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MODELLING STORM PERIOD FLUCTUATIONS IN SUSPENDED SEDIMENT - AN APPRAISAL

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Abstract

This paper discusses possible approaches to the simulation of suspended sediment concentrations in natural streams where there is a limited supply of available or semi-available sediment. Sources, and storages of available sediment in drainage basins are identified and order of magnitude estimates of their sizes given. Models of sediment accumulation and release for each storage location are discussed and demonstrated by simple un-parameterised computer simulations. The general structure and data requirements for a simulation model of a specific study reach are also described.

1. Introduction

Knowledge of the concentration and variability of suspended sediment in streamflow is important to many aspects of water resource management and research. There has, however, been surprisingly little progress towards the development of models which can predict suspended sediment behaviour in natural streams. In contrast, a great deal of data has been collected which illustrates the manner in which variables such as discharge, lithology, climate and land use affect both the concentration and variability of suspended solids in streamflow.

A considerable proportion of the data concerning suspended sediment has been collected by Geomorphologists whose interest has been in estimating present rates of fluvial denudation, eg. Arnett (1977). The approach most frequently adopted in Geomorphological studies has been the construction of statistical (regression) models of the sediment-discharge relationships in a stream. The *sediment rating curve* so produced is then combined with flow duration records to produce either a *load duration curve* or by integration over time an estimate of the total suspended solids removed from the drainage basin. Some of the problems involved in using contemporary data to estimate average erosion rates have been discussed by Meade (1969). Walling (1978) has discussed problems specific to the application of the rating curve technique.

Rating curves are, then, empirical or 'black-box' models of sediment streamflow interaction; no account is taken of the process mechanisms involved in generating or transporting the sediment they predict. This form of model has only limited value as a predictive tool since it cannot be applied beyond the data range used to construct it. Rating curves should not, for instance, be used to predict sediment concentrations for flows larger or smaller than those encountered in the observed data nor should it be applied to discharge sequences other than those of the period of observation. This second condition is an important limit to the rating curve technique and arises since nearly all variables and inputs to the fluvial system are not time invarient; that is they have some trend or periodicity.

A sounder approach to predicting the suspended sediment-discharge relationship in streams is through the well known principles of fluid mechanics (see section 3 below). Models based on these principles have only been developed to describe the amount and distribution of suspended sediment in a streamflow profile. These models show that suspended sediment concentration and distribution is directly determined by the hydrodynamic force (proportional over time to discharge in any reach) exerted on the stream bed by the flow. To extend these models, beyond the idealised conditions of steady flow over smooth homogeneous beds to an application in the constantly varying flow of natural, irregular, channels would require immense computational effort.

Evidence from rating curve studies indicates that in any case simple deterministic or stochastic models based on fluid mechanics theory might not be at all applicable to natural streams. The construction of rating curves for a wide range (in terms of size and environment) of drainage basins has shown varying degrees of statistical 'explanation' of suspended sediment concentrations by discharge. In some cases correlation between suspended sediment and discharge are not statistically significant. In these cases discharge is clearly less important than a number of other factors in determining suspended sediment concentrations. An indication of what these *other factors* may be is provided by the work of Walling (1974). Walling shows that variability in the sediment-discharge relationship (for any given discharge rate) occurs over two distinct time scales. These are;

(i) *Storm period:* Changes in suspended sediment concentration occur between rising and falling limbs of storm hydrographs;

(ii) *Seasonal:* Generally data for winter periods show higher suspended sediment concentrations than during the summer months.

In the rest of this paper possible explanations for variability in the sediment-discharge relationship of a stream are suggested together with some possible approaches to the simulation modelling of suspended sediment concentrations incorporating the principles of fluid mechanics where possible, which take into account processes that produce variability at constant discharge. The importance of scale and the availability of sediment for transport is stressed throughout.

2. What is suspended sediment?

By definition the suspended load of a stream is that part of its total load which is moving in suspension, rather than by rolling or saltating along the stream bed. Material moving in the latter modes is normally defined as the stream's *bed load.*

The size distribution of suspended sediment is determined by both the hydrodynamic (turbulent lift and drag) forces exerted by the stream flow and the size ranges of sediment available for movement in the drainage basin system. Suspended sediment particle size distributions for some rivers in the United States are shown in figure 1. The size distribution of sediment recorded in a river flow sample is extremely sensitive to the method of sampling used, since in the flow profile there is both a concentration and a particle size gradient. Examination of flow profiles (figure 2) shows that there is a general pattern in the suspended sediment distribution which matches the familiar logarithmic velocity distribution in open channel flow. The concentration gradient is strongest for sand (>0.062 mm) grain sizes since settling velocities and turbulent lift forces required to suspend this size fraction are much greater than those for silt/clay sized material. The distribution of sediment in the flow profile shown in figure 2 matches the distributions predicted by both deterministic and stochastic models of suspended sediment transport that have been developed (see section 3 below). The distribution of suspended sediment within a flow cross-section also shows a relationship with flow velocity/turbulence conditions (figure 3).

A common feature of models developed to predict suspended sediment concentrations in flow profiles is that they assume the channel bed to be the source of the suspended material, however it has been suggested that a difference in source exists between fine and coarse size fractions in transported river sediments. Vetter (1937) stated:

> The fine material, not available in the bed of the stream for many miles upstream ... must originate elsewhere on the river or on its tributaries and it cannot be expected that any fixed relationship should exist between discharge and the load of finer material.

The idea of separate source areas was further developed by Einstein, Anderson and Johnson (1940) who proposed that fine suspended material be called *wash load* - implicitly suggesting that the material was supplied directly (and without temporary storage in the channel bed) to the flow by soil erosion processes on the slopes of the surrounding drainage basin. Griffith (1944) amplified this point by suggesting that in terms of flow mechanics, the difference between bed sand and alluvial silt (wash load) was that the silt, unlike the sand, would not settle out of the flow because turbulent life at any flow rate was sufficient to maintain it is suspension. This view necessarily implies that wash load once it has entered the channel system cannot be deposited and will therefore not be found in a sample of the channel bed. This line of reasoning would, at first sight, appear to be supported by evidence from the Hjultrom curve (Hjulstrom, 1935) and the observed lack of fine(0.1-1 mm) material in river channel beds (Russell, 1968). Fine sediment in the 0.1-1.0 mm size range is the most transportable calibre in rivers since this is the minimum size range for which cohesive forces between particles are not significant.

Einstein and Chein (1953) showed in a series of experiments, however, that fine (<0.06 mm) material can be found on a stream bed composed of mixed sand/silt size ranges. Further experiments showed that the transport rate of homogenous fine material could be predicted from flow intensity using the same model (Einstein, 1950) applied to coarser grain sizes. In mixed material, however, the behaviour of the fines was found to be somewhat different. Einstein and Chein observed that, under conditions when the bed was mobile, a fining upwards sorting of material occurred, enriching the *surface layer* in the <0.06 mm grain size fraction from 5% (by weight) in the original material to 17% (by area). Einstein and Chein noted that this fraction represented nearly all the fine material in the experimental mixture. They suggested that in the case of the sand fraction (>1 mm diameter), since it forms the majority of the channel floor deposit, the bed acts as an effective *storage buffer* which ensures that the maximum rate of transport for any given flow intensity is maintained. Sediment movement is therefore always *transport limited* and so a unique relationship between transporting capacity (stream discharge) and sediment transport will be observed. In contrast, the fine material formed a much smaller proportion of the experimental bed, the storage buffer (consequently) had only a small volume and hence the flow-sediment transport relationship observed was *supply limited*. This is an important result since in a supply or availability limited situation the relationship between discharge and suspended sediment concentration cannot be uniquely defined and will be sensitive to variations in the rate of sediment supply and/or the depletion of sediment storages.

The experimental work of Einstein and Chein does not, then, support the view that suspended sediment has a different source to other sediment in the fluvial system.

In summary, suspended sediment is commonly material ranging in size from clay to fine sand. This sediment is distributed throughout the flow profile and cross-section in a way that reflects both the hydrological pattern of that flow and the 'concentration' of different sediment size fractions on the channel bed. In terms of the suspended sediment distribution in a flow profile, the relative lack (low concentration) of silt/clay material in the stream bed and the ease with which it is suspended produces the apparent difference in distribution between sand and silt/clay shown in figure 2. There is no evidence to suggest that fine suspended material originates from different parts of the drainage basin to those providing the other fractions of a stream's total sediment load.

3. Models of suspended sediment distribution in steady flow conditions

The preceding section has indicated the importance of the bed sediment mix, in terms of the availability of different grain sizes, as a determinant of the distribution and concentration of suspended sediment in streamflow. Before proceeding to a consideration of the storm period fluctuations in suspended sediment concentrations shown by many rivers it is appropriate to briefly discuss how the distribution and concentration of suspended sediment in flows has been modelled. Two approaches are described, the first is a deterministic (diffusion) model. The second which produces strikingly similar results, is a stochastic model.

3.1 Diffusion model

For any steady turbulent flow a number of 'time average' measurements can be made and used to describe it, eg. downstream velocity (u), bed shear stress (τ_o) or eddy size (l). During a time period T (which is large in comparison to the period of the average eddy size t_1) the average vertical speed of the fluid transfer can be defined as $\overline{V}_f$ and so the mass transfer from a level $y_1 \rightarrow y_2$ in the flow is given by:

$$V_{12} = \overline{V}_f TL \qquad (1)$$

where L = length of the region of flow under consideration, having a width of unity.

Since there can be no net vertical flow during the 'long' period T the transfer defined in equation 1 must be balanced by an equal and opposite flux:

$$V_{12} = V_{21} = |\overline{V}_f| TL \qquad (2)$$

For sediment suspended by the flow, the vertical sediment velocity differs from that of the flow by the particle settling velocity. Mass transfer between levels y_1, y_2 (above the channel bed) in the exchanged volumes V_{12} and V_{21} are therefore:

$$M_{12} = AC_1(1 - \frac{w}{|\overline{V}_f|})$$
$$M_{21} = AC_2(1 + \frac{w}{|\overline{V}_f|}) \qquad (3)$$

where w = particle settling velocity
C_1 = sediment concentration at y_1
C_2 = sediment concentration at y_2
A = $\gamma_s|\overline{V}_f|LT$
M = mass transfer

The sediment concentrations C_1, C_2 can be defined relative to the mean sediment concentration C (concentration at a level in the flow $y = (y_1 + y_2)/2$), ie:

$$C_1 = C - \frac{\partial C}{\partial y} \cdot \frac{1}{2}$$
$$C_2 = C + \frac{\partial C}{\partial y} \cdot \frac{1}{2} \qquad (4)$$

For a *stationary* turbulent flow the concentration C is a constant, implying $M_{12} = M_{21}$ and hence,

$$(C - \frac{\partial c}{\partial y} \cdot \frac{L}{2})(1 - \frac{w}{|\overline{V}_f|}) = (C + \frac{\partial c}{\partial y} \cdot \frac{L}{y})(1 + \frac{w}{|\overline{V}_f|})$$

and thus:

$$\frac{\partial c}{\partial y} + aC = 0 \qquad (5)$$

where $a = \frac{2w}{L|\overline{V}_f|}$ and has the dimensions of m^{-1}. Since the turbulent viscosity (μ_t) of the flow is proportional to;

$$\mu_t \propto \rho L|\overline{V}_f|$$

where ρ = density of water.

The product $L|\overline{V}_f|$ will also be proportional to *turbulent kinematic viscosity*, ie.

$$L|\overline{V}_f| \propto \frac{\mu_t}{\rho} = V_t$$

where V_t = turbulent kinematic viscosity.

Now V_t is itself defined as:

$$V_t = \frac{\tau/\rho}{du/dy}$$

where τ = turbulent shear stress

du/dy = velocity gradient.

And so the variable a in equation 5 can be rewritten as;

$$a = \frac{1}{\beta}\frac{w}{V_t} = \frac{we}{\beta} + \frac{1}{\tau}\frac{du}{dy} \qquad (6)$$

where β is a suitable constant of proportionality. Yalin (1977) suggests that the proportionality constant β in equation 6 will be a function of the flow Reynolds number. Equation 5 can be converted to a dimensionless form through the introduction of the dimensionless variable;

$$n = y/h$$

where h = flow depth

and the dimensionless functions;

$$f_\tau(n) = \frac{\tau}{\tau_o}; \quad f_n(n) = \frac{u}{v_*}; \quad f(n) = \frac{1}{f_\tau(n)} \cdot \frac{\partial f_n(n)}{\partial n}$$

where τ_o = bed shear stress

v_* = shear velocity ($\sqrt{\tau_o/e}$)

Thus equation 5 becomes;

$$\frac{\partial C}{\partial n} + b_* C = 0 \qquad (7)$$

which can be integrated to give,

$$\frac{c}{C_o} = e^{-\int_{n_o}^{n} b_* \, dn} \qquad (8)$$

where $b_* = ha_*$ and is the dimensionless parameter defined as;

$$b_* = \frac{w}{v_*}\frac{f(n)}{\beta} \quad \text{and } n_o = \frac{y}{h}$$

Equation 8 is the equation of diffusion . This general form of diffusion model was first developed by Rouse (Rouse, 1937; 1938) and is now widely used in texts dealing with sediment transport. Assuming the the shear stress distribution in a flow is *linear* and the velocity distribution *logarithmic* (Einstein, 1950), the functions $f_\tau(n)$ and $F_u(n)$ can be expressed as:

$$f_\tau(n) = 1 - n \tag{9}$$

$$\frac{\partial f_u(n)}{\partial n} = \frac{1}{kn} \tag{10}$$

where k = von Karman's universal constant.

The definitions given in equations 10 and 11 imply that f(n) is of the form;

$$f(n) = \frac{1}{k_n(1 - n)}$$

and therefore the parameter b_* can be rewritten;

$$b_* = \frac{1}{\beta}\frac{w}{v_*}\frac{1}{k_n(1 - n)}$$

Solving equation 8 now gives;

$$\frac{C}{C_o} = \exp\left[-\frac{1}{k\beta}\frac{w}{v_*}\int_{n_o}^{n}\frac{\partial n}{n(1-n)}\right]$$

$$= \exp\left[\frac{1}{k\beta}\frac{w}{v_*}\ln\left(\frac{\frac{1}{n} - 1}{\frac{1}{n_o} - 1}\right)\right]$$

$$= \left(\frac{\frac{1}{n} - 1}{\frac{1}{n_o} - 1}\right)^{\frac{1}{k\beta}\cdot\frac{w}{v_*}} \tag{11}$$

Experimental observations made by Vanoni (1941) show a very good correlation between observed and predicted (by equation 11) concentrations for $k\beta = 0.4$, implying the parameter β is close to unity.

A more complete discussion of the diffusion model, its derivation and more recent modifications to it is presented by Yalin (1977, p. 160-74).

It is clear from the form of the model described above that the dimensionless concentration C/C_o is *determined* solely by the magnitude of the ratio w/v_* (see equation 11). The accuracy of the model, though, is determined by how closely the shear stress and velocity distributions in the flow match the assumed linear and logarithmic patterns.

3.2 Stochastic model

Turbulent velocity fluctuations in streamflow when measured appear to be random. This fact alone suggests that a probabilistic (Stochastic) approach to modelling suspended sediment concentrations is appropriate. A number of stochastic models of suspended sediment movement and distribution have been developed (eg. Bugliarello and Jackson, 1964; Chiu 1967; Chiu and Chen, 1969), a general rationale to thse stochastic models following the presentation of Yalin (1977, p. 193 *et seq.*) is given below.

