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THE NATURAL HISTORY OF SLAPTON LEY NATURE RESERVE

VII. THE HYDROLOGY OF THE SLAPTON WOOD STREAM

A Preliminary Report

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I. *THE BACKGROUND*

The establishment of the International Hydrological Decade (1965–1974) has stimulated the documentation, study and analysis of the hydrological processes operating within the landscape. Many small representative and experimental catchments have been established to monitor both natural processes and the influence of man's activity on drainage basin dynamics (e.g. Ward, 1971). The development of the Vigil Network research programme, instigated in the United States (e.g. Leopold, 1962; Slaymaker and Chorley, 1964), has also provided a focus for the interest of geomorphologists in the rate of operation of fluvial processes in small catchments. The drainage basin is now accepted as a fundamental unit of study in geomorphology and related studies. Against this backcloth, catchment studies have been set up at many locations in Great Britain, both by geographers and by workers from other disciplines (N.E.R.C., 1970). Explanation is, therefore, perhaps required before another study is added to an increasing list.

Instrumentation of the Slapton Wood Catchment was started late in 1969. Foremost amongst the underlying reasons was the desire to extend the documentation of the Slapton Ley Nature Reserve to include various aspects of its hydrology. In this context, the term hydrology includes both quantity and quality characteristics of water movement within the drainage basin as well as certain aspects of fluvial geomorphology. This small basin was selected because the lower reaches of the Slapton Wood Stream flow through the reserve. This preliminary report follows papers published previously in this Journal which have described the morphology of the reserve and various aspects of its fauna and flora. In addition, it was thought that the study of a small drainage basin within the South Hams area would provide detailed information that was, to the authors' knowledge, not available in south-west Devon. Furthermore, the results obtained from a catchment developed on the Lower Devonian strata would afford interesting comparisons with data from catchments already established on the Cretaceous and Triassic rocks of south-east Devon (e.g. Walling, 1971*a* and *b*) and on the Carboniferous strata near Exeter (e.g. Walling and Gregory, 1970).

Research at Slapton has always been very closely associated with the teaching role of the centre, and for many years the drainage basin has been regarded as a fundamental unit of study. The establishment of an instrumented catchment has proved of great value because it affords an outdoor laboratory close to, and on land controlled by, the centre, and because it can provide background information for teaching purposes, which is a valuable supplement to a student's own observations. The detailed records of rainfall and streamflow and information on sediment and solute transport greatly facilitate explanation of the processes operating in a stream which may be seen for only a few days during a period of dry weather. This initial study has already inspired further detailed work within the Nature Reserve; in particular, the monitoring of levels of nitrate in streams flowing into the Ley and their relationship to nitrate concentrations within the lake and to the productivity of phytoplankton.

II. *THE INSTRUMENTED CATCHMENT AND ITS SETTING*

Slapton Wood Stream is the lowest tributary of the River Gara: it joins the Gara on its west bank where it flows into the marsh of the Higher Ley (Fig. 1 (A)). The instrumented catchment does not coincide with the total watershed of the Slapton Wood Stream, because the only suitable site for the installation of a streamflow gauging structure was some 600 metres from the confluence with the Gara. Despite the name of the drainage basin, only a small proportion (13·5 per cent) of the catchment is occupied by Slapton Wood (Fig. 1 (B)).

The general topographic setting of the instrumented catchment is illustrated in Figure 1 (A) and Plate I, and a morphological description of the surrounding area is provided by Mercer (1966). A quantitative summary of the major drainage basin characteristics is presented in Table I. The catchment is underlain by Dartmouth Slates, the lowest of the three divisions of the Lower Devonian. Where exposures occur, red and brown argillaceous beds with strongly developed slatey cleavage are evident. A thick mantle of slatey head, the legacy of Pleistocene periglaciation, infills the valley bottoms and valley head depressions to depths of up to an estimated five metres or more, so that at no point in the stream channel is the bedrock exposed. The soils developed on the slopes are of the acid brown earth type with depths of up to one metre recorded in soil pits. Furthermore, the slatey regolith produces an abundance of coarse soil-forming particles, so that the storage and infiltration capabilities of the soils themselves are very high.

Table 1. *Catchment characteristics*

Area	$0 \cdot 94$ km.^{2}
Relief	132 metres
Basin Length	1,529 metres
Relief Ratio	86 metres/km.
Stream Length*	1,500 metres
Drainage Density*	$1 \cdot 60$ km/km.^{2}

* The value of stream length and the associated value of drainage density are based upon the extent of the stream network under mean flow conditions.

The gently sloping ground ($<5°$) above the 91·5 metre (300 ft.) contour in the west and north of the catchment affords excellent mixed farming (Fig. 1 (B)). This contour generally coincides with a marked break of slope and below it the valley sides are much steeper (up to 25°). This topographic discontinuity is emphasized by the occurrence of scrub and woodland on the steep slopes bordering the stream (Fig. 1 (B)). The catchment is judged to be hydrologically "watertight", in view

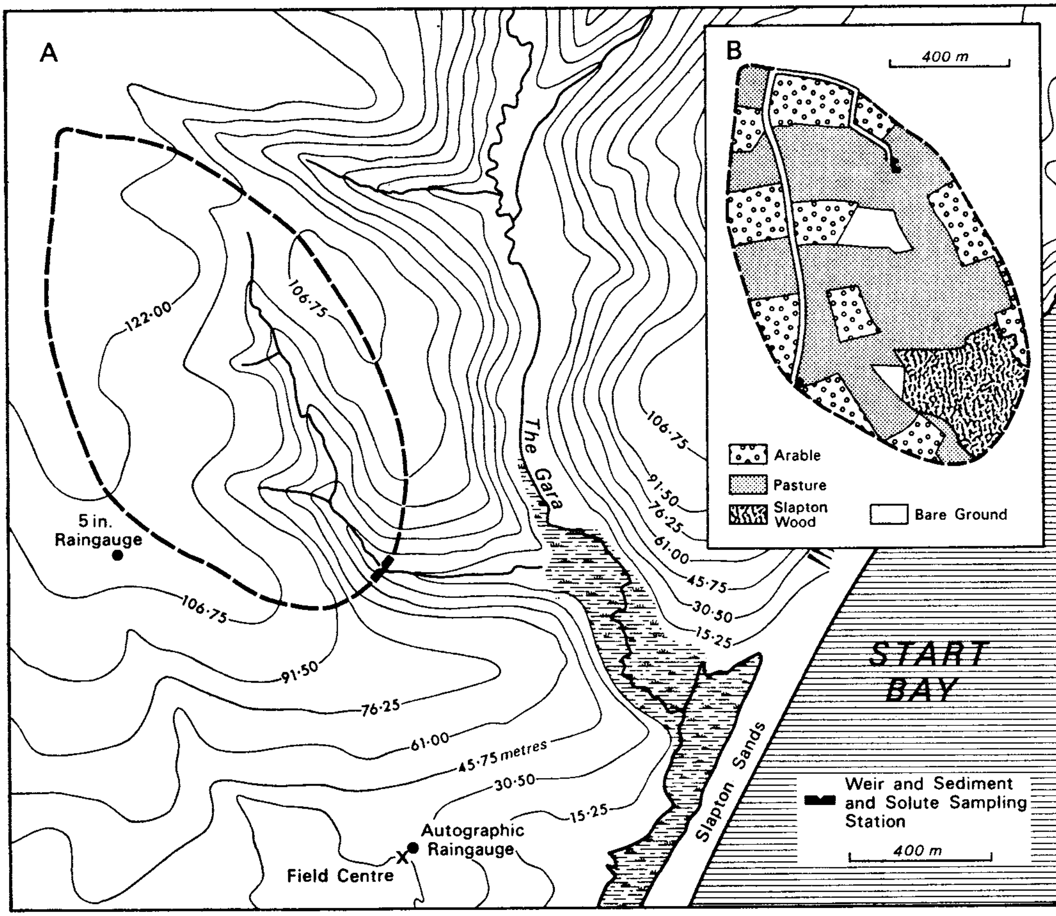

FIG. 1.
The physique (A) and the pattern of land use (B) of the Slapton Wood Catchment.

of the well-defined topographic watershed and the low permeability of the slate bedrock. The mean annual rainfall over the catchment, estimated from the ten-year record at the Field Centre, is 1075·5 mm. (42·3 inches) and the maximum daily rainfall within that period was 81 mm. (3·18 inches) on 28 July 1969.

