JOURNAL OF HYDROLOGY (N.Z.) Vol. 13, No. 1, 1974

THE TORLESSE STREAM VORTEX-TUBE SEDIMENT TRAP

J. A. Hayward* and A. J. Sutherland†

ABSTRACT

A system for measuring the yield and transport rates of bed-load sediments is described. The technique is based on the vortex-tube principle to remove bed load from the stream to an off-channel recovery area. The system allows for both continuous or intermittent recording of sediment movement. Some preliminary results which indicate the unsteady nature of bed-load transport are presented.

INTRODUCTION

Information about stream sediments is needed for many purposes. As part of a wider investigation into the behaviour and responses of an eroded mountain catchment (Hayward *et al.*, in prep.) it is of interest to determine the origin, yield, transport rates and size range of sediments being removed by the Torlesse Stream.

This stream is derived from a 385-ha basin on the east side of the Torlesse Range. It is typical of much of Canterbury's drier eastern high country, and ranges in altitude from 750 m to nearly 2000 m. The catchment has a stable mouth which was considered most suitable for the establishment of a gauging and sediment-measuring station. The land and channels grade steeply, supplying water and sediment to the Kowai River and thence into the Waimakariri system.

The characteristics of the suspended sediment are being determined by sampling with a D48 sediment sampler. Measurement of bed-load sediments, traditionally very difficult, presents much greater problems. A technique was sought which as far as possible avoided the need for sampling and its inherent errors, had a mini-

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* Tussock Grasslands and Mountain Lands Institute, Lincoln College, Canterbury.

† Civil Engineering Department, Canterbury University, Christchurch.

mum number of moving parts, and which would be of simple design, construction, and operation. A sediment trap based on the vortex-tube principle appeared to meet these requirements.

Vortex tubes have been used for many years to eject unwanted sand and silt from irrigation canals and ditches in several parts of the world. In the United States their use was pioneered by Parshall (1933) and Rowher (1933) and their hydraulic behaviour has been tested by Robinson (1962). Their use for measuring bed-load transport rates in a cobble-bottomed stream in Oregon has been described by Klingerman and Milhous (1970).

Fig. 1 shows a vortex-tube trap which is simply a tube open along the top and placed in the bed of a controlled section of stream channel at an angle to the direction of flow. Movement of water across the opening sets up a vortex pattern within the tube. The vortex has a component along the tube towards the downstream end, which can be opened to allow discharge into a work-pit area adjacent to the stream. Sediment moving on the stream bed drops or is drawn into the tube and trapped. It is carried to the downstream outlet and discharged into the work pit whenever the gate is opened.

By emptying the trap at regular intervals during a storm a rate measurement can be obtained. This represents a significant advance on former methods of bed-load study, which either sample (in lieu of a total measurement) or simply measure total yield for a storm.

DESIGN AND CONSTRUCTION

The Torlesse Stream leaves its catchment through a well defined opening approximately 7 m wide between a large rock outcrop and

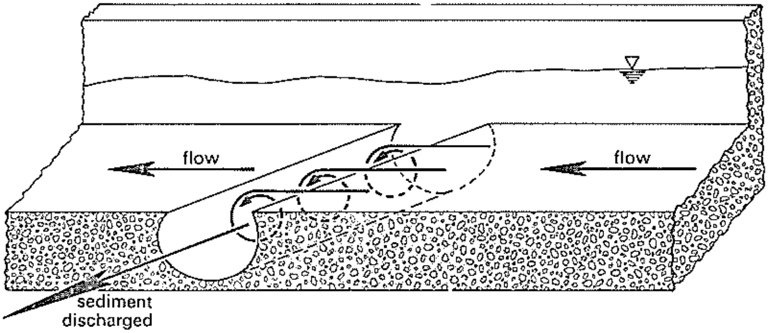

FIG. 1 — A vortex-tube sediment trap.