The vertical distribution of suspended material in streamflow can be treated as a Markovian process, the present state (height of particle in the flow) being dependent only on the step before. Let δy be a narrow width range in the flow under consideration and the distance $\delta x = \bar{u}\delta t$ between two sections n and n+1 of that flow be small enough (ie. δt is infinitessimally small) so as that all fluid emitted from point O of section n will be in section n+1 during the next time period. In the section n+1 the particles, moved by turbulent eddies (turbulent diffusion) will tend to be normally distributed in height. Solid particles in the flow will have a similar distribution except that the mean will be shifted down by $w\delta t$ (where w = settling velocity). Considering a flow in which the time interval of each change in position of a particle occurs as a 'step' over a constant virtually instaneous, time period Θ. The probability of particles being found in and displaced from different regions in the flow can be defined. For example, if y_n and y_{n+1} are the possible levels of a particle at the end of the n^{th} and $n+1^{th}$ steps then the conditional probability that a particle at level y_n is displaced into the region δy_{n+1} (which includes the level y_{n+1} is;

$$P(\delta y_{n+1}|y_n) = \delta p = f(y_{n+1};y_n)\delta y_{n+1} \qquad (12)$$

The function, $f(y_{n+1};y_n)$ will, due to the operation of the turbulent diffusion process, be a normal (Gauss) function;

$$f(y_{n+1};y_n) = \frac{1}{\sigma_\Theta\sqrt{(2\Pi)}} \exp\left|-\frac{|y_{n+1} - (y_n - w\Theta)|^2}{2\sigma_\Theta^2}\right|$$

where the value σ_Θ must be proportional to Θ (the time interval between steps) and to the average of the fluctuating velocities, ie.

$$\sigma_\Theta \propto \bar{v}'\Theta$$

From equation (12) it is seen that the probability of a particle arriving in the region δy_{n+1} is dependent upon the probability of it being at the level y_n during the previous time period. This probability is in turn dependent upon the particles level during the previous step. For a particle at height y_* at time n=0, this probability is therefore;

$$\delta P_{o,n}\delta P = f_n(y_n;y_*)\delta y_n f(y_{n+1};y_n)\delta y_{n+1}$$

The probability of arrival in the region via any of the possible 'routes' will be given by the sum;

$$\delta P_{o,n+1} = \Sigma\delta P_{o,n}\delta P \qquad (13)$$

Expanding equation 13 to the form of the previous equation:

$$f_{n+1}(y_{n+1};y_*) = \int_o^h fn(y_n;y_*)f(y_{n+1};y_n)\delta y_n$$

That is, as a general case, the density function for the step n+1 can be obtained from that for step n and the generating function $f(y_{n+1};y_n)$. Using this rule, assuming steady flow and a uniform distribution of particle sources along x at level y_*, the concentration C of suspended sediment can be defined:

$$C = \alpha_1 \sum_{n=0}^{\infty} f_n(y;y_*) \qquad (14)$$

where

$$f_n(y;y_*) = \int_o^h f_{n-1}(y_{n-1};y_*)f(y_n;y_{n-1})\delta y_{n-1}$$

and α_1 is a constant of proportionality.

The dimensionless concentration C/C_o can be obtained from equation (14) through the introduction of another constant;

$$\frac{1}{\alpha_0} = \sum_{n=0}^{\infty} f_n(y_o;y_*) = \frac{C_o}{d_1}$$

Substituting for α_1 in equation (14);

$$\frac{C}{C_o} = \alpha_0 \sum_{n=0}^{\infty} f_n(y_o;y_*) \qquad (15)$$

where α_0 = constant of proportionality.

Yalin (1977, p. 197) shows that by careful selection of parameters, crucially the time step Θ, equation (15) gives good agreement with observed data. The time step Θ in the model should be proportional to flow conditions, specifically h/v_*. Yalin concludes that the approach is liable to be valid for higher concentrations of sediment than the diffusion model since it does not include a mixing length (1) term which itself is a function of sediment concentration (see Vanoni and Nomicos, 1959; Hinz, 1959).

3.3 Summary

The two example models outlined above show that deterministic and stochastic approaches to describing the distribution of suspended sediment in streamflow have been developed. The former type of model assumes a linear shear and logarithmic velocity distribution within the flow, sediment concentrations being determined by the ratio between particle settling and flow shear velocities. The stochastic model, in contrast, is not based on such generalised (macro scale) flow characteristics but instead requires that generating functions of sediment/water transfers between levels in the flow be known. A significant feature of the stochastic model is that it is, in principle, applicable to predicting the movement of single particles; the diffusion model is not.

Both the models described above, however, concern themselves with the relationship between sediment and flow under conditions where the supply of sediment to the flow is both uniformly distributed within the flow channel and unconstrained. Both models are essentially therefore *transport limited* models of suspended sediment distribution. Whilst these models could perhaps form the basis for the development of a suspended sediment transport rate model the following sections attempt to demonstrate that alternative supply limited models of suspended sediment transport rates can be developed. The main advantage of a *supply* as opposed to *transport* limited approach is that storm period functions or hysteresis of suspended sediment concentrations can be predicted.

4. Storm period fluctuations of suspended sediment concentrations in streamflow

A conclusion drawn from the preceding section is that variability in the discharge-suspended solids concentration relationship of any channel reach is due to the combined effect of variations in the sediment supply to and storage within the reach.

Ignoring, for the present, possible effects of sampling errors, the commonest pattern of variability in sediment-discharge data is one form or another of *concentration hysteresis* during storm hydrographs.

Hysteresis in sediment-discharge rating curves can be both clockwise (positive hysteresis) or anti-clockwise (negative hysteresis), see figure 4b. The former implies that the peak of the storm sediment wave occurs before the water wave peak and the latter the converse (figure 4a). It has been suggested by Klein (1976) that the type of hysteresis shown by suspended sediment concentrations during hydrographs can be related to the size of the source drainage basin. Klein pointed out that as drainage basin scale changed, so too did the apparent source of the sediment removed in streamflow. For instance, McGuiness, Harrold and Edwards (1971) showed that in small basins suspended sediment yields were related to rainfall erosivity and plant cover whilst in larger basins runoff rate was a better predictor variable for sediment. Klein interpreted this observation as showing that in small basins *slopes* were the source for suspended sediment and suggested that transport of slope contributions through the overland flow/channel system might delay them and so produce a negative hysteretic effect. In larger basins Klein suggested that suspended sediment hysteresis would be clockwise since the major sediment source would be the channel system itself, although no mechanism to account for this positive hysteresis was proposed. (The importance of drainage basin size in determining a suitable approach to modelling suspended sediment concentrations and hysteresis is considered in section 5.2 below.)

A somewhat different explanation of negative hysteresis in suspended sediment concentrations was proposed by Heidel (1956). Observations of the Bighorn River, Wyoming showed that lags between discharge and suspended sediment concentration peaks increased downstream as the flood and sediment waves are routed through the channel system. The reason for this is the well-known effect that in channels the velocity of a flood wave is greater than the velocity of the channelled flow (Einstein, 1943). As the travel path of a flood wave increased, therefore, the lag between peak stage and peak suspended sediment concentrations will increase. Thus, Lewis (1921) reported a three day lag between peaks on the Tigris river, Iraq. The travel lag explanation of negative hysteresis is a complete reversal of the trend in hysteresis suggested by Klein, implying that the probability of negative hysteresis increases as basins become larger, ie. negative hysteresis will be commonly observed if the observation station is downstream of the sediment source (storm affected) part of the drainage basin.

Despite the apparent conflict between the two views the interpretations described above do share one theme; both imply that the source of suspended sediment recorded at a sampling station is other than the channel reach being sampled. Negative hysteresis is in both cases, produced by the effect of *transmission* through the fluvial system rather than the behaviour of sediment sources or storages. In the context of identifying a suitable approach to modelling storm period suspended sediment transport rates negative hysteresis, can t efore, be regarded as simply a local or 'channel routing' effect.

Examination of all available published data shows that positive hysteresis is, in fact, a much more general occurrence (see table 1). Positive hysteresis occurs in streams of varying size and in a wide range of environments.

The first question to be answered in determining a suitable approach to modelling storm period fluctuations in suspended sediment concentrations is, therefore, how is a positive hysteretic effect produced. A simple mechanism which produces positive hysteresis is through the exhaustion of the sediment supply. When exhaustion occurs, discharge increases beyond a certain level `` can find no more sediment to entrain and so concentrations decrease rapidly. Thus, positive hysteresis can be interpreted as representing a flushing out or exhaustion of some *available sediment storage* of finite size. The positive hysteresis pattern therefore identifies a situation where suspended sediment transport is *availability* or *supply* limited.

5. <u>Available sediment in the drainage basin</u>

If positive hysteresis of suspended sediment concentrations during storm hydrographs is produced by the exhaustion of an available sediment supply or storage, identification of possible sources and storage for this sediment is a first step towards establishing an appropriate model of hysteresis in suspended sediment concentrations. In the rest of this paper *available sediment* is defined as:

> Stored material which will be transported by streamflow
> during the next storm event.

An initial distinction can be made between two types of available sediment; that which is presently in contact with the river flow (bed storage) and that which is not, but will be when a rise in stream stage occurs (channel bank storage, runoff source area of a floodplain storage, etc.). For any storm some proportion (related to the peak storm discharge) of the available sediment stored in these sites will be removed.

A further distinction between types of available sediment can be made on the basis of the way it is released into streamflow. Two types can be identified; available sediment *sensu-strictum* and semi-available or stored sediment. On the slopes around a variable source area, for example, available sediment will be released into flow according to whether any sediment exists or not, ie.

$$S \propto Sa \quad \text{if} \quad Sa > 0; \quad S = 0 \quad \text{is} \quad \delta a < 0$$

where S = sediment released from available storage for time period

a = area in contact with flow discharge

This implies that any overland flow has sufficient transporting capacity to remove this limited amount of available sediment. In contrast, the semi-available sediment held on the bed of a channel beneath/behind a large cobble (see section 6.3b) will only be released to the flow once the cobble is removed, ie. release occurs only once some threshold has been exceeded; for the case cited:

$$S = 0 \quad \text{if} \quad Q < Q_* \qquad S' = S_{cap} \quad \text{if} \quad Q > Q_*$$

where Q = discharge rate

S_{cap} = sediment volume held in semi-available storage

Q_* = threshold value of discharge for sediment release.

It is important to recognise that for both available and semi-available sediment the rate and volume of sediment released from storage to streamflow per unit time is not directly related to discharge rate. In neither case therefore will a deterministic relationship between suspended sediment transport rates and discharge be found.

The pattern and timing of suspended sediment concentration hysteresis observed in streamflow during storm events will be determined by the location, size and type (available/semi-available) of sediment storages in the drainage basin. In the rest of this paper three possible storage locations are considered in detail, these are:

(i) Runoff source areas

(ii) Channel banks

(iii) Channel beds.

5.1 The importance of scale

Before considering possible mechanisms of available sediment ...ration and how its accumulation and release to streamflow might ... ...elled it is useful to consider which of the three storage location listed above is liable to be most important in drainage basins of different scales. The importance of scale as a determinant of the storage location which should receive most attention in an attempt to simulate suspended sediment hysteresis during hydrographs is demonstrated through a comparison of three drainage basins. These are;

(i) Slithero Clough, Yorkshire

(ii) Washburn river study reach between Thruscross and Fewston reservoirs, Yorkshire

(iii) East Fork Salmon river, USA.

Some characteristics of these drainage basins are shown in table 2. In the Slithero Clough and Washburn reach the bank and bed areas have been calculated from direct field survey. For the East Fork Salmon River a more approximate method has been used, employing hydraulic geometry relationships calculated for the basin channel system by Emmett (1975). A weighted (with respect to total channel network length) mean bankful depth and width for the whole basin has been calculated, from which bank and bed areas are determined.

The results in table 2 show how the importance of banks and channel bed areas change in both absolute and relative amounts between drainage systems of different size. Using these results together with bankful flow data an assessment of the capacity of banks and bed to supply suspended sediment to river flow during hydrographs can be made. For each catchment bankful discharge and suspended sediment concentration data has been used to estimate the amount of bank erosion or bed lowering that would be required to maintain peak suspended sediment concentrations for 24 hours (table 2, column e). It is noted that as basin size increased so the amount of bed lowering produced by such an extreme event (bankful discharge for 24 hours) deminishes. In the case of the Washburn reach and East Fork Salmon river the bed lowering is much less than one grain size of the D_{50} bed material. Clearly sediment stored within the channel of streams other than headwater reaches is not 'exhausted', even by such an extreme event. It is well known, though, that only a fraction of the sediment in a river channel becomes suspended, and that the size grades most liable to be suspended (>0.004<1 mm) are relatively depleted in channel bed deposits (see section 2). It could be suggested, therefore, that a positive hysteretic pattern in suspended sediment concentrations is due to this paucity of fine sediment. This can be shown not to be the case for the East Fork Salmon river. For any river, the fraction of total sediment that will be truly suspended by the flow is that size grade for which;

$$\frac{\tau}{\tau_{*d}} > 50 \qquad \text{(Einstein, 1950; Krishnapper, 1976)}$$

where τ = bed shear stress

τ_{*d} = critical tractive shear stress for size grade d.

At bankful discharge for the weighted 'mean' reach sine of the Ease Fork Salmon river, this condition is satisfied for grain sizes <2 mm. Particle size analysis of the river bed sediment by Emmett (1975) in a number of reaches showed that particles <2 mm diameter made up 16% of the total bed area. Sieve analysis of the <2 mm size fraction showed a mean size for the fraction of 0.2 mm. Assuming spherical particles, the total weight of <2 mm particles present in the channel bed surface would still be capable of maintaining bankful sediment discharge rates for c 68 hours. Positive hysteresis, of suspended sediment concentrations during storm events of less than this duration cannot therefore be due to a simple exhaustion of the fine sediment supply. The widespread occurrence of positive hysteresis, therefore, implies that a large proportion of the fine sediment on a channel bed is held in semi available storage or is completely unavailable for transport. Possible sites of sediment storage on channel beds are discussed in section 6.3.

The analysis above leads to the suggestion that the volume of fine material on the bed of large streams is so great that the single critical factor determining the importance of other available/semi-available sediment sources is determined by the extent to which the bed sediment is held in unavilable storage. For example, if a large proportion of the fine material on a channel bed is held only in a semi-available storage the storm period variation in suspended sediment input to the reach from a small tributary reach will be swamped by the continued and maintained supply of sediment from the channel bed.

In contrast to the Washburn and Salmon rivers, slope wash in the Slithero Clough headwater is the dominant source of sediment. Bed lowering calculations from table 2 indicate that in this catchment the very small channel (Shreve magnitude = 1) is not capable of supplying the bankful sediment discharge rate. The channel erosion (widening) required to support bankful sediment discharge rates over a 24 hour period would be a 0.5% increase in width, a rate of channel growth unlikely to be maintained. In contrast, the same amount of sediment represents only 0.001-0.002 mm of removal over the entire runoff source area (25-30% of catchment area at this rate of discharge).

To summarise, this analysis has indicated that in all but the smallest streams (Shreve magnitude <2) there is sufficient fine, suspendable sediment within the channel to account for and maintain over long periods observed peak suspended sediment discharge rates. Whether or not positive hysteresis occurs therefore is determined by the proportion of total bed sediment that is unavailable for sediment transport. Generally though, as channel size increases the amount of available or semi-available sediment on the channel bed becomes so large that the other (bank, runoff source area) sediment storages become less important components of the total available sediment supply. Thus far only the relative sizes of available sediment storages have been considered. It is important to recognise, however, that the most important storage location/type to model accurately is that which *contributes* most sediment per flow event, rather than simply the one with the greatest size. This implies that different storage locations may be the dominant sediment contributor for different flow ranges. It is, therefore, appropriate at this stage to examine the mechanisms of sediment generation, release and approaches to modelling them in all three of the available semi-available sediment storage locations considered above.

