Sediment discharge measurement and calculation

Techniques for use at river gauging stations

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Abstract

The terms 'wash load', 'suspended bed material load' and 'bed load' are not clearly defined but, if applied with care, provide a useful basis for sub-dividing the total discharge of sediment in a river for the purpose of measurement. The accuracy with which each of the three types of sediment transport must be measured will depend on their relative magnitudes and on the purposes for which data are being collected. This paper contains a proposed programme of measurements to be undertaken on a typical tropical river, one carrying appreciable wash load discharges and in which the suspended bed material discharges are large relative to the bed load discharges. The purpose of the programme is to provide data on the total discharge of sediment in such a river for studies of catchment erosion or reservoir sedimentation.

In outline, the proposed programme is as follows:

i) use an adequately calibrated turbidity monitor to provide a continuous record of wash load concentrations;

ii) undertake a short intensive programme of pumped sampling to provide information about the relationship between suspended bed material discharges and selected hydraulic parameters (principally river level);

iii) apply this relationship to recorded flow discharge data to provide values of suspended bed material discharge over the period of available hydrological data; and

iv) apply'empirical and theoretical methods to provide an estimate of the magnitude of the 'bed load' (including unmeasured suspended bed material load close to the bed) relative to the measured suspended bed material load.

The theoretical basis for this programme is examined in this paper. In particular, details of the assumptions made, and their implications, are provided. In addition, practical details of the field procedures and of the methods of analysis relating to pumped sampling in such rivers are described.

Contents

1	Review of sediment discharge measuring techniques	1						
1.1	Introduction	1						
1.2	Wash load	2						
1.3	Suspended bed material load	3						
1.4	Bed load	5						
1.5	Practical considerations in the selection of methods for sediment discharge measurement	6						
2	The measurement of suspended bed material load using pumped samplers	8						
2.1	Selection of suitable gauging stations	8						
2.2	Sediment sampling using pumped samplers	10						
2.3	Technical and practical considerations in pumped sampling	11						
3	Procedures for calculating sediment discharge values from the results of a pumped sampling programme	14						
3.1	Theoretical considerations	14						
3.2	Separation of particle size fractions	17						
3.3	Determination of velocity profiles	17						
3.4	Preparation of sediment flux profiles	19						
3.5	Calculation of total sediment discharge in a vertical	21						
3.6	Determination of bed load discharge	22						
3.7	The 'total load' formula of Ackers and White	26						
3.8	The 'total load' formula of Engelund and Hansen	27						
3.9	Estimating sediment discharges over long periods	27						
4	Summary of proposed sediment sampling programme	28						
5	Acknowledgements	30						
6	References	31						
	Data forms for use in the collection and analysis of pumped samples							
	Pumped sampling: field data record	1						
	Pumped sampling: size analysis of sand particles	2						
	Pumped sampling: summary of calculations							

Contents (Cont'd)

Figures

- l Typical record of river cross-section data
- 2 Derivation of sediment flux profile
- 3 Linear representation of data from Figs 2a and 2b
- 4 Typical sediment flux profiles for different particle sizes
- 5 Criteria for initial motion and suspension of sediment

List of symbols

A cross-sectional area at measuring station

A' coefficient in Ackers-White equation

- b width of cross-section
- c sediment concentration at a point on cross-section (mass per unit volume)
- c time averaged value of c
- c' turbulent component of c
- C coefficient in Ackers-White equation
- d depth of flow in a given vertical
- D representative particle size
- D_{gr} dimensionless grain size = $D[g(\gamma_s 1)/\nu^2]^{1/3}$
- F dimensionless fall velocity = $w/[g.D(\gamma_s-1)]^{\frac{1}{2}}$
- g acceleration due to gravity
- i water surface gradient
- k Von Karman constant (generally taken as 0.4)
- m coefficient in Ackers-White equation
- n coefficient in Ackers-White equation
- Q total liquid discharge through cross-section
- Q_s total sediment discharge through cross-section
- s gravimetric sediment flux at a point on cross-section
- s time averaged value of s
- \overline{S} time averaged sediment discharge through a specified area
- T_c water temperature
- v flow velocity at a point on cross-section

v time averaged value of v

- v' turbulent component of v
- v_{\star} shear velocity = (g.d.i)^{1/2} in wide open channels
- $\overline{v_{mean}}$ mean value of \overline{v} in a vertical
- V mean velocity through entire cross-section