III. *INSTRUMENTATION*

The scheme of instrumentation within the basin is not designed to be complete. It is primarily concerned with documentation of the inputs and outputs of the drainage basin system. Because of problems of security within the catchment itself, precipitation is at present being assessed from the records provided by a natural siphon autographic raingauge at the Field Centre, some 800 metres outside the watershed (Fig. 1 (A)). A limited correction for orographic effects has been applied, based upon the records from a 12·7 cm. (5 inch) storage gauge sited on the high ground about 100 metres from the south-west boundary of the catchment (Fig. 1 (A)). The autographic gauge at the Centre is fitted with a daily chart (1 cm./hour), which provides considerable detail on the intensity and duration of individual storms. More recently, an attempt has been made to assess the magnitude of evaporation losses in the area by installing a U.S. Weather Bureau Class A Evaporation Pan in the grounds of the Field Centre. The climatological station will soon be equipped with sunshine and windspeed recorders to provide the data necessary for the evaluation of the Penman evapotranspiration formula (e.g. Penman, 1948).

The output of streamflow from the basin is gauged by a 120° sharp-crested or thin-plate vee-notch weir. This form was chosen, in preference to the more commonly used 90° weir, to provide an effective compromise between lesser sensitivity of low flow measurement and the greater capacity to contain high flows. Water-level is continuously recorded by a Munro vertical-type water stage recorder installed over a stilling well. This is connected to the pool upstream of the weir by a horizontal pipe ensuring that the water level recorded is unaffected by surface disturbances. The detailed record of the water stage provided by the daily charts (1·8 cm./hr) from the recorder is converted to discharge by using a stage/discharge rating, based upon a weir formula (Hertzler, 1938). A computer routine has been developed to process the stage record defined by half-hourly stage values and to calculate values of daily mean and monthly mean discharge and total flow volumes for daily, monthly and annual periods.

Sediment and solute yields from the catchment are being measured at a location immediately upstream of the weir pool, where the flow is unmodified. Suspended sediment concentrations are being sampled at regular time intervals, and more frequently during storm runoff, using an improvised depth integrating sampler (cf. Gregory and Walling, 1971). Sediment concentrations are determined by filtration, utilizing glass fibre filter circles. At the same time, samples of stream water are collected for analysis of the solute content. Laboratory analysis of these samples determines the concentrations of (a) total dissolved solids (mg./l) by evaporation and measurement of specific conductance (μmhos.), (b) calcium, magnesium, sodium and potassium by an atomic absorption spectrophotometer, and (c) the nitrate nitrogen by a colorimetric method (e.g. Morris and Riley, 1963). Values of suspended sediment and solute transport at the time of sampling can be calculated as the product of stream discharge and the relevant concentration value. An attempt is being made to measure the yield of bedload from the catchment by using a pit-type bedload trap (cf. Gregory and Walling, 1971) installed across the total width of the channel. This has a steel outer wall and a removable inner steel container. The inner container is emptied frequently during storm runoff, in order to assess the amount of bedload moved (kg./hr.) at specific levels of discharge. Unlike the measurements of suspended sediment and solute concentrations, which provide sample point values, the bedload trap provides an estimate of the load moved within a given time and, provided that it is emptied regularly and not allowed to overfill, it is possible to collect the total yield from the catchment. However, problems of overfilling inevitably occur during times of extreme flood and it has occasionally been necessary to estimate the load during periods when the trap was overtopped.

IV. *PRELIMINARY RESULTS*

Analysis of the records and data provided by the first complete twelve-month period of observations has been undertaken, to give a preliminary insight into the hydrological processes operating within the instrumented basin. In addition, it is hoped that this initial evaluation of results will reveal any problems inherent in the approach and in the scheme of instrumentation, and it may well indicate themes worth future attention. Although streamflow data was available from the winter of 1970, the period of record under consideration extends from 1 April 1971 to 31 March 1972, as it was only then that measurements of sediment and solute yields were available. This period is perhaps not as convenient as a "water-year" (1 October to 30 September), the conventional period for hydrologic analysis. However, because streamflow values were closely similar at the beginning and at the end of the period (10 l/s), and in both cases represented baseflow unaffected by storm rainfall, it is reasonable to assume that levels of storage were also similar, a condition necessary for simple evaluation of the water balance.

IVa. *THE WATER BALANCE*

Evapotranspiration losses from the catchment can be estimated using the simple water balance equation,

$$\text{Evapotranspiration} = \text{Rainfall} - \text{Runoff} \pm \triangle\ \text{Storage}.$$

The total rainfall for the study period was 832·5 mm. and the runoff was 333·4 mm. Assuming that the changes in storage ($\triangle$ storage) were negligible, the value for evapotranspiration can be calculated as follows:

$$\begin{aligned}\text{Evapotranspiration} &= 832{\cdot}5\ \text{mm.} - 333{\cdot}4\ \text{mm.} \pm 0\\ &= 499{\cdot}1\ \text{mm.}\end{aligned}$$

The value of evapotranspiration of 499·1 mm (19·6 inches) can be compared with the Penman estimate of potential evapotranspiration calculated for Plymouth, which amounts to 595·3 mm. (23·4 inches). The estimate derived from the water balance equation is only 83 per cent of the Penman estimate but this is to be expected because the latter is an estimate of *potential* loss as distinct from *actual* loss. Potential loss will exceed actual loss when the soil is dry and there is therefore an appreciable soil moisture deficit (S.M.D.) which results in a restriction of evapotranspiration. This is almost certain to have been the case during the summer months of the study period because a simple calculation of the monthly levels of S.M.D. suggest that it may have been as high as 200 mm. (*c.* 8 inches) during October. The S.M.D. level at which values of actual evapotranspiration fall below potential levels is termed the "root constant" and Penman (1963) has suggested a root constant value for pasture of approximately 75 mm. (3 inches). The monthly values of potential evapotranspiration for Plymouth have been converted to estimates of actual losses within the Slapton Wood Catchment by using a mathematical technique suggested by the Ministry of Agriculture, Fisheries and Food (1967). This provides an estimate of actual evapotranspiration for the study period of 513 mm., which is close to the 499·1 mm. derived from the water balance equation. It is hoped that future availability of meteorological data from the Field Centre and the information provided by the evaporation pan, will make these calculations more meaningful for this particular location. However, in the absence of more sophisticated data, the monthly proportions of actual evapotranspiration loss indicated by the corrected Penman estimates have been applied to the annual water balance estimate, to provide values of monthly losses from the instrumented catchment (Fig. 2 (A)). Using these values, and the data collected on monthly rainfall and runoff (Fig. 2 (A)), estimates of the