6. Approaches to modelling the production of available sediment in drainage basins

6.1 Runoff source areas

(a) Processes and observations

Erosion on hillslopes has been a subject of quantitative research for more than 40 years. Various workers have shown how vegetation, rainfall, slope and soil factors effect the rates of soil removal (for review see Evans, 1980). The majority of published work has, however, considered the processes of soil erosion (dominantly rainsplash and overland flow) from a *transport limited* standpoint. This is partly because both empirical (eg. Zingg, 1960) and more rigorous experiments (Foster and Meyer, 1972; Moyersons , 1975) have been carried out on bare surfaces or agricultural land. Such sites probably have either a virtually infinite available sediment storage (due to the disturbed nature of the vegetation/soil cover) or practically no available sediment where a bare surface has become crusted or surface sealing has occurred. In either case results obtained from experiments will tend to show a degree of correlation between sediment transport rate and the hydrodynamics of the eroding flow than would be the case on a 'natural' slope (where the volume of available sediment stored will be of finite but significant size). It is likely that vegetation has an influence beyond simply determining the volume of loose sediment stored on a slope. It is well known, for example, that vegetation decreases rainsplash and wash erosion through a combined 'umbrella' and surface mulching effect (the reduction of rainfall impact forces and overland flow velocities, etc.). On a densely vegetated surface, such as a dynamic source area, around a stream head or on a flood plain the detachment forces exerted by splash and wash may be reduced to such a degree that surface flow is effective only as an agent of sediment transport and not erosion. In such a case sediment transport rates are once again *supply limited.*

Although the reasoning above is grossly oversimplied (the extent to which the argument is true will depend, for example, on the flow Reynolds number and the surface grain size distribution), observations have been made that can be interpreted as supporting a supply limited concept of slope wash erosion. Observations of wash rates around the stream head of the Slithero Clough catchment showed that annual totals (sums of weekly collections in sediment traps) of sediment were related to wash volumes as;

$$S = 194Q^{0.66} \quad \text{(see figure 5)}$$

McCaig (1980, 1981) suggested that the exponent of this relationship was affected by a 'new flow' sediment contribution to the first few millilitres of wash generated at a site during the period of sample collection (ie. a limited supply of available sediment). Two features of the sediment trap data set which support this view are;

(i) The highest sediment concentrations, for each trap, were, generally, associated with the smallest volumes of flow collected.

(ii) The differences between the sediment concentrations in small (only a few ml of flow collected) and large (trap filled) volumes for individual traps were larger than the differences between the 'trap filled' concentrations for traps in different locations, ie. the apparent increase in sediment concentrations recorded with increasing flow depths is less than the decrease in sediment concentration following the exhaustion of the 'new flow' available sediment supply.

McCaig (1980, p. 300) suggested that the sediment which comprised this 'new flow' sediment contribution (calculated to be around 9 mgm^{-2} of runoff generating area) was generated by two suites of processes. The first suite suggested was termed *'bioturbation'* and includes processes such as the disturbance of the soil surface by grazing animals, soil fauna and soil flora. The second suite of processes that might generate this available sediment are *physical* processes such as wetting/drying and freeze/thaw. The two suites may operate in concert, for example, physical processes may be significant in breaking down detached aggregates and degrading surface irregularities produced by the bioturbation processes.

In addition to the 'new flow' available sediment supply observations at the Slithero Clough site suggested that a large amount of sediment was held in semi-available storage in ephemeral lines of flow around the stream head. Quite large amounts of sediment (<10 g) of sediment were noted to accumulate upslope of blockages in ephemeral flow lines. Such lines generally ran between *Molinia* sp tussocks, the blockages being formed by litter accumulations between adjacent tussocks. Periodically these blockages were washed away, or erosion around them released the sediment trapped behind them. This pulsed release of sediment from semi-available storage seems a reasonable model to suggest as a way of accounting for observed short period suspended sediment concentration fluctuations in streamflow from the Slithero Clough catchment (figure 6).

Further evidence that the availability of sediment in stream head areas is more important than hydraulic mechanisms in determining amounts of sediment carried by wash is provided by the report of Oxley (1974). Observations in a very small catchment showed that sediment concentrations in streamflow were higher after periods of drought than at other times. Oxley established a relationship between antecedent moisture conditions and sediment production, suggesting that during dry periods the rate of infall of fine sediment to ephemeral channels from their banks increased (ie. available sediment generated by *physical* processes). Oxley also observed that sediment accumulation occurred in ephemeral sills and other drainage courses upslope of surface irregularities, sediment being frequently trapped by leaf debris in the manner described previously.

(b) Approach to modelling

The previous discussion has indicated that both available and semi-available sediment is found in runoff source areas, and that this sediment accounts for observed flow-sediment relationships. Before considering an approach to modelling sediment generation and release from a runoff source area the relative importance of the 'new flow' available sediment supply and the semi-available sediment held behind flow blockages should be assessed. Calculations of annual wash transport rates around the Slithero Clough stream head (McCaig, 1981) show that more than 96% of the total sediment removed was generated from ephemeral drainage lines. This difference in magnitude between removal from drainage lines and the surrounding slopes is much greater than could reasonably be accounted for by a larger total 'new flow' sediment contribution due to the greater frequency of flow in these areas. Since the field observations have indicated that most 'flow blockage' available sediment storages are in ephemeral drainage lines it is reasonable to conclude that sediment generated and released from this form of storage accounts for the majority of total sediment transport. In terms of the volume of sediment held as available or semi-available storage in the two site types, calculations from field data suggest a 0.38 kg maximum for the 'new flow' sediment storage and 2.5-7 kg for semi-available sediment in ephemeral drainage lines.

An appropriate model of sediment contribution to streamflow from runoff source areas is therefore one which views the sediment transport per unit time period from these areas as being the sum of a number of releases from point sources. The accumulation of sediment in these storages can be considered as due to the filtering of flow draining the slope and so will be related to:

(i) flow sediment concentrations
(ii) volume of flow 'filtered'.

The first factor will in turn be partly determined by the 'new flow' sediment contribution produced by the suites of processes discussed above.

The release of sediment from 'flow blockage' semi-available storage can be modelled as a stochastic process. A flow chart for a simple computer model of sediment release from a number of point sources during simulated hydrographs is shown in figure 7. The assumptions included in the model are;

(i) Semi-available sediment is held in a number of discrete storage sites;
(ii) Release from storage is a random event which can occur provided that surface flow is occurring at the storage site location;
(iii) The number of sites capable of contributing sediment to the flow is a function of flow rate (ie. runoff is generated from a spatially dynamic source area);
(iv) Each storage site can contribute sediment to flow only *once* per runoff event (ie. regeneration of stored sediment occurs over time periods longer than a single storm hydrograph).

The model incorporating these assumptions produces results that are very sensitive to the number of storage sites assumed. Generally, suspended sediment concentrations increase with increasing discharge rates, but the increase becomes more irregular as either the number of storage sites is decreased or the ratio of site storage capacity to sediment transport rate approaches unity. The effect of storage site numbers on predicted suspended sediment concentrations for constant discharge rates is shown in figure 8 (in this figure a constant number of storage sites capable of contribution is assumed). The pattern of variation produced with small numbers of source sites is similar to the short period turbidity record for the Slithero Clough shown in figure 6.

For a simulated hydrograph this stochastic model of sediment release produces a discernable positive hysteresis of suspended sediment concentrations (figure 9a). A suspended sediment-discharge scattergram produced by multiple runs of the model for a variety of storm sequences is strikingly similar to that constructed with observed data from the Slithero Clough catchment (figure 9b, 9c).

In summary, observations indicate that an *availability* limited model of sediment contributions to streamflow from runoff source areas is valid. The principal storage of semi-available sediment found in a field study was behind flow blockages (surface obstructions within drainage lines). A model is suggested which treats available/semi-available sediment generation (accumulation) as a function of flow rate and slope sediment contributions (sediment release from semi-available storage) as occurring randomly from a number of possible storage sites. Evidence from the field study site suggests that the number and density of storage sites increases with overland flow volume implying that as the proportion of total runoff from a slope occurring as overland flow increases so to does the degree of correlation between sediment transport and discharge rate (see previous discussion of figure 8).

6.2 River channel banks

(a) Processes and observations

River channel banks show that a stream is capable of erosion. Data, originally presented by Glymph (1957) (see table 3) indicates that the proportion of total erosion accounted for by channel erosion (which includes bank erosion) can be as high as 53%. Coldwell (1957) suggested from surveys of arial photographs that; "Bank erosion may cause a greater part of the erosion in a watershed than was previously supposed". More recent studies by Wolman (1959), Lewin (1972); Knighton (1973) and Hooke (1979) have recorded impressive rates of bank erosion but have done little else to support Coldwell's contention. In contrast to these studies many streams display banks which for the greater part of their length are quite stable, especially where the vegetation cover and its root mat combine to protect and bond the bank together. In these conditions sediment removal from the banks may again be determined by availability rather than simply the transporting/detaching power of the flow.

In a statistical analysis of the controls of river bank erosion Hooke (1979) found a high level of statistical significance between the amount of bank removal and an antecedent precipitation index, suggesting that physical processes such as wetting/drying or (probably more importantly) a reduction in bank cohesion (resulting from wetting) are important in determining the amount of bank erosion. Such processes may also operate at a smaller scale than bank collapse, serving to detach individual soil peds, etc., and could therefore also be responsible for generating available sediment on channel banks. As with the case of variable source areas a suite of 'bioturbation' processes may also generate available sediment. Of the volume of sediment detachment by either physical or bioturbation processes on a river bank only a proportion will be 'stored' as available sediment. Much of it will drop under gravity into the stream channel. The proportion retained on the bank will be determined by bank shape and surface cover. On a densely vegetated, non-vertical, channel bank therefore volumes of stored available sediment should approach a maximum.

A pilot survey of available sediment volumes held on the well vegetated 1.5 m high banks of the Washburn study reach showed that between 0.2–30.0 gm^{-2} of sediment could be removed by suction, drawing material vertically away from the bank face. The material picked up by suction was of three types; (i) organic debris; (ii) soil peds; (iii) fluvially derived sand. The amount of sediment collected in a quadrat sample increased with height up the bank. The greatest totals were recorded at the bank top, the majority of the sediment in this position being organic debris. The fluvially derived sand was found in discrete locations; trapped behind vegetation clumps and on the flatter parts of the banks. The median sediment weight collected in the pilot survey was 5.2 gm^{-2}, the medians for bank base (just above base flow level) and bank top were 1.36 gm^{-2} and 6.4 gm^{-2} respectively. These figures indicate that during a bank-full discharge event the loose material stored on the total bank area of the study reach is capable of generating 20.8 kg of sediment. The bankful sediment discharge rate of the reach is <0.3 kgs^{-1}, assuming an even distribution of sediment along the banks of the reach the available sediment stored on the banks could maintain this rate of sediment discharge for only around 70 seconds. Since discharge does not rise to the bankful level instantaneously, however, the sediment supply will not be exhausted quite so quickly, loose available sediment trapped on stream banks could therefore be a significant component of suspended sediment concentrations during the rising limb of a storm hydrograph.

(b) Approaches to modelling

Approaches to modelling the amount of sediment produced and held on a bank face by non-fluvial processes operating between hydrograph events are considered in this section. The work of Hooke (1979) and Thompson (1964) has shown that rates of erosion of fluvial features (specifically channel banks and gully heats respectively) can be related by empirical regression analysis to a number of site or environmental factors (antecedent precipitation, rainfall intensity, etc.). The rate of available sediment production could be related by these methods to similar variables. The pilot survey indicated that different bank materials recorded different amounts of available sediment and so the substrate effect would also have to be included in such a model. Intuitively, then, a set of factors which are liable to be most important in predicting the rate of fine sediment detachment per unit time period are:

(i) Ratio of clay/sand or silt/clay in river channel bank
(ii) Amount of organic material (including soil fauna)
(iii) Antecedent precipitation index
(iv) Number of days of frost
(v) Peak rainfall intensity.

The nature of the bank is also important in determining the amount of the generated material which is retained on the bank. Here the most significant factors will be:

(i) Bank gradient

(ii) Bank surface 'irregularity' (Bank profile length/bank top - bank bottom straight line length)

(iii) Vegetation cover

(iv) Peak stage height (ie. proportion of bank over which regeneration processes can be considered active during the period).

Possible models for the mehcanism which releases the accumulated available sediment should now be considered. At the simplest level, and being consistent with the definition of available sediment given in the previous sections, release could be modelled to occur immediately flow encounters the sediment. In contrast, Kirkby (1977) has suggested that release of available or stored sediment from this sort of storage may be proportional to the level of storage, proposing a flushing model including a release function of the form;

$$S = \left(\frac{S_*}{S_o}\right)^n$$

S = sediment released to flow

S_* = total sediment available or stored

S_o = 'capacity' storage amount.

Results from the release model using a constant accumulation rate are shown in figure 10. Included in this figure is a curve intended to represent 'normal' bank erosion, sediment transport due to these processes being modelled as a power function of discharge. Comparison of the curves shown in figure 10 shows that it is the available sediment generated by non-fluvial processes that accounts for positive hysteresis of suspended sediment concentrations during storm hydrographs.

In summary, various research reports suggest that both bank erosion and available sediment production on channel banks may be related to a number of hydrometeorological and substrate variables. Sediment generated by these processes will either fall directly into the river flow or be held as available sediment. Where the channel bank available sediment storage is the largest sediment storage then an appropriate model of suspended sediment concentration fluctuations will need to focus on the processes of available sediment generation, release being simply related to stream stage.

6.3 River channel beds

The discussion of sediment storage locations and their sizes in section 5.2 has indicated that as channel size increases the amount of sediment, even fines, present in the channel bed increases to an amount far greater than, say, annual sediment discharge totals. For example, Midgley (1979) calculated the channel of the Crimple Beck, North Yorkshire draining only 8.2 km^2 contained sufficient sediment to account for recorded annual sediment discharges (bed and suspended load) over a thirty year period.

Since positive hysteresis of suspended sediment concentrations during storm events is such a common occurrence though, it is clear that only a fraction of the sediment in a channel is either available or semi-available in the sense of the definitions given previously. In fact, channel bed sediment, which will contribute to suspended sediment concentrations, must be of the later type; else it would have already been removed. This implies that fine sediment on the channel bed is held in some type of semi-stable storage and will be released to the flow if some threshold discharge rate is exceeded. An initial question to consider, then, is how and where is fine sediment stored in a channel?

On any channel bed it is usual to find some pattern of sediment sorting produced by the changing flow conditions in different reaches; coarse material being found on riffle/bars, etc., and finer grades along the channel margins. A pilot survey of the Washburn study reach has shown that the fines present in the channel bed are found in two principle sites of accumulation. Firstly fines tend to collect in the lee of gravel and cobble sized stones and secondly even finer material coats stones of all sizes, in association with algae growth, in parts of the flow which at low discharge rates could be described as *backwaters*.

Accumulation in the first site is due to the formation of low velocity eddies below the zone of flow separation in the lee of particles protruding up into the flow (figure 11). Once suspended material has settled through the zone of flow separation it becomes trapped in these eddies. This mechanism of fines accumulation is well known to sedimentologists the sedimentary structure known as flaser bedding (Reineck and Wunderlich, 1968) being formed by silt deposition in the lee of sand bed forms.

The pilot, quadrat, survey of the Washburn channel bed showed that 4-15% of the total bed area was occupied by these sites of accumulation. The size of individual sites ranged between 0.002 m^2 - 0.09 m^2. The number and size of sites varies with the mean grain size of the cobbles/gravel forming the sites; large boulders produce a few large sties, fine gravel many small sites. Particle size distributions of the material that has accumulated in the lee of cobbles are shown in figure 12.

