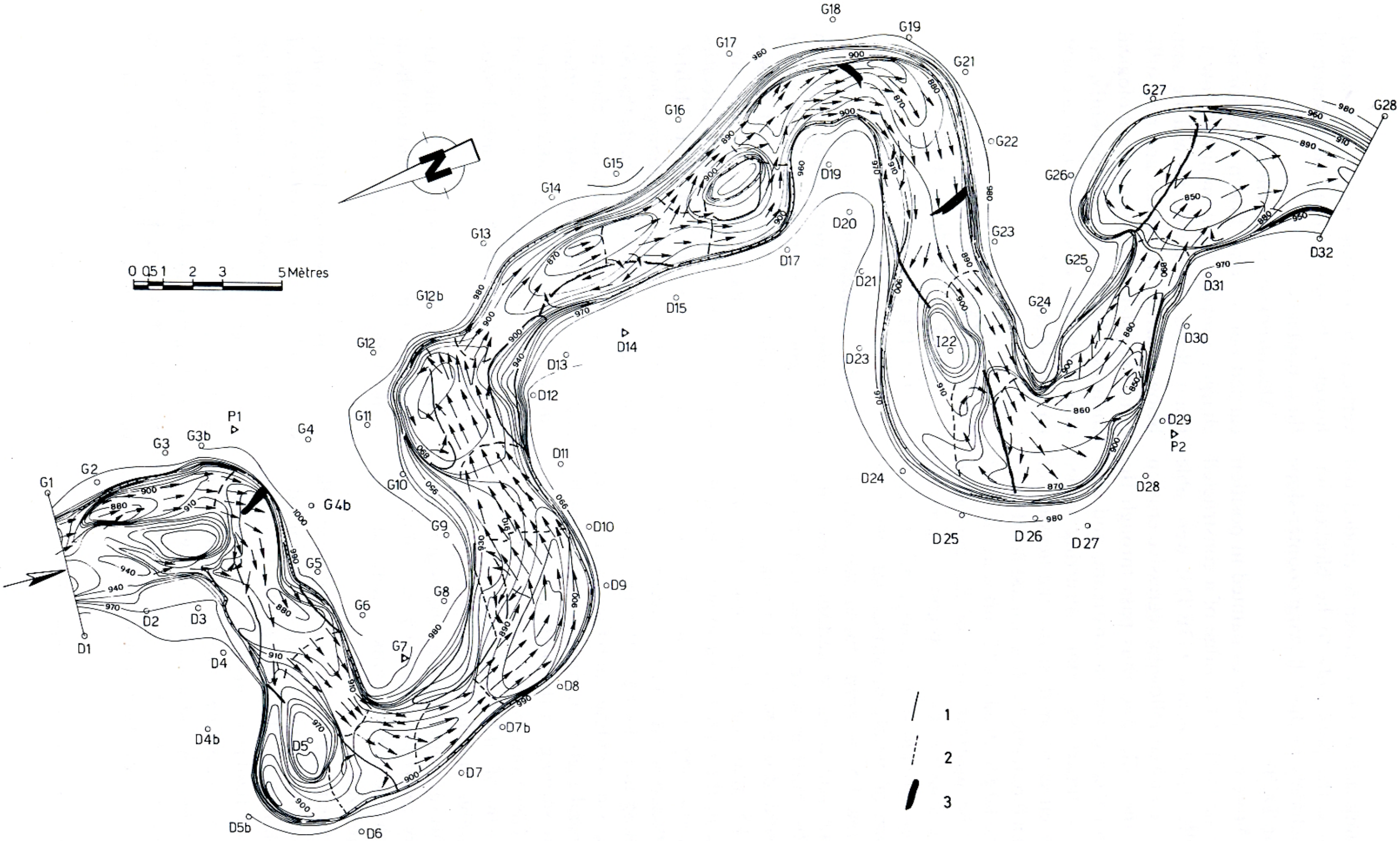

Figure 2: *Orientation of the surface current for a discharge slightly superior to mean discharge ($0.4\ m^3/sec$).*
1. Limit between main flow and calm or countercurrent zones; 2. Limit between zones of diffluence and confluence; 3. Old trunks set in the bank.

sociated with the last loop of each of the meanders, the diffluence occurs downstream of the crest of the loop (respectively downstream of points G12 and G27, fig.2); at discharge below bankfull stage, this diffluence creates a cell with a counter current with the fact that the river bank is shaped by a plunge-pool process at times of discharge in excess of bankfull stage (PETIT 1984).