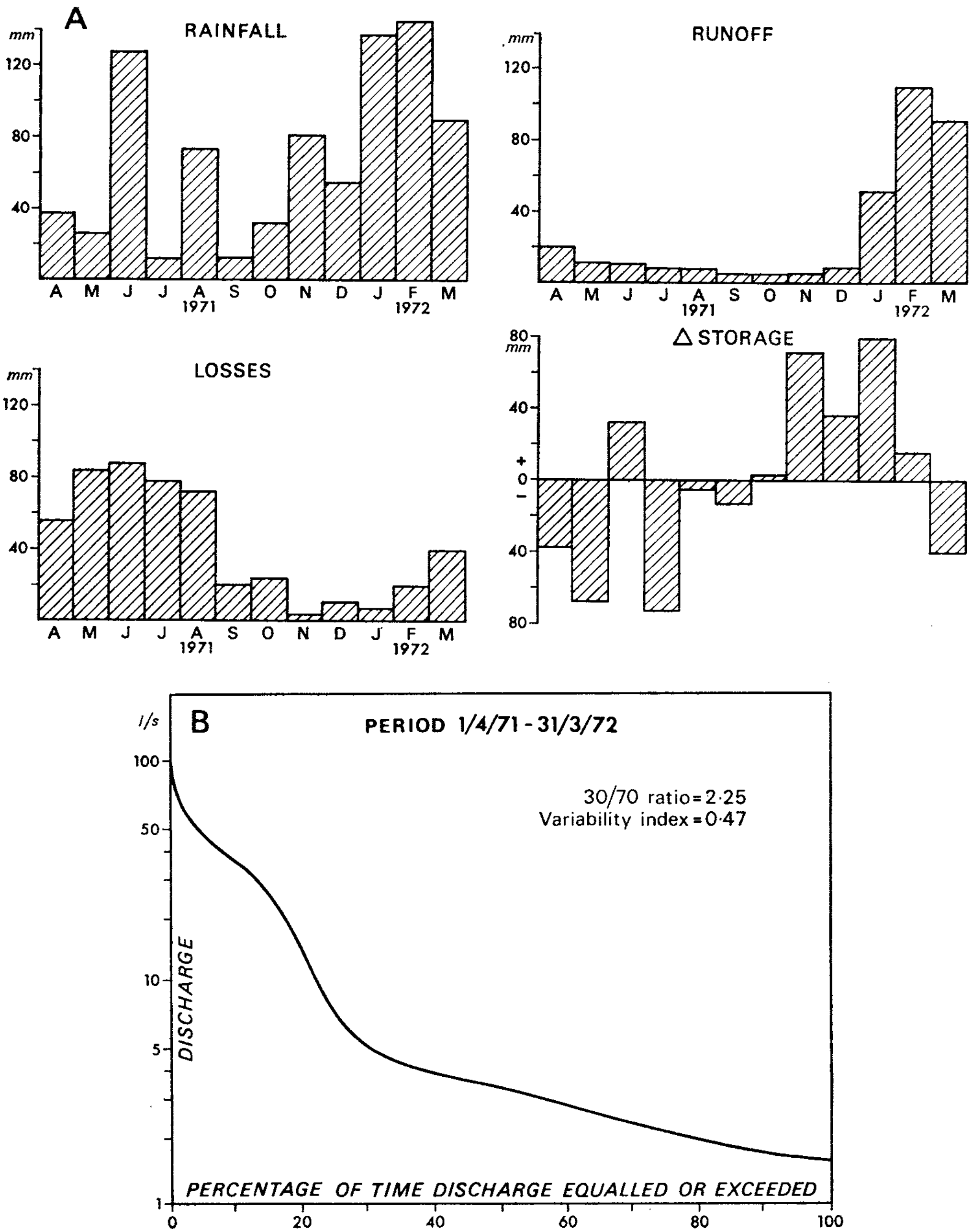

FIG. 2.
Monthly estimates of the four major water balance components (A) and the streamflow duration curve (B) for the study period.

monthly change in storage component ($\triangle$ storage) of the water balance have been calculated (Fig. 2 (A)). This component can be as much as $\pm$75 mm. (3 inches) for individual months, indicating a considerable storage potential within the catchment. In addition the values of monthly $\triangle$ storage estimated for this particular twelve-month period indicate that 208 mm. (8·2 inches) of rainfall entered storage during October to February, to be subsequently released during the summer months. Because of the poor aquifer properties of the slate bedrock, it is thought that the majority of this storage is provided by the soil and underlying regolith and by the head deposits in the floors of the valleys. This suggestion draws support from the work of Hewlett (1961) which demonstrated that storage within the soil and regolith was itself sufficient to account for the baseflow discharges within steep-sided watersheds in the Appalachians, U.S.A.

IVb. *GENERAL RUNOFF CHARACTERISTICS*

The streamflow duration curve for the study period in Figure 2 (B) provides a useful summary of the pattern of discharge. The duration curve was derived from instantaneous values of discharge taken from the recorder charts at thirty-minute intervals and shows the percentage of time that a given discharge magnitude was equalled or exceeded: e.g. flows over 50 l/s occurred during 3 per cent of the time. The discharge rates ranged between 1·5 l/s and 79 l/s. The shape of the duration curve and, in particular, the variability of the flows can be described by several indices (Fig. 2 (B)). The 30/70 ratio expresses the ratio of flows exceeded 30 per cent of the time to those exceeded 70 per cent of the time: the value of 2·25 obtained for the 30/70 ratio is close to the 2·4 suggested by Hall (1967) to be characteristic of south-west Devon. The Variability Index, originally proposed by Lane and Lei (1950), is essentially the standard deviation of the logarithms of flows occurring at duration intervals of 10 per cent between 5 per cent and 95 per cent of the time.

An attempt has also been made to estimate the proportions of storm runoff and baseflow comprising total runoff from the instrumented catchment by using the time based concept of hydrograph separation proposed by Hewlett and Hibbert (1967). This involves separation of a stream hydrograph into *quickflow* and *delayed flow*, by projecting a line upwards at a gradient of 0·545 l/s. km.^{2} hr from the beginning of each hydrograph rise, to meet the recession limb of the hydrograph. All flow above these lines is designated quickflow, whilst all flow below them is designated delayed flow (Fig. 4 (A)). Following the suggestions of Hibbert and Cunningham (1967), a computer routine has been devised to perform this separation on the annual streamflow hydrograph defined by the half-hourly instantaneous flow values (Table 2). A striking feature is the very small proportion of quickflow, amounting to only 1·15 per cent of the total runoff, in contrast to the values of between 15·5 per cent and 50·15 per cent obtained from five small catchments in south-east Devon (Walling, 1971*a*). The steep slopes of the lower portions of the catchment and the slate bedrock would seem, at first sight, to favour the occurrence of storm runoff or quickflow, and the low quickflow proportion must be explained in terms of the highly pervious soil and regolith within the catchment, which inhibit surface runoff and saturation. These provide ample storage for storm rainfall which is later released slowly as baseflow or delayed flow. Woodland over some of the catchment further reduces the likelihood of storm runoff (e.g. Sopper and Lull, 1967).

Table 2. *Annual flow separation for the Slapton Wood Catchment*

	mm.	%
Total Flow	333·44	100·00
Quickflow	3·83	1·15
Delayed Flow	329·61	98·85

Monthly Quickflow Contributions (per cent of monthly flow):

A	M	J	J	A	S	O	N	D	J	F	M
0·39	0·03	1·10	0·04	3·10	0·00	0·18	0·55	0·94	1·43	1·50	1·01

Records taken over a longer period are needed for an analysis of flood and low flow frequency characteristics which would qualify any conclusions concerning the magnitude of flood flows and minimum discharges from the catchment. Even so, the maximum recorded discharge of 84 l/s. km.^{2} (7·7 cubic feet per second per square mile) is lower than would be expected from a qualitative assessment of the catchment topography and the rainfall input.

IVc. *STORM RAINFALL/RUNOFF DYNAMICS*

The unusually small proportion of quickflow from the catchment has stimulated a more detailed investigation of the storm runoff dynamics. Inspection of individual storm runoff hydrographs indicates that the proportion of storm rainfall accounted for by storm runoff or quickflow is very small and generally in the range 0·2 per cent to 3·0 per cent (Fig. 4 (B and C)). These values can be accounted for by precipitation falling on to the stream channel itself and by direct runoff from the adjacent saturated areas. A strip of land six metres wide encompassing the 1,500 metres of channel shown in Figure 1 (A) would amount to 1 per cent of the total catchment area. Other workers, including Ragan (1968), have described similar situations where only a small proportion of the drainage basin contributes to storm runoff and the *Partial Area* concept of runoff formation has been introduced to provide an alternative to the traditional Horton concept of storm runoff production (Horton, 1933) where storm runoff can be produced by the whole catchment, if rainfall intensity exceeds the infiltration capacity. Classic overland flow from the watershed slopes is replaced by direct runoff from the saturated areas bordering the stream and the surrounding seepages. Throughflow, i.e. flow through the soil above a percolation limiting horizon, could also contribute to the storm hydrograph both directly, and also indirectly by providing the source of water to the saturated areas (e.g. Weyman, 1970).