Calculations of the possible importance of this type of semi-available sediment storage can now be made. The volume of the possible sediment storage area in the lee of any obstruction can be related to obstruction height. Field observations suggest that a fairly conservative estimate of storage area is given by:

$$v = \frac{1}{6} \Pi h^3$$

Taking a mean obstruction size for the entire reach of 5 cm height, the approximate maximum sediment storage will be 138-520 kg for the bed area coverage (4-15%) observed in the channel. The particle size analyses of entrapped sediment shows however that only 15-20% of this total is in the size range (<1.0 mm) which might be expected to be suspended under storm flow conditions in the reach. An order of magnitude estimate of the possible 'suspended sediment supply' held in the lee of cobbles is therefore, 20.7-104.2 kg. For recorded bankful discharge sediment transport rates from the reach then, the capacity of this type of storage would be exhausted after 1-6 minutes. These very approximate calculations indicate that the amount of fine sediment stored in the lee of cobbles is 1-6 times larger than the amounts of channel bank available sediment calculated in the previous section.

The second area of fines accumulation in the Washburn reach is on the surface of stones in backwater areas. Algal growths, coating the upper surfaces of stones are a feature of these sites and may serve to entrap colloidal and silt grade material. The association of algae growth with 'dead' or backwater sites is possibly due to water temperatures, especially under sunny conditions, being somewhat higher than in the main flow. The amounts of fines held on stones appears to be greatest in backwater sites just below tributary inflows, suggesting that sediment accumulation in these sites may, as in the case of ephemeral drainage lines, be due to a 'filtering' of sediment from source area runoff.

Analysis of fine material washed from the surface of stones in backwater locations indicated that this material accounted for 0.015% - 0.08% of individual stones weights. Assuming stones to be spherical and that all deposited material is on the upper hemisphere these values indicate a coverage of fines of 6-24 gm^{-2} in backwater sites. Two points should be noted;

(i) results are very variable and much larger sample sizes than those used at present are needed to give accurate estimates;

(ii) preliminary results suggest that the amount of algae on stones may be a function of time since last hydrograph.

Using the results given above it is again possible to estimate the total amount of sediment that might contribute to suspended sediment concentrations held in this type of storage. Assuming that backwater areas occupy a 0.2 m wide strip down either bank of the study reach (at low flows), this total is 4.8 - 18.74 kg.

The result suggests that this storage site types is somewhat less important than, channel bank storage, but that it might account for around 12% of the available sediment storage associated with the Washburn channel system.

(b) Approach to modelling

(i) Lee-side of cobbles

The movement of sediment grades of all sizes in streamflow is determined by the hydroynamic force of that flow. The suspended sediment distribution models outlined in section 3 show that both a deterministic and stochastic approach to sediment transport can be developed. In the case of large cobbles acting as sediment traps it is the stability and effectiveness of this trap which must be modelled as part of a simulation of storm period variations in suspended sediment concentrations. Cobbles are bed load material and the problem of the stability and movement of individual bed particles in streamflow is best approached using a stochastic model.

Consider first the accumulation step. The volume of sediment held at any one time in the semi-stable lee side storage of all the cobbles of diameter d on the bed will be a function of:

(i) The number of sites
(ii) The site size ($\propto$ d)
(iii) The rate of suspended sediment settling (itself a function of concentration and flow rate)
(iv) The mean length of time that sites remain stable (ie. mean time between saltation steps of particles in the d size class).

The last factor indicates that the bed is a dynamic storage, and that even during a period of relative accumulation (between hydrographs) the distribution of sediment between storages of different sizes is liable to change. For example figure 13 shows the changing average level of sediment stored (as a proportion of storage capacity) under conditions of constant sediment accumulation for different grain size classes. Clearly, the greatest accumulation is in the lee of the most stable particles, implying that the redistribution of sediment leads to an increasing unavailability of sediment.

Sediment is released from the storage trap when the bed particle first moves (by saltation or rolling) across the stream bed. Since only the *first movement* of individual particles releases fine sediments a hysteretic effect during hydrographs is produced. For any grain on a channel bed movement is initiated when the instaneous life or drag forces exerted by the flow are greater than either the gravity or friction forces associated with that particle respectively. These forces may be defined as;

$$F_{drag} = c.\cos \Theta \rho D^2 u^2 \tag{16}$$

$$F_{lift} = c.\cos \Theta \rho D^2 v^2 \tag{17}$$

$$w = (\rho_s - \rho) g \frac{\Pi}{6} D^3 \tag{18}$$

$$FF = (w - F_{lift}).\tan \Phi \tag{19}$$

where F_{drag} = downstream drag force

F_{lift} = vertical lift

w = mass of particle

FF = friction force

D = grain diameter (u)

g = acceleration due to gravity

v = vertical instantaneous velocity

u = downstream instantaneous velocity

Φ = coefficient of friction

ρ = density of water

ρ_s = density of solid

c, Θ = constants

Movement of a particle on the stream bed occurs when the drag force exerted on the particle exceeds the friction force holding it in place. It is clear from the definitions of forces given above, therefore, that movement is a function of instantaneous velocity. It is known that both downstream and vertical instantaneous velocity fluctuations due to turbulence are normally distributed with a constant standard deviation for all discharge rates at certain levels in a flow. The relationship between vertical and downstream fluctuations is also known. For any given mean flow velocity then, the probability ($P_{(v')}$) of any instantaneous velocity can be calculated. Using equations (16)-(19) the instantaneous velocity (v'_i) required to move (detach from the bed) a bed particle of size D_i can be calculated. The probability of the bed particle moving (P'_i) during the time δt is then simply equal to the probability of this instantaneous velocity occurring, ie. $P'_i = P(v'_i)$. A detailed description of the method of calculating probabilities for the threshold of bed particle movement is given by Naden (1981). The probability P'_i of particle movement can then be converted to a probability of at least one detachment during any time $t = n\delta t$ for which discharge and mean velocity are constant;

$$P_{*i} = 1 - (1 - P'_i)^n$$

where P_{*i} = probability of *at least one* detachment during time $t = n\delta t$

n = number of instantaneous time intervals per time t (experimental data presented by McQuivey (1973) indicates that an instantaneous fluctuation is of the order of 0.01 seconds).

And so the weight of sediment released from cobble-lee storage sites associated with bed particles of size D_i per unit time is;

$$S_i = P_{*i} \times N_i \times V_i \times \rho_s$$

The changing number of sites capable of contributing sediment in each time period is calculated as;

$$N_{ij} = N_{ij-1} - (N_{ij-1} \times P_{*ij}) + I_{ij-1}$$

where j denotes time periods

I = number of sites 'replenished'.

An example of the suspended sediment concentration pattern through a hydrograph predicted by this model is shown in figure 16. In the model the volume of sediment in each storage site is related to cobble size as;

$$V_i = \frac{1}{6} \Pi D_i^3$$

Although a positive hysteresis in suspended sediment concentrations is the main feature of this pattern, the details and scale of the response to changes in discharge rate are dependent upon the size and relative abundance of the different bed material size grades.

(ii) Fines in backwater areas

Fine sediment accumulation on the upper surface of bed material in backwater areas between hydrographs is due either to the precipitation of suspended sediment from the flow or to the inputs from bank processes discussed in section 7.2a. The even distribution of fines over surfaces in those areas suggest the former is the dominant process.

The precipitation of sediment will be dependent upon the backwater flow velocity suspended sediment size and suspended solids content of the main flow. Algal growth may be significant in determining the amount of precipitation through their effect on the surface roughness of stones. For constant flow conditions, then, the amount of fine sediment precipitated at any location will be simply a function of time.

The potential sediment supply (release) from 'backwater' sites can be modelled in much the same way as the bank available sediment supply. That is, the precipitated sediment will be resuspended when flow velocities increase during a hydrograph. The amount of sediment resuspended per unit change in discharge rate is related to the amount of precipitated sediment and the change in 'backwater' area that accompanies the change in discharge. Backwater areas could be conveniently defined for the purposes of the model as those parts of the river channel reach which have insufficient velocities to maintain suspension of particles whose size is equal to the mean size of suspended sediment particles in the river flow. The pattern of suspended sediment concentrations during simulated hydrographs predicted by a model incorporating these processes will be identical to that produced by the model of bank available sediment release described in section 6.2b (figure 10).

7. Summary and requirements for the development of calibrated simulation models of storm period suspended sediment concentrations

The common occurrence of positive hysteresis in suspended sediment concentrations during stream hydrographs has been interpreted in this paper as an indication that suspended sediment concentrations are determined by the availability of fine suspendable material rather than the transporting capacity of streamflows.

Four sites of available and semi-available sediment storage have been suggested, these are:

(i) Runoff source areas

(ii) Channel banks

(iii) Channel beds

(a) In relation to bed sediments

(b) In relation to bed location

Mechanisms of sediment generation and release observed in the field have been described, and an assessment of the relative sizes and importance of the different available storages has been made. It appears that for drainage basins which support a stream channel of Shreve Magnitude $\mu > 2$ the available sediment storage of runoff generating areas is, relatively, the least significant.

Simple models of sediment generation and release for each type of storage have been suggested. These models divide, broadly, into two types;

(i) Models of available sediment; sediment release occurs once flow is 'in contact' with the sediment storage;

(ii) Models of semi-available sediment; sediment release to flow is a 'random' event which follows the local exceedance of some critical threshold.

For both types of model, and all storage locations appropriate sediment accumulation models are ones related to the conditions and length of time occuring between hydrographs.

7.1 Proposed simulation model for the Washburn Study Reach

The calculations of the sizes of runoff source, bank and bed available/semi-available sediment storages in the Washburn study reach are summarised in table 4. No data is available for the volumes of sediment in variable source areas contributing to the reach, but scaling of the Slithero Clough data suggests between 0.1 - 0.5 kg as available 'new flow' sediment and 2.5 - 12 kg for semi-available sediment in ephemeral drainage lines.

The largest available sediment storage in the study reach is that associated with channel bed material (lee-side of cobbles). A proportion of this bed storage volume, though, should be regarded as unavailable storage, since for maximum flow rates in the reach cobbles >20 cm diameter are virtually immobile. Fine material held in such sites has been subtracted from the minimum total given in table 4. Since the volume and weight of sediment held in cobble-lee sites is a function of particle diameter cubed, this discounting requirement rapidly reduces the volume of sediment capable of contributing to suspended sediment concentrations (eg. if 5% of the total site forming cobbles exceed 20 cm the total storage should be reduced by 20-50% depending upon the frequency distribution of other stone sizes).

Table 4 shows, then, that in the Washburn study reach the three sediment storage locations associated with the channel are all of approximately the same size. This approximate equivalence implies that a simulation model of suspended sediment concentrations in the Washburn must include submodels of accumulation/release for all three storages.

7.2 Data requirements for a Washburn simulation model

The conclusion to an appraisal of a research problem should consider the testing and calibration of the process models and hypotheses suggested in that appraisal. This report has discussed essentially simple mechanisms of available and semi-available sediment generation which require further validation with field data before they can be incorporated as submodels in a simulation model of suspended sediment concentrations. Specifically, for this project empirical relationships between a number of variables must be established and then incorporated into a physically based model of sediment supply. The relationships required and other data necessary for model calibration are listed in table 5.

7.3 Conclusion

This appraisal of how a supply limited suspended sediment transport model capable of producing positive hysteresis during storm hydrographs might be developed has concentrated on the details of sediment sources and processes of sediment generation. The preceding section suggests that a four storage-process unit simulation model of suspended sediment supply rates can be calibrated for a study reach using easily obtainable field data.

It is possible to use the *micro-scale* model described here as a basis for deducing the form of a more general *macro-scale* suspended sediment transport model. The formulation of such a general model requires that the details of specific processes be subsumed within the model. In this case, therefore, the general model must be set out in terms of discharge (Q) and time (t) only. This can be done and the form of the general model discovered by considering again the four storage site types described previously.

First, consider suspended sediment transport from runoff source areas. Suspended sediment transport rate is a function of discharge since both the number of sediment storage/source sites capable of contributing to the flow and their probability of contribution (see section 6.1a) are related to discharge. A general model of suspended sediment transport rates from this site type is therefore;

$$S = aQ^J$$

Adding to this a simple term to account for available sediment generation and exhaustion gives;

$$S = aQ^J - K \int (Q - w)dt$$

Exactly the same form of model can be used to describe suspended sediment transport rates from the cobble-lee available sediment storage site since the total amount of sediment released from this site type per unit time is once again directly related to present and previous flow rates (see section 6.3).

For bank and backwater available sediment storages, the models described in sections 6.2, 6.3 can be generalised to

$$S \propto \left(\frac{dQ}{dt}\right)^m$$

The rate of sediment transport from these site types is simply equal to the rate of sediment supply which is proportional to the rate of change of stream stage. When stage rises ($dQ/dt > 0$) sediment is released from storage, when stage falls ($dQ/dt < 0$) deposition in backwater areas will reduce total suspended sediment transport rates. Combining these general models for the different storage sites, the *macro-scale* model that underlies the process-based model outlined in the previous sections is seen to be

$$S = aQ^J + b\left(\frac{dQ}{dt}\right)^m - K \int (Q - w).dt$$

Clearly, at this stage this model is only a tentative one. Its future development, parameterisation and testing all require a great deal more work to be carried out at the micro (process-mechanisms) level of study.

Acknowledgements

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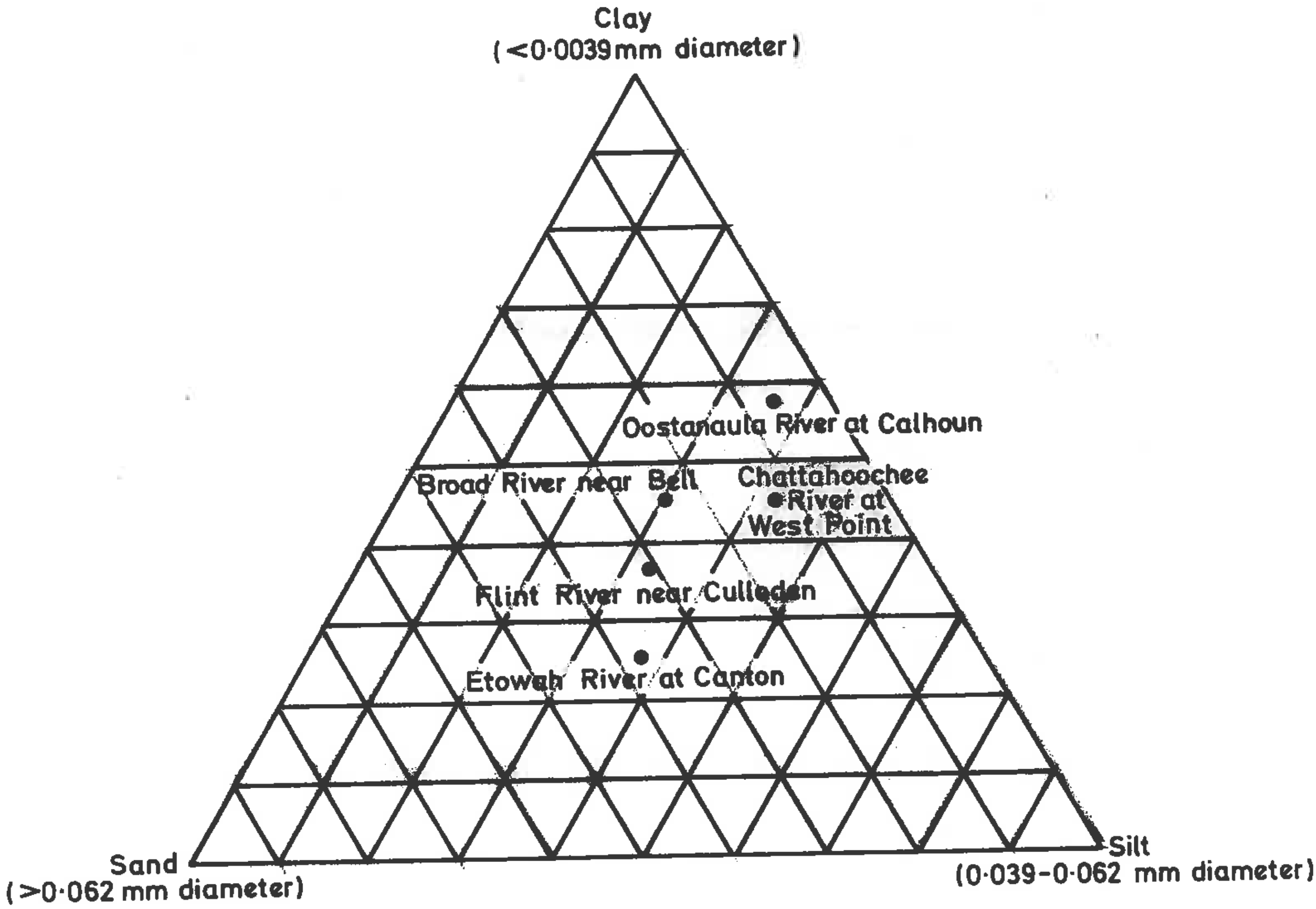