The transverse components of the current measured on the basis of an identical cross-section in different sites in the sector well illustrate this organisation of the current into diffluence and confluence (fig.3). Only exceptionally do the lateral components of the current organise themselves into a continuous cell with a horizontal axis orientated in the direction of the current, so that no continuous helidoical movement throughout the full length of the meanders can be formed. Thus, the organisation of the current observed in the Rulles differs from the schema suggested principally by BATHURST, THORNE & HEY (1975), BRIDGE & JARVIS (1982), LEOPOLD (1982). This seems to result from the morphology of the river under investigation. Indeed, the dimensions of its bed are restricted, so that riffles and pools alternate more frequently. Additionally, the presence of very high constructed riffles and numerous small islands is noted. These elements give rise to successive widening and narrowing, thus forcing it to organise itself into confluence and diffluence, which clearly militates against the development of helicoidal movement.

Velocity distribution in the sections is closely linked to this organisation of the current. In confluence, the generalised acceleration of the current caused by the narrowing of the section, is reflected by high velocity throughout almost all the section, notably close to the bottom (fig.4A).

Conversely, in diffluence (as in the case of pools with the exception of their counter-slope), high velocities occupy a more restricted part of the section, and velocity gradients close to bottom are less marked than in confluence. Thus maximum velocities measured 10 cm from the bottom barely reach 60 cm/sec in the pool as opposed to 75 cm/sec on the riffle (fig.4). As observed by KELLER (1971), bottom velocities increase more in the pools than in the riffles with increasing discharge. But in this case, they are still more important in the riffles for a discharge near the annual flood.

Moreover, it will be recalled that pebbles of 2 to 3 cm in diameter were eroded in the bottom of pools, or were able to pass through in floods approaching bankfull stage. However, current velocities registered in such sites even in time of greater flood (57 cm/sec at 10 cm above bottom) remain distinctly lower than the critical erosion velocities as inferred from the diagrams of HJULSTROM & SUNDBORG (1956) (1.5 m/sec at 10 cm above bottom for erosion of elements of this size).

Indeed, in the study of an Ardenne stream, MERCENIER (1973) had already shown that velocities which had enabled erosion to take place on pebbles of 4.5 cm were lower by half than the critical erosion velocities. According to this author, these differences result from the fact that, in turbulent flow, instantaneous velocities fluctuate considerably around the mean and can thus peak to levels sufficient to erode pebbles. However, instantaneous velocity measurements, as seen above, by means of electromagnetic sounding have shown that fluctuations in these velocities are

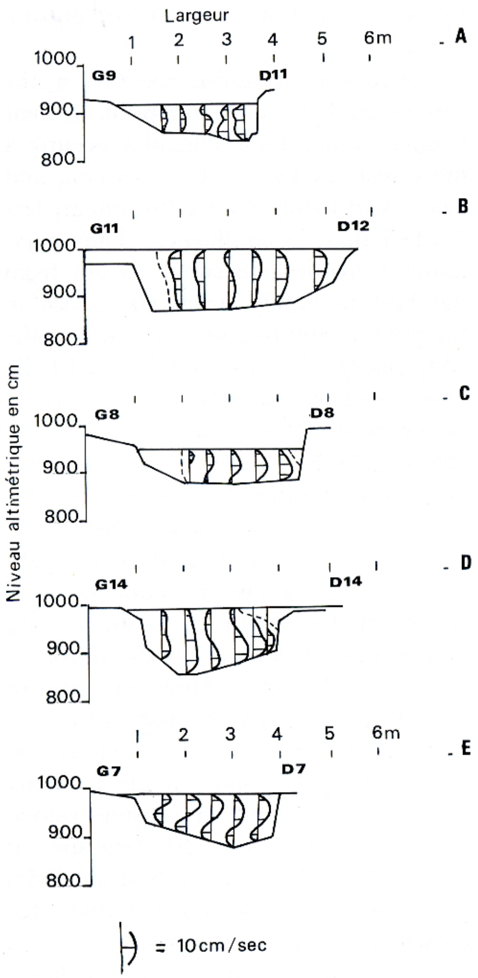

Figure 3: *Transverse components of the current in different sites:*

A: Confluence in the reach upstream of a constructed riffle (cross-section G9-D11).

B & C: Marked diffluence at the head of a pool (sections G11-D12 and G8-D8).

D: Diffluence at the lowest point of a pool (section G14-D14).

E: Organisation into a continuous cell at the lowest point of a pool situated slightly downstream of the crest of a loop (section G7-D7).

(Heights exaggerated 2x).

relatively small and in any case do not suffice to explain such differences.

