Working Paper No 312

THE PATTERN OF WASH EROSION AROUND AN UPLAND STREAM HEAD.

Mike McCaig

The pattern of wash erosion around an upland stream head

Mike McCaig
Research Fellow
School of Geography
Leeds, LS2 9JT.

Abstract

Results from sediment traps set up around a Pennine stream head have shown that surface wash volumes and sediment transport rates are closely related to the area drained per unit contour length at the sampling point.

Mapping area drained (a) and slope gradient (s) together as the variable ln(a/s) showed a complex pattern in the study catchment due to the occurence of natural pipe systems. Relationships between ln(a/s), wash frequency, wash volume and sediment transport have been examined and maps produced. The results show that frequently wet drainage line areas (high ln(a/s) which occupy only 2 - 7% of the catchment area account for around 80% of the erosion accomplished by surface wash beyond the headward extent of the perennial stream channel.

The ln(a/s) variable has also been incorporated into a hydrologically based simulation model of erosion in and around the stream head. The model has been used to investigate the influence of different catchment hydrological characteristics on the pattern of erosion.

List of figures

List of tables

The pattern of wash erosion around an upland streamhead

1. Introduction

One of the main purposes of field measurement in Geomorphology is to collect data with which to develop and test process based models of sediment transport. Measurement studies in pursuit of this purpose can be divided into 3 complimentary types, these are studies of;

(i) Process mechanisms

(ii) Relationships between process rates and dynamic variables (eg rainfall intensity, flow depth etc)

(iii) Relationship between processes and landforms

The first two study types require experimental measurements (as defined by Ahnert, 1978) made under laboratory or experimental conditions where control of individual parameters can be maintained. The third type of study relies, in contrast, on observational measurements of process rates and patterns under natural conditions. This paper describes the sampling design and methods used to determine the pattern of wash erosion around a simple landform; an upland stream head in the Central Pennines of Yorkshire.

2. Study catchment description

Work was carried out in the 4.3 hectare catchment of the Slithero Clough, near Ripponden, Yorks. The catchment covers the South facing side of Joiner Stones Hill (grid ref: SE 009102), rising from 301m OD to 360m at the highest point in the catchment. The bedrock geology is massive Namurian Millstone grit of the Kinderscout series (Wray, *et al*, 1930). The slope itself is convex-linear in profile with a small lithologically produced scarp just below its wide, flat, summit surface. Above the scarp the catchment is truncated below the slope divide by a water supply catchwater (built in the Nineteenth century) which follows the 360m contour (figure 1).

On the hillside the Slithero Clough has formed a valley 4m deep by 7m wide at its outflow. Stream flow is perennial to 60m upslope of this point. The perennial flow limit occurs at the junction of two major lines of drainage, beyond which the topographic expression of the surface drainage becomes relatively indistinct. Drainage from the Easterly part of the catchment reaches the perennial stream through a network of natural pipes, the largest pipe being 0.3m in diameter. The pipeflow source area is the flatter part of the slope above the scarp. This area has a typical 'wet moorland' *Erica sp* vegetation community (Moss, 1931), developed over a peat cover which reaches a depth of 2m in places. On the mid-slope, below the scarp, a mixed grass vegetation community dominated by *Molinia sp* is found on a thin (13-30 cm) sandy *ranker* type of soil. The Westerly part of the catchment contains only a few small pipes. The main drainage feature in this part of the catchment is a wet boggy area just below scarp. This bog drains to the perennial channel through a wide Juncus flush (the term flush is used here as defined by Ingram 1967). Rainfall, evapotranspiration and runoff totals for the study year Nov 1977-Nov 1978 were 1130mm, 540mm and 606mm respectively.

3. Considerations for a sampling design and appropriate methods

The following sections describe the considerations which determined the sampling design and methods used in the study catchment.

3.1 Approach to producing a process map

The most obvious method of describing the pattern of wash erosion on a landform is through the construction of a map of wash and sediment transport rates. It would be impossible, however, to measure wash rates at a sufficient number of points to produce any sort of accurate map. The only way a process map can be produced is if some empirical relationship between location (topographic position) and the process being studied can be established. For the case of surface wash, the familiar 'saturation excess' model of runoff generation described by Kirkby and Chorley (1967) (figure 2), suggests which variables will determine, for a given effective rainfall distribution, the volume and frequency of overland flow generated. These are: (i) inflow and (ii) outflow subsurface flow rates, (iii) soil moisture storage capacity and (iv) losses to groundwater. Saturated subsurface discharge rates can generally be described by Darcy's law (Darcy 1856):

$$V = K\frac{d\psi}{dx} \qquad (1)$$

where V = subsurface flow rate

K = soil constant

$\frac{d\psi}{dx}$ = total potential gradient, including gravitational and moisture potential (which is equivalent to topographic gradient alone in a completely saturated soil mass)

For the slope element drawn in figure 2, therefore, the equation of continuity between inflow, outflow and moisture storage is:

$$V_{a_*} - V_{a'_*} + \frac{\delta q}{\delta x} = \frac{ds}{dt} \qquad (2)$$

where $\frac{ds}{dt}$ = change in storage level

$a_*\ a'_*$ = inflow and outflow cross section areas

$\frac{\delta q}{\delta t}$ = increase in flow due to drainage from element

Clearly, therefore, the storage deficit (rainfall required to generate overland flow) is least for those parts of a slope where in the downslope direction either $\frac{d\psi}{dx}$ decreases or area drained per unit contour length increases or both. The effect of increasing gradient for points draining the same area is to decrease overland flow frequency and volume, since more rapid drying occurs due to increased drainage rates. Conversely, increases in area drained per unit contour width for the same gradient increases overland flow frequency etc. An appropriate combination of the two overland flow controlling variables is, therefore, as the ratio: a/s (where a = area drained per unit contour width, s = tangent of topographic slope). This ratio has large values in hollows and becomes small on spurs. Taking natural logarithms of the ratio for convenience, maps of $\ln(a/s)$ can be produced for any landform from a topographic map of suitable scale and field survey (or air photographs) to determine patterns of surface and subsurface drainage. The map produced for the Slithero Clough (figure 3) was originally drawn from a field survey of 1:1000 scale. The small scale was found necessary because of the complex drainage pattern resulting from the presence of natural pipes in the catchment.

The pattern of the variable $\ln(a/s)$ should (according to the saturation excess model of runoff generation) then correspond to the pattern of local overland flow production. If empirical relationships between field observations of wash frequency, volume and $\ln(a/s)$ values can be established relatively detailed 'process maps' can be produced. However, it must be noted that these maps will only be accurate if the following assumptions are satisfied:

(i) The saturation excess (storage controlled) model of overland flow generation is applicable to the study site

(ii) Systematic variations in soil moisture storage capacity (ie soil depth and hydraulic conductivity) with topography do not significantly affect relationships between $\ln(a/s)$ and wash processes.

If a further empirical relationship between wash and sediment transport can be established from field data the maps produced can be used to determine the pattern of wash erosion around the stream head.

3.2 Determination of empirical relationships between ln(a/s) and wash frequency/volume

The standard technique for establishing empirical relationships between variables in Geomorphology and other observational sciences is through statistical analysis. It is important, therefore, that the data set (sample) on which analysis is to be performed should be representative of the population from which it is drawn. Given that the purpose of this study is to establish a relationship applicable to the complete range of $\ln(a/s)$ values encountered, the crucial questions of sampling design to be answered are:

(i) How many sample points are required?

(ii) What sort of layout of these sampling points is required?

a. <u>Sample size determination</u>

The sample size required to determine the true population characteristics of a variable depends upon the variability within the sampled population. Estimation of sample sizes requires, therefore, that a study variables' population distribution and an estimate of its standard deviation be known (information that is usually obtained by a pilot survey). Such is the degree of variability in natural landscapes, however, that even the size of pilot survey required to give a realistic estimate of a variables standard deviation is often beyond the scope of the research project. In this project insufficient time was available for a pilot survey to be undertaken and so the sample size used was determined only by the maximum amount of field effort that could be maintained. In effect this approach assumes that the variability of the variables being monitored is so great that a degree of 'undersampling' will occur with any sample size. Sampling theory shows, though, that it is sample size rather than sample fraction which determines the precision of the sample mean as an estimate of the population mean. That is, the sampling variance of a sampling mean is related to the true population variance as:

$$V_s = V_p \cdot \frac{1}{n} \left(\frac{N - n}{N} \right) \qquad (3)$$

where V_s = sample variance

V_p = population variance

N = number of individuals in population

n = number of individuals in sample

Since $N \gg n$ equation 3 can be simplified to

$$V_s = V_p \cdot \frac{1}{n}$$

In a case where no estimate of the population variance is available increasing sample size to the maximum possible appears, therefore, to be a reasonable solution to the sample size problem. Another consideration that determines the sample size taken is whether the number of samples is sufficient for certain statistical techniques to be applied to the data set. In the present study empirical relationships between ln(a/s) and wash characteristics will be sought through linear regression analysis.

The linear model is:

$$y = ax + B + \mathcal{E}$$

and assumes that the error terms, ε, are independent of x and are normally distributed with a mean of zero and a constant variance. In order to fit an unbiased regression line a true estimate of the mean error, $\bar{\varepsilon}$, is required. According to the central limit theorem, the sampling distribution of error terms will approximate a normal distribution and will therefore have a mean close to the population mean when sample size exceeds 30.

b. Sampling Pattern

To produce a realistic map using the approach outlined in section 3.1 an important requirement of the relationship established between ln(a/s) and wash characteristics is that it should be equally applicable to the entire range of ln(a/s) values encountered across the landform. In short, the sampling pattern adopted must draw samples from a 'representative' range of locations.

The assumed wide variability of wash processes and the limited number of sampling points to be set up in the present study suggest immediately that a simple random distribution of sampling locations is inappropriate. A standard approach to sampling highly variable populations is through the use of a stratified sample. An appropriate stratification principle for the present study is on the basis of site morphology. Four sample site types were recognised which together cover the entire surface area of the catchment. These were:

(i) Drainage line - active (DLA)

A surface depression formed presumably by fluvial erosion, with signs of that type of erosion between clumps of vegetation, there being conspicuous bare soil areas between individual grasses etc.

