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Erosion and sediment transport processes in step-pool torrents

J. G. WHITTAKER & T. R. H. DAVIES
Agricultural Engineering Department, Lincoln College, University of Canterbury, New Zealand

ABSTRACT In upland regions, streams often exhibit a step-pool morphology where water cascades between relatively deep pools. The capacity of such streams to entrain adjacent slope material depends not only on water flow rate and channel slope, but also on the degree of infilling of the pools by sediment. This situation has been idealized, using a laboratory channel containing regularly spaced baffles. The results appear consistent with findings of studies of real torrents. The laboratory investigation has revealed that the erosive capacity of step-pool streams reaches a maximum (for a given flow rate) when the pools are almost full of sediment; that is, when sediment transport rates are high. This behaviour is conducive to erosion of adjacent slopes and contrasts with that of lowland alluvial streams. Despite steady inputs, water and sediment outputs from the laboratory channel were often independently unsteady. Step-pool streams thus seem to display intrinsic unsteadiness, particularly of sediment movement. This parallels reports of coherent sediment "waves" moving slowly through mountain torrents. Such behaviour is consistent with recent findings on the thermodynamics of nonlinear systems. These findings seem to relate also to low-slope alluvial channel processes. Conventional linear analysis may be inappropriate for these situations.

INTRODUCTION

In the steep, upper catchment areas typical of many mountainous regions, valley side slopes commonly extend to the very banks of the stream in the valley bottom. Movement of material down such slopes is largely controlled by stream bank erosion and undercutting of the toe of the slope by the stream.

Steep mountain streams often exhibit a staircase appearance, where a series of rocky steps alternate with relatively deep pools. This step-pool structure acts as an energy dissipator at low flow rates. At high flows (or at moderate flows with a high sediment load where pools become filled with sediment), the structure is less effective as an energy dissipator, leading to higher flow velocities and a greater ability to entrain adjacent slope material.

In order to study this variation in the erosive capacity of a step-pool stream, the stream system has been idealized in a laboratory channel containing regularly spaced baffles. A tilting, recirculating flume of width 0.13 m and length 9.2 m was used, the slope of which could be varied up to 25%. Baffle plates 0.27 m high were spaced at 0.5 m intervals along the flume bed. A rotating tube sediment feed device capable of supplying 16 kg min^{-1} of 4 mm gravel was mounted on the upstream end of the flume. Mean flow velocities were measured using the salt-velocity method (Davies & Jaeggi, 1981). Mean flow velocity was used as an indicator of the stream's relative erosive capability, being directly proportional to unit stream power (Yang, 1972). Variation of erosive capability through a single step-pool unit is now being studied.

VARIATION IN EROSIVE ABILITY

Tests were performed at four slopes. At each slope, a series of flow rates was investigated, for each of which the variation of mean flow velocity <v> with sediment transport rate Q_S was examined. A test was considered to have achieved equilibrium when the measured sediment output rate from the tail of the flume equalled the input rate. Photographs were taken to allow examination of flow and scour depths. Results of these tests are shown in Fig.1.

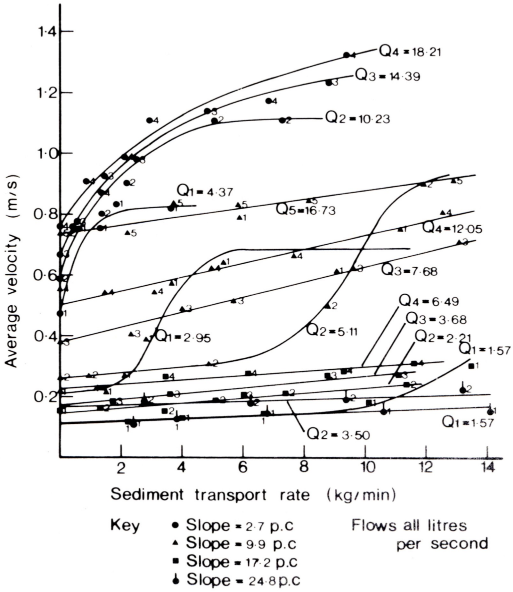


FIG.1 Average velocity versus sediment transport rate.

