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CHANNEL DEVELOPMENT IN TWO STREAMS OF CONTRASTING BED-LOAD AND REGIME

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ABSTRACT

In a small Ardennes stream with a gravel bed load and markedly variable regime, the highest bed shear stresses occur during flows exceeding bankfull discharge when pebbles of 5 to 6cm diameter can be eroded. Riffles always appear as depositional sites, as tractive forces are lower there. Only particles smaller than 1.5cm are carried across them, and for several tens of metres, by a single flood flow. Bed load transport is relatively unimportant (about 110kg y^{-2}) as conditions likely to promote such particle movement at all sites along the stream occur infrequently (12 days per year).

By contrast, in a stream of more moderate regime and sandy bed load, shear stresses are sufficient at all sites to promote movement of sandy and gravelly material, even in the absence of high discharges, and a significant quantity of bed material (about 2tonnes y^{-1}) is transported.

INTRODUCTION

Morphological changes to two small stream of differing behaviour - one with gravelly bed load and markedly varied discharge (in the Belgian Ardennes), the other with almost entirely sand-sized bed material and almost constant discharge (in the Belgian Lorraine) - have been related to such parameters as discharge, velocity, and bed shear stress. It was thus possible to determine the key discharges at which hydraulic conditions led to modification of the channel and to bed load transport, and thereby establish the effective competence of these streams. The bed load transport of both streams was measured using sediment traps.

DYNAMICS OF A STREAM WITH GRAVELLY BED MATERIAL AND VARIABLE DISCHARGES

The Rulles stream is incised into the southern slope of the Ardennes. At the locality where the seven sections were studied and the water level recorder was established, the 16km^2 catchment drains lower Devonian quartzites and quartz phyllites whose impermeability leads to an irregular flashy runoff. During catchment 1980 study period discharges ranged from 0.006-4.5 m^3 s^{-1}, the higher figure being nearly equivalent to the 1 in 5 year flood on the Gumbel distribution (Degee and Petit, 1981).

Moreover, bankfull discharges, established by field observations as equivalent to 1.3m^3 s,$^{-1}$ are equalled or exceeded 2.5 times a year, even in the relatively dry study period. Such frequent flooding favours meander cut-offs by chute development as well as the dissection of the flood plain surface by small channels which accelerate meander cut-off and leave small islands in the major channel (Petit, 1984).

The stream is cut in a subhorizontal alluvial plain of compacted silt. Although contact with the bed rock is infrequent, small lenses of pebbles (abouth 5 cm in maximum diameter) outcrop in the banks. This supply of pebbles favours riffle formation and the topographically high riffles act as dams (Richards, 1982) to encourage overtopping of the banks even at relatively low discharges (Petit, 1984).

The morphological changes observed during the five year study may be summarised as follows (Fig 1):

(i) Upstream of the riffles (for example, profiles G9-D11 and G25-D30) stable accumulations of small pebbles (1.5-2cm diameter) develop after floods exceeding the bankfull discharge. They form a regular pavement which can resist the 1 in 5 year flood.

(ii) Downstream of the riffles, headward erosion occurs, even at discharges less than bankfull (for example, profiles G10-D12 and G26-D30).

(iii) In the pools, layers of small pebbles are reworked by flows slightly less than bankfull discharge. However deepening of the pools is somewhat restricted by the large pebbles (10cm diameter) partly covering their floors.

(iv) On the back slopes of the pools (for example, profile G8-D10) small pebbles are deposited by flows just below bankfull but are eroded again, at least over part of the section, by higher discharges.

To explain these changes, velocities and bed shear stresses were established at the various sites for discharges from base flow to major floods. The shear stress was derived from a method using the hydraulic radius and the slope of the energy grade line (Graf, 1971), the latter being derived from the downvalley slope of the water surface and the change from upstream to downstream of the kinetic energy which is a function of the square of the velocity (Carlier, 1972).