(ii) Drainage line - inactive (DLI)

A similar surface depression to (i) above, but without any sign of current erosive activity, and only limited bare ground between vegetation

(iii) Slope (S)

The undissected slope draining to the drainage lines

(iv) Drainage line side slopes (SS)

Those slopes facing normal to the flow direction of drainage lines

Besides acknowledging the functional significance of different morphologies, these divisions fulfil (as far as is possible) the stratification principle of strata variance minimization and mean difference maximization with groups being generated during the winter period (Nov 77-Mar 78).

5.3 The relationship between ln(a/s) and wash frequency/volume: annual results

The data set produced from the field instrumentation has indicated that discharge, saturated areas and catchment storage are inter-related. In particular, wash volumes are significantly correlated with maximum discharges and storage levels attained during sampling weeks. These results confirm that the saturation excess model of runoff generation is applicable to the study catchment, and so to map annual wash frequencies and volumes from a ln(a/s) map is justified. To produce the map, empirical relationships between ln(a/s) and these variables have been established through linear regression analysis (figures 7a, 7b). Scatter in these plots is due to the effects of:

(i) Isolated occurrence of infiltration excess runoff

(ii) Natural pipes

(iii) Occurrence of both channelled and non-channelled overland flow in drainage lines

The first source of scatter is only significant for sites of infrequent flow (small ln(a/s)). The second and third factors are the more important, being most significant in drainage line (large ln(a/s)) sites. The occurrence of natural pipes in the catchment made accurate determination of ln(a/s) values difficult. Despite careful mapping some anomalies have clearly arisen in the data set. These are: (i) sites with large ln(a/s) are underlain by natural pipes and therefore record low wash volume/frequencies; (ii) sites with small ln(a/s) values downslope of pipe efflux's that record high wash volume/frequencies.

The third factor listed above, ie the occurrence of channelled flow in drainage lines, is the most difficult to include in a map of surface wash over the landform. With increasing drainage area channelled flow rapidly becomes the most important component of total runoff. Channelled flow at the study site was observed along drainage lines ($\ln(a/s) \geqslant 9$) in indistinct anastomising courses formed between clumps of Molinia sp. The volumes of flow collected by sediment traps placed in drainage lines, therefore, depended on whether the trap collecting strip intercepted one of these lines of flow. As well as accounting for the wide scatter of points at the upper end of the ln(a/s) range the failure of the sediment traps to consistently collect channelled runoff means that the linear relationship fitted in figure 7b will not be valid for $\ln(a/s)$ values $\geqslant 9$.

An estimation of the relationship between total surface runoff (ie wash and channelled flow) and ln(a/s) can, however, be obtained by replotting figure 7b with runoff totals recorded by streamflow gauges at the catchment outflow and in an adjacent stream head included in the data set (figure 8). It is not unreasonable, however, to use the linear relationship obtained from the sediment trap data to map wash frequencies and volumes for $\ln(a/s) \leqslant 9$. The contour maps produced are shown in figures 9a, 9b.

5.4 Flow sediment relationships

To estimate sediment transport and erosion totals around the stream head it is necessary to establish a relationship between wash volumes and sediment totals. Once more the main problem is to include sediment transport by both channelled and unchannelled flow.

Examining the wash-sediment relationships for the sediment trap data set first, regression analysis of annual totals gives the result:

$$S_{(mg)} = 194\ Q_{(L)}^{0.66} \qquad (4)$$

$$r = 0.806$$
$$sig = 0.001$$

Inclusion of slope gradient as an independent variable is a multiple regression did not significantly improve the correlation coefficient obtained.

The exponent for wash volume computed above contrasts markedly with results obtained in other studies (see for example discussion by Carson and Kirkby, 1972, p 212). Generally other studies have shown that:

$$S \propto Q^2$$

In seeking an explanation of why the wash volume exponent is so low for this data set, the most important factor is again the failure of the traps to consistently collect channelled flow. It might be expected, for example, that the exponent of the sediment-flow relationship will increase with increasing flow depth. (Since the sediment transporting capacity of channelled flow is much greater than that of unchannelled wash). This trend is confirmed from analyses of weekly group mean wash and sediment totals (table 5), wash volume exponents for the sampling groups decreasing in the order DLA > DLI > SS > S. The low exponents obtained might, therefore, be explained by the limited transporting capacity of the flows sampled.

In contrast, however, there is considerable field evidence to suggest that sediment transport in both channelled and unchannelled runoff is detachment rather than transport limited.

The sediment trap data set, for example, shows that the highest sediment concentrations recorded in wash samples collected by each trap occur when sample volumes are small ($\leqslant$250ml). This feature of the data set is interpreted as indicating that there is a rapid exhaustion of a 'new flow' available sediment supply when overland flow begins. The generation processes of available sediment are reviewed by McCaig (1981). It is suggested therefore, that an appropriate wash-sediment relationship for unchannelled overland flow is of the form:

$$S = aQ^b + \Omega$$

where Ω = a new flow sediment contribution. However, regeneration of the available or 'new flow' sediment supply is related to time between flow events. Consequently for samples of overland flow collected on, say, consecutive days only the first sample will contain the 'new flow' sediment contribution. In effect, therefore, the data set contains samples of two different wash-sediment relationships, one of the form:

$$S = aQ^b + \Omega \qquad (5)$$

and another:

$$S = aQ^b \qquad (5a)$$

The winter period (November-March) recorded both the greatest volume (around 80% of annual totals) and greatest frequency of flow for all traps. Consequently, most samples where relationship 5a is valid are drawn from the upper end of the range of collected flow volumes and most samples where eq 5 is applicable are drawn from the lower end of this range. The effect of this mixture in the data set on the parameters of the wash-sediment relationship (of the form $S = aQ^b$) estimated using annual sediment/wash totals is to decrease the exponent (b) and increase the constant (a). Thus the method of sampling used in the study and the importance of an availability limited sediment supply appear to have combined to produce the unusual result found in eq 4.

The parameters of the flow (discharge) sediment relationship for channelled flow can be established from records of suspended sediment concentrations and discharge (figure 10a). Turbidity records made by the continuously monitoring installation, show that pulses of sediment occur independently of variations in discharge (fig 10b), suggesting that sediment transport by channelled flow is also detachment rather than transport limited. Given the poor correlation between suspended sediment concentrations and discharge shown in figure 10a, the flow-sediment relationship for the stream is best described simply by the median of the observed data. For 400 samples taken in the 0.01-25 ls^{-1} flow range the median suspended sediment concentration os 9 mgl^{-1}, or expressed in the same terms as equation 4:

$$S = 9Q^{1} \tag{6}$$

The problem of establishing a single flow-sediment relationship for both channelled and unchannelled surface flow can now be conveniently resolved. That is, the parameters of the flow-sediment relationship determined from the analysis of streamflow records can (assuming that sediment transport in both channelled and unchannelled flow is detachment rather than transport limited) be substituted into equation 5 and used to estimate the new flow sediment constant Ω. Making this substitution a calculated mean new flow sediment constant for sediment trap samples of $<$250 ml volume is 9 mg per metre square. of runoff generating area drained per unit contour length. The flow-sediment relationship used to estimate sediment transport by both channelled and unchannelled flow in the following sections is therefore:

$$S = 9Q^{1} + \Omega \tag{7}$$

where $\Omega = 9\ mgm^{-2}$ per storm/flow event if flow begins during that event.

This flow-sediment relationship is included in the computer simulation model described in section 6.

5.5 <u>The distribution and pattern of erosion</u>

Using the sediment-flow relationship suggested above the distribution of erosion and its relationship to ln(a/s) can be examined. To begin, combining equation 7 above with the wash frequency/volume - ln(a/s) relationships shown in figures 7a, 8, produced the results shown in figure 11. In this figure 'new flow' sediment contributions are considered to decrease to zero as flow becomes perennial.

Figure 11 can now be used as a basis for the determination of sediment source areas around the stream head. First, the total contour outflow width for drainage from each ln(a/s) class must be calculated from the ln(a/s) map. The contour outflow width for each ln(a/s) class is calculated as:

$$\frac{\text{area of elements in ith ln(a/s) class}}{a_i}$$

where a_i = area drained per unit contour width which for the average slope gradient of the ith class produces the class mean ln(a/s) value

Using the widths calculated, sediment transport total and erosion for each ln(a/s) class can be calculated. The result of this calculation (table 6) shows that erosion from ephemeral drainage lines (ln(a/s) 11-12) accounts for around 80% of the total erosion occuring upstream of the perennial stream head position. Drainage lines forming this ln(a/s) class occupy only 2-7% of the total catchment area. Of the total solid-sediment discharge from the stream head recorded during the study year (260 kg, 60.4 kg ha^{-1}), the results indicate that 58% is accounted for by erosion of the perennial channel head.

6. Extension of results

Thus far, the results discussed relate only to a single, possibly atypical, stream head. A question which should be considered is how the distribution and pattern of erosion around stream heads which have different hydrological characteristics compares with that recorded here. A second important question is how different rainstorm event magnitude and frequencies might affect the observed patterns. The only convenient approach to examining these questions is through the development and use of a computer simulation model.

A brief description of, and some limited results produced by, simple model are included, therefore, in the rest of this paper as a demonstration of how the field results can be extended to a consideration of these questions.