Fig. 1 Suspended sediment particle size distributions for some U.S. rivers
(Taken from Kennedy 1964)

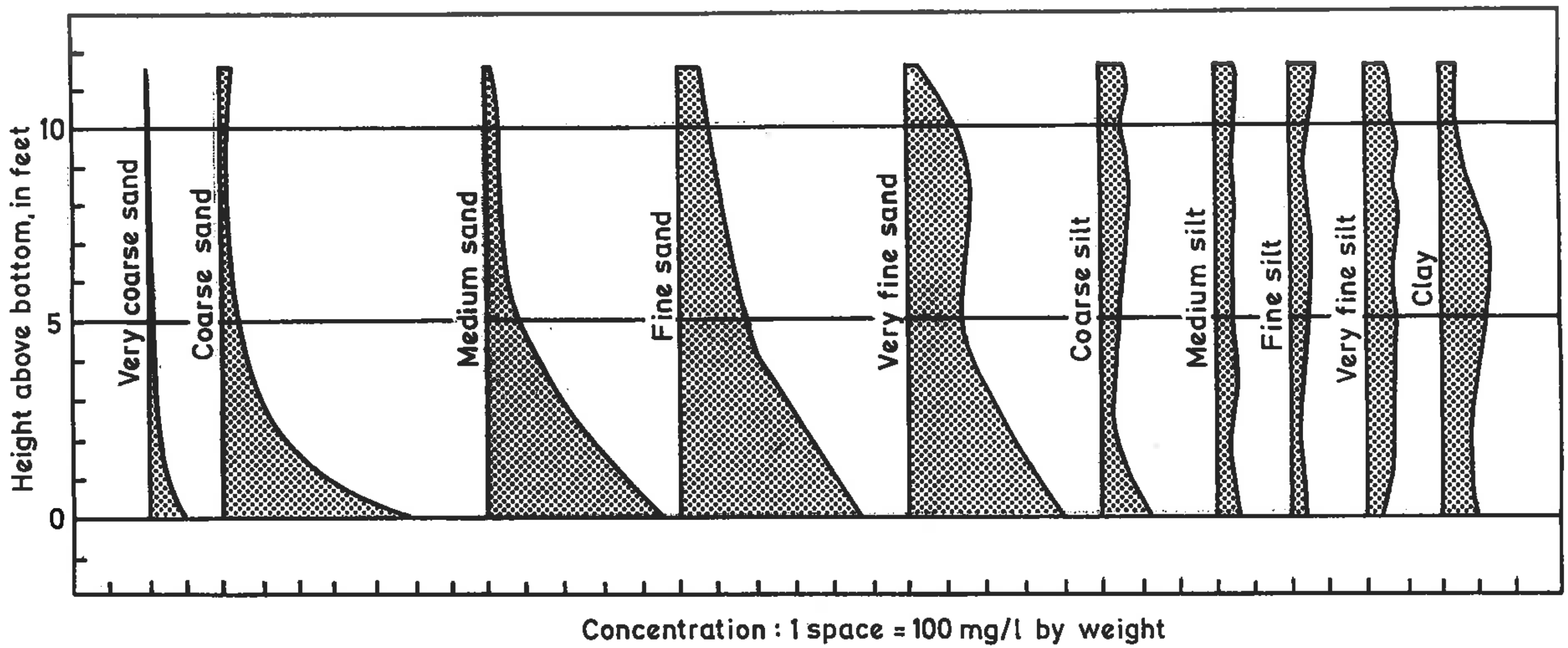
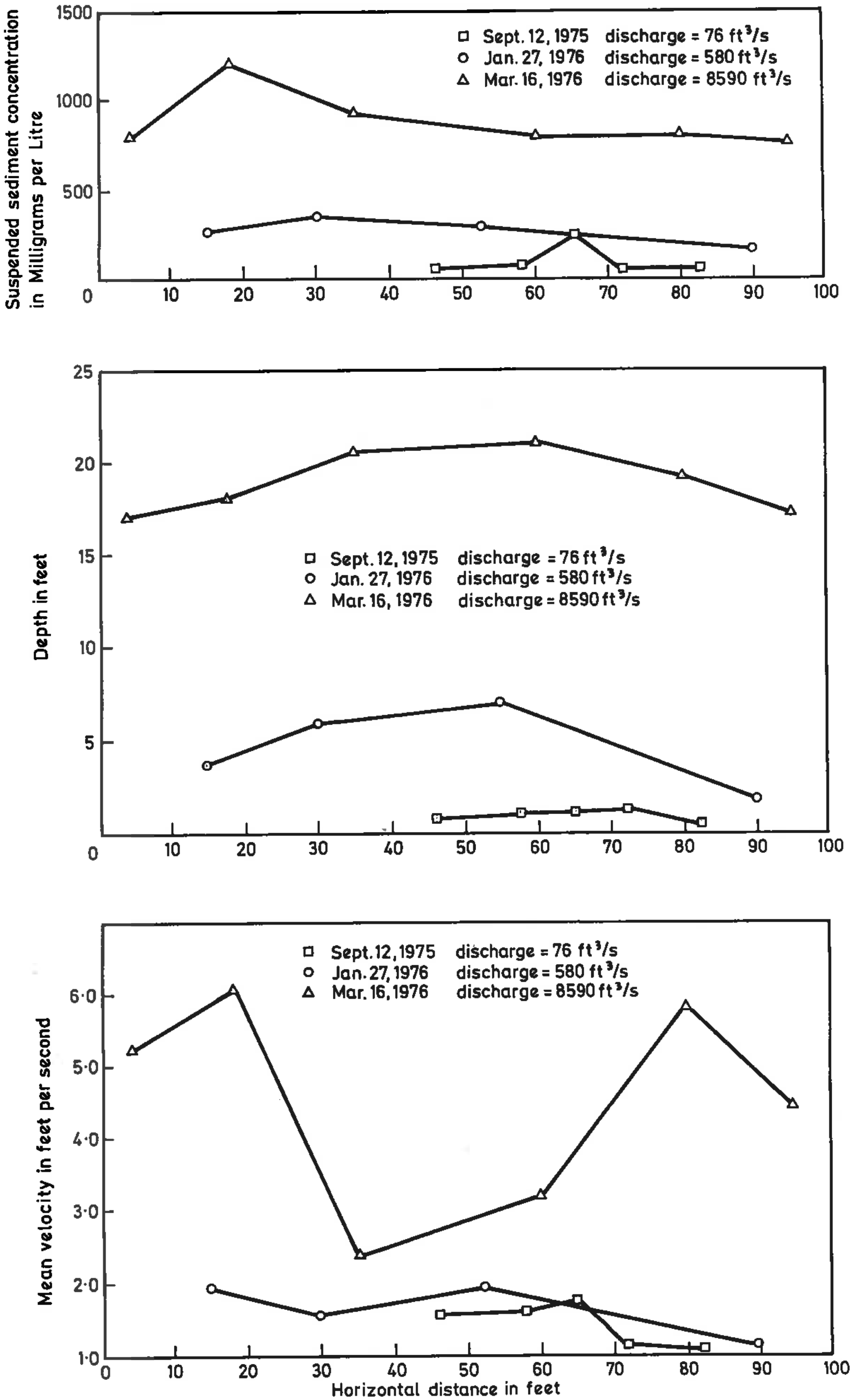
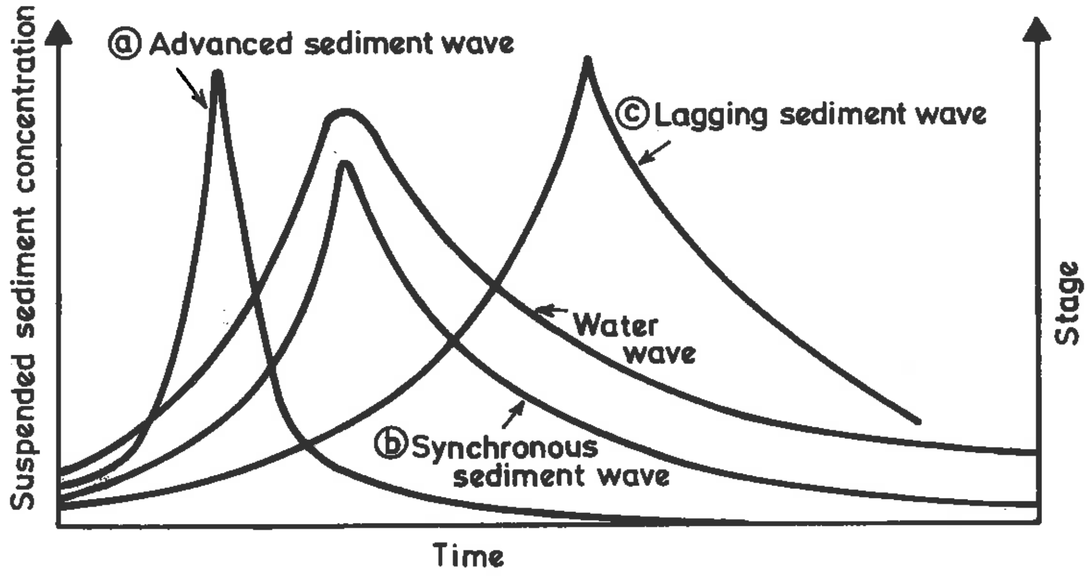
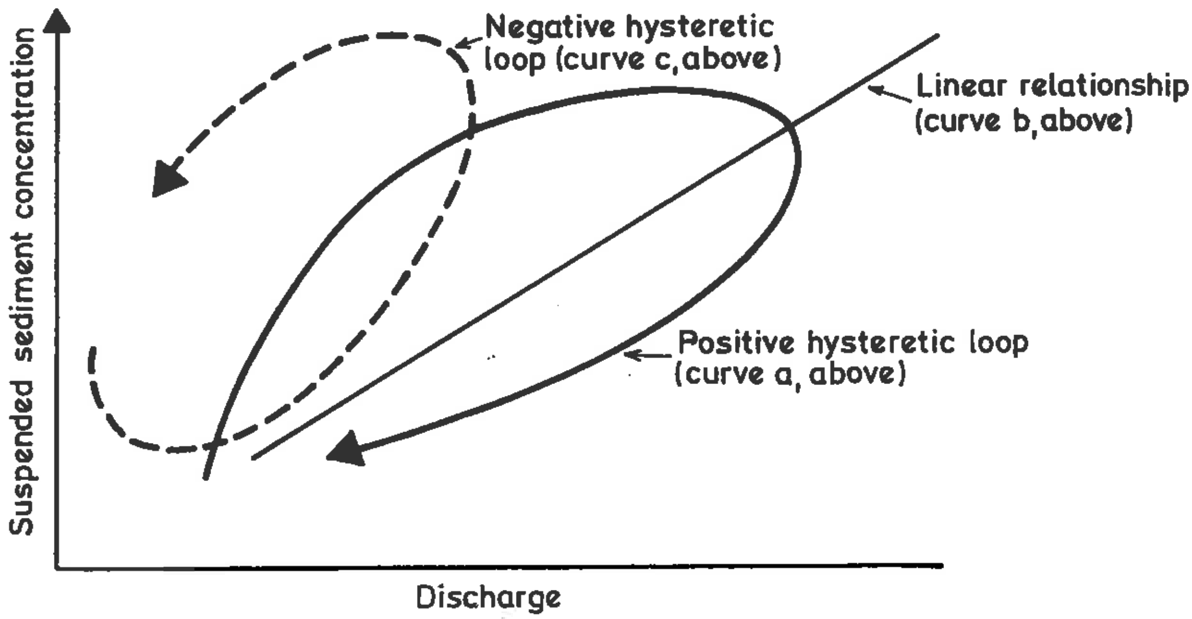


Fig. 2 The distribution of suspended sediment through a flow profile (Missouri River at Kansas City)


Suspended sediment concentration in Milligrams per Litre
1500
1000
500
0
10
20
30
40
50
60
70
80
90
100
Sept. 12, 1975 discharge = 76 ft^3/s
Jan. 27, 1976 discharge = 580 ft^3/s
Mar. 16, 1976 discharge = 8590 ft^3/s
Depth in feet
25
20
15
10
5
0
Mean velocity in feet per second
6·0
5·0
4·0
3·0
2·0
1·0
Horizontal distance in feet



a. Hydrograph forms



b. Concentration discharge curves

Fig. 4 Types of hysteresis in suspended sediment streamflow relationships

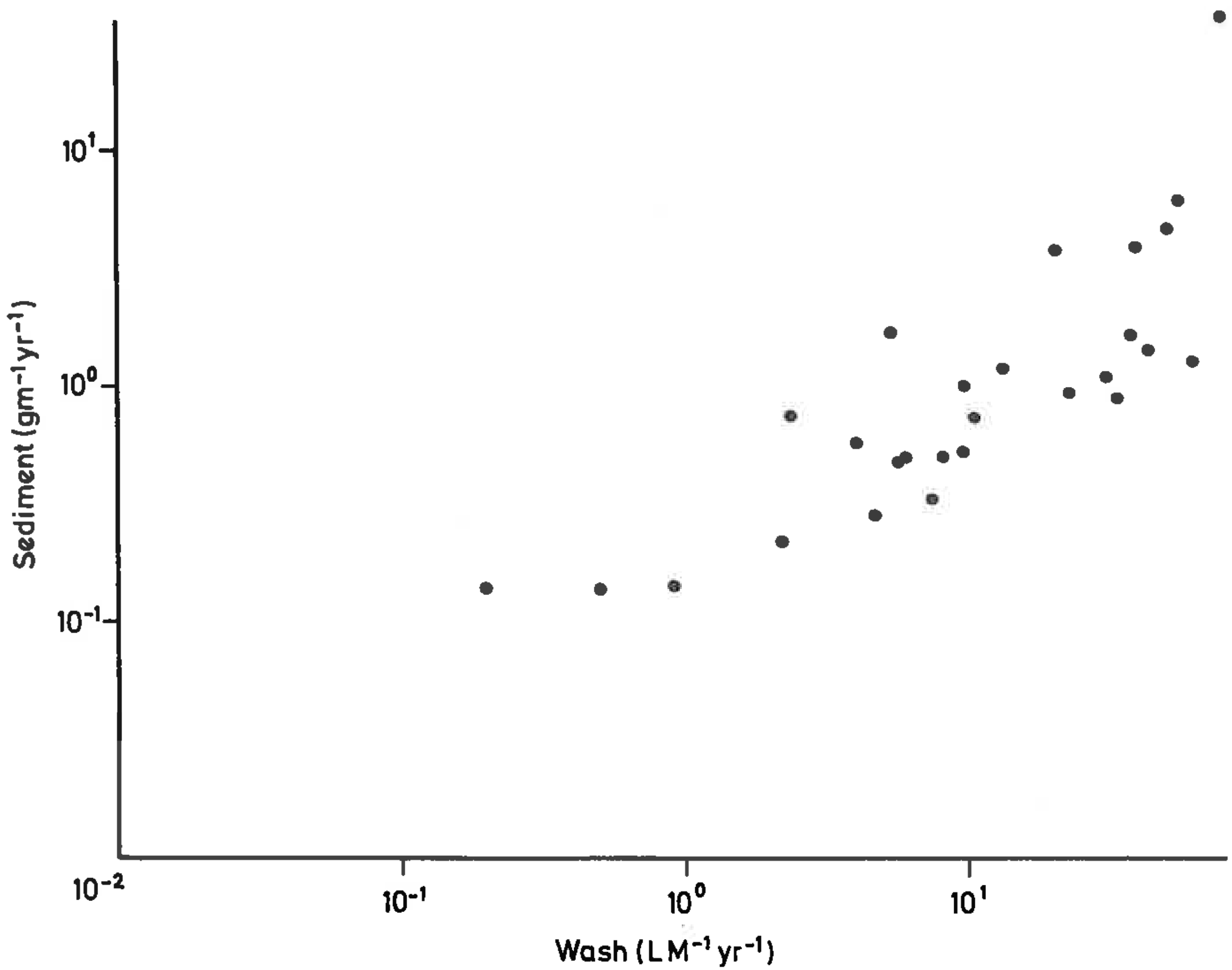


Fig.5 Sediment collected in sediment traps: scattergram of sediment and wash totals (annual)