Moreover, we have seen upstream of riffles, durable accumulations of pebbles of 1.5 to 2 cm in diameter are deposited, although the current velocities are equivalent to (or even greater than) those registered in the pools, where pebbles of this size will be eroded.

4 EVALUATION OF SHEAR STRESS

Shear stress was evaluated in the first instance by having recourse to the following equation:

$$\tau = \gamma R_h S_e \qquad (1)$$

where

γ = the specific weight of the fluid,

R_h = the hydraulic radius,

S_e = the slope of the energy grade line.

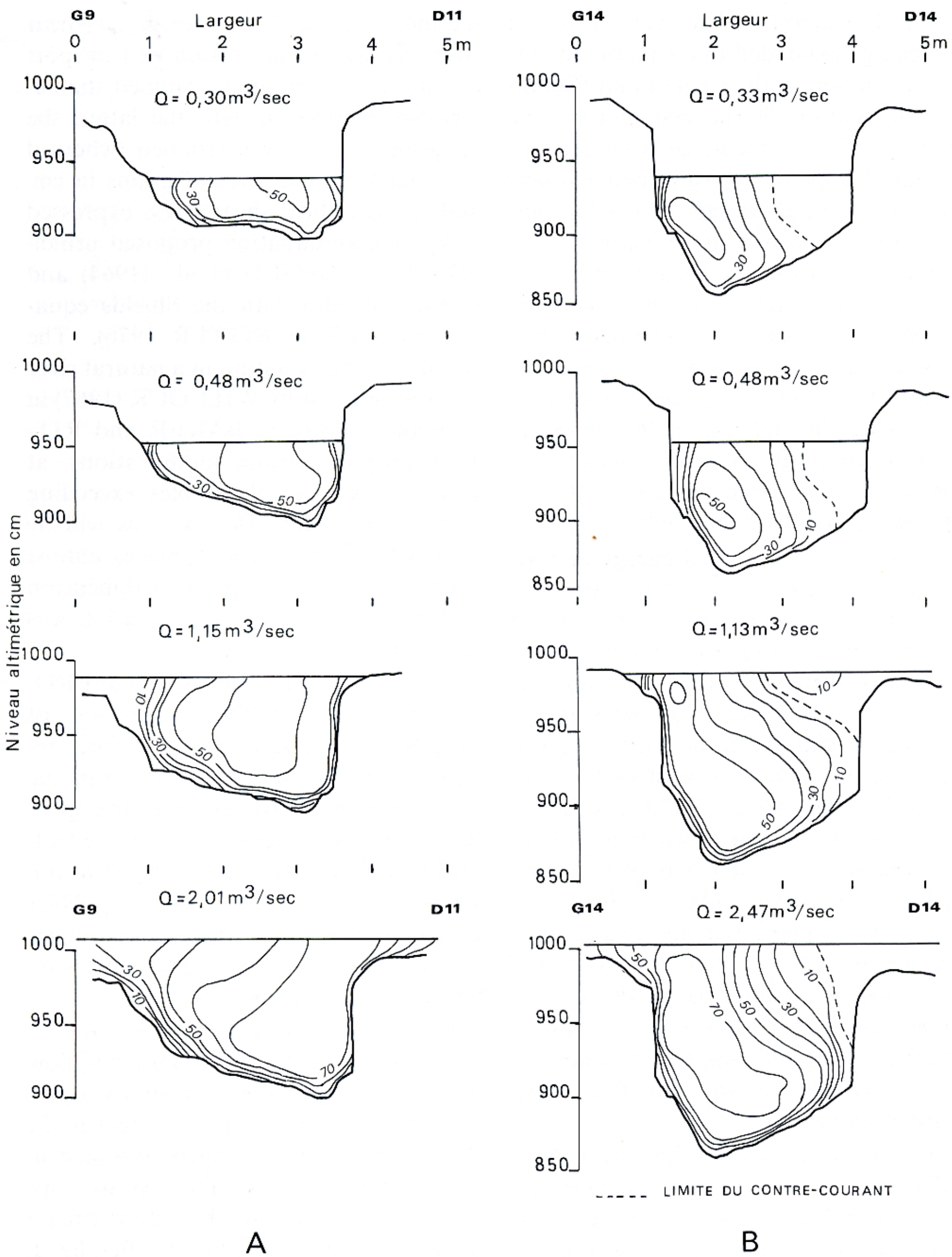

Figure 4: *Distribution of velocities for differing discharges:*
A: In the reach upstream of a constructed riffle (section G9-D11).
B: At the lowest point of a pool (section G14-D14).
(equidistance of lines of equal velocity 10 cm/sec; heights exaggerated 2x).