6.1 A model of overland flow generation

The results discussed previously have shown that the saturation excess model of runoff generation is valid for the study catchment. Kirkby (1975) has suggested that an appropriate relationship between soil moisture storage levels and discharge is:

$$q = q_o \; e^{h/m} \; . \; s \tag{8}$$

where q = discharge

q_o = maximum (saturated) subsurface discharge rate

h = soil moisture storage level

m = storage 'recession' parameter, determined by soil characteristics

s = slope gradient

Referring back to figure 2, the relationship between discharge and soil moisture is:

$$\frac{1}{w} = \frac{\partial(q_o \; . \; w \; . \; e^{h/m} \; . \; s)}{\partial x} + \frac{\partial h}{\partial t} = i \tag{9}$$

where w = element width

i = instantaneous rainfall rate

Equation 9 contains two parts, a discharge due to changing drainage area and a discharge due to the depletion of the storage (by drainage) over time, is

$$q = q_{(x)} \cdot q_{(t)}$$

$$h = h_{(x)} + h_{(t)} \tag{10}$$

substituting equation 10 into equation 9 and introducing the constant α simply as a mathematical device gives:

$$\frac{1}{w} \frac{d\left(q_o \cdot w \cdot e^{h_{(x)}/m} \cdot s\right)}{d\,x} = \left[i - \frac{dh_{(x)}}{dt} \right] e^{-h_{(x)}/m} = \alpha \tag{11}$$

Solving for $h_{(x)}$;

$$q_{(x)} = q_o \cdot e^{h_{(x)}/m} \cdot s = \frac{\alpha}{w} \int w\,dx = \alpha a$$

where a = area drained per unit contour width

$$\therefore \quad h_{(x)} = m \ln (a/s) + m \ln(x) - m \ln(q_o) \tag{12}$$

Now during a period of steady continuous rainfall soil moisture storage attains a steady state, ($q_{(t)} = i$), and so the right hand side of equation 11 reduces to:

$$e^{h_{(t)}/m} = i/\alpha$$

Solving for $h_{(t)}$;

$$h_{(t)} = m \ln(i) - m \ln(\alpha) \tag{13}$$

Finally combining equations 9 and 10:

$$h = h_{(x)} + h_{(t)} = m \ln(a/s) - m\ln(q_o) + m\ln(i) \tag{14}$$

which shows that for spatially uniform q_o and i, ln(a/s) is the critical determinant of overland flow generation, ie the criterion for overland flow generation at any point is:

$$a/s > q_o/i \; e^{h/m}$$

For non-steady state conditions $q_{(t)}$ should be substituted for (i) in equation 14 above. For the purposes of a simulation model values of $q_{(t)}$ can be approximated by the mean catchment runoff rate. This is calculated from the solution to the storage model originally presented by Kirkby 1975:

$$q_* = \frac{i}{1 - e^{-i/m} + i/_{q_{*_o}} \; e^{-i/m}}$$

where q_* = runoff rate at end of the period

i = rainfall during time period

q_{*_o} = runoff rate at beginning of time period

m = storage 'recession' parameter

The volume of overland flow generated per unit time period from the ith slope element is simply determined as:

$$q_{of\,(i)} = q_o \; e^{h(i)/m} \, . \; s_{(i)} - q_o$$

6.2 Model results

The model described above has been used to simulate runoff and erosion from the study catchment under observed and hypothetical conditions. A comparison of simulation results with observed data is shown in figure 12. The results, shown in figure 12 were produced using 'best fit' estimates of the model parameters m and q_o together with the wash-sediment relationship described in section 5.4.

The effect of different catchment hydrological characteristics on the distribution of sediment transport and erosion can be assessed by introducing different parameter values into the model. The model parameters m and q_o define the rapidity of hydrograph recession and maximum subsurface flow rates respectively. The effect of increasing values of both is to simulate an increase in soil depth and saturated hydraulic conductivity. Predicted wash frequencies and sediment transport totals for two contrasting soil types(shallow, low saturated hydraulic conductivity; deep, high saturated hydraulic conductivity) are shown in figure 13a, b. The differences in predicted sediment transport rates are greatest for low ln(a/s) values. Assuming that a certain annual sediment transport rate is required to form/maintain ephemeral channels, the result indicates that channels will tend to be more numerous around a stream head in, say, a clay covered catchment than one with a sandier brown earth type of soil. The result also suggests that in the former case the divideward limit of ephemeral channel development will respond more sensitively to small changes in annual sediment transport rates (magnitude and frequency effects) since the gradient of the ln(a/s)-sediment transport curve is generally less steep.

The importance, in terms of at a point erosion, of different rainstorm event magnitudes in the four different sample site types identified in the study can be assessed through use of the model. Table 7, for example, shows the relative amounts of erosion predicted for the largest storm recorded during the study year. The relative importance of this single event clearly decreases with increasing flow frequency. A similar trend is shown by results produced using artificial rainfall sequences; indicating that a more extreme type of rainfall distribution will produce, relatively, more widespread erosion on the slopes around the stream head - a similar effect to that produced by decreases in subsurface flow rates.

7. Conclusion

Studies in instrumented catchments over the last decade or so have concentrated on recording the occurence and rates of Geomorphological processes. As these processes become better understood and models are established it seems a natural development for catchment studies to concentrate more on the relationships between process and landform patterns. In this study the pattern of wash erosion around a stream head has been determined using the surrogate mapping variable ln(a/s). The appropriateness of using ln(a/s) as a basis for the map is indicated by a consideration of the saturation excess model of runoff generation. By employing this variable (which can be mapped directly from topography) the problems of producing a wash map are reduced to those of establishing empirical relationships between ln(a/s), wash frequency, volume and sediment transport. The key sampling problems are, therefore, the determination of (i) sample size, (ii) sampling pattern.

The use of surrogate mapping variables identified from consideration of process models is suggested as a simple yet general solution to the problem of mapping process-landform relationships.

References:

Ahnert, F. 1980. A note on measurements and experiments in Geomorphology. Zeit Fur Geomorphologie, Sp Bd 35, 1-10

Carson, M.A. and Kirkby, M.J. 1972. Hillslope form and process. Cambridge University Press. London

Darcy, H. 1856. Les Fontaines' publiques de la Ville de Dijon. Dalmont. Paris

Horton, R.E. 1933. The role of infiltration in the hydrological cycle. Trans Am Geophysical Union 14, 446-460

Ingram, H.A. P. 1967. Problems of hydrology and plant distribution in mires. J Ecology,55 711-724

Kirkby, M. J. 1975. Hydrograph modelling strategies, in Peel, R. , Chisholm, M. and Haggert, P. (eds), Processes in Physical and Human Geography. Bristol Essays. Heinemann Education Books, 69-90

Kirkby, M. J., Callen, J. C., Weyman, D. R. and Wood, J. 1976. Measurement and modelling of dynamic contributing areas in very small catchments. Working Paper 142. School of Geography. University of Leeds

Kirkby, M. J. and Chorley, R. J. 1967. Throughflow, overland flow and erosion Bull International Association of Scientific Hydrology, 12,5-21

McCaig, M. 1981. Modelling storm period fluctuations in suspended sediment-- an appraisal. Working Paper 311. School of Geography. University of Leeds

Moss, J. 1913. Vegetation of the Peak district. Cambridge

Stuart, A. 1962. Basic ideas of scientific sampling. Griffiths statistical monographs and courses, 4. London

Wray, D. A., Stephens, J. U., Edwards, W. N. and Bromehead, C. E. N. 1930. The geology of the country around Huddersfield and Halifax. Memoirs of the Geological Survey of England and Wales - explanation of sheet 77, 221pp

Table 1. Sampling site types - proportions of total catchment area

Sample site type	Area	% of Catchment area
DLA	1172.7	2.7
DLI	598.7	1.39
S	37800.0	87.7
SS	2324.0	5.3

Table 2. Distribution of sediment traps between sampling site types

Sampling site type	Number of records
DLA	10
DLI	6
S	8
SS	7

Table 3. Timing and occurence of surface saturation around the perennial stream head hollow during a storm

Site type	ln(a/s)	Timing of saturation after initial stage rise ( )	Discharge at saturation (1_s - 1)	Catchment storage* at saturation (mm)
DLA	11	0.5	2.42	+ 2.3
DLA	10.5	1.6	2.97	+ 2.5
DLE	6	3.5	3.8	+ 6.7
SS	3.0	4.5	5.7	+ 8.8
SS	2.7	7.0	8.1	+ 13.81

* relative to arbitrary zero at beginning of storm

Table 4. Correlation matrix: sample site type wash and sediment totals with hydrometeorological variables

Sampling site type	Max daily discharge	Catchment water storage	Max daily effective rainfall	Max 30 min rainfall intensity
DLA	0.51	0.51	0.47	0.11
DLI	0.46	0.42	0.17	0.18
S	0.339	0.42	0.25	0.12
SS	0.422	0.57	0.22	-0.02

– = significant at 1% level

Table 5. Wash-sediment relationships for different sampling sites (group mean data)

Sample site type	Regression equation	'r'	sig
DLA	$S_{(ng)} = 126\ Q_{(i)}^{0.71}$	0.978	0.001
DLF	$S = 81.3\ Q^{0.63}$	0.975	0.001
S	$S = 31.6\ Q^{0.55}$	0.838	0.001
SS	$S = 60.2\ Q^{0.5}$	0.967	0.001
Annual totals (all traps)	$S = 194.9\ Q^{0.66}$	0.806	0.001

Table 6. Distribution of sediment transport and erosion for ln(a/s) classes

ln(a/s) class	Class downslope contour outflow width	Sediment Transport (kg yr $^{-1}$)	Erosion (inflow-outflow) (kg yr $^{-1}$)
1- 1.99	5.89	0.001	-
2- 2.99	37.3	0.0037	0.003
3- 3.99	405.2	0.1216	0.118
4- 4.99	506.0	0.4554	0.334
5- 5.99	545.7	1.527	1.132
6- 6.99	311.6	2.488	0.960
7-7.99	134.6	3.360	0.870
8- 8.99	51.9	3.630	0.270
9- 9.99	19.85	4.560	0.930
10-10.99	7.35	11.02	6.46
11-11.99	2.73	60.06	49.04
12-12.99	1.0	260.0	150.8

Table 7. Contributions of rainstorm/erosion events to total annual sediment transport rates

Sample site type	Predicted flow frequency (day yr -1)	Total annual sediment transport due to largest observed storm* (56 mm)	Sediment transport for 10 mm storm-dry**	Sediment transport for 10 mm storm-wet	Sediment transport for 10 mm storm-dry	Sediment transport for 10 mm storm-wet
DLA	282	9	10.2	14.8	15.6	20.1
DLI	130	13	15.1	22.7	19.6	25.7
S	37	26	20.0	40.0	50.0	70.0
SS	46	23	25.0	37.5	50.0	75.0