Trials using marked pebbles of known diameter at different sites helped to verify that the calculated shear stress was a reliable parameter for explaining the erosion and transport of the pebble load (Petit, 1983). The bed shear stress was also derived from the shear velocity obtained from the Prandtl-von Karman velocity profile equation with a roughness parameter equivalent to the bed material diameter (Sundborg, 1956; Larras, 1972). These stresses were much smaller than those obtained by the first method, and were only used to assess transverse variations of shear stress.

This calculation of the shear stress using the hydraulic radius and energy grade line led to the following conclusions.

In the base of pools, shear stresses are low at baseflow, but increase rapidly with discharge to values during floods which are sufficient for the erosion of pebbles of 5 to 6cm diameter. On the back-slopes of the pools a similar, but smaller, increase of tractive force with discharge occurs so that the pebbles eroded in the pools are not carried up the back slope and only relatively small particles are carried further downstream.

In the sections immediately above the riffles, bed shear stresses are low at base flow and increase with discharge. Flows which exceed bankfull cannot carry the coarsest particles from the back-slopes ofthe pools as observed by Andrews (1979). Only material less than 1.5cm in diameter can cross the riffles and then be carried several tens of metres downstream, as indicated by the trials with marked pebbles. However, immediately downstream of the riffles, high bed shear stresses, even at low flows, can cope with material supplied from upstream.

Although the maximum competence of the stream, given by its ability to erode pebbles of 5 to 6cm diameter, is quite high, it is highly localised in occurrence. Riffles limit the size of material transported by rolling and saltation, as observed by Lisle (1979).

On the other hand, discharges capable of shifting bed material occur an average of only 12 days a year, thus explaining the small mean load of 110kg y^{-1} measured in the bed load traps. This is much lower than the 750kg y^{-1} measured by Mercenier (1973) in small streams draining from the Tailles plateau in the Ardennes, or the more than 1000kg y^{-1} in a small tributary of the Hoyoux in the Condroz (Dave, 1975). These two other streams had much steeper gradients (7% and 3% respectively) than the Rulles, but smaller catchments (1.4km^2 and 4.3km^2). On the other hand, in a river with similar characteristics to the Rulles, in Entre Vesdre et Meuse, with a slope of 1% and catchment area of 27km^2, a bed load of 150kg y^{-1} was measured (Lennertz, 1976).

DYNAMICS OF SANDY BED LOAD, MODERATE REGIME STREAM

The Rouge Eau stream in Belgian Lorraines drains the dipslope of a calcareous Jurassic sandstone escarpment. The catchment of just under 10km^2 has a mean slope of 1.6%. The permeable substrate moderates the range of discharges to five year extremes of 70 and 220 l s^{-1} with a mean discharge of 130 l s^{-1}. Bankfull flow did not occur in the five year study period.

Material available for transport is overwhelmingly well sorted, fine sand coming from disintegration of the sandstone (median diameter 170 microns, Krumbein sorting index of 0.36). Sometimes, small steep outcrops provide the stream with some pebbles which affect morphological processes. Thus the following discussion is divided into two sections, one dealing with the reaches with sand bed load only and the other with the confluence with tributaries where a gravel load predominates.

Geomorphic changes in the sandy reaches of the stream In the vicinity of the study area the stream has an irregularly meandering pattern (Fig. 2). Elongated pools occur in the meander curves, but there are no dominant riffles and few general downstream variations in depth and cross-section.

The stream is not markedly incised into the flood plain as the banks are unstable, the floodplain itself being formed of sand. Markedly finer, more resistant material (21% finer than 20 microns), possibly the result of deposition in a former lacustrine environment, outcrops at the base of certain pools, apart from which the bed material is virtually entirely sand. Even at low flows sand grains can be seen rolling along the channel bed. Coarser fragments up to 3mm diameter can be seen behind transverse dunes but are less frequently moved than the sand.

Over three years the following changes were observed:

(i) Only slight deepening of the pools, related to the more resistant outcrops on their floors.

(ii) Lateral erosion, even without extreme flows, of the concave banks from the bend apex to beyond the point of inflexion (near reference G12 and below G13, Fig.2).

(iii) Stable and growing sand accumulation on convex banks (15cm thick below reference D10, for example).