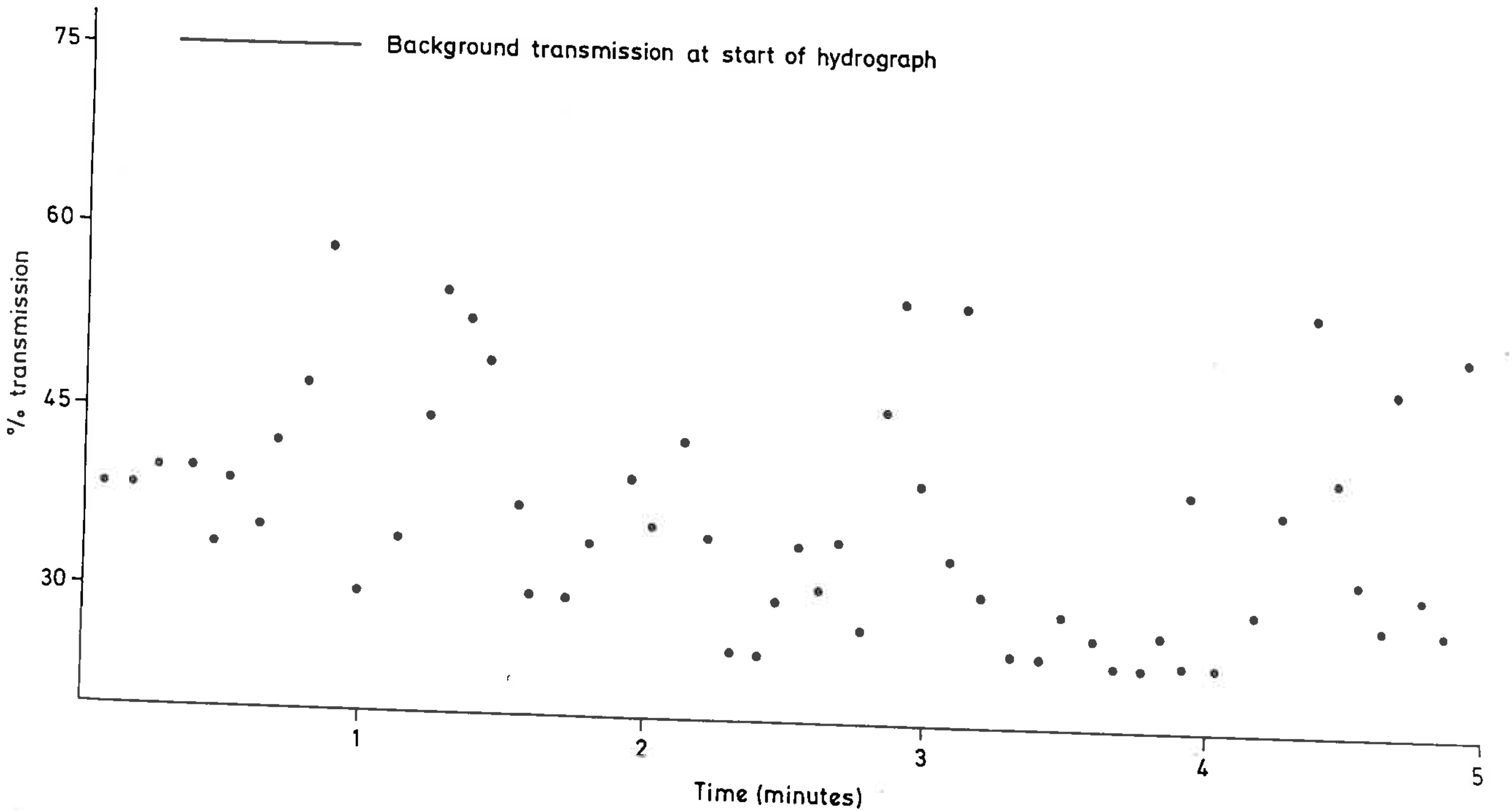
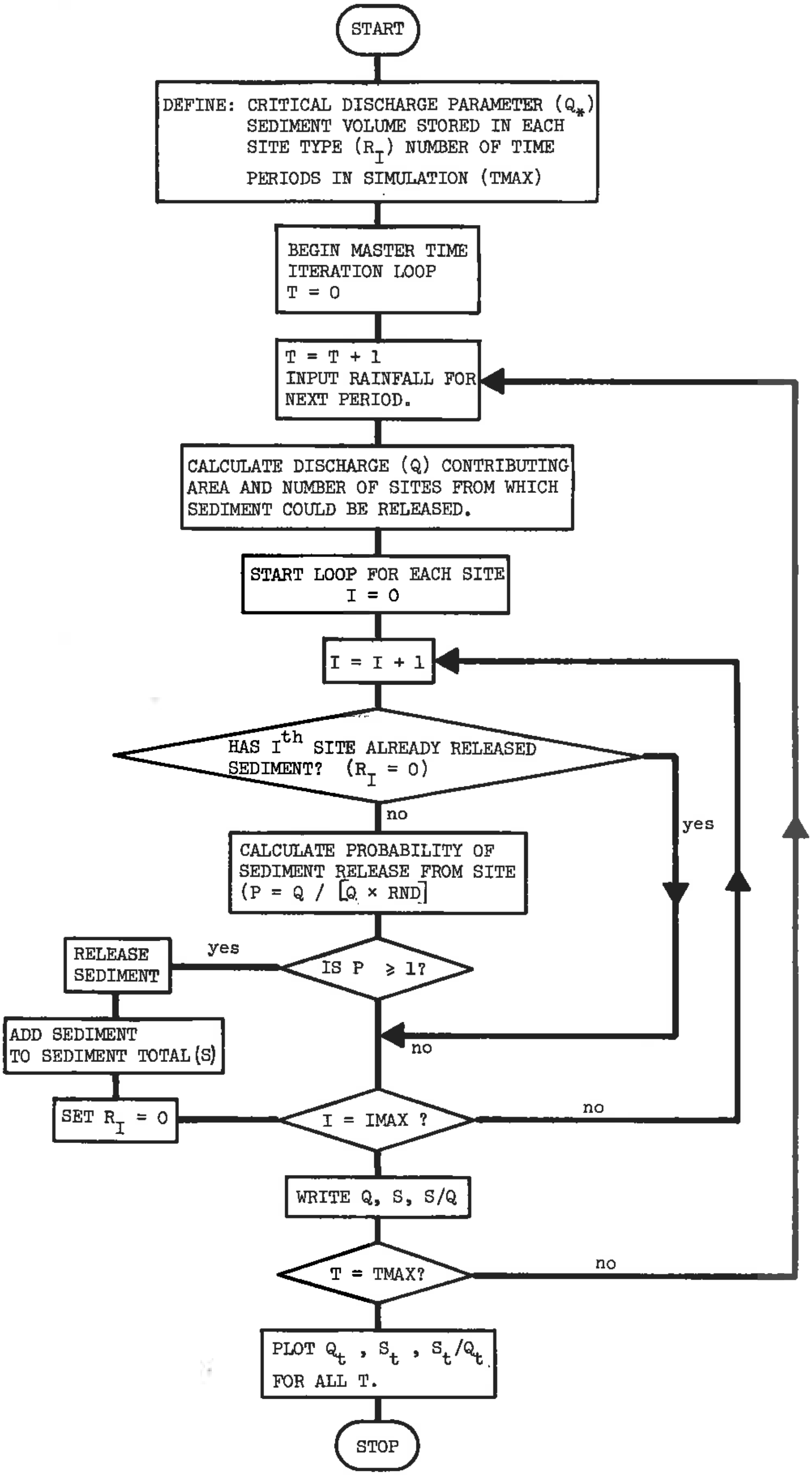


Fig.6. Five minute record of streamflow turbidity in the Slithero Clough catchment


START
DEFINE: CRITICAL DISCHARGE PARAMETER (Q_*) SEDIMENT VOLUME STORED IN EACH SITE TYPE (R_I) NUMBER OF TIME PERIODS IN SIMULATION (TMAX)
BEGIN MASTER TIME ITERATION LOOP T = 0
T = T + 1 INPUT RAINFALL FOR NEXT PERIOD.
CALCULATE DISCHARGE (Q) CONTRIBUTING AREA AND NUMBER OF SITES FROM WHICH SEDIMENT COULD BE RELEASED.
START LOOP FOR EACH SITE I = 0
I = I + 1
HAS I^{th} SITE ALREADY RELEASED SEDIMENT? (R_I = 0)
yes
no
CALCULATE PROBABILITY OF SEDIMENT RELEASE FROM SITE (P = Q / [Q × RND]
IS P ≥ 1?
yes
RELEASE SEDIMENT
ADD SEDIMENT TO SEDIMENT TOTAL (S)
SET R_I = 0
no
I = IMAX ?
no
WRITE Q, S, S/Q
T = TMAX?
no
PLOT Q_t , S_t , S_t/Q_t FOR ALL T.
STOP

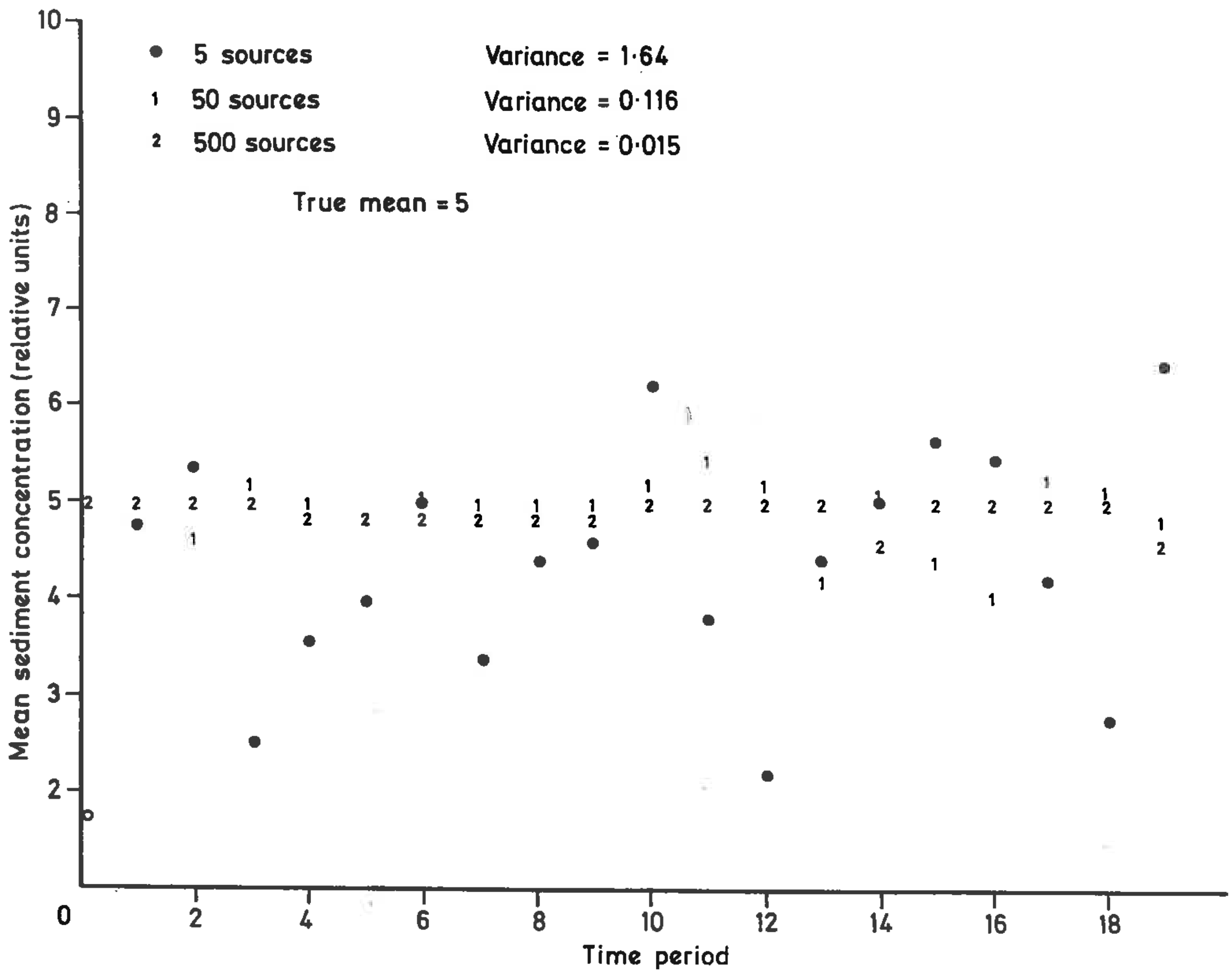


Fig. 8 The effect of increasing the number of sediment source sites on output sediment totals at constant discharge