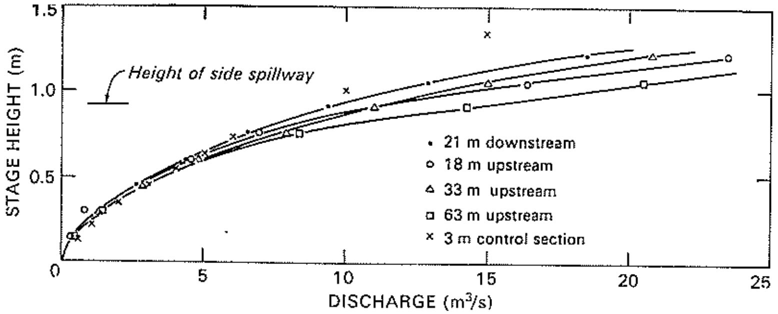

FIG. 2 — Stage–discharge curves for Torlesse Stream and proposed control structure.

a steep bank. The outcrop provided an excellent foundation which was used to anchor the control structure. At the time the trap was designed there was little hydraulic, hydrological, or sediment information available for the Torlesse Stream catchment. The control structure was therefore designed to relate as closely as possible to the upstream and downstream channel. A longitudinal slope of approximately 1:15 persisted for a distance of 200 m upstream, and for low to medium flows the stream had a width of less than 4 m.

To determine a suitable flume width, stage–discharge curves for four stream cross sections near the flume site were estimated by assuming a Manning's *n* of 0.055. These curves are plotted in Fig. 2, which shows that for a 3-m-wide section there should be little difference between the stage–discharge relationship of the control section and that of the adjacent channel for flows up to 6 m^3/s.

Velocities through the section would be largely controlled by the upstream flow conditions. viz a steep rough channel. To compensate in part for the large drop in roughness. the control section was designed to have a slope of 1:220, the value obtained by use of the Manning equation. A section length of 8 m was adopted.

As a safety feature, the true right-hand wall of the section was built 0.91 m high with its top edge 0.2 m lower than the left-hand wall. At very high flows (approximately 9 m^3/s) this will act as a side spillway and prevent flooding of the work area behind the left wall. A slope of 1:40 was incorporated across the section to improve the measurement of low flows by confining them to the left-hand wall.

Results from Klingerman and Milhous' (1970) experience were not to hand at the design stage, so the vortex tubes were designed following Robinson's criteria (1962). These are set out in Table 1.

TABLE 1 — Vortex tube design criteria.

Robinson's criteria	Torlesse trap
(1) Width of tube opening – between 15 and 30 cm	27 cm
(2) Tube angle – 45° to flow	45°
(3) Tube length less than 4.5 m	4.24 m
(4) Tube length/width of opening should not exceed 20	15.7

Robinson also suggested (i) that the shape of the tube was not particularly important provided that material entering the tube is not allowed to escape back into the channel, (ii) that constant-section channels are as effective as tapered ones, and (iii) that the elevation of the upstream and downstream lips can be the same.

To ease construction a length of 0.3-m-diameter steel pipe with the top removed to give an 0.27-m opening was selected to form the tube. This opening was thought large enough to trap the larger sizes of bed load, and the resulting tube shape would inhibit any tendency for trapped material to be returned to the flow.

Laboratory Testing

To test the performance of the proposed vortex tube a 0.6-m-wide section was built and tested in the Fluid Mechanics Laboratory at the University of Canterbury. A false floor 8 m long and 0.6 m wide was placed in a 1.1-m-wide flume. The vortex tube was set into this floor at 45° to the flow direction and 5 m from the upstream end (Fig. 3).