Fourteen individual storm runoff events, where the storm rainfall and resultant storm hydrographs were easily isolated, were studied in detail. The amount of rain, and three hydrograph parameters, namely, runoff depth (mm,), runoff percentage (quickflow as a percentage of the storm rainfall), and hydrograph rise (increase in discharge above the previous level of delayed flow, l/s) were determined, and the three hydrograph parameters were plotted against storm rainfall (Fig. 3 (A_{1-3})). In each case the correlation coefficients are extremely low (significance levels $t>25$ per cent). This feature is worthy of comment because relationships can usually be established between storm rainfall amount and storm runoff depth (e.g. Osborn and Lane, 1969). In the case of the Horton overland flow model, increases in storm

PLATE I

The Slapton Wood Catchment and the adjacent area. (Reproduced with the kind permission of Fairey Surveys Ltd., Maidenhead, Berkshire.)

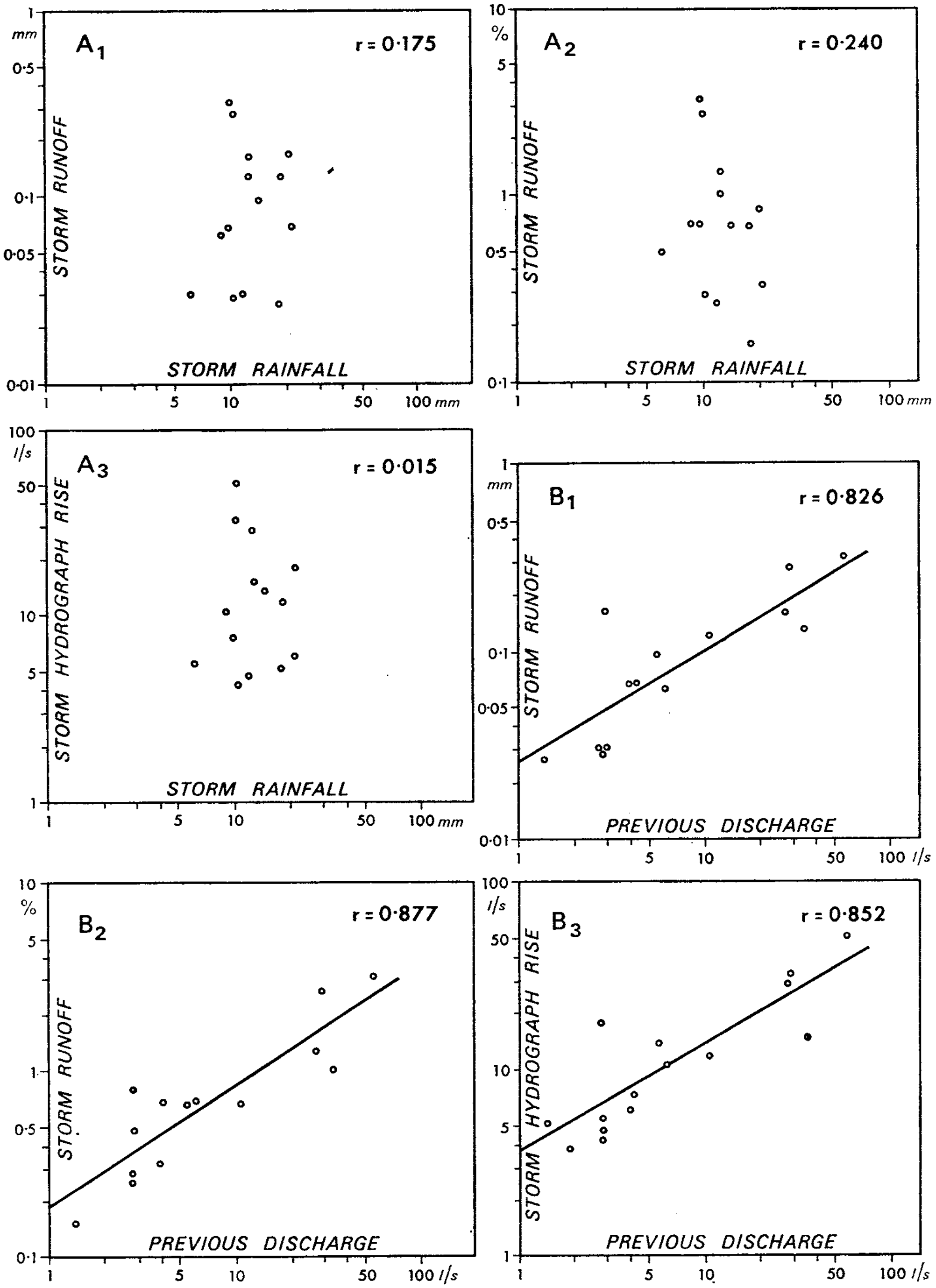

FIG. 3.
Relationships between three storm hydrograph parameters and (A) storm rainfall amount and (B) the level of discharge preceding the storm runoff event.

rainfall are generally associated with increases in storm runoff, because larger storms are themselves associated with either increased intensity (intensity exceeds infiltration capacity) or increased duration (infiltration capacity decreases during a storm). In the Partial Area model an almost direct linear relationship might be expected, because, assuming a constant source area, runoff would be directly proportional to rainfall input to the source area.

The small number of storm events analysed to date precludes any definitive conclusions, but it would seem more appropriate to view storm runoff production in the Slapton Wood Catchment as conforming to the *Variable Source Area Concept* in which the source area of storm runoff is accepted as being only a small proportion of the total catchment area (e.g. Dunne and Black, 1970; T.V.A., 1965), but it may expand and contract in response to prevalent moisture conditions. Expansion could be by headward extension of the drainage net or by lateral growth of the saturated area bordering the stream. The level of discharge occurring before a storm has been used as an approximate index of catchment moisture conditions and therefore of the extent of the contributing area, and in Figure 3 (B_{1-3}) clear relationships have been established between this index and the three hydrograph parameters. In each case the correlation coefficients are significant (t at $<0\cdot1$ per cent level). The extent of the contributing area therefore seems more important than the amount of rain in explaining the storm runoff response of this catchment. The storm hydrograph can be viewed as being produced by a small proportion of the basin corresponding to the channel and the adjacent saturated areas which may themselves vary in extent. Assuming that 100 per cent runoff occurs from the contributing area, then, in the fourteen events considered, the extent of this area would have ranged between 0·15 per cent and 3·18 per cent of the total catchment. However, these values cannot be strictly correct because, even if runoff from the saturated areas was 100 per cent, the contributing area might expand during a storm.

Because the storm hydrograph response from the catchment can be adequately accounted for in terms of direct runoff from the saturated area adjacent to the stream channel, throughflow would appear to be of minor importance in contributing directly to the storm runoff. Without evidence from measurements of water movement within the soil this conclusion must be tentative, but it is partially substantiated by the fact that the storm runoff peaks lag only a short time behind the storm rainfall and the hydrographs rise and fall very steeply (e.g. Fig. 4 (B and C)). Direct runoff from the saturated areas could be expected to reach the stream channel very quickly, to cause a rapid rise and to cease very soon after the cessation of rainfall; whereas throughflow velocities, estimated at 20–30 cm./hour (Kirkby and Chorley, 1967), would give rise to a much slower and extended response. Throughflow can, however, be thought of as providing a lateral movement of water down the slopes of the watershed under unsaturated conditions, and as feeding the saturated area at the foot of the slope. As such it contributes directly to the delayed flow of the stream and is important in determining the extent of the saturated areas adjacent to the stream. Only when saturated conditions expand up the valley sideslopes would throughflow increase sufficiently to provide a significant contribution to the storm hydrograph. One particular storm event, which occurred outside the study period on 23 January 1971, exhibits a runoff response that could be viewed as demonstrating a throughflow contribution to the storm hydrograph. On this occasion antecedent moisture conditions were very high (preceding delayed flow discharge = 60 l/s)