* all figures as percentages of annual total

** dry conditions = initial q rate 0.5 mm day^{-1}

wet conditions = initial q rate 5.0 mm day^{-1}

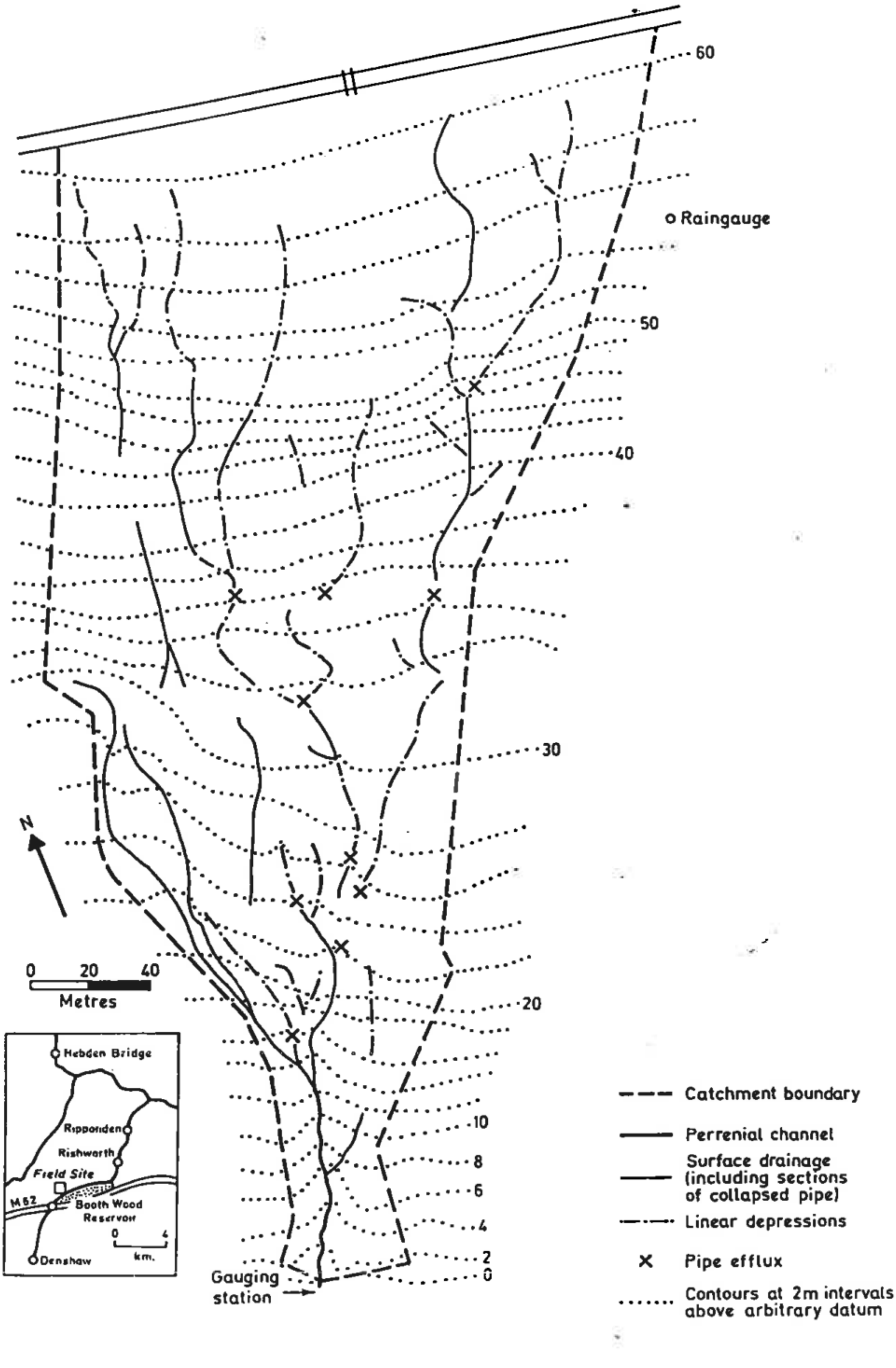
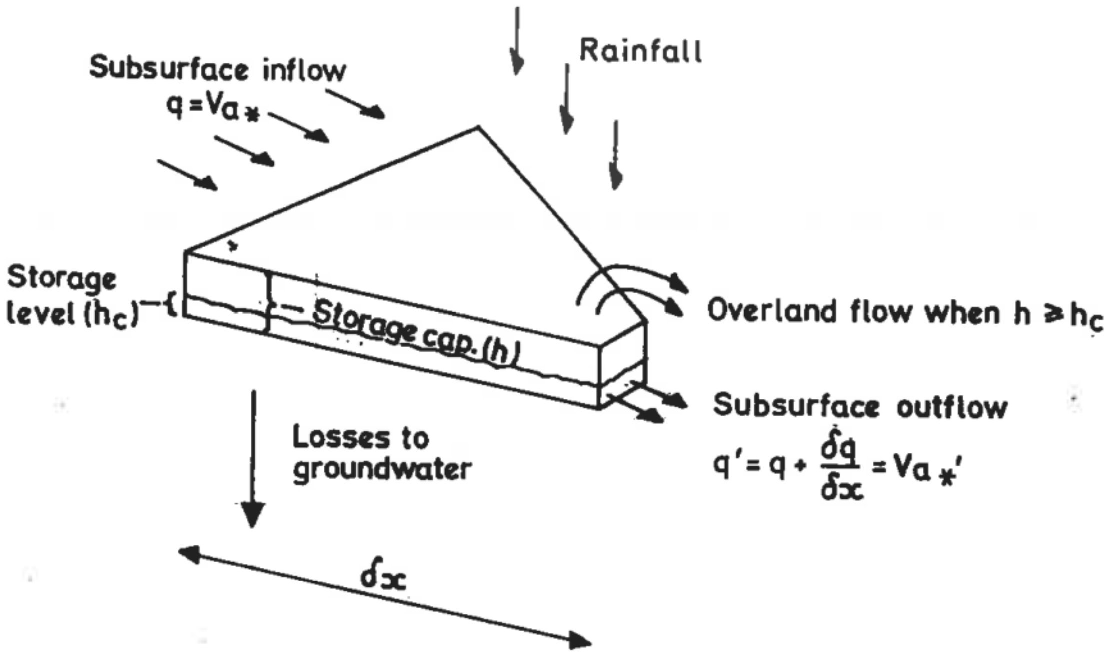


Fig.1 The Slithero Clough streamhead



For both inflow and outflow $V = K \dfrac{d\psi}{dx} \triangleq K' \cdot s$

where s = tangent of topographic slope

ψ = total potential gradient (including both gravitational and moisture potential)