The last-mentioned in fact represents the energy expended to overcome the internal friction of the current and friction on the bottom of the bed and on the riverbanks. It is calculated from the longitudinal slope of the water plane (quantity of potential energy, which has undergone a transformation between two points), and from the longitudinal variation of the term $\alpha \cdot v^2/2g$, which expresses the variation in kinetic energy, and in which v represents the mean velocity of the current, g the acceleration due to weight and α a coefficient equal to 1 (CARLIER 1972), but which can reach values between 1.03 and 1.36 in a natural river (SELLIN 1969).

Variations in potential energy and kinetic energy are closely related; thus the increases in velocity, where narrowing of the section occurs, necessitates obligatorily a transformation of the potential energy, that is to say that the slope of the water plane will be more marked there (such is the case upstream of riffles). However, when a sudden widening occurs (as in the case downstream of riffles and the head of the pools), current velocity diminishes, whereas the slopes of the water plane remain considerable. So the amount of potential energy does not respond instantly to the decrease in kinetic energy, as a result of current inertia; the energy dissipated by friction is henceforth considerable and the energy slope pronounced.

Moreover, we verified that shear stress calculated on the basis of equation (1) was a reliable criterion permitting an explanation of erosion and transport of the pebble load. Indeed, the displacement of marked pebbles of known diameter (from 0.5 cm to 6 cm) was followed in different sites, and the shear stresses calculated by this method were set against critical shear stress (τ_c) (shear stress necessary for erosion or transport of an element of predetermined diameter). In connection with the latter, the equation $\tau_c = d$ was retained (where d represents the diameter of grains in cm, and τ_c the critical shear stress expressed in kg/m^2), an equation proposed principally by LEOPOLD et al. (1964) and which coincides with the Shields equation (BAKER & RITTER 1976). The validity of this equation in a natural river was brought out by WILCOCK (1967) in particular, although BAKER and RITTER propose certain modifications, at least in the case of pebbles exceeding 5 cm in diameter. However, as will be seen below, the Rulles displaces almost exclusively pebbles of smaller dimension and that is why the initial equation was retained.

However, according to REID & FROSTICK (1984, 1986), extensions of Shields curves understimate the force required to initiate motion, considering the importance of microscale bedforms (pebble clusters, for instance) in delaying bedload transport. On the other hand, as observed by PETIT (1986), coarse pebbles can be set in motion with smaller forces, by the removal of the finer particles on which they are resting.

Shear stress was evaluated over a range of discharge from minimal flow (6 l/sec) to heavy flood of almost quinquennial proportions (4.6 m^3/sec) in 31 cross sections, which can be grouped in the six types of sites referred to: upstream of constructed riffles, downstream of constructed riffles, run-off riffles, head, lowest point and counterslope of pools. In each of the profiles a linear regression between shear stress and discharge was established; the correlation coefficients are, apart from a few rare exceptions, superior to 0.90. A synthesis of these results is given in fig.5A; the value of the independent term of the regression line is shown in abscissa (the x axis), that of the angular coefficient in ordinate (the y axis).

In this way, the position of a point on the graph represents the evolution of shear stress as a function of the discharges in a given site, an evolution which is featured besides on the small schema in the inset (fig.5B). Lines of equal shear stress were also drawn for three characteristic discharges: median discharge (0.15 m^3/sec) bankfull discharge (1.3 m^3/sec) and annual flood discharge (3m^3/sec) (fig.5C).

Four individual groups emerge.

In the lowest points of pools and the head of pools, the shear stress is relatively low at times of minimal flow, but increases significantly with discharge, so that at highest flood levels it reaches, at least locally, values sufficient to allow displacement of pebbles of 5 to 6 cm in diameter. Conversely, the large residual pebbles cannot be displaced. Thus their size gives an estimate of the **maximum competence** of the river.

In the counter slopes of pools, shear stress is also low at minimal flow and also increases with discharge, but less markedly than in the pools. As a result, the large pebbles eroded in the pools are blocked in their counter-slope and only relatively small elements (2 to 3 cm) can be eroded or pass over it at times of highest flood.

In the reach upstream of constructed riffles, shear stress is relatively weak in conditions of minimal flow and increases little with discharge. In flood conditions in excess of bankfull stage, it is thus less than that which obtains in the counterslope of pools, so that pebbles eroded in the pools are blocked here. Only small elements (in the order of 1.5 cm) can get across the riffles and thus travel several dozen metres under the influence of a single flood. These elements therefore represent the **actual competence** of the river, and the size of the elements composing the constructed riffles therefore gives an estimate of this competence.