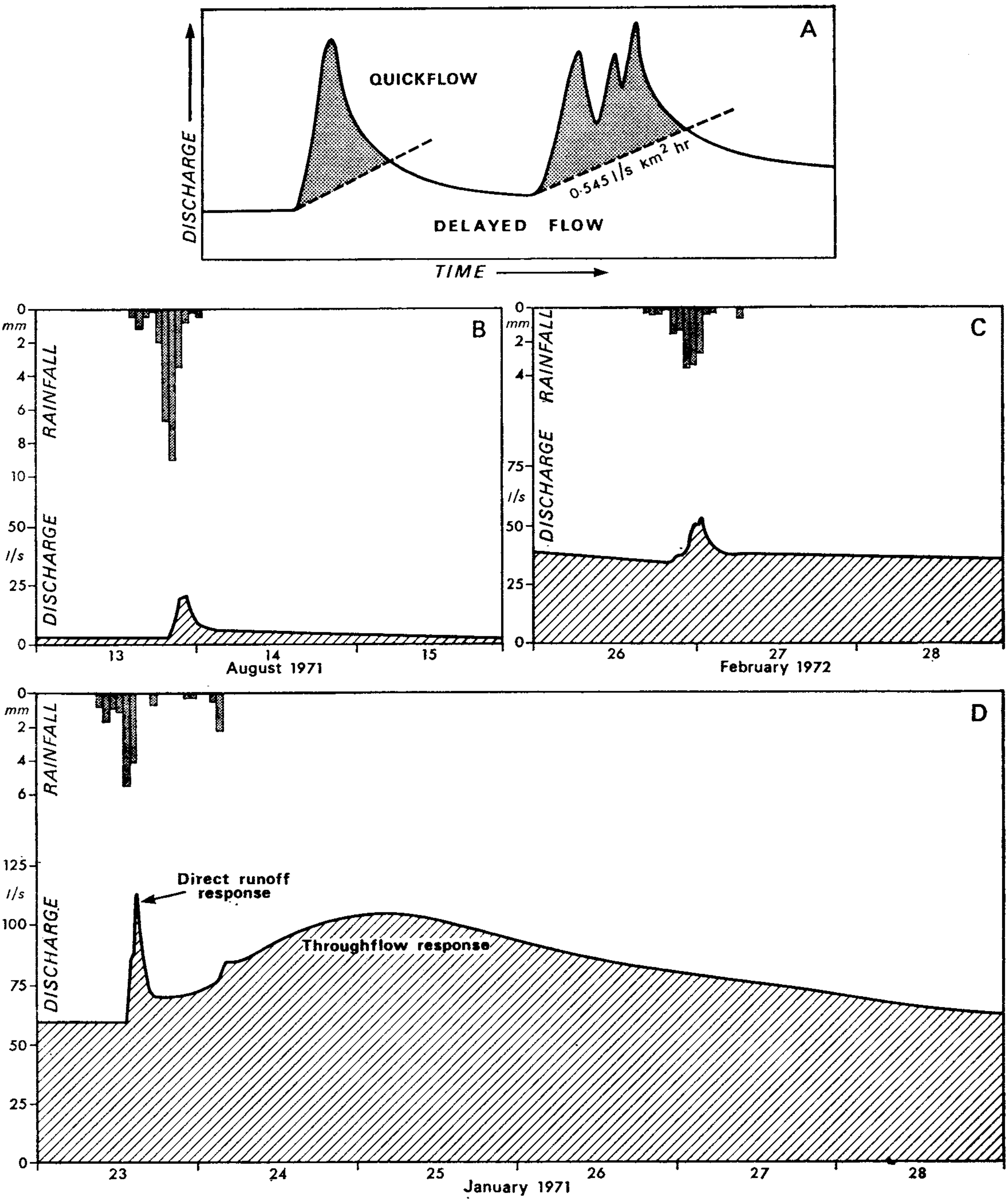

FIG. 4.

An hypothetical example of the technique used to separate the runoff hydrograph into quickflow and delayed flow components (A). (B), (C) and (D) illustrate examples of the catchment response to storm rainfall under conditions of progressively greater moisture status. In the first two cases the storm hydrograph is the result of direct runoff from the channel and the areas bordering the stream whilst in the third case (D) a secondary throughflow response can also be distinguished.

and saturated conditions could have extended up the lower slopes during the storm. The normal rapid hydrograph response was followed by a period of slowly rising discharge giving a secondary hydrograph (Fig. 4 (D)), which peaked about 36 hours later and which was attributed to throughflow. Weyman (1970) distinguished a similar storm runoff response, in the East Twin Brook, a small upland basin in the Mendip Hills, Somerset, with a throughflow lag time of up to 36 hours. However, in that catchment the moisture conditions necessary for the generation of a throughflow peak often occurred.

IVd. *SUSPENDED SEDIMENT PRODUCTION*

An indication of the pattern of suspended sediment production within the catchment is provided by the suspended sediment concentration/discharge relationship or suspended sediment rating presented in Figure 5 (A). The precise form of this rating can be usefully compared with those obtained from streams in south-east Devon by Walling (1971*b*). The magnitude of the maximum concentrations are very different. In the Slapton Wood Catchment the maximum observed concentrations are around 70 mg./l., whereas values in excess of 1,000 mg./l. were measured during storm runoff events in south-east Devon. This characteristic can be ascribed partly to the underlying slate, which produces soil, regolith and channel forming material lacking in clay-sized material for transport in suspension (i.e. a restricted supply of sediment), and partly to the lack of high storm discharges (i.e. a lack of transporting capacity). Furthermore, since the area contributing to surface runoff is small (Section IVc) the source of the supply of material from the surface of the watershed is very limited in areal extent. Subsurface throughflow carries very little material in suspension.

The slope of the line fitted to the logarithmic plot of sediment concentration versus discharge (Fig. 5 (A)) must also be considered as an important index of the suspended sediment dynamics of a catchment. This slope corresponds to the constant or exponent b in the equation.

$$\text{Log concentration} = b \log Q + c$$

or

$$\text{Concentration} = c^1 Q^b$$

Where Q = discharge

c^1, c = constants.

This rating plot possesses an exponent less than 1·0. This is unusual because most streams exhibit values between 1·0 and 2·0 and in south-east Devon the values were generally nearer 2·0. This characteristic can be tentatively ascribed to the restricted nature of the supply of fine-grained material to the channel for transport in suspension. In general, suspended sediment load can be viewed as a non-capacity load, in other words the stream could carry more if it was available, and the precise extent to which the transporting capacity is satisfied is reflected in the slope of the rating curve. In this particular case, the low exponent value of less than 1·0 is associated with meagre supply availability. The considerable scatter about the straight line relationship superimposed on to the rating plot indicates that other factors, apart from the level of discharge, are important in controlling the levels of concentration within the stream. There is scope for a more detailed study of the