K = soil constant

a_* = cross-section area

Fig. 2 Saturation excess model of runoff generation

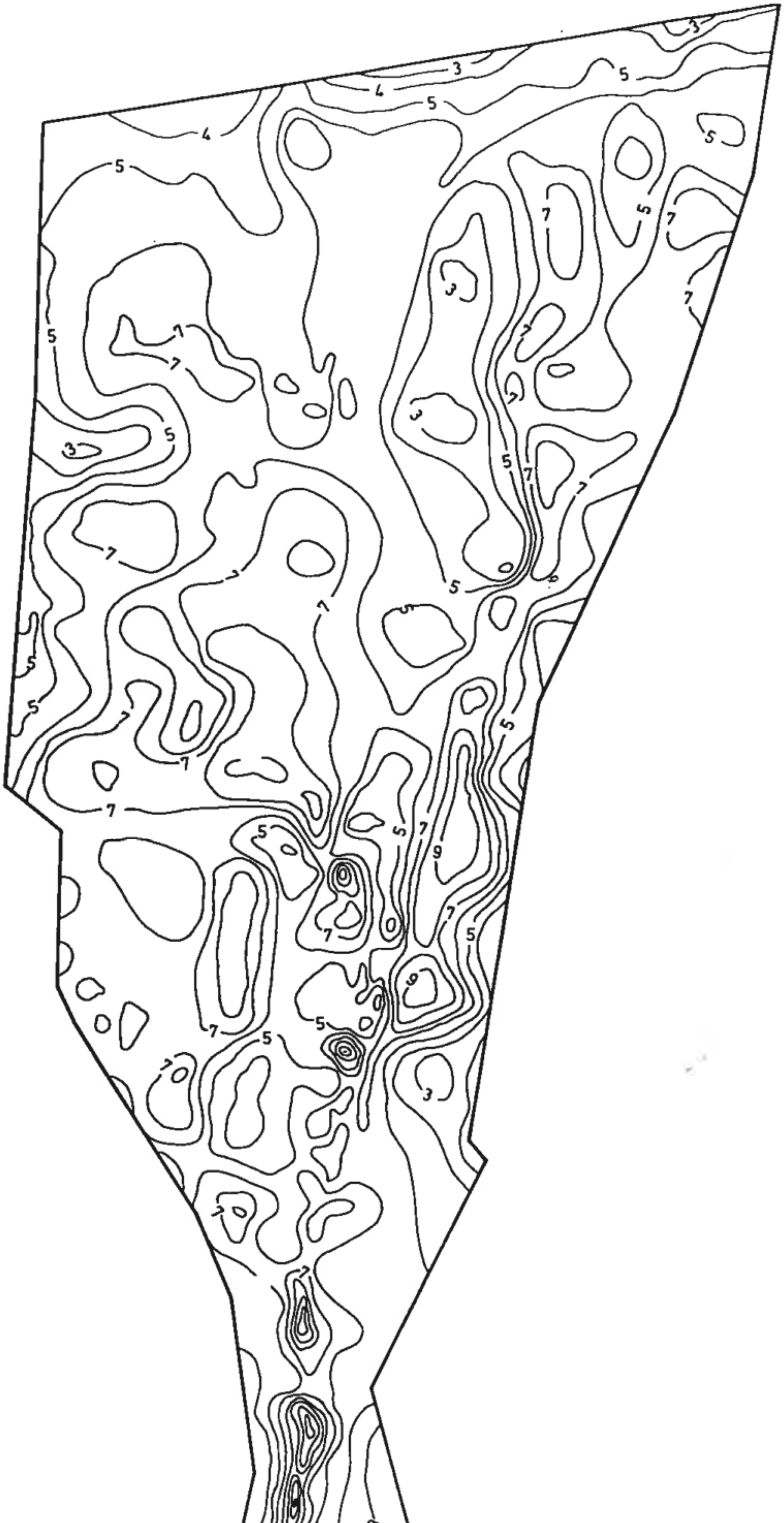


Fig. 3 Ln (a/s) contour map

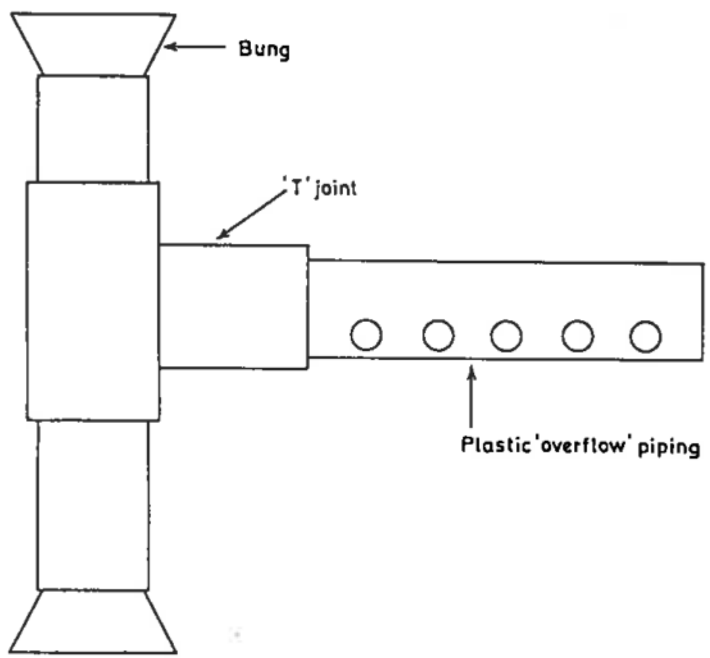


Fig. 4a Runoff recorder

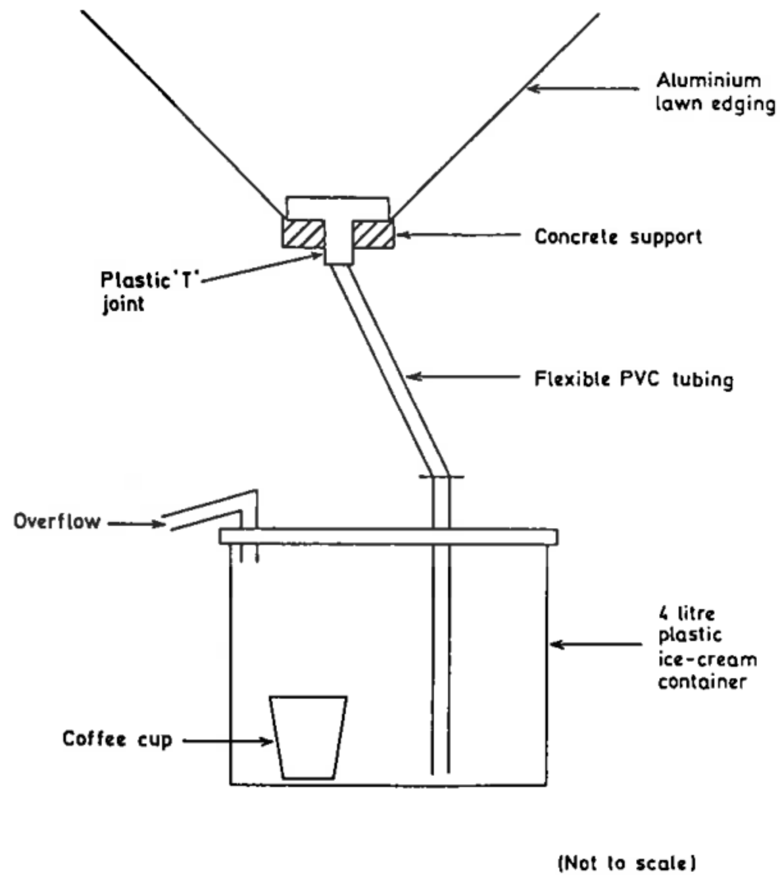


Fig. 4b Runoff/sediment trap

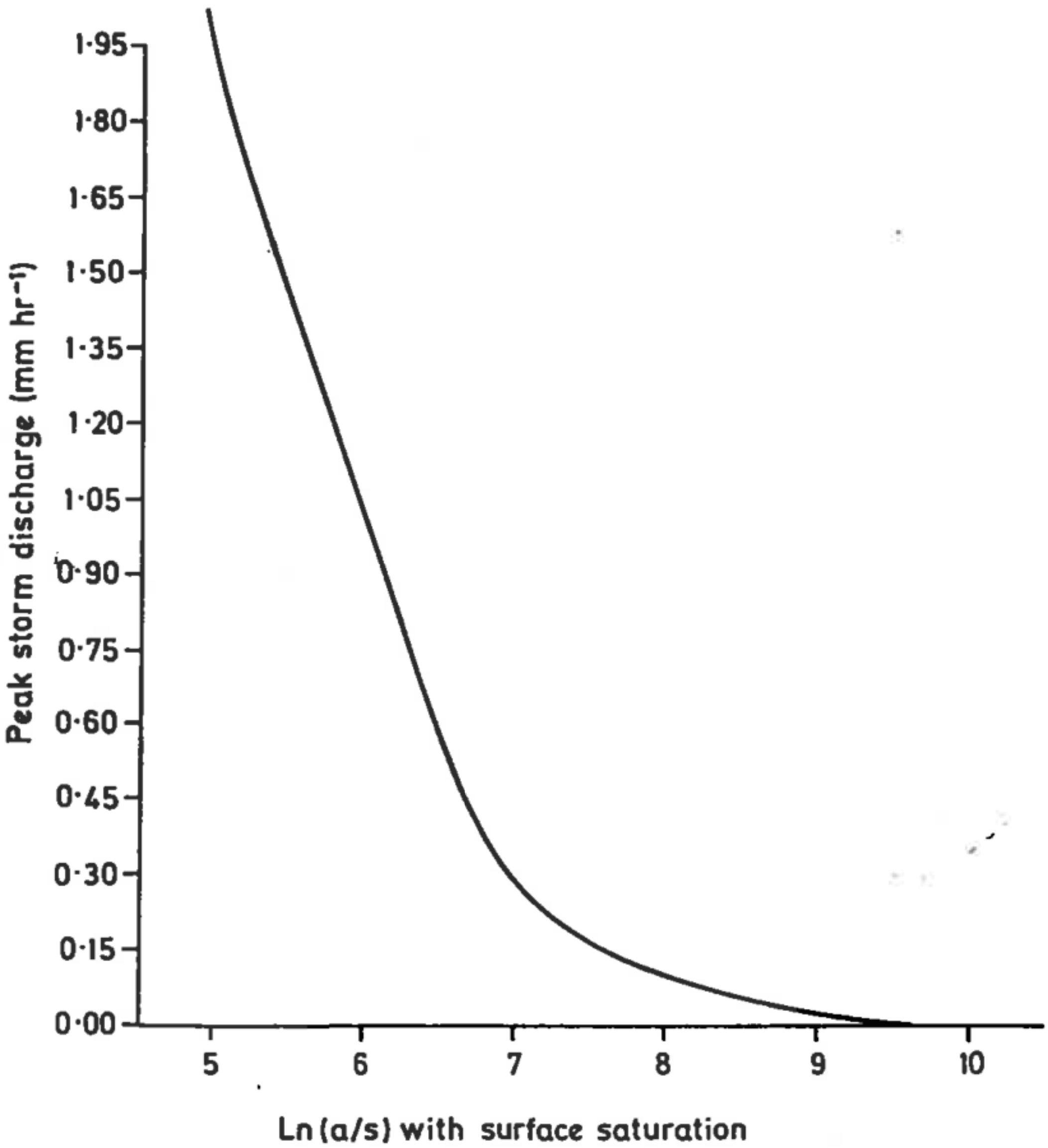


Fig. 5 Relationship between Ln (a/s) associated with surface saturation and storm discharge rate