In the reach downstream of constructed riffles and in the run-off riffles, shear stress is already considerable even in low discharge, so that even in such conditions, there is erosion of pebbly material, which is then deposited—but only temporarily—in the pools. However, the increase of shear stress with discharge is less than in the pools, so that at times of highest spate, it is really in the latter that maximum shear stress occurs.

The four individual groups are thus linked in pairs and offer a certain spatial continuity. This dual association is representative of a geomorphological viewpoint: high shear stress where erosion is predominant, low shear stress in sites of accumulation.

However, shear stress determined by this method represents an average applying to the profile as a whole, without taking into account possible lateral variations on the bottom and the river banks. These, however, can be determined by tracing the orthogonals to the isotaches, following a method suggested by LELIAVSKY (1954) and used partiocularly by BHOWMIK (1982). Indeed, along these surfaces there are no lateral variations in the amount of movement, and the component of the weight of a column of water contained between two orthogonals is fully applicable on the bed or the river bank.

The use of this method demonstrated that lateral variations in shear stress on

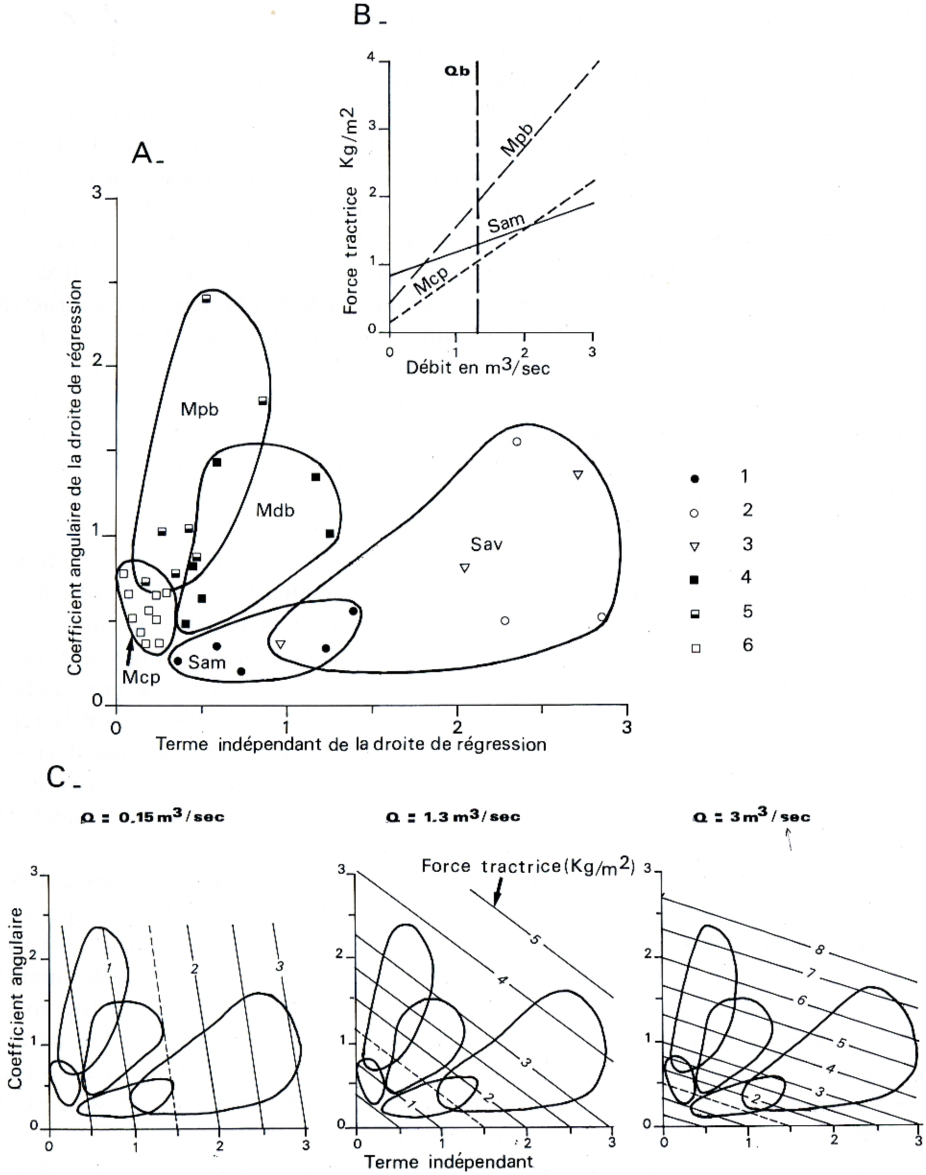

Figure 5: *Evolution of mean shear stress as a function of discharges in different sites:*
A: Synthesis of equations of the type $\tau = a + bQ$ obtained by linear regression between the shear stress (τ) evaluated by equation (1) and discharge (Q).
sites analysed: (1) Reach upstream of constructed riffles (Sam); (2) Reach downstream of constructed riffles (Sav); (3) Run-off riffles; (4) Head of pools (Mdb); (5) Lowest point of pools (Mpb); (6) Counter-slope of pools (Mcp).
B: Evolution of shear stress with discharge at the lowest points of pools (Mpb), in the counter-slope of pools (Mcp) and in the part upstream of riffles (Sam).
C: Lines of equal shear stress drawn from equation obtained by regression for three characteristic discharges; median discharge (0.15 m^3/sec), bankfull discharge (1.3 m^3/sec) and annual flood discharge (3 m^3/sec).

the riffles are small owing to the relatively homogeneous distribution of velocities (PETIT 1983). Moreover, it was found that most of the shear stress is exerted on the bottom and very little on the riverbanks. Conversely, in the pools, which as a general rule are associated with the loops of the river, lateral differentiations in shear stress are greater in view of the arrangement of the isotaches, an arrangement which, moreover, makes the use of this method far from easy in such sites.