Slope = 2.7%

For a given flow rate Q, <v> increased rapidly with Q_S, until a threshold was reached, corresponding to complete filling of the pools with sediment. For higher values of Q_S there was no further increase in <v>, and plane bed flow with deposition above the level of the baffles occurred.

Slope = 9.9%

Initially, <v> increased only slightly with Q_S (Q const) until, with the two lowest flow rates, drowning of pools by sediment began to occur, and <v> increased more rapidly. Again, a threshold was reached at which the pools were filled with sediment and the increase in <v> ceased. At higher flow rates no significant drowning of pools or increase in <v> was observed.

Slope = 17.2%, 24.8%

Only the lowest flow at slope = 17.2% showed an increase in <v>, and that at a high value of Q_S. For the other flows, no significant drowning of the pools occurred.

For a given flow rate, it is seen that as pools became filled with sediment, an increase in <v>, and hence erosive capability, does indeed occur; however, drowning is much more difficult to achieve at steep slopes, requiring very large values of Q_S at moderate flows. Maximum velocity is attained when the pools are completely drowned. It is significant that field studies (Hayward, 1980) describe and illustrate severe bank undercutting due to the drowning of pools by sediment. Of particular interest is that erosion is likely even at relatively low flows as pools become filled with sediment. It seems likely that a positive feedback may increase the erosion capability in that as the pools in a reach of stream are partly infilled, erosion of adjacent banks becomes possible, further increasing the degree of infilling and thereby bank erosion. This may explain the occurrence and movement of coherent "slugs" of sediment through a stream system (Hayward, 1980; Ashida *et al.*, 1976; Beschta, 1981), although, as shown in the following section, such behaviour seems inherent in a step-pool stream. As yet, it has not been possible to relate laboratory flow rates closely to those causing equivalent behaviour of prototype streams. Visual appearance suggests that, in the field, flows high enough to drown a step-pool system without sediment input would be of the order of a 100 to 1000 year flood. However, drowning by a combination of high flow and sediment transport rates can easily occur in a 10 to 25 year event (Hayward, 1980).

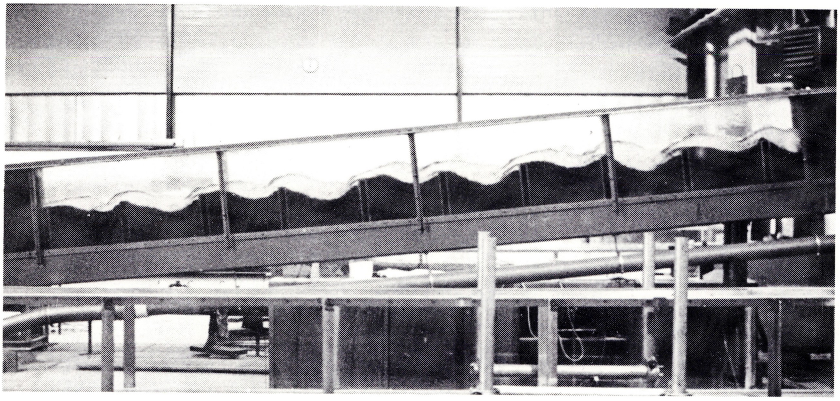
Thus, at high sediment transport rates, a step-pool stream may, depending on the flow, become very erosive. This contrasts with the behaviour of lowland alluvial rivers, where low sediment input rates are generally thought to lead to bank and bed scouring.