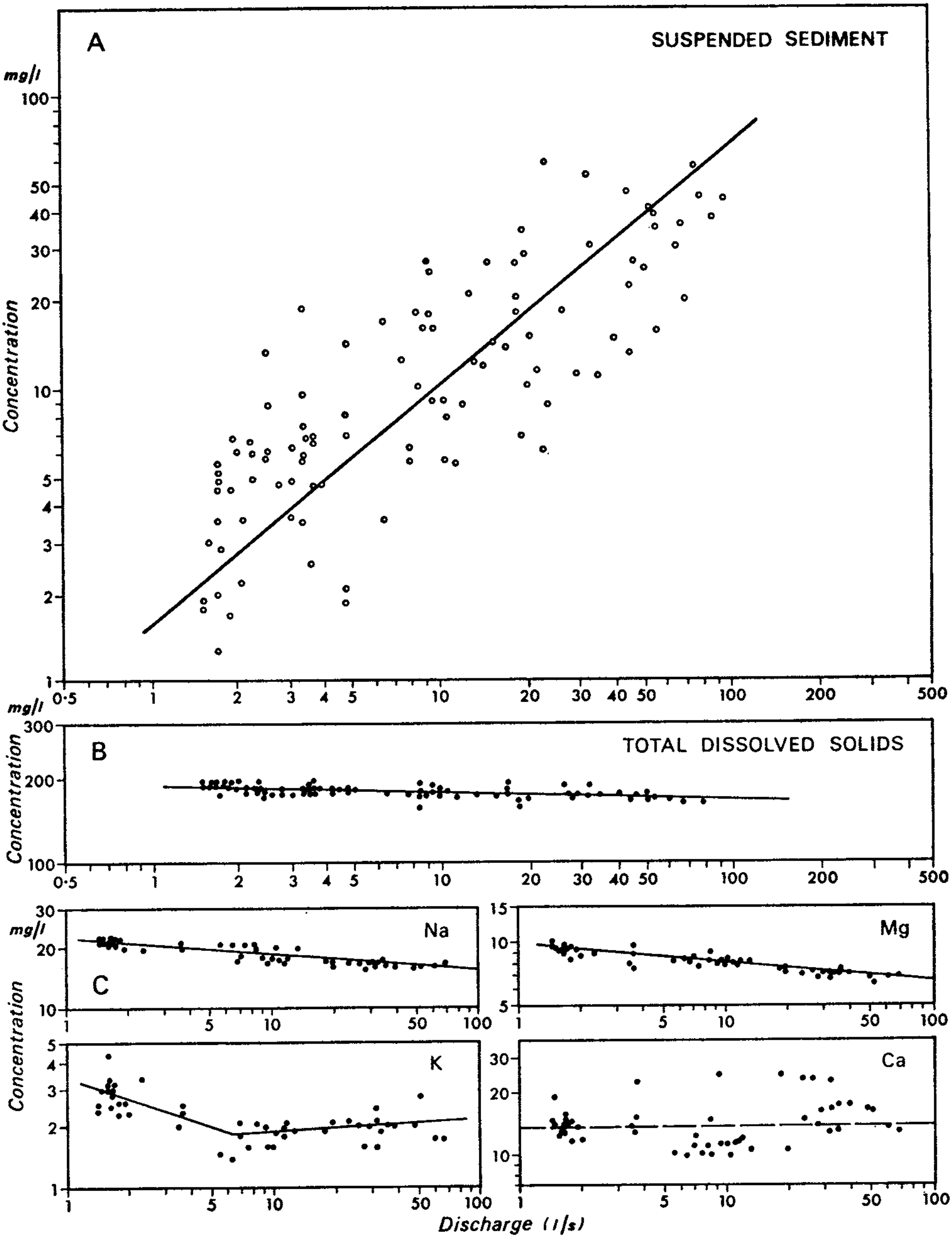

FIG. 5.
Suspended sediment and solute concentration/discharge relationships for the Slapton Wood Stream.

pattern of suspended sediment production and transport, particularly in relation to the variable source area dynamics of runoff production.

Utilization of the rating plot equation along with the computer file of half-hourly discharge values makes possible the evaluation of the total suspended sediment load for each day. This procedure is open to errors associated with the scatter exhibited by the rating plot, but in the absence of more frequent or automated sampling (e.g. Walling and Teed, 1971), or continuous monitoring of turbidity (e.g. Fleming, 1969*a*), it provides a valuable "best estimate". The total monthly loads of suspended sediment for the study period are presented in Figure 6 (A) and the general pattern of suspended sediment production can be seen to reflect closely the monthly distribution of runoff volumes (Fig. 3 (A)). Ninety-five per cent of the suspended sediment yield was produced in the months of January, February and March.

IVe. *BEDLOAD YIELD*

The results from the bedload trap provide an estimate of the total bedload yield of 580 kg., from the instrumented catchment during the study period. This yield was produced solely during the months of February and March, the months of maximum runoff (Fig. 6 (B)). Study of the bedload trap catches at clearly defined levels of discharge provides an insight into the pattern of bedload production. Figure 7 (A) suggests that there is a threshold level of 42 l/s below which no transport of bedload occurs and this conclusion is supported by field observation. Transfer of the data to logarithmic co-ordinates (Fig. 7 (B)) enables the relationship between discharge and bedload transport rate to be approximated by a power function similar to that derived for suspended sediment,

i.e. Bedload Transport Rate α $Q^{3 \cdot 3}$
where Q = Discharge.

The value of the exponent (3·3) reflects the interrelationship between discharge and the tractive force of the moving water. The value obtained in this study is similar to that found for the River Clyde in Scotland by Fleming (1969*b*). This field data will provide scope for future work on the derivation and evaluation of a suitable bedload formula for theoretical calculation of the bedload yield of streams similar to the Slapton Wood Stream (e.g. A.S.C.E., 1971).

To study the particle size distribution of the bedload, four samples from the trap container have been sieved and the results are presented in Figure 7 (C). No clear relationship between particle size composition and discharge magnitude has been distinguished, but it seems that size composition is controlled by the detailed pattern of scour and fill within the channel rather than being a simple function of discharge magnitude (cf. Fleming, 1971).

IVf. *SOLUTE PRODUCTION*

Values of total dissolved solids (T.D.S., mg./l.) are closely related to the measurements of specific conductance (S.C., μmhos at 25 °C.) taken on the samples and the formula T.D.S. = 0·65 S.C. has been used to estimate the dissolved solids concentration of samples which were not analysed by the evaporation procedure. The total dissolved solids rating presented in Figure 5 (B) is analogous to the suspended sediment rating: it provides an indication of the pattern of solute production within the study catchment. Concentrations vary very little with discharge and the average

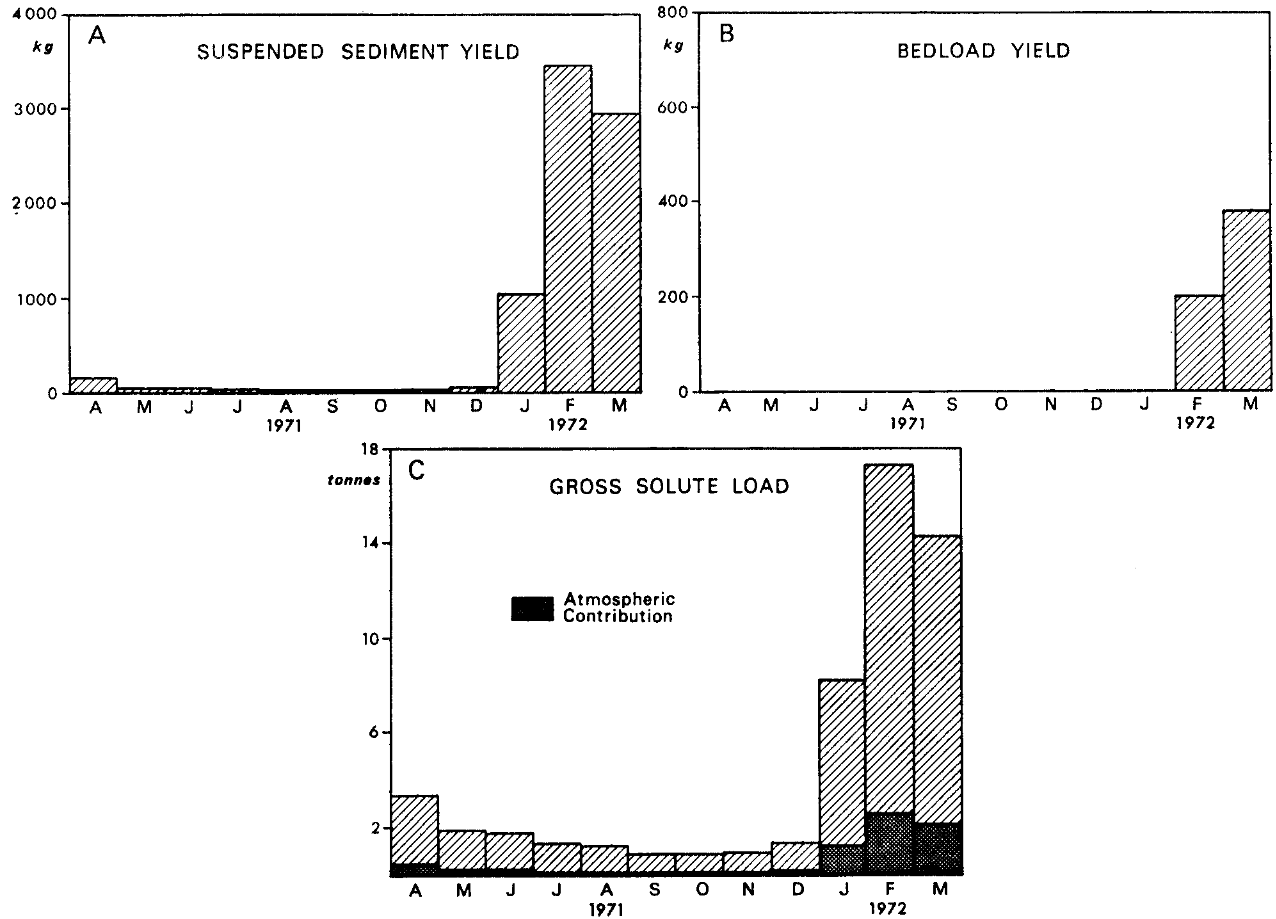

FIG. 6.
Estimates of the monthly yields of suspended sediment (A), bedload (B) and gross solute load (C) for the study period.

is approximately 185 mg./l. However, a slight reverse slope to the line through the data plot indicates that there is a tendency for concentration to decrease with increasing discharge. This can be explained in terms of a dilution effect. The minimum flows, which represent delayed flow from long-term subsurface storage, exhibit maximum concentrations. Increased flows are associated with a progressive dilution of this component by direct storm runoff which, because of its shorter residence time, possesses lower solute concentrations.