Two tube shapes were tested. The first was the 0.3-m-diameter semicircular shape described above. The second had a square cross section with 0.25-m sides. The upstream and downstream lips were

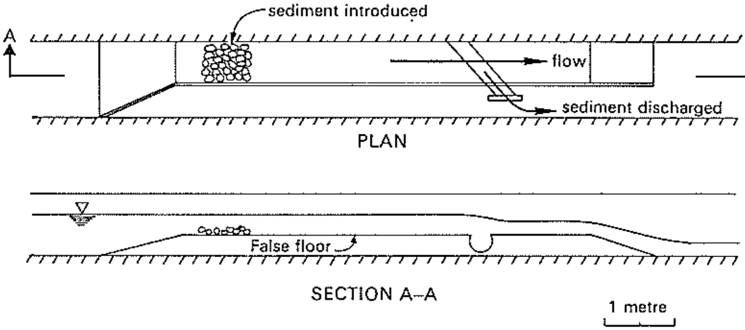

FIG. 3 — Laboratory model of vortex tube.

at the same level and flush with the floor. The tubes extended through the side wall of the structure and could be either blocked off or allowed to discharge into the flume. Discharges were measured using one of the laboratory's calibrated pits, and flow depths were determined with point gauges.

Sediment was introduced approximately 3 m upstream of the vortex tube by hand pouring from a weighing tray. This formed a small bar across the flow which was subsequently eroded over periods of up to 15 minutes. During this time the behaviour of the tubes could be observed and, when all the sediment had moved through the flume, their trapping efficiency determined.

A variety of sediment sizes was tested under a wide range of flows. Table 2 shows some typical results. They are from a series of tests using the semicircular tube to recover three size ranges of material. For each test in Table 2 the tube outlet was closed and a 9.1-kg sample was introduced upstream.

TABLE 2 — Laboratory tests with semicircular vortex tube.

Sediment size (mm)	*Water velocity (m/s)*	*Water depth (m)*	*Froude No.*	*Prototype discharge (litre/s)*	*Percentage retained*
<9.5	0.91	0.10	0.92	278	98.5
<9.5	1.04	0.18	0.78	555	23.4
<9.5	1.13	0.25	0.72	834	3.7
9.5–19.0	1.07	0.18	0.81	555	98.5
9.5–19.0	1.13	0.25	0.72	834	96.9
9.5–19.0	1.19	0.32	0.67	1110	25.6
19.0–38.0	1.16	0.24	0.76	834	100
19.0–38.0	1.22	0.31	0.71	1110	89

The results indicate that trapping efficiencies of 90 percent and above can be obtained. The efficiency is reduced markedly for the finer sizes, particularly at the higher discharges. Part of the loss can be attributed to material passing right over the tube. However, the larger portion is caused by the strong induced vortex in the tube, which was observed to throw trapped material back into the main flow downstream of the trap. Tests with the square-section tube showed greater trapping efficiencies, with material being able to remain in the corners where the vortex flow is not so effective.

With the tube outlets open, very much higher efficiencies were obtained for the finer materials. In this case the sediment was sluiced from the tube as rapidly as it was deposited, giving little time for any to be ejected by the vortex flow. Sluicing through the outlet was not as effective with the square tube.

Three main points emerged from the laboratory tests:

(1) When the trap is functioning, tube outlets should be open and the sediment removed continuously.

(2) The trap should consist of two parallel tubes so that sediment which escapes from the first tube of semicircular section may become trapped in the second, which should be of square section.

(3) A design based on Robinson's criteria would be satisfactory, at least for the tested range of flows, viz up to 1100 litres/second.

Accordingly, two tubes 0.5 m apart were incorporated into the control structure. They protruded through the left-hand wall and discharged into a concrete-floored work pit. A vertically sliding plate (miner's gate) was provided at the end of each tube. This gate has the advantage, essential in determining sediment rates, of being easily and quickly opened or shut regardless of the water and sediment flow.

Facilities designed adjacent to the structure included the work pit, a monorail and hoist, weighing platform, extensive wingwalls upstream to ensure that the structure cannot be bypassed, and a protective apron downstream to prevent scour or undermining. The structure is shown in Fig. 4. The vortex tubes can be seen discharging into the work pit in Fig. 5.