These changes demonstrate a trend towards meander development that is, however, inhibited by small obstacles which produce significant local vertical and lateral erosion of easily eroded banks and the channel bed. Sheltered areas behind such obstacles are the location of sand deposition, which is also encouraged by frequent log jams of stumps and boughs from the alder trees which cover the floodplain.

Except where these obstacles occur, the evolution of the different measurement sites corresponds to that of the meanders as a whole providing there is steady flux of material. In this way there seems to be an equilibrium between the forms and the material transported.

Measurement of velocities with a midget current meter close to the bed revealed high velocities near the bed (up to $0.27 m s^{-1}$ at 1.5cm from the bed). Moreover, apart from the effect of the obstacles (profiles G6-D6 and G7-D7, Fig. 3) velocity distributions in the quasi-rectilinear sector and in the meander corresponds to sandy river observations by Dietrich *et al.* (1979). At the beginning of the bend (profile G11-D9) maximum velocity is towards the convex bank probably because there is a tree on the opposite bank (between reference points G8-G9). The location of highest velocity only shifts to the concave bank below the apex of the meander curve (profile G12-D9) remaining there to beyond the inflection point (profile G15 D10). Elsewhere velocities can be explained in terms of the position of zones of erosion and sedimentation.

Bed shear stresses were also calculated by two methods: a) that relying on the hydraulic radius and energy gradient described earlier and b) that depending on the shear velocity derived from the Prandtl-Von Karman equation.

When using the first method of calculating the shear stress, it should be noted that the water surface slope varied little from one site to another, always around 0.21% for approximately the mean discharge. On the other hand, mean velocities were much the same at all sections as there are few marked irregularities of the channel bed, so that the energy gradient and the water surface slope are approximately the same. Thus the shear stresses are similar at all cross sections, $0.36 kg m^{-2}$ at profile G6-D6 and $0.49 kg m^{-2}$ at profiles G12-D9 and G15-D11.