UNSTEADINESS OF WATER AND SEDIMENT FLOW

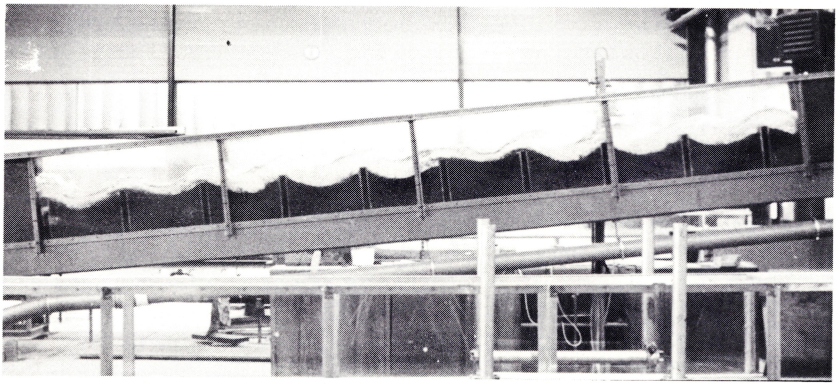
It is well known (Morris, 1968) that clear water flow over regularly spaced baffles can give rise to periodic roll waves. This phenomenon was observed in some of the present tests. The roll waves occurred when the discharge coefficient for flow over a baffle increased due to the water surface in the pool upstream of the baffle rising beyond a certain level. This increase in discharge resulted in washing out of the hydraulic jump immediately upstream of the baffle into the pool downstream of the baffle. The water level in the upstream pool thus fell, while that in the inundated pool rose. The same process subsequently occurred with greater amplitude at the next baffle downstream: the region of high water level propagated and amplified through successive pools. The fall in the level of the original pool caused a decrease in outflow over the baffle. Because inflow then exceeded outflow, this level rose again, setting another wave in motion. These roll waves have never been reported in the literature on naturally-formed step-pool steams. This is probably because the irregularity of natural step-pool sequences tends to damp out such waves.

However, Dement'ev (1962) reported velocity pulsations in mountain rivers of the USSR with periods down to the researcher's measuring limit of about 30 s. Pulsations short enough to correspond to roll-waves could have occurred. The magnitude of the pulsations increased with roughness of the bed, and with increasing velocity of flow. Dement'ev (1962) inferred that the pulsations were due to turbulence.

It was noted in the present tests that, with steady inputs of water and sediment, both the water and sediment outputs were often independently unsteady. Slow moving sediment waves were manifested by periodic variations in the degree of pool infilling along the channel (Fig.2). A pattern was observable (Table 1).



Run 11: slope = 9.9%, Q = 7.65 ls^{-1}, Q_s = 13.1 kg min^{-1}.



Run 16: slope = 9.9%, Q = 12.07 ls^{-1}, Q_s = 12.6 kg min^{-1}.

FIG.2 Sediment waves

TABLE 1 The occurrence of sediment waves

Flow state	*Behaviour of model with increasing Q_s*
Stable	*Sediment waves may develop; (these modify the flow with possible instability).*
Periodic roll waves	*The flow instability decreases. Sediment waves may develop, and with consequent flow modification lead to complex flow instability.*

This suggests that the sediment "slugs" seen in natural channels may be generated by localized bank erosion and be retained in their coherent form as they pass along the channel by an intrinsic tendency toward non-uniformity in sediment motion.

Many aspects of the behaviour of sediment-transporting turbulent flows point toward similar inherent non-uniformities. They include the development of bed forms, meanders and riffle-pool sections in initially uniform channels. Current theories of sediment transport and channel formation tend to account for such non-uniformities by means of empirical coefficients. Rather, the behaviour of natural streams seems strikingly similar to the behaviour of such nonlinear thermodynamic systems (Davy & Davies, 1980; Karcz, 1981) as described by, for instance, Nicolis & Prigogine (1977).

Very briefly, a linear thermodynamic system returns to a uniform state when slightly disturbed, as, for example, does a bed of sand under laminar flow. This behaviour is restricted to conditions close to equilibrium. Farther from equilibrium, where the thermodynamic system is nonlinear, a disturbance may generate an instability which, with positive feedback, drives the system to a new dynamic equilibrium state in which large scale structural order is present. The new state is called a dissipative structure (Prigogine, 1978). Such a state can only be maintained by a sufficient flow of energy and matter. The analogy between nonlinear behaviour and the development of bed forms is very clear. The bed form develops from an initial disturbance which is amplified; in the same way a dissipative structure is the result of a perturbation which is amplified by nonlinear processes. In both cases, the result is a large scale (relative to the initial disturbance) spatial ordering. The sediment and water waves observed in the present tests are seen to have arisen from such nonlinear processes. Thus, the writers contend that attempts to derive analytical models for the behaviour of natural channels in both lowland and highland situations should involve recent advances in the understanding of nonlinear system behaviour, rather than continuing to manipulate linear analyses to fit what are essentially nonlinear conditions.

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