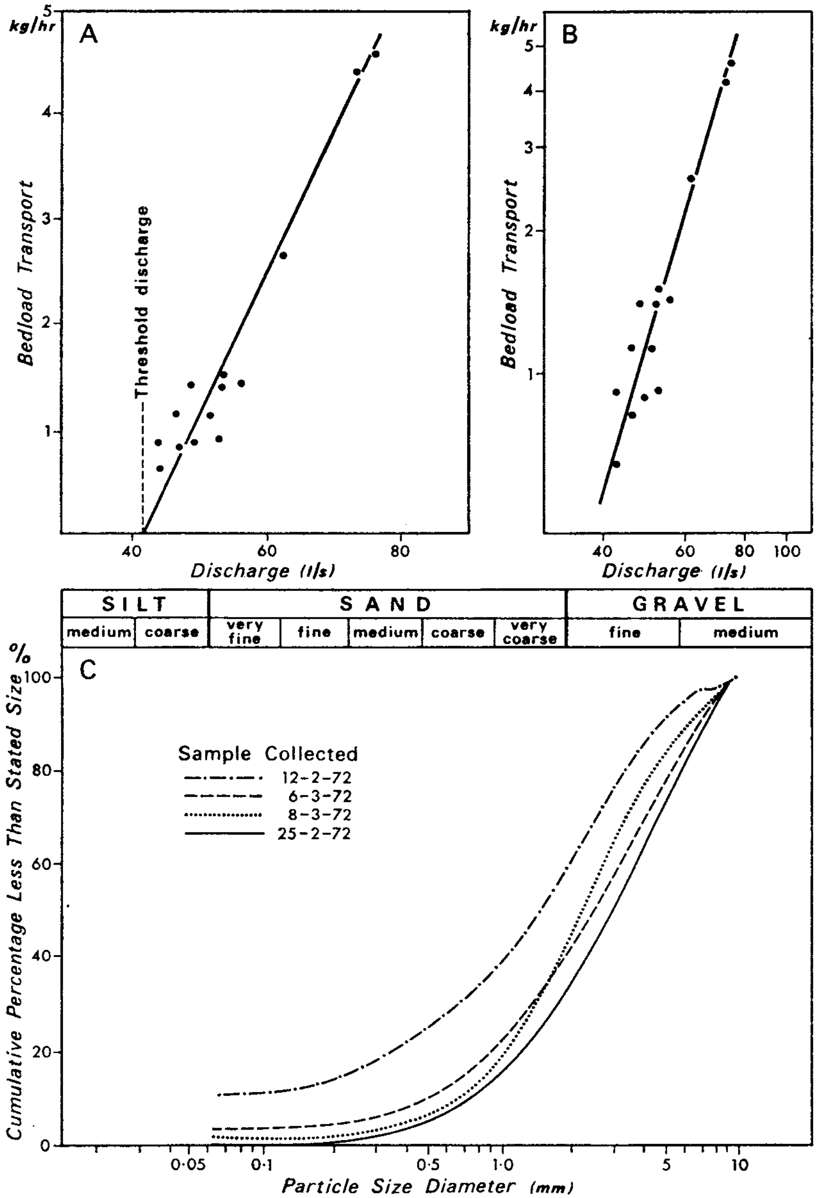

FIG. 7.

Relationships between the rate of bedload transport and the level of discharge based on linear (A) and logarithmic (B) co-ordinates. Particle size distribution of four bedload samples (C).

A small proportion of the solute load of the stream comes from cyclic salts from the atmosphere. Preliminary analysis indicates that the solute concentration of rainfall in the Slapton Wood Catchment is approximately 10 mg./l. Assuming that the solute content of water lost from the catchment by evapotranspiration remains in the system, the atmospheric contribution to the solute content of the stream flow can be tentatively calculated as equivalent to

$$\frac{\text{Rainfall}}{\text{Runoff}} \times \text{Solute concentration of Rainfall} = \frac{832 \cdot 5}{333 \cdot 4} \times 10$$

$$= 25 \text{ mg./l.}$$

This is approximately 14 per cent of the average solute concentration in the stream. The solute rating relationship defined in Figure 5 (B) has been used in a computer routine with the half-hourly values of discharge to estimate the daily and monthly solute loads (Fig. 6 (C)).

The pattern of monthly yields necessarily reflects the quantity of runoff (Fig. 3 (A)) as total solute concentrations vary very little between different levels of flow. The contribution made to the monthly solute yields from atmospheric sources have also been estimated (Fig. 6 (C)) and the total contribution during the study period amounted to 14·7 per cent of the gross solute load. The pattern of production of K, Na, Ca, and Mg ions has also been studied. Sodium and magnesium (Fig. 5 (C)) show a similar downward trend with increasing discharge to that exhibited by total dissolved solids, although the slopes are more marked. The rating plots for potassium and calcium are not so easy to interpret. A compound rating line has been sketched on to the K diagram, and the form of this can be tentatively accounted for in terms of runoff dynamics. Potassium ions are readily leached from the soil (e.g. Cruickshank, 1972) and it is, therefore, not unreasonable to expect relatively high concentrations in minimum flows which originate as delayed flow from the lower levels of storage within the soil and regolith of the catchment; furthermore, concentrations would decline as increasing streamflow includes water from the upper levels of storage where leaching has already occurred. Fertilizer application within the catchment is a source of potassium and could be used to explain the increase in potassium concentrations at high flows as surface runoff transports it into the stream.

There is no clear relationship between calcium concentrations and discharges perhaps partly because of analytical inaccuracies but more likely because factors other than the volume of stream discharge are important in controlling the concentration levels of this particular ion. The movement of solutes within a drainage basin cannot be considered solely in terms of hydrological processes; the same solutes are also involved in biological nutrient cycles (e.g. Johnson *et al.*, 1969). When the supply of an element is in critical biological balance variations are to be expected in the concentration of that element in a stream.

The relationship between the concentrations of individual ions and streamflow (Fig. 5 (C)) have been combined with the half-hourly discharge data to calculate estimates of the daily and monthly loads of these ions. Atmospheric sources may account for 29·4 per cent, 11·9 per cent, 6·8 per cent and 13·0 per cent of the annual yields of K, Na, Ca, and Mg respectively.

The nitrate nitrogen content of stream water samples has been frequently determined as part of a wider investigation into the input of nitrate into Slapton Ley, and also to provide a further index of the operation of hydrologic processes within the Slapton Wood Catchment (Fig. 8 (A)). When samples taken in the growing season are distinguished from those taken in the dormant season (Fig. 8 (A)), there is no conclusive evidence of the effects of biotic activity on stream nitrate levels. However, the tendency for nitrate concentration to increase with increasing discharge contrasts with the decreasing concentrations of total solute load and the majority of the cations. This upward trend suggests that the major source of nitrates is in the upper levels of the soil so that maximum concentrations occur in the runoff from the upper levels of storage and from the surface. This source of nitrate is probably associated with the application of nitrogenous fertilizer within the catchment. The monthly nitrate loads calculated from the frequent samples are shown in Figure 8 (B)), and they closely reflect the pattern of runoff where they indicate that 85·3 per cent of the total nitrate yield occurred during the months of January to March. The stream load of 1,885·6 kg. can be compared with an estimated application of 4,236 kg. of nitrate nitrogen in fertilizer over the catchment area during the same twelve months.