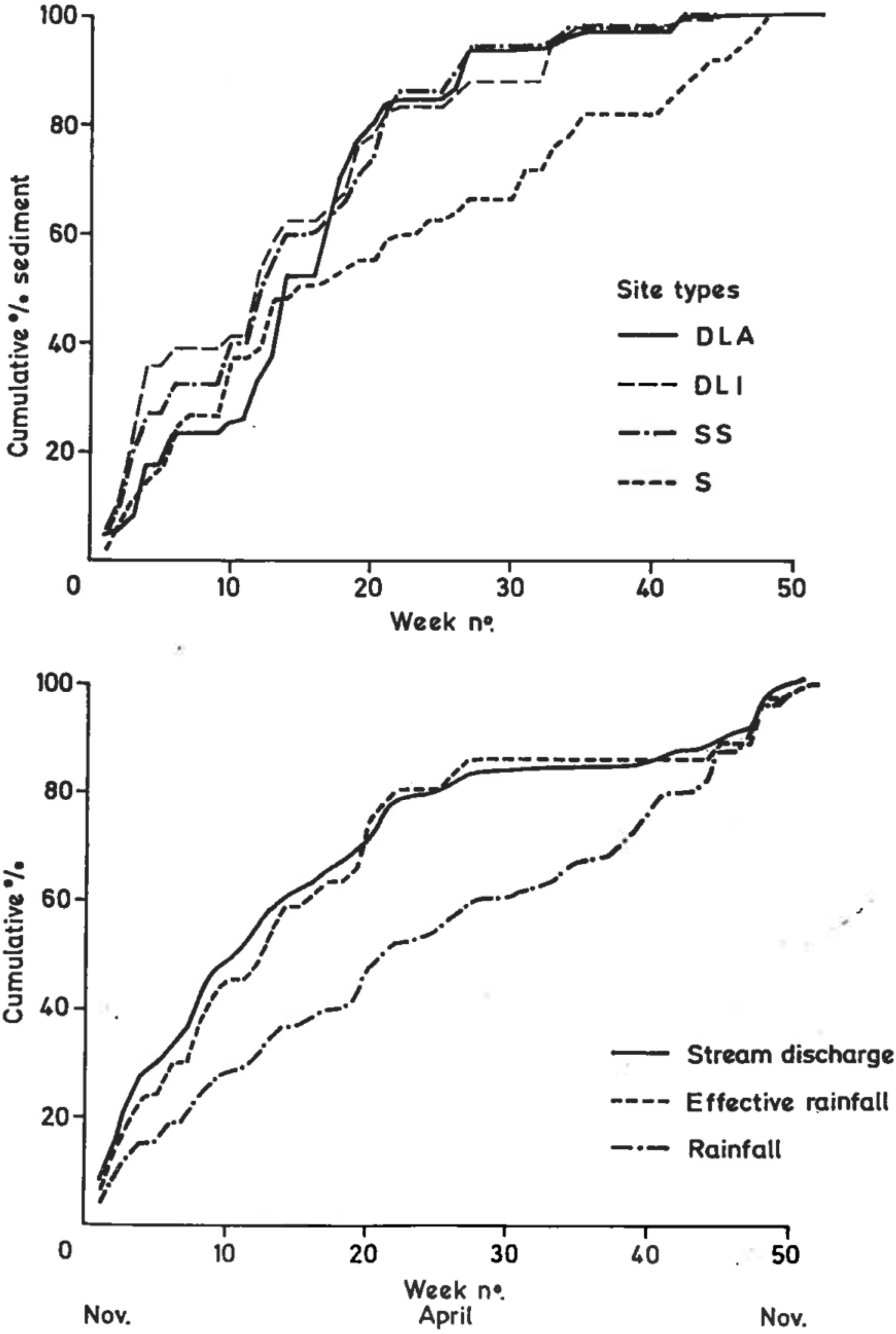


Fig.6 Seasonal distributions of wash, rainfall and discharge

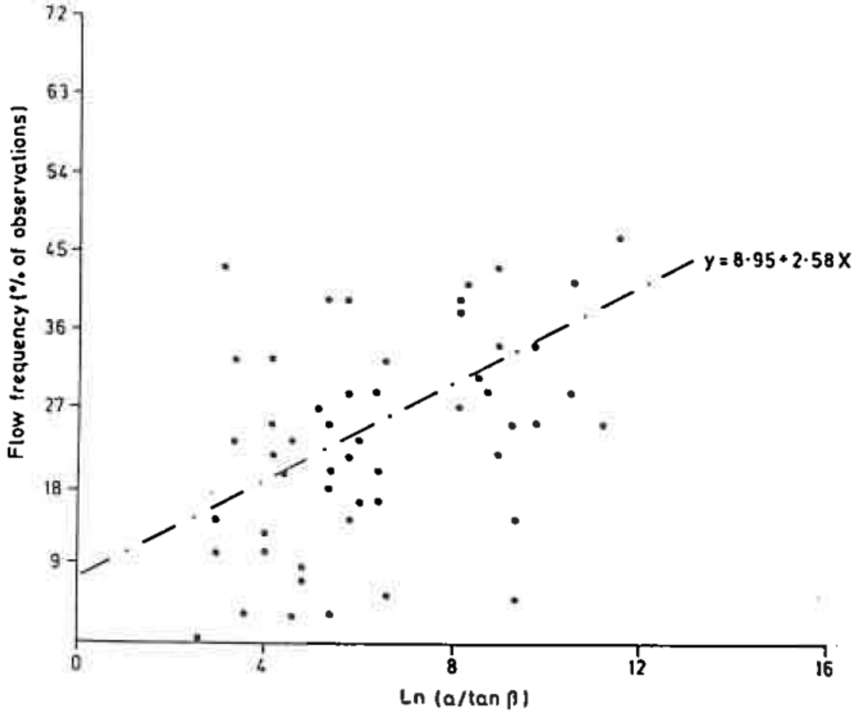


Fig. 7a Relationship between Ln (a/s) and wash frequencies

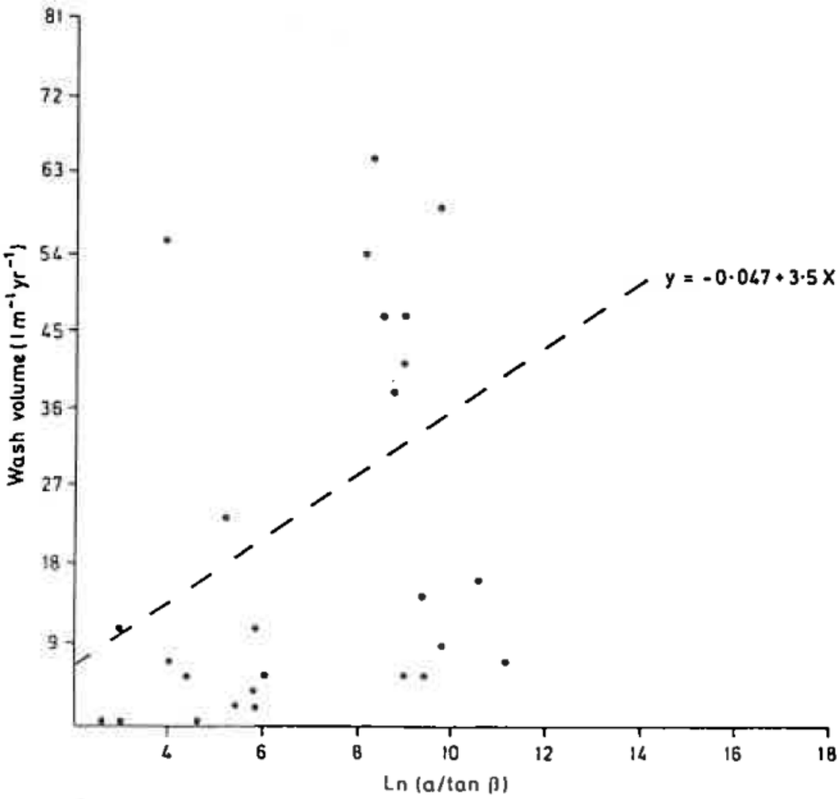


Fig. 7b Relationship between Ln (a/s) and wash volumes

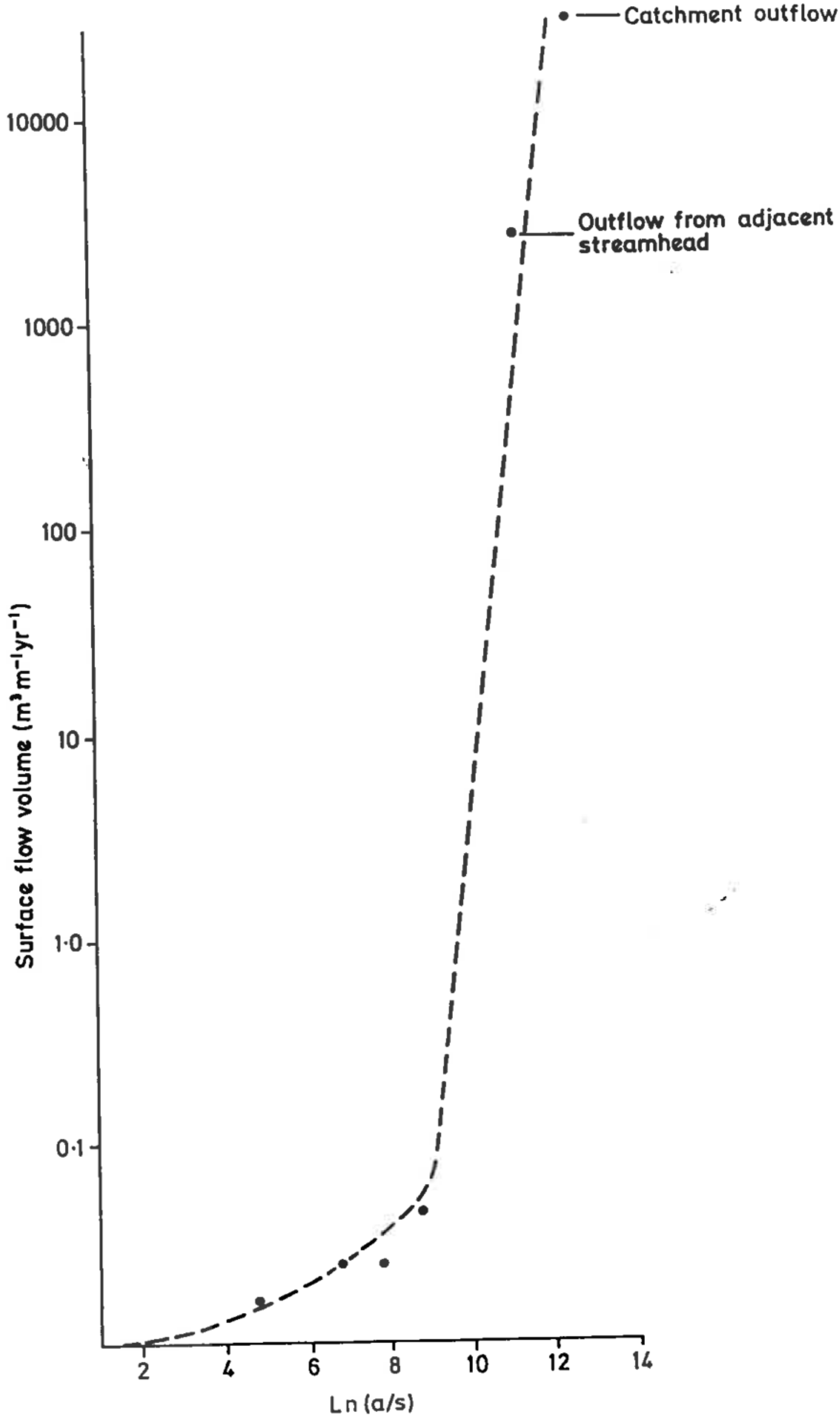