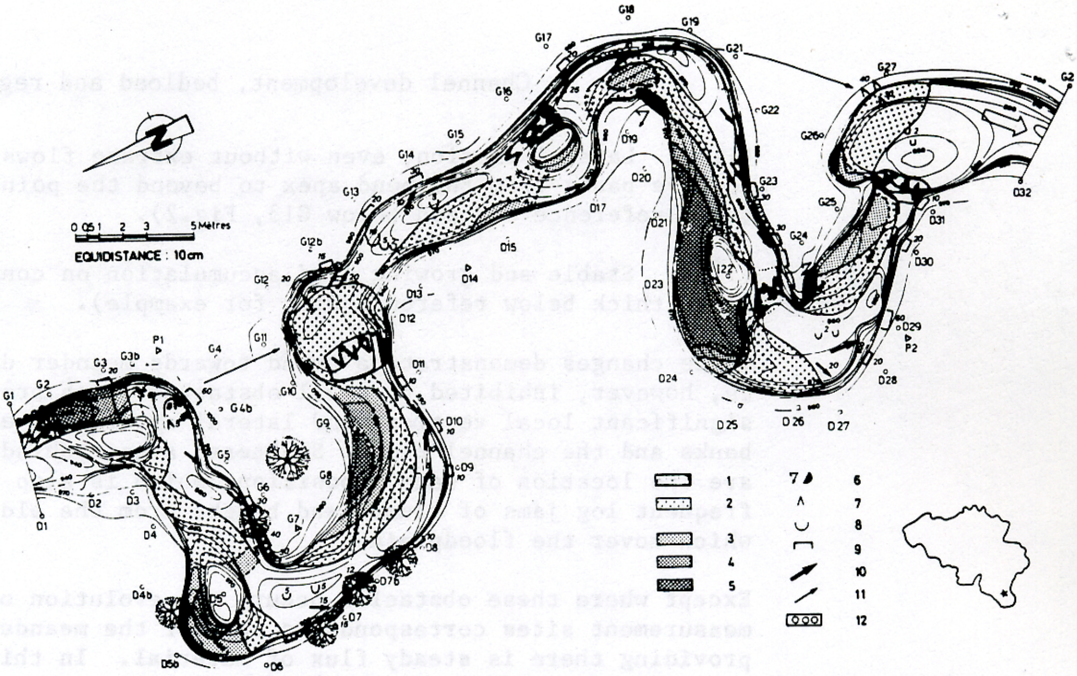


Figure 1: Geomorphological changes observed over five years in a stream of markedly varying regime with a gravelly bed load (the Rulles). 1. zones of marked headward erosion; 2. temporary deposits of bed load; 3, 4, and 5. stable accumulations of thickness respectively less than 10cm, between 10 and 20cm thick, and more than 20cm thick; 6. overhanging bank as result of undercutting; 7. headward erosion; 8. vertical erosion; 9. lateral erosion; 10. oblique erosion; 11. route taken by overbank flood-flows; 12. lenses of pebbles outcropping in the banks. Figures in italics express the quantity of erosion observed in centimetres.

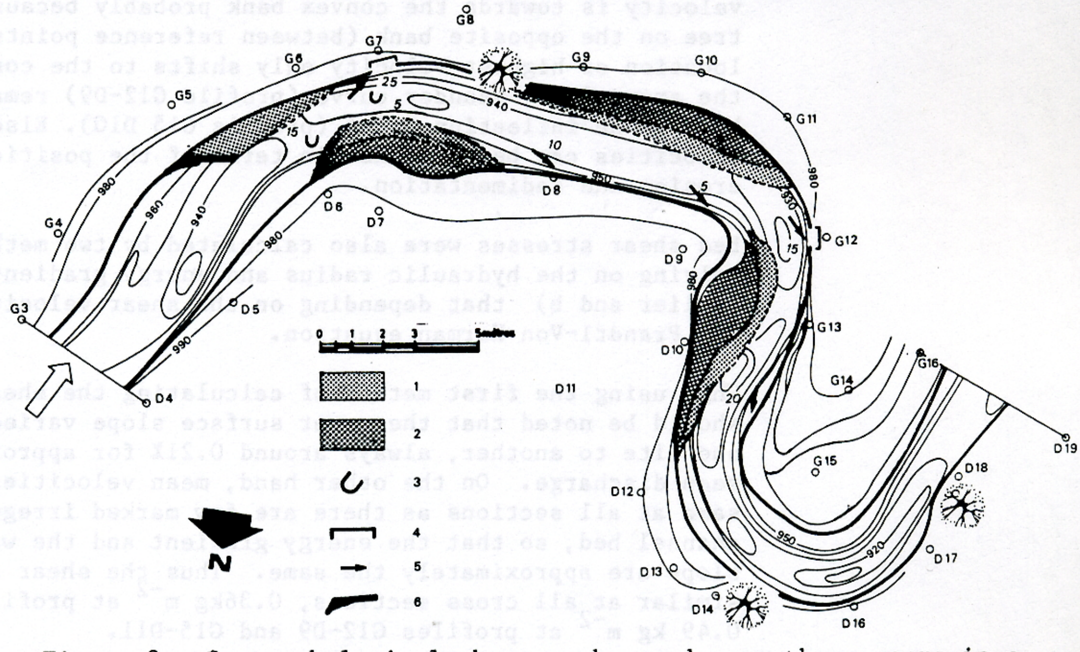


Figure 2: Geomorphological changes observed over three years in a sand-bedded stream of stable regime (La Rouge Eau). 1. zone of presently accreting deposits; 2. zone of relatively old, stable deposits; 3. vertical erosion; 4. lateral erosion; 5. oblique erosion; 6. small obstacles. Figures in italics express the quantity of erosion observed in centimetres.

Figure 3 (right): Distribution of velocity at approximately mean discharge in different cross-sections of a stream with predominantly sandy bedload.