IVg. *THE PATTERN OF DENUDATION*

The very short period of record makes it difficult to present substantive conclusions concerning the pattern of denudation within the Slapton Wood Catchment, but certain features can be distinguished. The magnitude and relative importance of the three major components of the denudation system, namely, suspended sediment

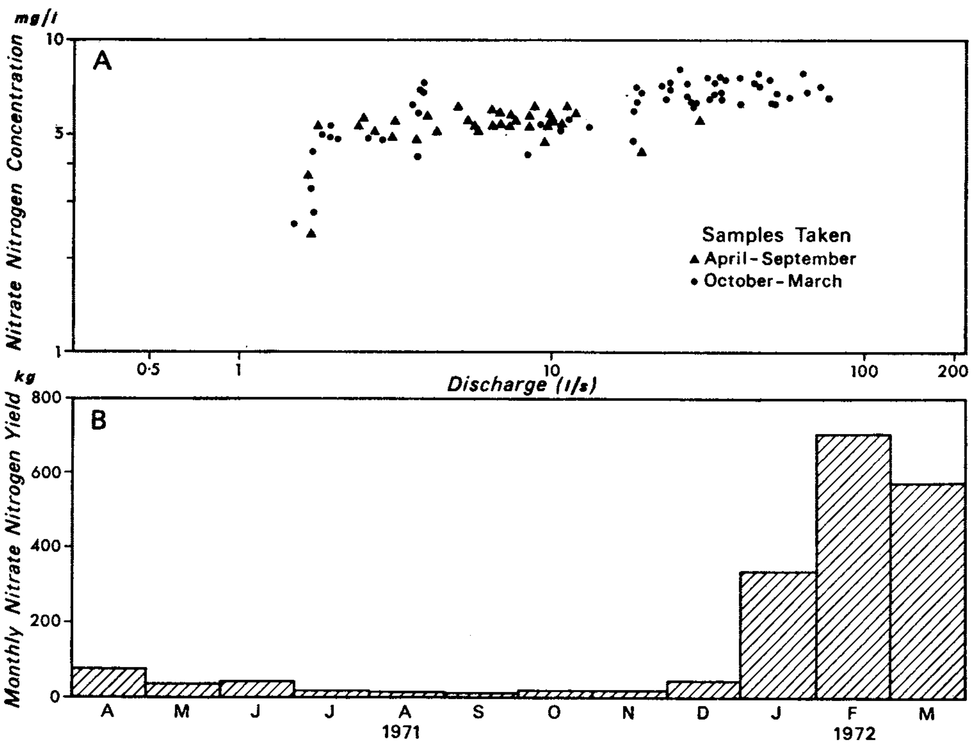

FIG. 8.
Some characteristics of nitrate yield from the Slapton Wood Catchment showing (A) the concentration/discharge rating and (B) the estimated monthly yields for the study period.

yield, bedload yield, and solute yield are listed in Table 3. A distinction can be made between the gross solute yield and the yield corrected for input of cyclic salts from the atmosphere. The solute yield is of greatest importance, exceeding the suspended sediment load by approximately six times. This is surprising since chemical denudation is often considered significant only in limestone terrains. The values contrast with those from catchments documented in south-east Devon (Walling, 1971b) where the ratio of dissolved load to solid load was nearer the range 1 : 1 to 2 : 1. A similar ratio of chemical denudation to suspended sediment production (5 : 1) was observed by Cleaves *et al.* (1970) in a small watershed developed on the schists of the Maryland Piedmont, U.S.A., but in this case, it was argued that high intensity flood events of low frequency (i.e. rare) were important in removing

Table 3. *The magnitude of the denudation components*

	Load (kg.)	Gross total load (%)	Net total load (%)
Suspended Sediment Load	7,853	12·68	14·53
Bedload	580	0·94	1·07
Gross Solute Load	53,464	86·38	—
Net Solute Load	45,627	73·71	84·40
Atmospheric Solutes	7,837	12·66	—

The gross and net solute loads are defined as the loads including and not including, respectively, the atmospheric contribution. The values of total load are similarly defined.

weathered material from the catchment as solid sediment load, and that over an extended period the ratio would become closer to 1 : 1. This possibility cannot be discounted for the Slapton Wood Catchment. The bedload yield during the study period amounted to 7·4 per cent of the total solid load, a value within the range 5–12 per cent suggested for a stream of this nature (Sheppard, 1963). The importance of bedload transport could increase during periods of extreme flooding.

One hundred per cent of the bedload, 95 per cent of the suspended load and 74 per cent of the solute load were removed during the winter months of January, February and March (Fig. 6) when storm runoff events would have been most important. In this context the frequency aspect of the denudation components must be considered (e.g. Wolman and Miller, 1960). The sediment and solute yield data and the discharge record have been analysed in order to determine the proportions of the individual denudation components transported by flows of different magnitudes and durations. For this purpose, flow magnitude has been expressed as the percentage of time a value of discharge was equalled or exceeded (as in a flow duration curve). Table 4 indicates that nearly 70 per cent of the bedload was transported by flows occurring only 2 per cent of the time (i.e. within 175 hours) and that nearly 72 per cent of the suspended load was transported by flows occurring 10 per cent of the time (876 hours). The tendency for the majority of the denudation to be affected by high flows occurring for only a small proportion of the time, shown by the suspended sediment load and particularly by the bedload data, is less marked in the case of the dissolved load. This is because solute concentrations remain relatively stable at all levels of flow, whereas suspended sediment concentrations and bedload transport rates increase with increasing discharge.

Table 4. *Frequency aspects of sediment and solute transport from the Slapton Wood Catchment*

Flow Frequency %	Percentage of Load moved by flows equalled or exceeded with the stated frequency		
	Suspended Load	Bedload	Solute Load
0·05	0·86	2·67	0·39
0·10	1·76	5·3	0·77
1·00	14·9	43·0	7·0
2·00	25·5	68·7	12·8
5·00	47·8	98·0	27·5
10·00	71·7	100·0	46·7
20·00	93·1	100·0	71·0
50·00	98·7	100·0	88·0

Sediment and solute yield data may be used to calculate rates of erosion and values of surface lowering, but such estimates must be interpreted with caution. It is dangerous to accept the results from a short-term study as indicative of the long-term average, and if extrapolation backwards in time is attempted, it should be realized that climate, vegetation, land use and other controlling factors might have been different in the past. Furthermore, it is wrong to assume that erosion acts uniformly over the surface of a catchment; the channel is an important focus of mechanical erosion and the ideas presented concerning the Variable-Partial Area concept of runoff production mean that both solute and suspended loads are likely to be produced preferentially from certain areas of a watershed. However, with these reservations in mind, an erosion rate of 23·00 $m.^3/km.^2/yr$ or a rate of surface lowering of 23·00 mm/1,000 yrs. has been calculated for the study catchment, assuming a density conversion factor of 2·5 $tonnes/m.^3$, and using the value of solute load corrected for the atmospheric contribution. At this stage no allowance has been made for the contribution to the dissolved load of the stream made by application of fertilizer to the fields within the catchment.

This value is only about 50 per cent of those exhibited by small catchments on the Upper Greensand and Keuper Marl of south-east Devon.

V. *CONCLUSIONS*

A longer record will provide opportunities for more analyses of the hydrology of the Slapton Wood Stream, but the first year of results from the instruments installed in the study catchment have demonstrated several distinctive features. In particular, the storm runoff dynamics are of interest in view of the small volumes of quickflow produced by storm events, and the Variable Source Area concept can be used as an explanatory model. More detailed documentation of runoff production (e.g. Weyman, 1970), including the use of apparatus for monitoring subsurface moisture conditions and movement, is required to investigate the importance of throughflow in storm runoff production. An extension of this work might enquire into the implications of the Variable Source Area concept in the production of sediment and solutes and the interrelationships between runoff components and water quality (e.g. Pinder and Jones, 1969).

The importance of the solute component in the denudation system is also noteworthy, although a longer period of record would render any estimate of its precise importance more meaningful. More detailed analysis of the solute content of precipitation is also required if variations in solute levels in the stream and the importance of chemical denudation are to be studied in more detail.

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