Fig. 8 Relationship between Ln (a/s) and total annual surface runoff

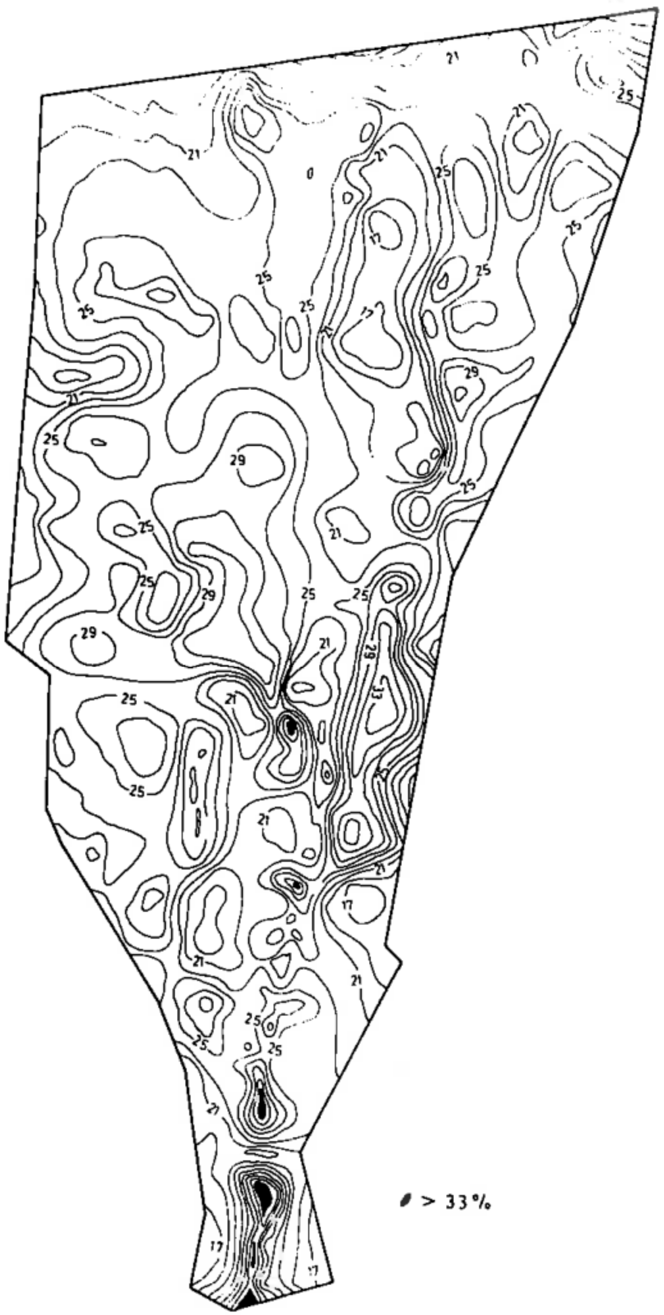


Fig. 9a Contour map, wash frequency (% of weekly observations)

Fig 9b Contour map, wash volume ($l\,m^{-1}\,yr^{-1}$)

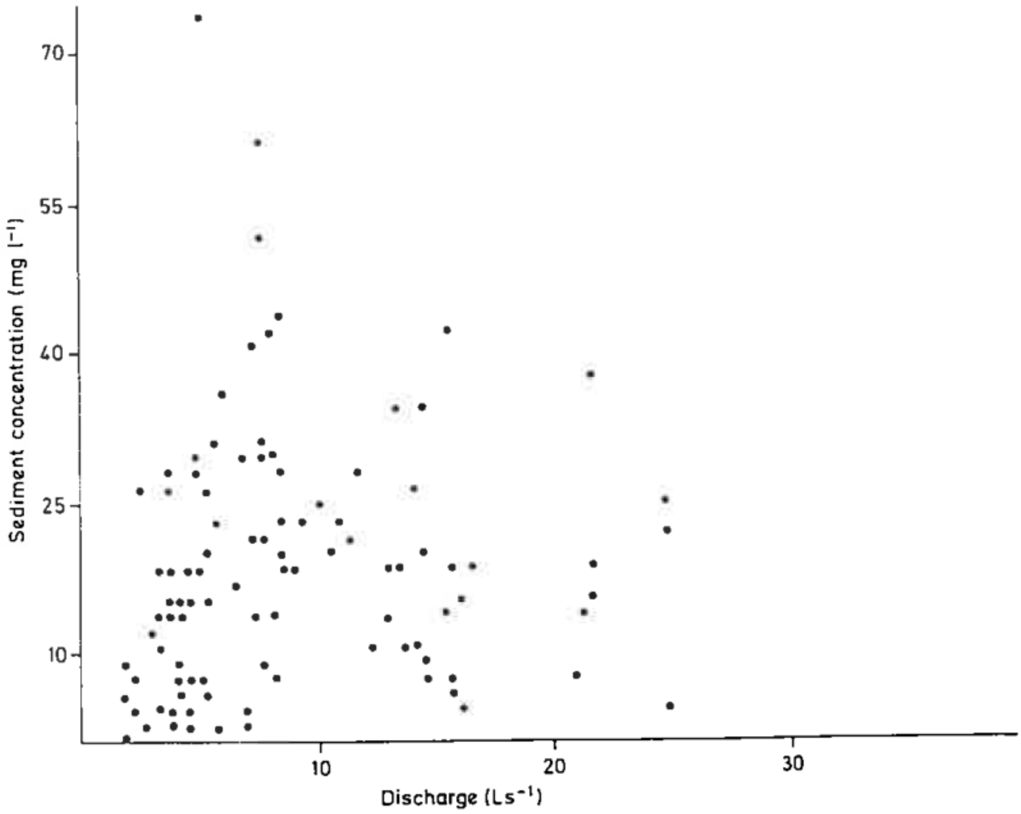


Fig. 10a Suspended solids - stream discharge relationship

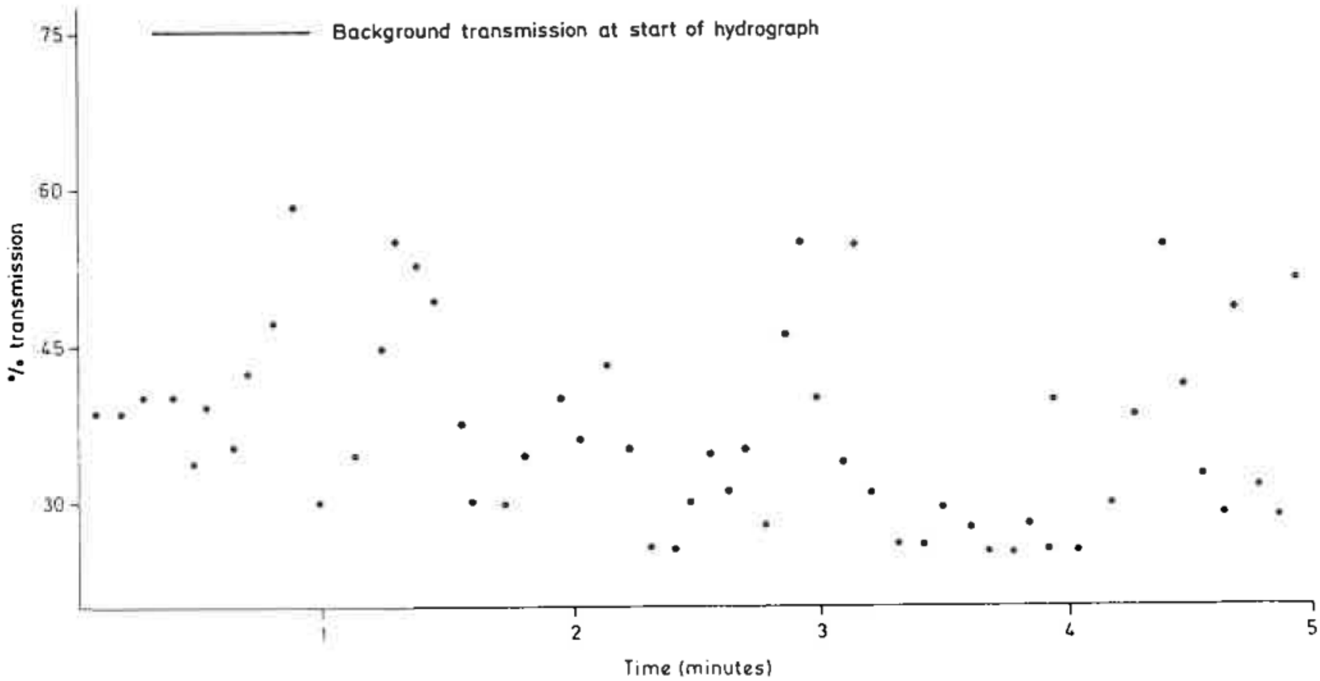
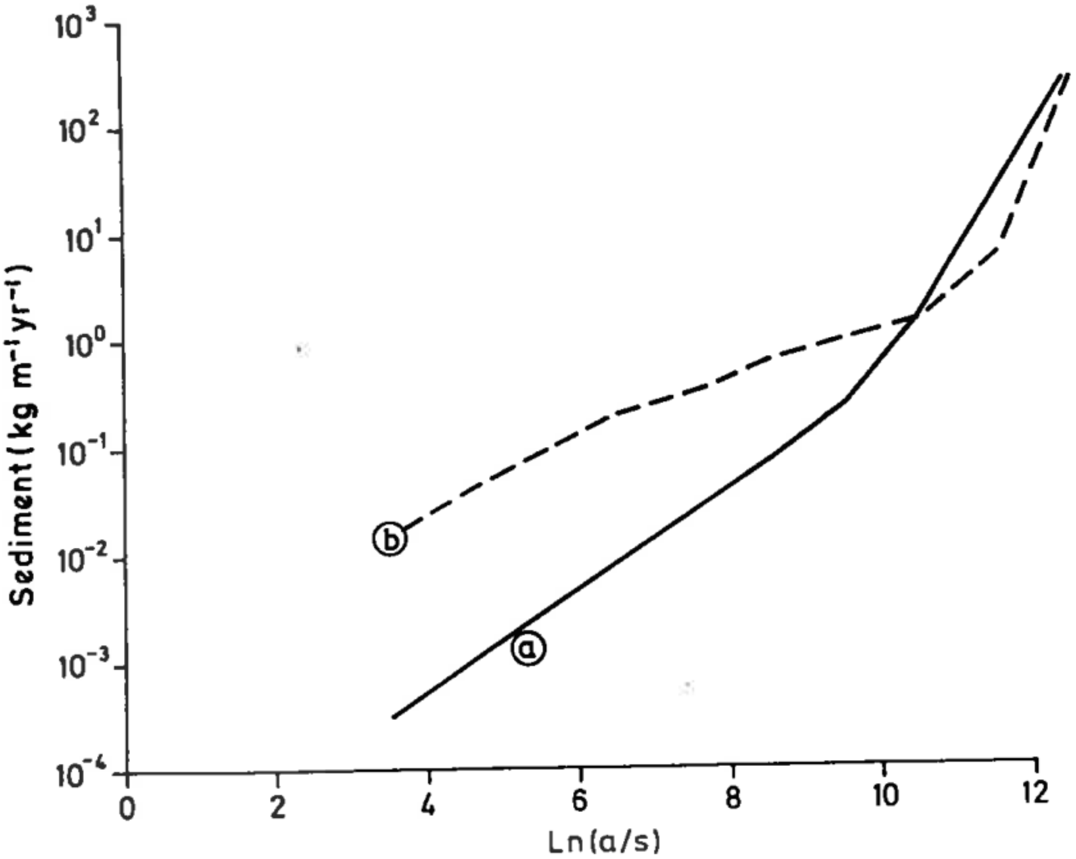