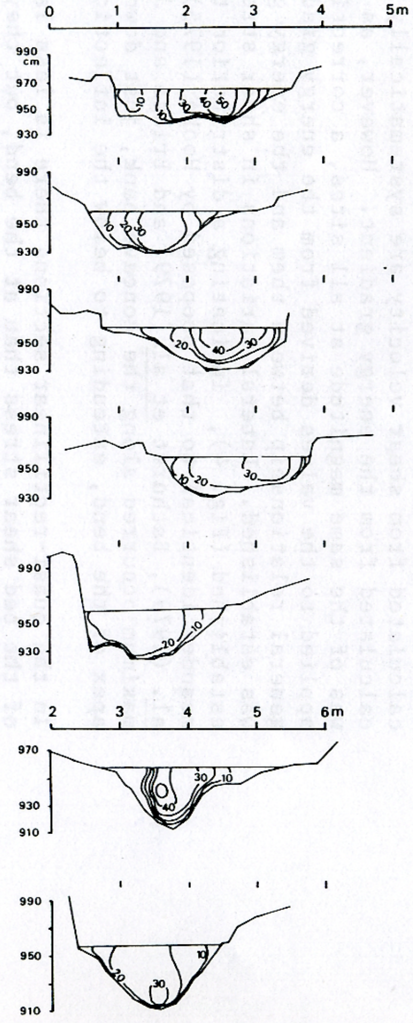
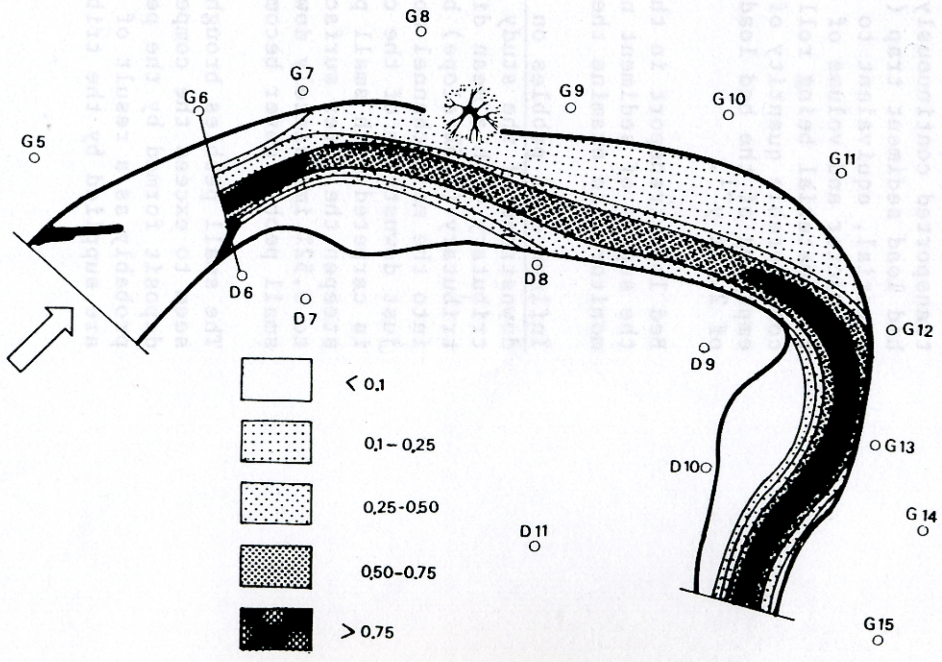


Figure 4 (below): Distribution of tractive stresses (in kg m^{-2}) at approximately mean discharge in a reach of a stream with predominantly sandy bedload.



Nevertheless, as was also noted the Rulles stream, shear stresses calculated from shear velocity are systematically less than those calculated from the energy gradient. However, as the variation was of the same magnitude at all sites, a correction factor was applied to the values derived from the energy gradient and a general relationship between them and the energy gradient values was established. Lateral variations in shear stress could thus be established (Fig. 4), indicating a distribution through the meander identical to that proposed by Hooke (1975), Dietrich et al. (1979), Bathurst et al. (1979) and Bridge and Jarvis (1982). A maximum occurred along the concave bank, just downstream of the apex of the bend, extending to below the inflection point.