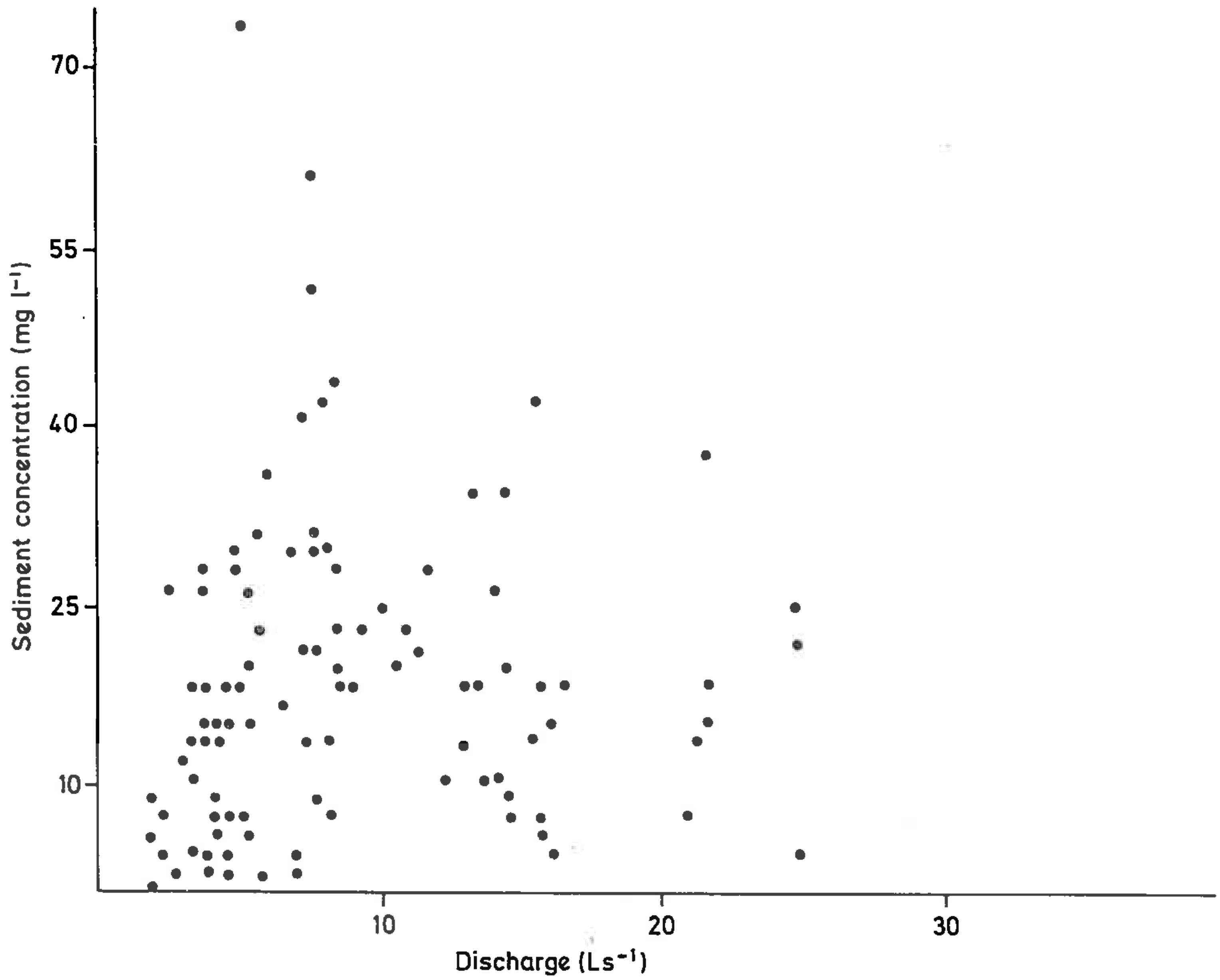


Fig. 9c. Suspended solids - stream discharge relationship : Slithero Clough

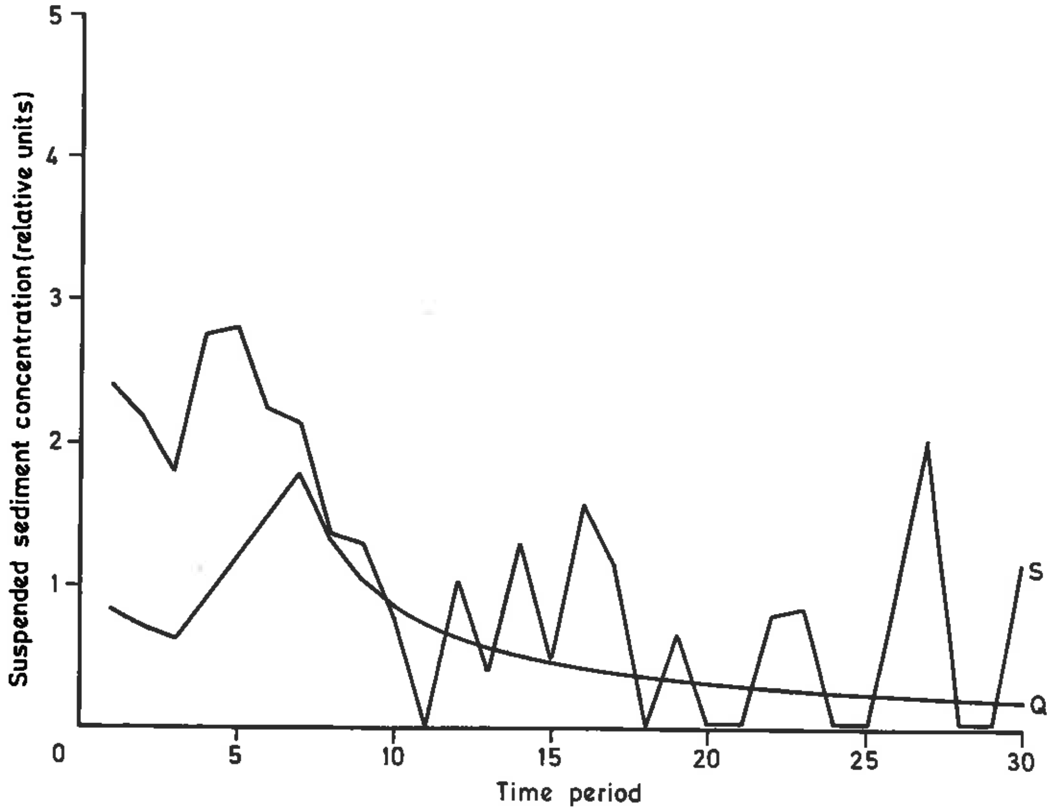


Fig. 9a Hydrograph and sediment response produced by vairiable source area model (random release from storage site)

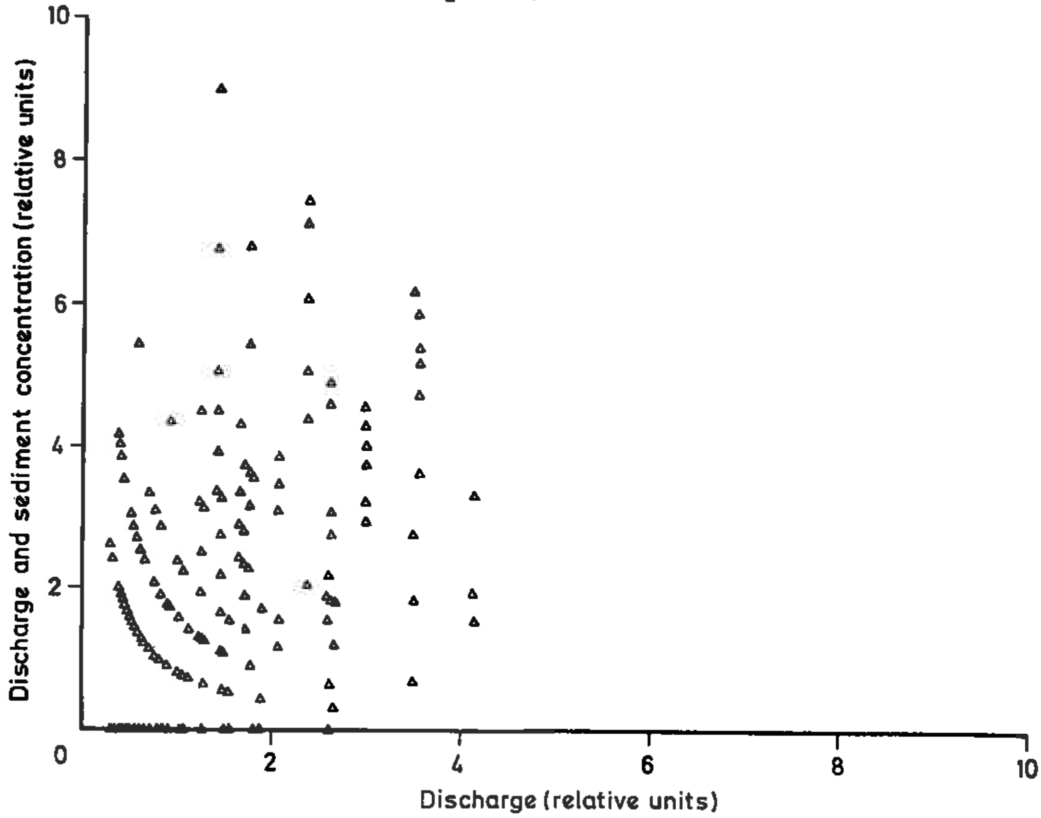


Fig. 9b Sediment-discharge scattergrain produced by multiple runs

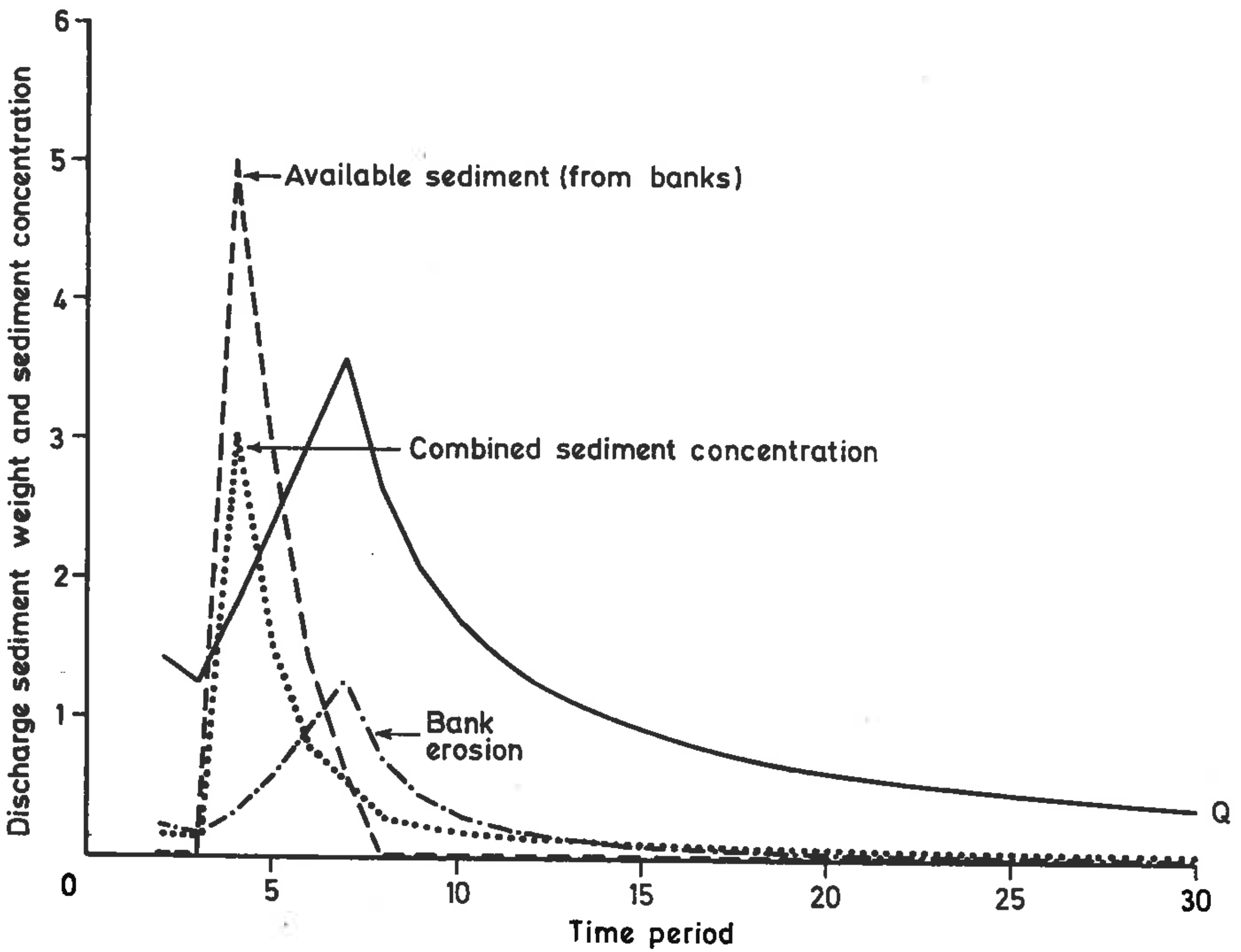


Fig. 10 Simulated sediment-hydrograph relationship produced by a bank available sediment model (all vertical scales in relative units)

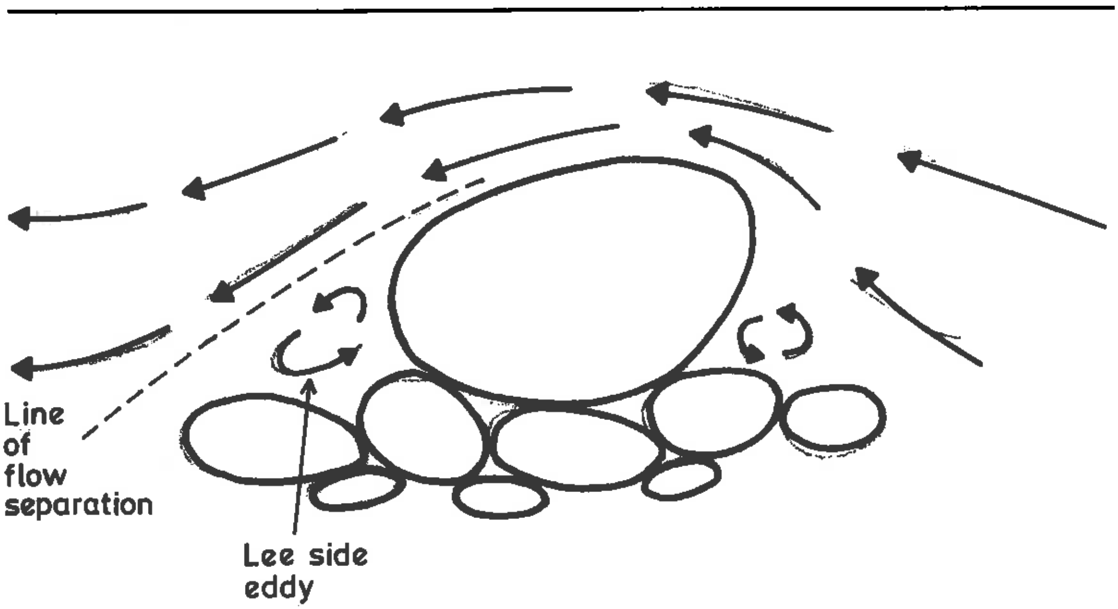


Fig. 11 Flow separation and eddy formation in flow over a cobble

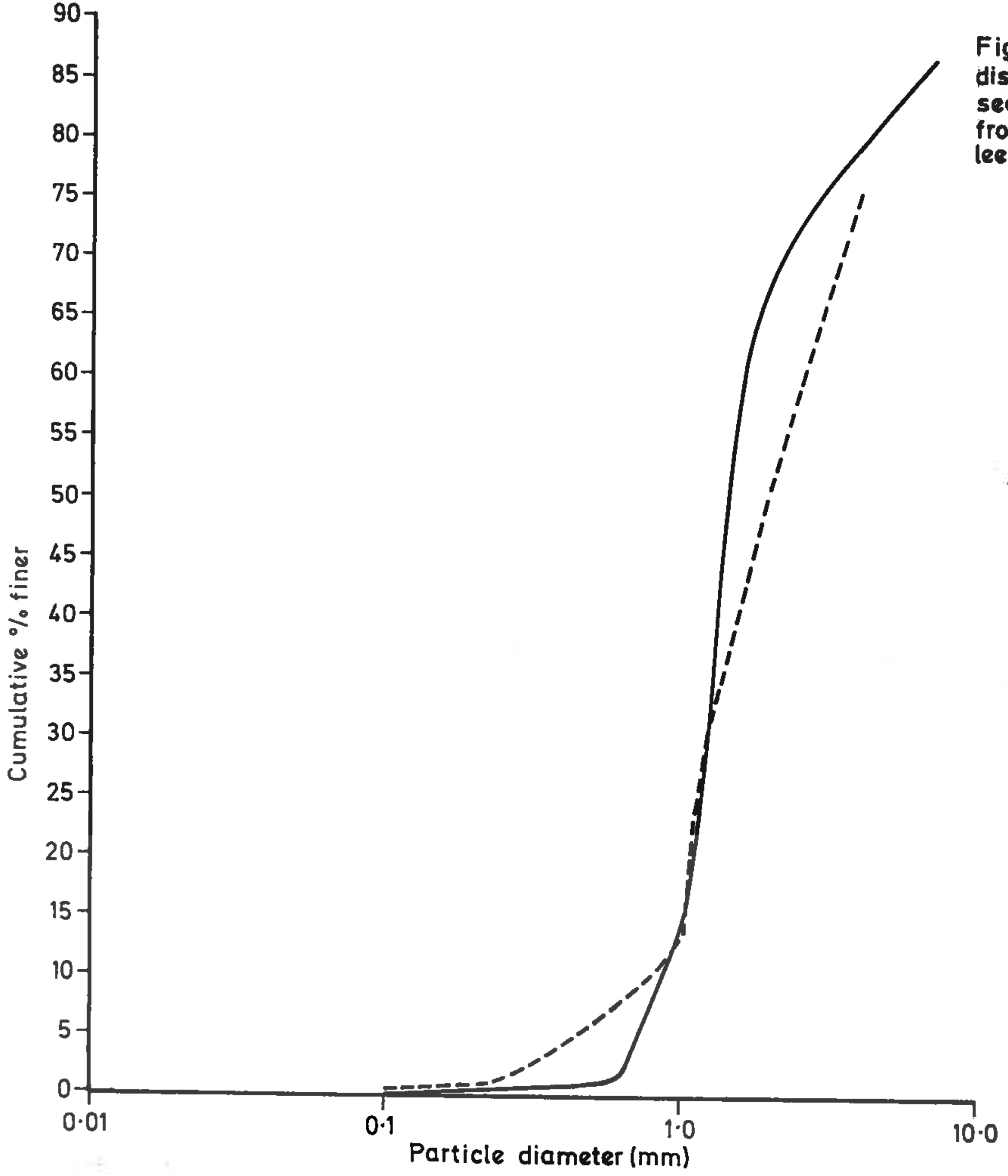


Fig. 12 Particle size distributions of sediment collected from the cobbles-lee eddies