Fig 10b Example 5 minute record of streamflow turbidity during a storm hydrograph



ⓐ Estimated from field data

ⓑ Predicted by simulation model (see section 6)

Fig.11 Relationship between Ln (a/s) and annual sediment transport

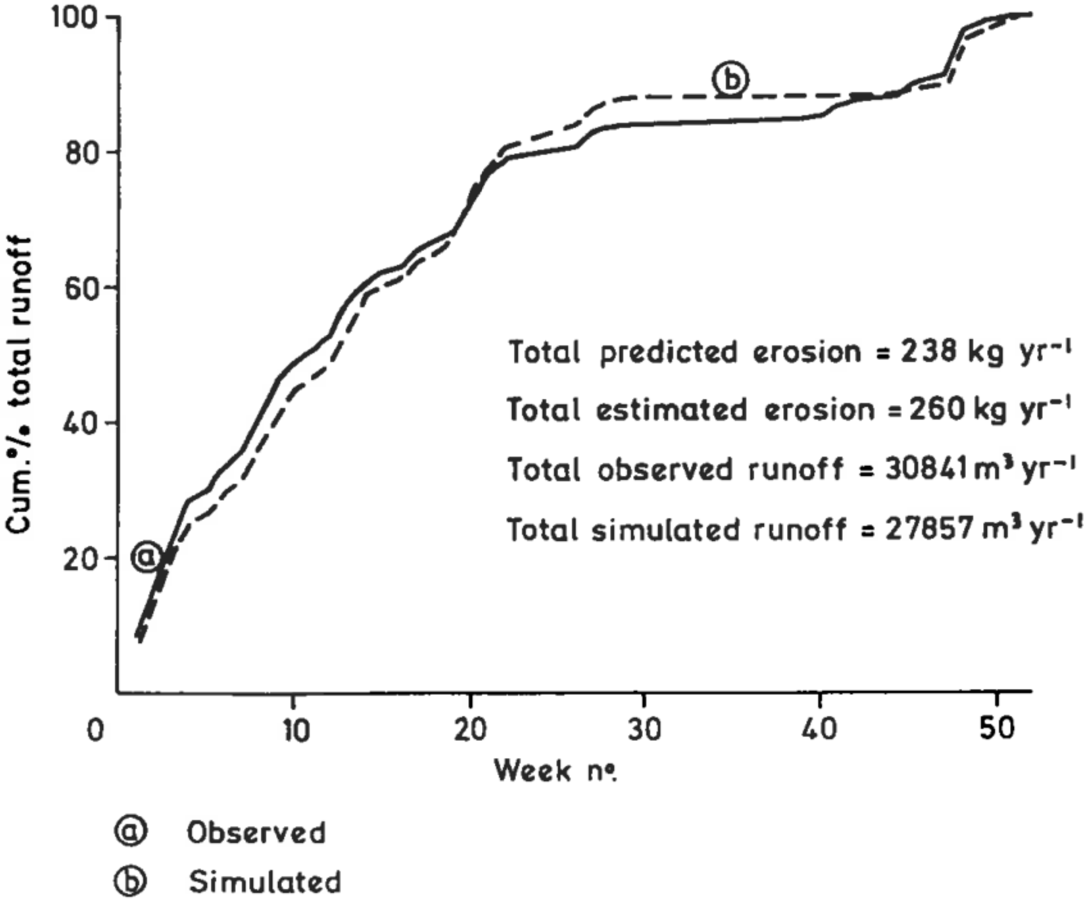


Fig. 12 Comparison of observed data and model results

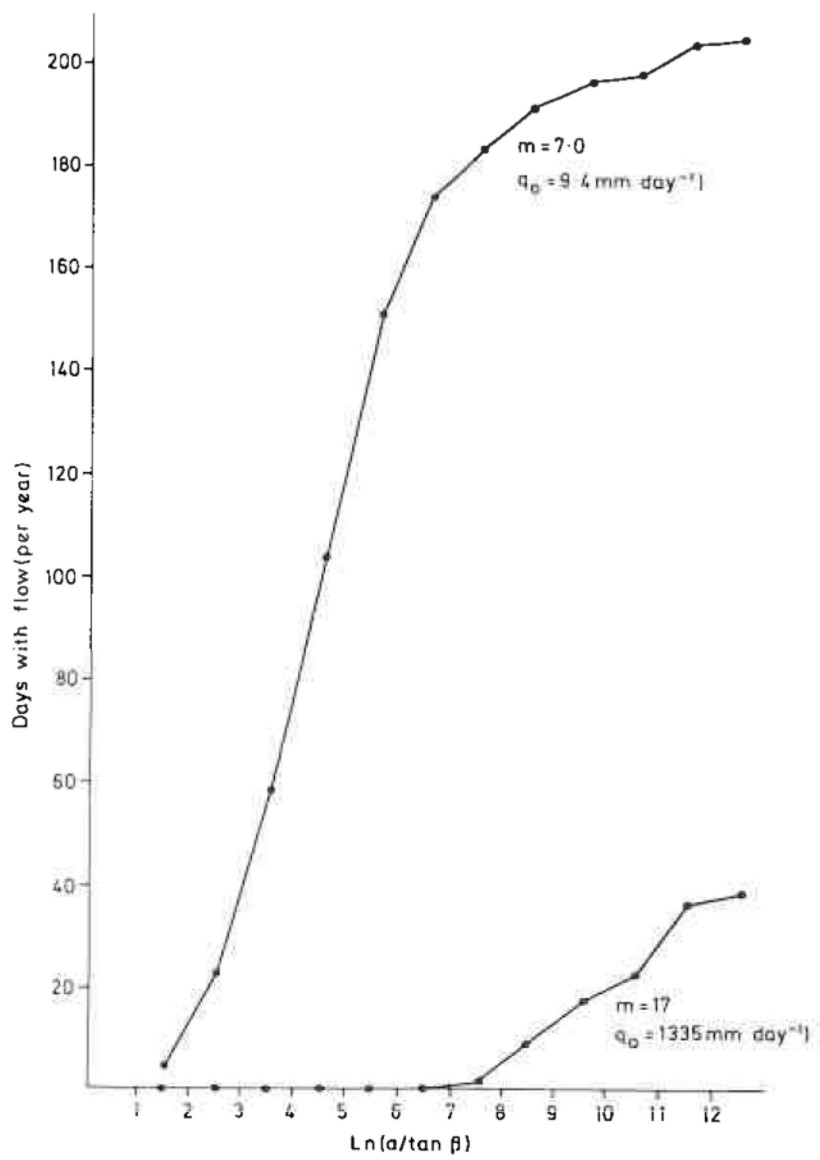


Fig. 13a Relationship between Ln(a/s) and annual wash frequencies

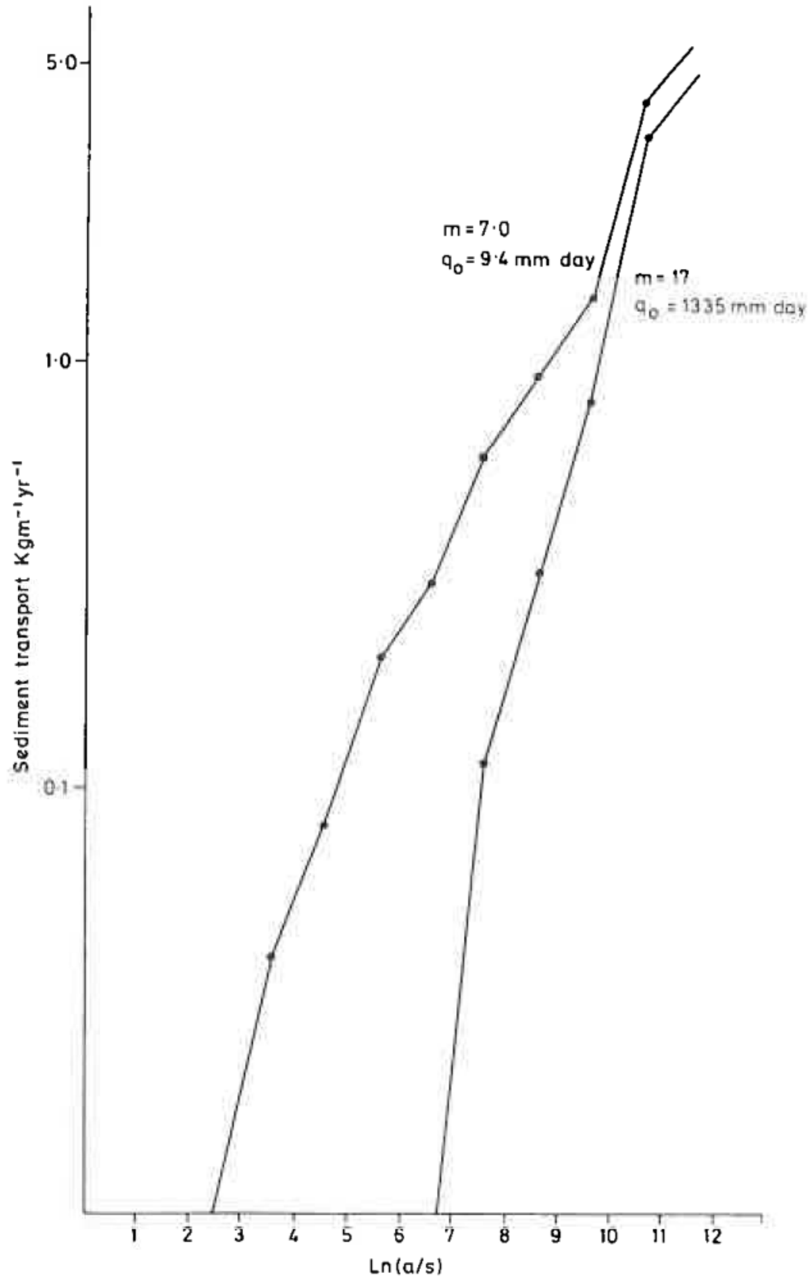


Fig. 13b Relationships between Ln(a/s) and annual sediment transport