In the quasi-rectilinear sections there is less lateral variation of the bed shear stress than at the bend, but they retain, at least over part of the section, values sufficient to transport coarse sand and even fine gravel even at flows around the average discharge. This situation, quite different from that in the Rulles, enables bed load material supplied to the stream to be transported continuously. The first 19 months of operation of the bed load sediment trap (Fig. 5), saw a catch of $1.92m^3$ of material, equivalent to a load of $1.6\ t\ y^{-1}$. In view of the character and volume of deposition near the barrier erected to trap material being rolled along the bed, there was probably a considerable quantity of unmeasured bed load transport. A second emptying of the bed load trap two months later indicated a yield of $2.1\ t\ y^{-1}$.

Bed load transport in this stream is thus considerable. Clearly, the supply of sediment needed examination and several springs were monitored to examine their role in the supply of material.

Influence of pebbles on stream behaviour A few dozen metres downstream of the study reach, the Rouge Eau receives a small tributary with a mean discharge of $15\ l\ s^{-1}$. This steep tributary (4.5% slope) brings small pebbles up to 1.3cm diameter into the main channel modifying its behaviour (Fig. 6). Thus, just downstream of the confluence (section G7-D10) the channel bed is carpeted with small pebbles which cause depths to vary and steepen the water surface slope from 0.17% above the confluence, to 0.52% immediately downsteam and 0.25% below the point where the small pebble cover becomes discontinuous.

The small pebbles brought into the main channel raise the bed and seem to exceed the competence of the stream. Nevertheless, the deposit formed by the pebbles seems to retain a constant form, probably as a result of the removal of as many small pebbles as are supplied by the tributary. By making two distributions of

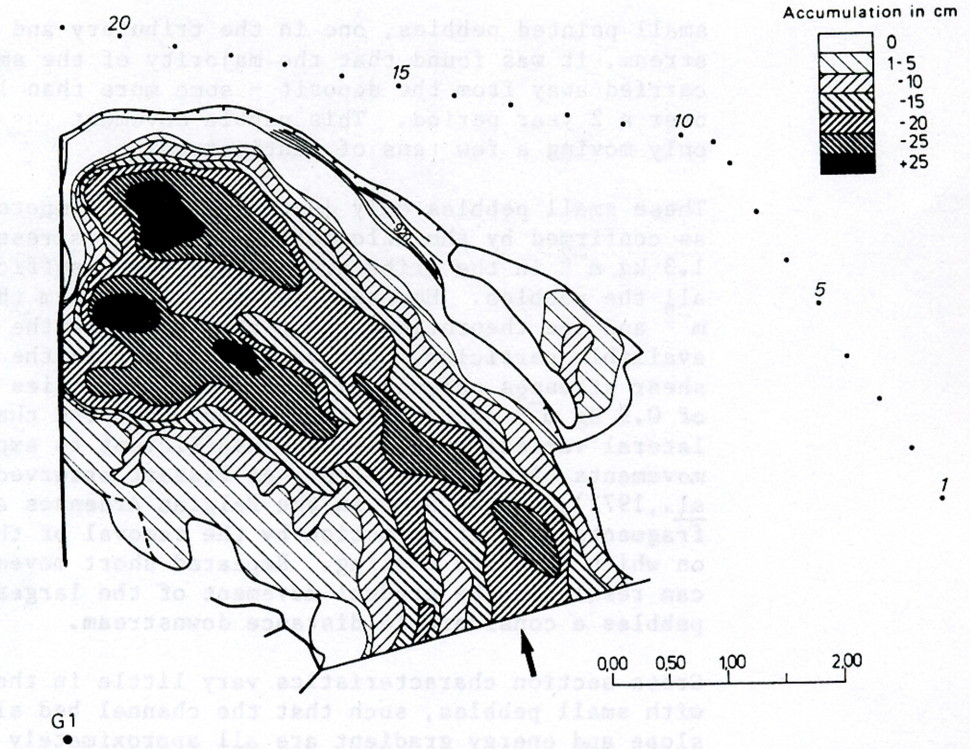


Figure 5: Accumulation of sediment behind a bed load trap after 19 months of operation.