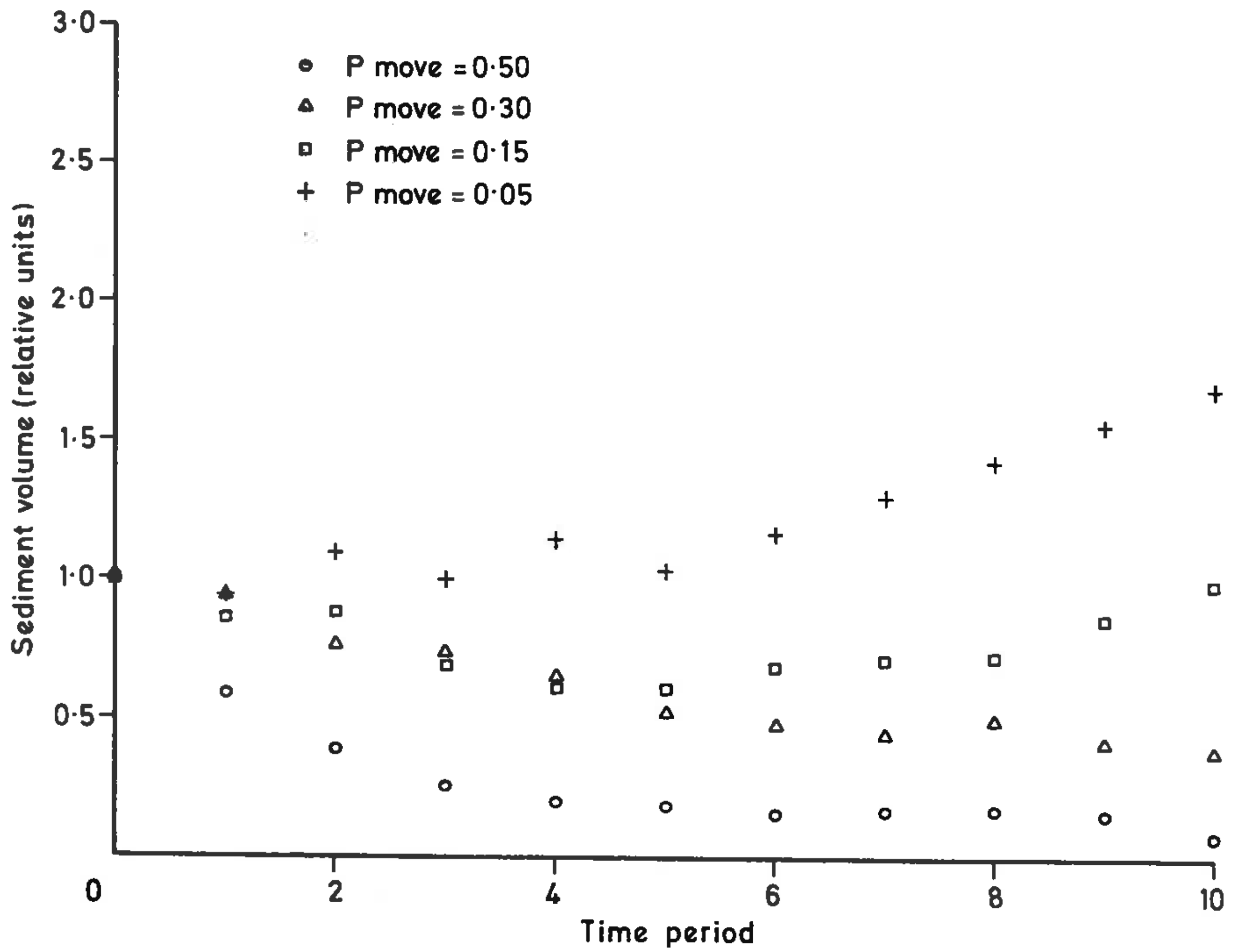


Fig. 13 Accumulation of sediment in most stable sites under constant flow conditions

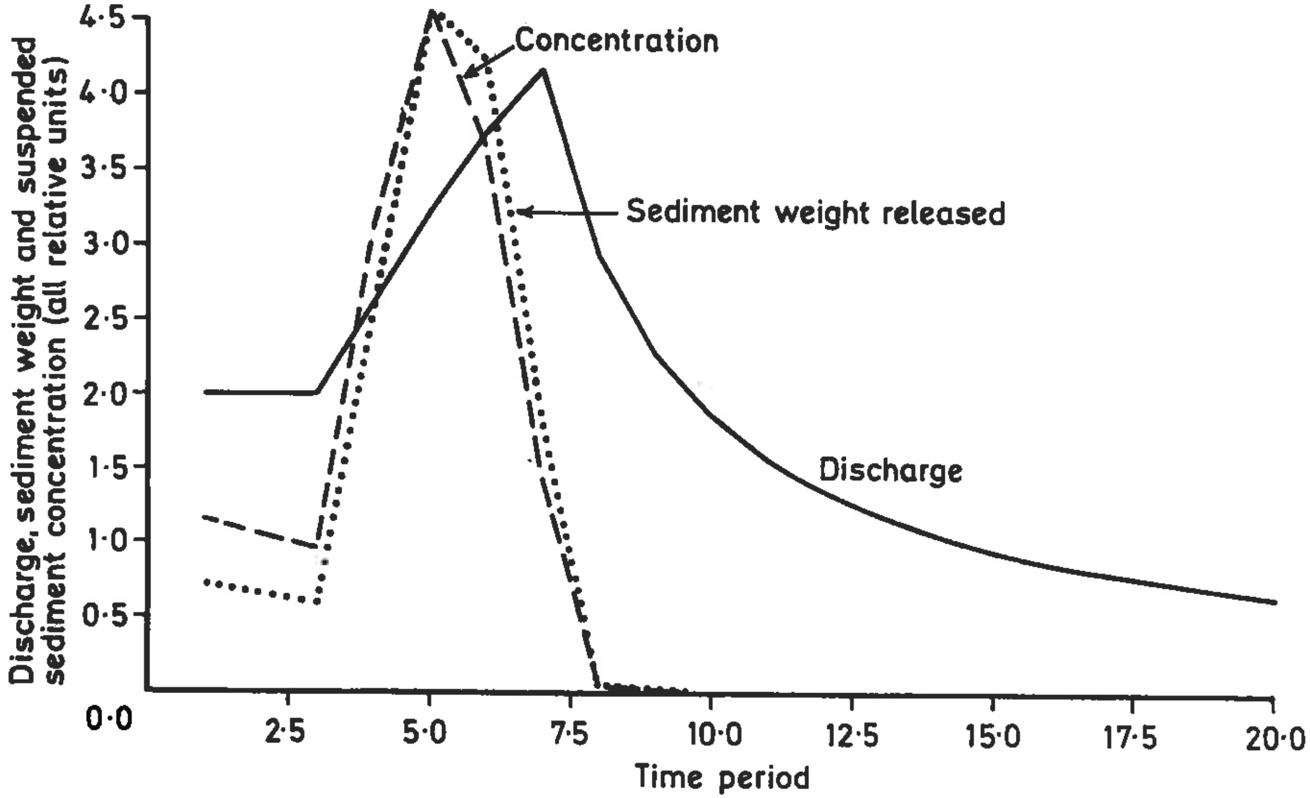


Fig. 14 Hydrograph and sediment response for cobble-lee sediment release model (no accumulation routine)

Table 1. Characteristics of some streams showing positive hysteresis in suspended sediment concentrations

Location	Discharge range (cfs)	Annual ppt	Bed source material	Susp. Sed. particle size ratio (silt/clay:sand)	Peak concentration mgl^{-1}	Reference
Swatara Creek Penn., USA	0-800	47"	-	-	10-1600	Stuart et al. 1967
Broad River Georgia	200-8000	45"	-	15:1	150-600	Kennedy, 1964
Etowah River Georgia	600-4000	45"	Alluvial silt/loam	6:1	14-1900	Kennedy, 1964
Kiowa River Colorado	0-5980	16.6"	Alluvial sand	1:1	70,000+	Mundorf, 1964
Deep River Carolina	200-400				1,000-5,000	Johnson, 1943
Big Creek Alpharetta, Georgia	227-1320	45"	sandy loam	-	$c10-c100$	Faye et al., 1980
Rosebarn Catchment, Devon	0-5.3	35"	-	-	1-10000	Walling, 1974
Washburn, Yorks.	0-500	45"	mixed till	1:1?	20-100	Present study
Sycamore Creek, Arizona	0-1350	12-20"	Alluvium Igneous/ Metamorphic	-	60000+	Fisher and Minckley, 1978

a	b	c	d	e	f	g	h	i
Stream	Drainage area (km^2)	Shreve magnitude	Bankful discharge	Bankful Susp. sed. concentration (mg/l)	Bed area (% of d.a.)	Bank area (% of d.a.)	Bed lowering* (mm)	Bank lowering* (mm)
Slithero Clough	0.04	1	25 l/s	70	0.01	0.042	3.27	1.09
Washburn Study reach	6.97		15 m^3s^{-1}	15**	0.3	0.07	0.93	2.02
East Fork Salmon river	1403.4	208	52.6 m^3s^{-1}	600	3.32	0.2	0.007	0.084

*Lowering that would be produced by 24 hrs @ bankful sediment discharge rate.

**This figure is the outflow sediment concentration additional to inflow from water released into the reach from the top-of-reach reservoir.

Table 2. Characteristics of 3 example streams

Location		Size of drainage area	Relative sediment source				
State	County		Sheet	Gully	Stream channel	Valley trenching*	Other
		sq mi	pct	pct	pct	pct	pct
New York	Erie and Wyoming	437	47	...	53	...	...
New Jersey	Mercer	47.8	74	15	11	...	...
Maryland	Harford	1.7	76	4	18	...	2
Ohio	Fairfield	49.1	79	8	10	3	...
Ohio	Highland	43.8	71	10	19	...	...
Illinois	Coles	1.41	42	58	...	...	...
Illinois	McLean	67.3	86	8	6	...	...
Illinois	Franklin	4.03	90+	...	...	...	...
Illinois	Jackson	3.10	90+	...	...	...	...
Illinois	Sangamon	265	90+	...	...	...	...
Illinois	Knox	13.1	95+	...	...	...	...
Illinois	Knox	9.14	95+	...	...	...	...
Illinois	Hancock	2.9	82	16	1	...	1
Illinois	Henderson and Warren	18.0	84	8	8	...	...
Illinois	Adams and Pike	72.3	72	10	18	...	...
Wisconsin	Vernon and Monroe	28.0	47	11	42	...	...
Minnesota	Fillmore	37.5	87	4	9	....	...
Minnesota	Swift and Kandiyohi	87.7	100	...	...	...	...
Minnesota	Swift and Chippewa	319	100	...	...	...	...
Iowa	Lucas	14.2	74	20	5	1	...
Iowa	Mills	12.5	56	24	...	19	1
Iowa	Plymouth	13.6	100	...	...	...	...
Iowa	Sioux	9.1	100	...	...	...	...
Missouri	Johnson	19.7	69	21	3	7	...
Missouri	Lincoln	14.0	53	25	22	...	...
Kansas	Johnson	6.0	85	9	...	...	6
Mississippi	Marshall	0.166	35	65	...	...	...
Mississippi	Marshall	0.211	40	60	...	...	...
Mississippi	Marshall	0.071	15	85	...	...	...
Mississippi	Marshall	0.209	58	42	...	...	...
Mississippi	Lafayette	0.448	14	86	...	...	...
Mississippi	Lafayette	0.162	11	89	...	...	...
Mississippi	Lafayette	0.169	24	76	...	...	...
Mississippi	Lafayette	0.136	25	75	...	...	...
Mississippi	Lafayette	0.143	21	79	...	...	...
Mississippi	Carroll	0.154	73	27	...	...	...
Mississippi	Carroll	0.235	60	40	...	...	...
Mississippi	Carroll	0.360	69	31	...	...	...
Mississippi	Carroll	0.160	35	65	...	...	...
Mississippi	Yalobusha	0.125	23	77	...	...	...
Mississippi	Yalobusha	0.070	11	89	...	...	...
Mississippi	Yalobusha	0.199	24	76	...	...	...
Mississippi	Tate	0.063	26	74	...	...	...
Mississippi	Tate	0.159	65	35	...	...	...
Mississippi	Tate	0.121	47	53	...	...	...
Arkansas	Logan	4.1	77	15	8	...	...
Oklahoma	Washita	51.9	95	5	...	...	...
Oklahoma	Washita	22.2	90	10	...	...	...
Oklahoma	Washita	2.7	78	21	1	...	...
Oklahoma	Washita	0.7	95	3	2	...	...
Oklahoma	Washita	5.9	92	5	3	...	...
Oklahoma	Washita	1.5	98	1	1	...	...
Oklahoma	Washita	0.4	100	...	...	...	...
Oklahoma	Roger Mills	1.6	35	65	...	...	...
Oklahoma	Roger Mills	0.6	35	65	...	...	...
Oklahoma	Roger Mills	0.16	30	70	...	...	...
Oklahoma	Roger Mills	0.036	50	50	...	...	...
California	San Diego	112	56	...	...	44	...
California	Contra Costa	150	50	...	41	...	9

Table 3. Sediment sources (% total sediment contribution) in some American drainage basins (taken from Glymph, 1957)

Table 4. Sediment storages in the Washburn Study reach

Variable Source area	Available sediment (kg) Min	Available sediment (kg) Max	'Stored'/sediment (kg) Min	'Stored'/sediment (kg) Max
	0.01	0.5	2.5	7
Channel banks	5.44	25.6		
Channel bed;				
(i) Cobble lee sites	-	-	10.3.5	104.2
(ii) Backwater area	-	-	4.8	18.74
TOTAL	5.45	26.1	17.65	129.94

Minimum combined total: 23.1

Maximum combined total: 153.0

Table 5. Data requirements and empirical relationships necessary to develop a suspended sediment simulation model for the Washburn Study Reach.

Data requirements

- Bank area
- Bed area
- Bed composition
- Discharge records
- Upstream sediment inflow

Empirical relationships

	Dependent variable	Independent variable
Between:		
	(a) Bank sediment availability;	(i) Bank material
		(ii) Bank surface cover
		(iii) Climatic/hydrological/ seasonal factors
	(b) Backwater sediment accumulat	(i) Discharge
		(ii) Algal growth
		(iii) Background sediment concentration
	(c) Backwater area	Discharge
	(d) Velocity	Discharge*

*For all subsections of the study reach.