In order to determine local shear stress, another method was adopted, which has recourse to friction velocity (u_*):

$$u_* = \sqrt{\frac{\tau}{\rho}} \quad (2)$$

where
ρ = the volume mass of the liquid.

The friction velocity can be determined by means of an equation, which links it to the vertical gradient of velocity:

$$\frac{u}{u*} = \frac{1}{k} ln \frac{y}{k_s} \quad (3)$$

where
k = what is known as Von Karman's constant, and which is generally valued at 0.4 when the suspension load is small, as obtained in the case of the Rulles (PETIT 1985);
y = the depth from the bottom where the velocity u was measured;
k_s = a parameter of roughness, which, in case of a river with a rough bottom, is rated $\frac{d}{30}$
d = the diameter of the material of which the bottom of the bed is constituted (SUNDBORG 1956; BRIGGS & MIDDLETON 1965).

In this way, by transformation, one obtains PRANDTL-VON KARMAN's equation in its most common formulation (LARRAS 1972) :

$$\frac{u}{u*} = 8.48 + 5.75 log \frac{y}{d} \quad (4)$$

Shear stress calculated by equation (4) determines $u*$ and then by equation (2) is systematically lower than those obtained by equation (1). However, they remain in the same order of magnitude in the case of riffles—owing to the fact that, here, velocity gradients in close proximity to the bottom are pronounced—but are distinctly lower in the pools. However, since the differences are relatively constant in one and the same site at times of different levels of discharge, and since these differences maintain an order of magnitude that is identical in sites of the same type, we have, for want of anything better, applied to shear stress determined by equations (2) and (4), a ratio established between the mean of these shear stresses and the shear stress calculated by means of equation (1). In this way it proved possible to delimit transverse variations in shear stress at the different sites (fig.6).

The pattern of maximum shear stress forces—at the foot of the convex bank at the beginning of the loop, passing on to the foot of the concave bank and being maintained beyond the inflexion point, which separates this loop from the one following—appears in a form similar to that put forward by HOOKE (1975) from experiments carried out in a flume, and by DIETRICH et al. (1979) in natural rivers. It must be taken into account, however, that the distribution of shear stress put forward in fig.6 is taken to be for discharge slightly below bankfull stage, and that in times of greater flood—which are in no way exceptional in view of the frequency of bankfull discharge in the river investigated—certain modifications are registered in the distribution of shear stress, in particular an increase in the counterslope of pools,