The structure was built by staff of the Tussock Grasslands and Mountain Lands Institute from January to May 1972. The 60 tonnes of concrete used in the reinforced control section was mixed on site using screened gravels from the river bed.

OPERATION

At streamflows up to approximately 100 litres/second the entire flow is diverted through the first vortex tube. With increasing flows the intensity of the vortex is increased and the proportion of diverted streamflow is reduced. The vortex has always been strong enough to carry the bed load associated with the particular flow from the stream through the wall of the control section and into the work pit.

The vortex tubes discharge into a steel-mesh basket lined with an hydraulic filter cloth which will retain all sediment sizes down to fine sands. Each time the basket is filled it is moved, using the monorail and hoist, to the weighing platform. Material not retained for size analysis is then moved back along the monorail and returned to the stream below the control structure.

For transport rates up to 2000 kg/hour all the sediment can be trapped, weighed and placed back in the stream. The tube gate is

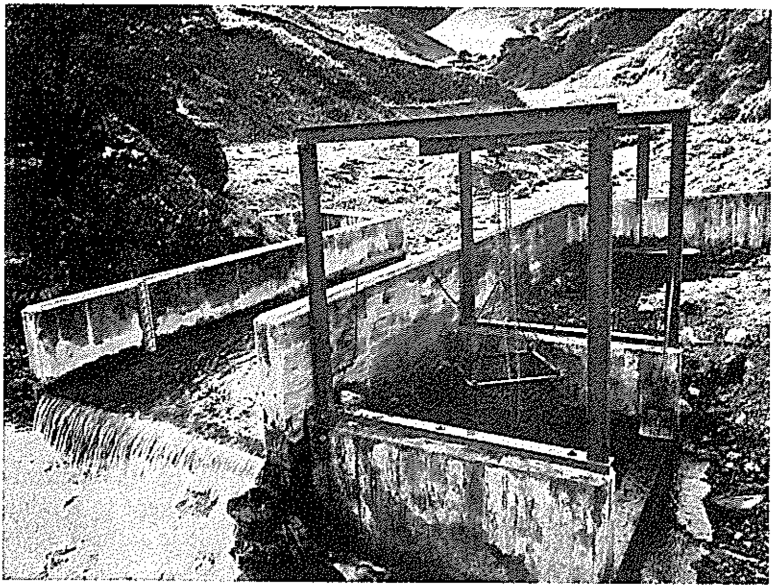

FIG. 4 — Torlesse Stream control structure. Major divisions on scale are tenths of a metre.

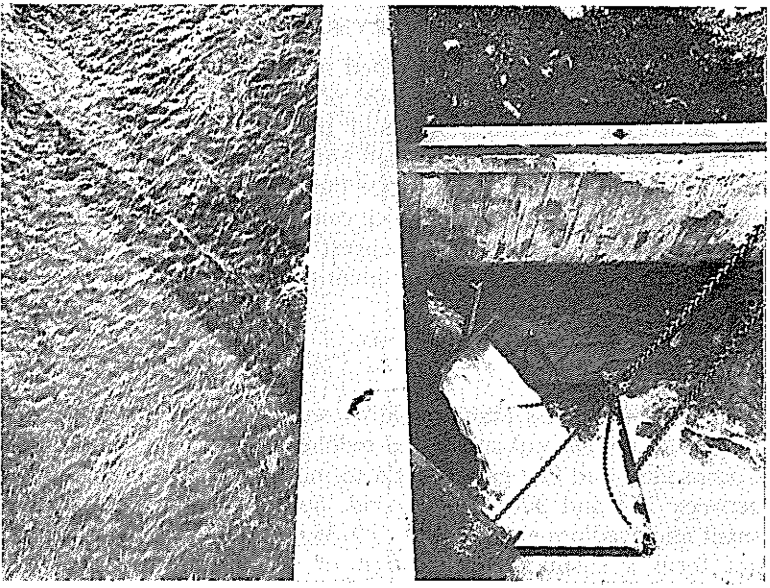

FIG. 5 — Vortex tube discharging into work pit.

open while the basket is being filled (5–20 minutes), and is closed while the basket is removed for weighing (2–3 minutes). During this latter time some material may be lost from the tube by being thrown back into the flow, but at these low flows this is certainly a minimal amount.