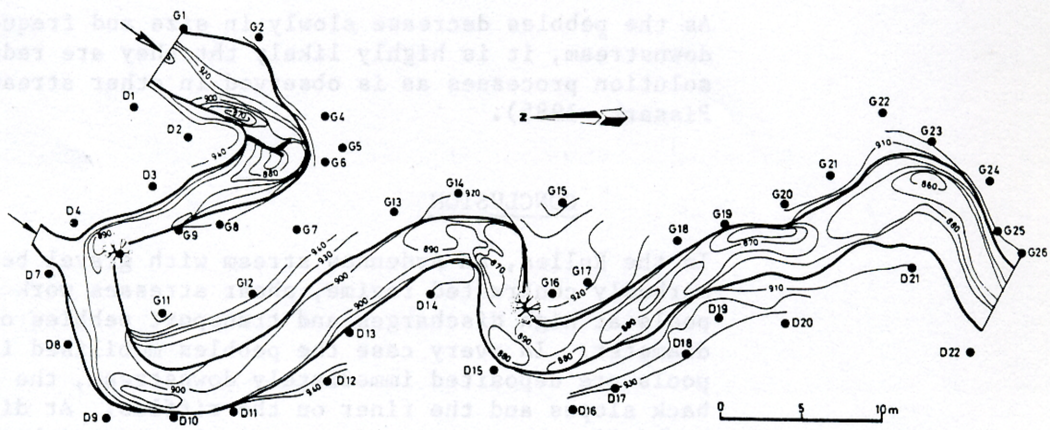


Figure 6: Channel bed topography, showing influence of influx of fine pebbles from a tributary on the morphology of the stream with sandy bedload. Deep pools occur in the sandy reach above the confluence; a shallow reach lacking riffles and pools occurs below the junction (G10-D7 to G13-D14); and the riffle-pool sequence is re-established when the pebble cover disappears (below G14-D14). Contours in cm above arbitrary datum; heavy line represents the banks.

small painted pebbles, one in the tributary and one in the main stream, it was found that the majority of the small pebbles were carried away from the deposit - some more than 15 m downstream - over a 2 year period. This pebble movement was not uniform, some only moving a few tens of centimetres.

These small pebbles only just exceed the competence of the stream, as confirmed by the calculations of shear stresses, which exceed 1.3 kg m^{-2} in the tributary and are there sufficient to carry all the pebbles. However, in the main stream they average 0.6kg m^{-2} and are theoretically not able to carry the coarsest available particles. The variations across the channel in the shear stresses calculated from shear velocities are small, values of 0.9 kg m^{-2} occurring in the centre of the channel. Such lateral variations alone are insufficient to explain all the movements of small pebbles. As Pissart observed (in Bastin *et al.*,1972), on the Soor in the Belgian Ardennes some coarse fragments are set in motion by the removal of the finer particles on which they are resting. Repeated short movement of this nature can result in the gradual movement of the largest of the small pebbles a considerable distance downstream.

Cross section characteristics vary little in the reach carpeted with small pebbles, such that the channel bed slope, water surface slope and energy gradient are all approximately the same (at least from section G11-D11 to G13-D14). The energy gradients derived from Manning's equation with a roughness coefficient of n = 0.05 are similar to those observed in the field, unlike those for the sandy reach described earlier.

As the pebbles decrease slowly in size and frequency of occurrence downstream, it is highly likely tht they are reduced in size by solution processes as is observed in other streams (Duchesne & Pissart, 1985).

CONCLUSION

In the Rulles, an Ardennes stream with gravel bed load and markedly contrasted regime, shear stresses work on the base of pools at high discharges and transport pebbles of 5 to 6cm diameter. In every case the pebbles mobilised in the base of the pools are deposited immediately downstream, the coarsest on the back slopes and the finer on the riffles. At discharges close to bankfull, the tractive forces are lowest on the riffles being able to carry only particles of less than 1.5cm diameter. These small particles can be carried across several riffles in a single flood, travelling several tens of meters. Thus bed load transport throughout the stream only occurs at bankfull discharge and above. Although relatively frequent in comparison with other streams, such discharges only occur 12 days a year and thus the annual bed load transport of around 110kg is relatively small.