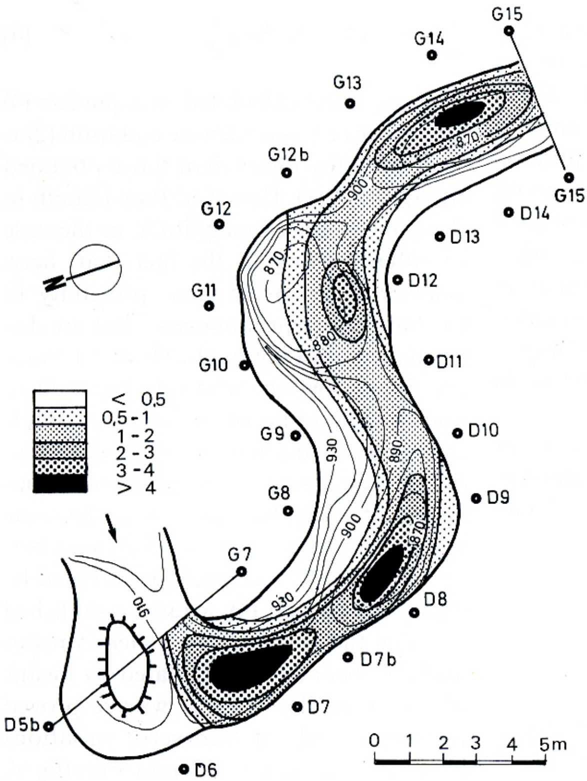

Figure 6: *Distribution of shear stress (expressed in kg/m^2) for discharges slightly below bankfull discharge (between 0.7 and 0.8 times the Qb).*

an increase which is certainly moderated, but which nonetheless tends to extend the zone of raised shear stress further downstream in the loop. This type of development as a function of discharge is moreover consistent with observations recorded by BRIDGE & JARVIS (1982).

5 CONCLUSIONS

Shear stress calculated from the energy line slope appears as a reliable criterion in the explanation of observed geomorphological changes: displacement of pebbles at the bottom of pools, which are then filtered in the counterslopes of pools, relatively stabilized accumulation in the upstream parts of riffles, regressive erosion in the downstream part of riffles.

This method of evaluation of shear stress seems well adapted to a river such as the Rulles, probably owing to the fact that the transverse components of the current are only exceptionally organised in a continuous cell. Internal current friction would thus be moderated to a greater extent than in rivers, where the lateral components of the current are organised in continuous cells. Indeed, in the case of the Rulles, the current is organised in generalised zones of diffluence and confluence, so that the transverse components of the current in relation to one and the same vertical are oriented in the same direction. Hence, distortions in the heart of the flow seem destined to be slighter and the energy dissipated by internal friction to be reduced further, so that the energy line slope integrates for the most part the dissipation of energy by friction on the bottom and the walls.

This organisation of the current into zones of confluence and diffluence is itself conditioned by the presence of narrowing of the bed (constructed riffles, islets), and by the widening which directly ensues. These frequent variations in depth and breadth are themselves due to the geomorphological context in which the river is evolving. Indeed, pebbly grains frequently surface in the banks and the pebbly material thus made available to the river conditions the build-up and reinforcement of riffles, so that narrowing of the pool section is considerable.

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REFERENCES

[ALLEN 1965] ALLEN, J.R.L.: A review of the origin and characteristics of recent alluvial sediments. Sedimentology, **5**, 89–191.

[ANDREWS 1979] ANDREWS, E.D.: Scour and fill in a stream Channel, East Fork River, Western Wyoming. Professional Paper, U.S. geol. Surv., 1117.

[BAKER & RITTER 1975] BAKER, V.C. & RITTER, D.: Competence of rivers to transport coarse bedload material. Geol. Soc. of Americ. Bul., **86**, 975–978.

[BATHURST et al. 1979] BATHURST, J.C., THORNE, C.R. & HEY, R.D.: Secondary flow and shear stress at river bends. Journ. of hydraulics Div. Amer. Soc. Civil Engineers, **105**, 1277–1295.

[BHOWMIK 1982] BHOWMIK, N.G.: Shear stress distribution and secondary currents in straight open channels. In: Gravel-bed rivers. HEY, BATHURST & THORNE (eds). Wiley & Sons. 31–61.

[BRIDGE & JARVIS 1982] BRIDGE, J.J. & JARVIS, J.: The dynamics of a river bend: a study in flow and sedimentary processes. Sedimentology, **29-2**, 499–541.

[BRIGGS & MIDDLETON 1965] BRIGGS, L.I. & MIDDLETON, G.V.: Hydromechanical principles of sediment structure formation. In: Symposium: primary sedimentary structures and their hydrodynamic interpolation. Society of Economic Paleontologists and Mineralogists Special Publication, Tulsa, Oklahoma, U.S.A., 1965, 5–16.

[CARLIER 1972] CARLIER, M.: Hydraulique générale et appliquée. Eyrolles, Paris, 565 p.

[DEGEE & PETIT 1981] DEGEE, P. & PETIT, F.: Détermination de la période de retour de certains phénomènes hydrologiques. Notes de recherches. Soc. Géogr. de Liège, **1**, 46–56.

[DIETRICH et al. 1979] DIETRICH, W.E., SMITH, J.B. & DUNNE, T.: Flow and sediment transport in a sand bedded meander. Journ. of Geology, **87-3**, 305–315.