Rates in excess of 2000 kg/hour can only be handled by a programme of sampling in time. For these higher flow rates it is desirable to keep the tube gate open at all times. To achieve this, a sluice way is fitted beneath the outlet of the vortex tube. The sluice way carries the water and gravel across the work pit and discharges it into the stream channel. To make a measurement the outlet is closed, at time zero, the sluice is removed and replaced by the basket, the gate is opened and the sediment collected for a measured time. Typically, the gate would be closed for 20–30 seconds and the basket would fill in 1–3 minutes.

Because the bed load transport appears to be an unsteady phenomenon the periods between samples must be kept to a minimum. With two or three men working it is possible to sample every 10 to 20 minutes for periods up to 30 to 40 hours. Since many storms last for a number of days, an obvious improvement is to motorize the hoist-monorail system. This is under consideration at the present time.

PRELIMINARY RESULTS

Experience with only a limited number of storm events has shown that the structure as designed provides a satisfactory method for measuring bed-load yields and transport rates. The square-section tube has trapped only small amounts of material, indicating that within the limits of experience the main tube has been highly efficient. Quantitative results, which can only be regarded as indicative, are presented here. They suggest the magnitudes with which the project will have to deal, and point to interesting areas for more detailed investigations.

Visual Observation

At flows of less than 200 litres/second the stream transports very small amounts of suspended sediment and negligible bed load. Coarse sand and fine gravel begin to move as bed load at flows of between 200 and 300 litres/second. Such flows carry occasional small and medium-sized stones (20–35 mm, 35–80 mm) which do not form a significant proportion of total sediment load until streamflow is in the range 300–600 litres/second. At these flows the composition of the bed material has been observed to vary considerably.

Observations at intermediate flows (600 to 2000 litres/second) suggest that bed-load sediments move in confined bands through the middle one-third of the control section rather than being uniformly distributed across it. This has been an important observation, since at one time it was planned to divide the vortex tube so that only the section adjacent to the outlet would supply debris to the work pit. Such a sampling technique would result in considerable underestimates of sediment load and has therefore been abandoned. The higher bed-load rates were thus handled by temporal sampling only.

Streamflow

Originally it was intended to include a discharge-measuring structure downstream of the control section. However, several alternative designs indicated that the cost of such a structure would exceed that of the vortex trap. When an attempt to rate an upstream section of the channel failed, the control section itself was rated. The rated section is at the staff gauge downstream of the vortex tubes (Fig. 4). The stage-height invert is at the lowest point of the section. The derived rating curve (Fig. 6) tends to be insensitive for this control section. This, together with the difficulties in determining mean depth, implies that the uncertainties of measuring stream discharge can be greater than would normally be hoped for. (Depth measurements are made more difficult by the surface waves which develop at flows greater than about 300 litres/second, when the flow is near critical, and by the standing waves created when the vortex

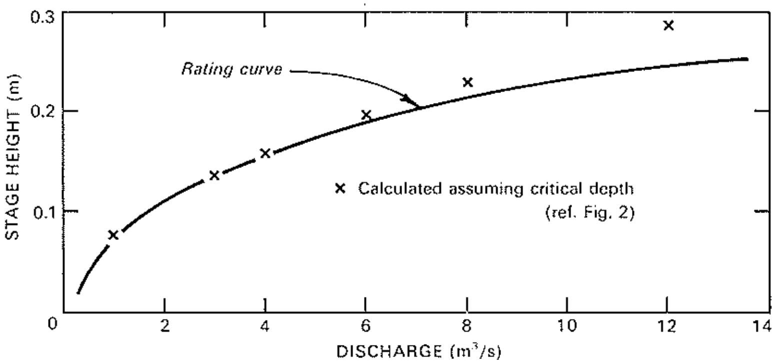

FIG. 6 — Measured rating curve.

tubes are in action.) Also shown in Fig. 6 are the points calculated under the critical depth assumption used for Fig. 2.