By contrast, in the Rouge Eau, a stream with fairly steady regime and a sandy bed load, the shear stresses are high enough all along the river (at 0.5kg m^{-2} approximately) to transport coarse and and small pebbles even though there are no high discharges, with a resulting high volume of bed load transport of about 2 t y^{-1}. The behaviour of this predominantly sandy stream is modified by the small pebbles discharged from a tributary which exceed the competence of the main stream. However, these pebbles can be moved a short distance as the finer material beneath gets washed away.

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References

Andrews E D (1979) Scour and fill in a stream channel, East Fork River, Western Wyoming. US Geol. Survey Professional Paper 1117.

Bastin B, Juvigne E, Pissart A & Thorez J (1972) La vallée de la Soor (Hautes-Fagnes): Compétence actuelle de la rivière, dépôts glaciaires ou périglaciaire. (Compte-rendu de l'excursion du 3 juil. 1971) Extr: Les Congrès et Colloques de l'Univ. Liège: Comptes-rendus de la réunion Union Géogr. Intern. pour l'Etude des processus géomorphologiques actuels, P Macar & A Pissart eds, 295-321.

Bathurst J C, Thorne C R & Hey R D (1979) Secondary flow and shear stress at river bends. Am. Soc. Civ. Eng. J. Hydr. Div. 105, 1277-95.

Bridge J S & Jarvis J (1982) The dynamics of a river bend: a study in flow and sedimentary processes. Sedimentology, 29, 499-541.

Carlier M (1972) Hydraulique générale et appliquée. Eyrolles, 565pp.

Dave C (1975) Etude de la dynamique fluviale d'un petit ruisseau de type torrentiel. Le ruisseau du fond de Wavelinse. Mém Lic. Sc. géogr., inédit, conservé à l'Univ de Liège, 148.

Degee P & Petit F (1981) Détermination de la période de retour de certains phénomènes hydrologiques. Notes de Recherches, Soc. Geogr. Liege 1, 46-56.

Dietrich W E, Smith J B & Dunne T (1979) Flow and sediment transport in a sand bedded meander. Journ. of Geology, 87, 305-15.

Duchesne F & Pissart A (1985) Valeur statistique des comptages de cailloux de différentes lithologies. Application aux cailloux de l'Ourthe. Bull. Soc. Géogr. Liège 21, 13-23.

Graf W H (1971) Hydraulics of sediment transport. McGraw Hill, New York, 513 pp.

Hooke R L (1975) Distribution of sediment transport and shear stress in a meander bend. Journ. of Geology 83, 543-65.

Larras J (1972) Hydraulique et granulats Eyrolles, Paris, 254.

Lennertz L (1976) Etude de la dynamique fluviale d'une rivière de l'Entre Vesdre et Meuse La Gueule. Mém. Lic. Sc. Géogr. inédit, Conservé à l'Univ de Liège, 180.

Lisle T (1979) A sorting mechanism for a riffle pool sequence. Geol. Soc. of America Bull 90, 1142-57.

Mercenier J (1973) Dynamique fluviale dans un petit bassin du rebord méridional du plateau des Tailles. Mém. Lic. Sc. Géog., Univ de Liège inédit, 148.

Petit F (1983) Les processus de faconnement en milieu natural du lit d'une rivière à sédiment limono-caillouteux. La Rulles en forêt d'Anlier. Thèse de doctorate en Sc. Géogr., L'Univ. de Liège, 648 pp.

Petit F (1984) Les processus contrôlant l'évolution du tracé d'une rivière ardennaise. Z. Geomorph NF, Suppl. Bd. 49, 95-109.

Petit F (1985) Relation entre la fore tractrie et le faconnement du lit d'une rivière à charge caillouteuse (La Rulles-Ardenne) (en préparation).

Richards K (1982) Rivers: form and process in alluvial channels. Methuen, London, 358 pp.

Tricart J (1977) Précis de Géomorphologie. Géomorphologie dynamique générale. Sedes, Paris, 345.

Wilcock D N (1967) Coarse bed load as a factor determining bed slope. Colloque sur la morphologie des rivières. Assemblée Générale de Berne, Assoc. Intern. d'Hydrologie Scientifique 75, 143-150.