[GRAF 1971] GRAF, W.H.: Hydraulics of sediment transport. McGraw Hill New York, 513 p.

[HOOKE 1975] HOOKE, R.L.: Distribution of sediment transport and shear stress in a meander bend. Journ. of Geology, **83**, 543–565.

[IPPEN & DRINKER 1962] IPPEN, A.T. & DRINKER, D.A.: Boundary shear stress in curved trapezoidal channels. Journ. hydraulics Div. Amer. Soc. Civil engineers, **88**, 143–179.

[JOHANSSON 1976] JOHANSSON, C.E.: Structural studies of frictional sediments. Geografiska Annaler, **58a** , 201–302.

[KELLER 1971] KELLER, E.A.: Areal sorting of bed-load material: the hypothesis of velocity reversal. Geol. Soc. of America Bull., **82**, 753–756.

[LARRAS 1972] LARRAS, J.: Hydraulique et granulats. Eyrolles Paris, 254 p.

[LELIAVSKY 1954] LELIAVSKY, S.: Précis d'hydraulique fluviale (trad. "An introduction to fluvial hydraulics"). Constable & Cie, Londres. Dunod, Paris, 1961, 256 p.

[LEOPOLD et al. 1964] LEOPOLD, L.B., WOLMAN, M.G. & MILLER, J.P.: Fluvial processes in geomorphology. Freeman & Co., San Francisco, 522 p.

[LEOPOLD 1982] LEOPOLD, L.B.: Water surface topography in river channels and implications for meander development. In: Gravel-bed

Rivers. HEY, BATHURST & THORNE (eds.). J. Wiley & Sons, 359–388.

[LISLE 1979] LISLE, T.: A sorting mechanism for a riffle pool sequence. Bul. Geol. Soc. of Amer., **90**, 1142–1157.

[MERCENIER 1973] MERCENIER, J.: Dynamique fluviale dans un petit bassin du rebord méridional du plateau des Tailles. Mém. de Licence en Sc. Géog., inêdit, conservé à l'Univ. de Liège, 148 p.

[PETIT 1983] PETIT, F.: Les processus de façonnement en milieu naturel du lit d'une rivière à sédiment limono-caillouteux. La Rulles en forêt d'Anlier. thèse de doctorat en Sc. Géogr., inédit, conservée à l'Univ. de Liège, 648 p.

[PETIT 1984] PETIT, F.: Les processus contrôlant l'évolution du tracé d'une rivière ardennaise. Z. Geomorph. N.F., Suppl.Bd. **49**, 95–109.

[PETIT 1985] PETIT, F.: L'évolution de la charge en suspension d'une rivière ardennaise au cours de périodes de crue. Bull. Soc. Géogr. Liège, **21**, 97–104.

[PETIT 1986] PETIT, F.: Channel development in two streams of contrasting bed-load and regime. BGRG Conference Proceedings Volume, Manchester. River Channel Dynamics. GARDINER (ed.). Wiley & Sons, 611–622.

[PETIT & SCHUMACKER 1985] PETIT, F. & SCHUMACKER, R.: L'utilisation des plantes aquatiques comme indicateur du type d'activité géomorphologique d'une rivière ardennaise. Colloques phytosociologiques, **XI**, Végétation et Géomorphologie, GEHU Ed. Lille, 691–710.

[REID & FROSTICK 1984] REID, I. & FROSTICK, L.E.: Particle interaction and its effect on the thresholds of initial and final bedload motion in coarse alluvial channel. In: KOSTER, E.H. & STEEL, R.J. (eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists Memoir, **10**, 61–68.

[REID & FROSTICK 1986] REID, I. & FROSTICK, L.E.: Dynamics of bedload transport in Turkey Brook, a coarse-grained alluvial channel. Earth Surface Processes and Landforms, **11**, 143–155.

[RICHARDS 1982] RICHARDS, K.: Rivers, form and process in alluvial channels. Methuen London, 358 pp.

[SELLIN 1969] SELLIN, R.M.J.: Flow in channels. Mac Nullan, St Martin's Press, 149 pp.

[SUNDBORG 1956] SUNDBORG, A.: The river Klarälven. A study of fluvial processes. Geografiska Annaler, **2–3**, 127–316.

[TRICART 1977] TRICART, J.: Précis de Géomorphologie. Géomorphologie dynamique générale. SEDES, Paris, 345 p.

[WILCOCK 1967] WILCOCK, D.N.: Coarse bedload as a factor determining bed slope. Colloque sur la morphologie des rivières. Assemblée générale de Berne, Assoc. Intern. d'Hydrologie scientifique, **75** , 143–150.

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