Robinson (1962) in his review noted that the Froude number of the flow over the tubes should be approximately 0.8. In the Torlesse trap, Froude numbers range from near unity at flows of 200–300 litres/second up to an estimated 1.5 at 2000 litres/second. Robinson also noted that for water depths less than 1.5 times the tube opening, which equals 0.405 m for the Torlesse trap, the Froude number has little effect on trapping efficiency. A depth of 0.405 m corresponds to a flow of approximately 2800 litres/second. For higher flows the trapping efficiency could well be reduced below those figures obtained in the laboratory.

Particle Size

The smallest of the trapped particles are in the coarse sand range, and have appeared for all flows capable of moving bed load. The largest are dependent, in the main, on the size of the storm. In May 1972 a rain-on-snow event produced a peak discharge of the order of 5000 litres/second. At this time ancillary equipment had not been installed and it was possible to do no more than watch the vortex tube eject rocks with dimensions up to 400 mm and masses up to 20 kg.

Sieve analyses of trapped material show large variations even for the same streamflow. Table 3 is indicative of the large variations encountered. The causes of this variability are the subject of further investigation. One explanation may be related to the variable composition of the sources from which the bed load is derived.

Storm Yield

In July 1972 a fresh which peaked at 200 litres/second yielded 150 kg of sand and fine gravel over a period of 18 hours.

TABLE 3 — Composition (percentage weight) of bed material, 29 August 1973.

Time (hours):	1106	1218	1445
Flow (l/s):	700	700	700
Transport rate (kg/min):	94.0	52.4	70.0
Percentage weight of bed material			
Particle size <2 mm:	12.2	2.6	0.5
Particle size 2–10 mm:	38.2	28.4	16.9
Particle size 10–20 mm:	26.6	34.3	28.1
Particle size 20–35 mm:	21.0	27.5	25.7
Particle size 35–80 mm:	0	7.2	22.0
Particle size 80–100 mm:	0	0	6.8

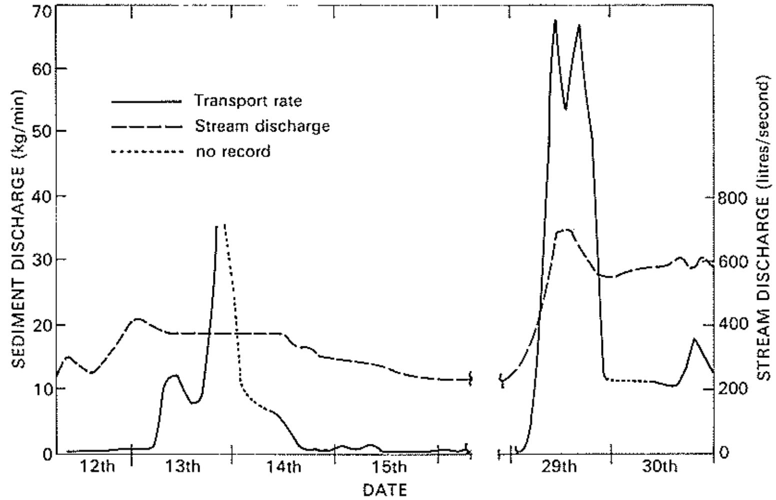

FIG. 7 — Bed-load transport rates (3-hour average) and stream discharge for part of August 1973.

In August 1973 a snow-melt event produced flows of between 400 and 700 litres/second. These yielded 78 000 kg of material (maximum size 80–100 mm) over five days.

Transport Rates

Fig. 7 shows a record of sediment transport rates made over six days of the August snow melt of 1973. The curve is derived from three-hour averages, and is thus smoothed. There is still a strong impression of bursts of bed load coming through the control section which seem quite unrelated to water discharge. The bursts contain violent fluctuations in transport rate, as can be seen in Table 4 and Fig. 8. Table 4 shows the maximum and minimum values recorded in separate two-hour periods on 13 August during a period of constant stream discharge. The actual measurements over a three-hour period are plotted in Fig. 8, where transport rates vary from 2.5 kg/min to 76 kg/min.

Visual observations made during this testing suggest that the fluctuations are indeed real and not just a quirk of the method of measurement. The bed-load transport is thus a very unsteady phenomenon, depending strongly on factors other than the streamflow. In this case some event occurring upstream has evidently made available to the stream a supply of transportable sediment. Bank failure, breakdown of an armoured bed, or sudden movements

TABLE 4 — Measured bed load rates during period of constant flow, 13 August 1973. The water discharge for all readings was 370 litres/second, and the mean depth for all readings was 0.115 m.

Time: 2-hour period starting	*Bed load rate (kg/min)*		*No. of observations*
	Max.	*Min.*	
0600	22.3	0.23	6
0800	15.9	6.5	6
1000	26.7	6.6	7
1200	6.6	1.4	6
1400	22.0	4.4	6
1600	19.3	2.9	7
1800	76.4	2.6	11
2000	44.6	8.6	6

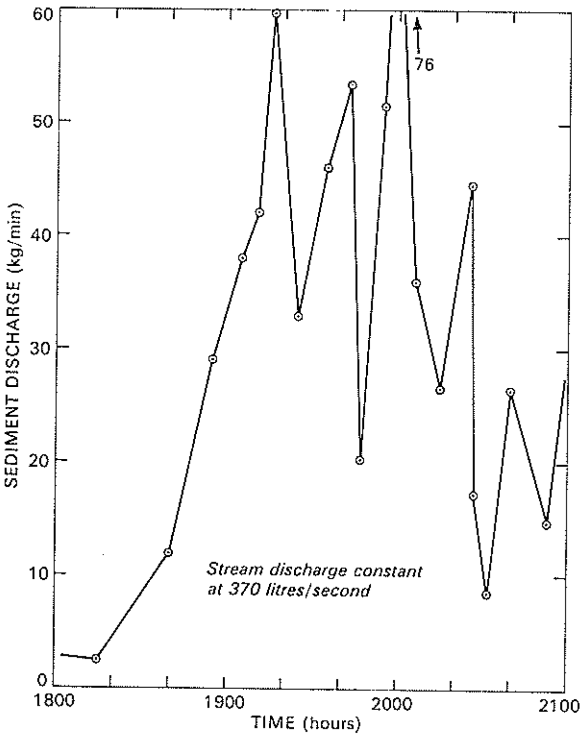

FIG. 8 — Details of 3-hour section of record made on 13 August 1973.

of large boulders as a result of steady erosion around their bases are all possibilities.

Calculations using the Meyer-Peter, Shields and Du Buoys bed-load formula for 50-mm sediment predict transport rates of the order of 1200 kg/min for the flow conditions of Fig. 6. This is very much greater than even that reached by the maximum fluctuation. Even allowing for the well known inaccuracies (factors of 10 or more) in such predictions, the stream is not transporting sediment to its full capacity. The bed-load discharge must therefore be controlled by the sediment supply and not by the water flow.

The unsteady and probably unpredictable nature of the bed-load transport will be a major portion of this continuing study.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of: the Nuffield Foundation for a grant of $3000 towards the cost of the vortex-tube trap and base hut facilities; Mr T. D. Heiler for assistance in design; Messrs I. Fryer and E. J. Stevens for their help with construction; Mr J. T. Johnson for his advice on aggregate suitability; Messrs R. A. Stratford, C. B. Ward, E. Costello and C. A. Shumway for field assistance; Mr and Mrs Maurice Milliken, Brookdale Station, without whose generosity and help this project would not be possible.

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