- w fall velocity of particle of given size
- X mean sediment concentration in cross-section (ratio of weight of sediment to weight of water)
- y distance upwards from river bed
- Y dimensionless mobility number = $v_{\star}^2/[g.D(\gamma_s-1)]$
- z parameter in expression for concentration distribution = $w/k.v_*$
- δ height of an element on the vertical (for numerical integration)
- γ_s specific gravity of sediment particles
- v kinematic viscosity of water
- e density of water

Review of sediment discharge measuring techniques

Introduction 1.1

1

Over the past fifty years a large number of techniques have been developed for measuring and estimating the rate of sediment transport* in rivers. In the USA, in particular, considerable effort has been given to the evaluation of such techniques with a view to their standardization but this work has met with only partial success. On the one hand, the large number of variables which determine sediment transport rates limits the extent to which simplifications and generalizations can be applied. On the other hand, unless such simplifications and generalizations can be made, few countries could provide the necessary resources and personnel to sustain long-term programmes of data collection over a widespread network of gauging stations.

In the present paper the factors which influence the choice of sediment sampling technique are summarized. For further details a large number of references are available; see for example, Vanoni (1975). The techniques of pump sampling offers a number of advantages over other sampling methods and is applicable in a wide range of river conditions. Details are provided, in this paper, of a method by which continuous records of sediment discharge data may be obtained, for certain gauging stations, from a short period of pump sampler measurements in conjunction with continuous monitoring of turbidity.

In the measurement of sediment discharge a distinction is generally drawn between wash load and bed material load; although there is no widespread agreement about the precise definition of these terms. Wash load comprises those particles which are not present in appreciable quantities in the material of the river bed. The concentration of such particles in the flow at a given location and time is determined primarily by their rate of input to the river system, that is, by the erosion of the catchment upstream. Bed material load, the movement of particles which are found in the bed of the river, may be subdivided into suspended bed material load and bed load. The former comprises particles which are lifted from the bed and are supported in the flow by turbulent eddies but which from time to time settle back to the bed; the latter comprises particles which move by rolling or sliding in more-or-less permanent contact with, and supported by, the bed. In both categories of bed material transport the magnitude of the sediment discharge is determined primarily by the local hydraulic conditions in the channel at any given time. The difficulties

^{*}In this paper the terms sediment transport rate and sediment discharge are used fairly loosely to refer to the total mass of sediment particles, or particles of a specified size range, passing a given cross-section in a specified or implied time period. The term sediment flux is given a more precise definition: the instantaneous or time averaged rate of sediment transport per unit area through a small element in a cross-section (units, kg/m²/s). It is, thus, a measure of the intensity of sediment discharge through a point on a given cross-section.

of obtaining a precise categorization of these three modes of sediment transport are apparent in the above 'definitions'. The characteristics of the three modes of transport are described more fully below. The principal methods of measuring their magnitude are also outlined.

Wash load 1.2

The most important characteristic of wash load is that, apart from small random variations, its concentration in the flow at a given location and time is uniform for all points on the cross-section. Thus, provided that the concentration of wash load particles can be determined at a single point on a given cross-section, an instantaneous value of the wash load sediment discharge through that section can be readily calculated as the product of the concentration and the mean flow discharge at the time of sampling. The flow discharge may be obtained either directly, using a current meter, or indirectly using an existing stage-discharge relationship.

The measurement of wash load concentrations presents some minor practical difficulties. In essence, the field work is extremely simple. A sample can be taken at any point in the cross-section; moreover, the sampling method is not critical. Thus, a hand-held bottle filled from the bank or from a boat provides an adequate sample for analysis. For a true wash load determination, however, the sample should contain no particles of bed material. Since, under normal flow conditions, the concentration of suspended bed material particles at the water surface is very low this condition is generally ensured by taking a surface sample. Nevertheless, it may be necessary in some situations to remove bed material particles from the sample before the concentration of wash load particles is determined. One way in which this may be done is by sieving out particles larger than a given size. Attempts have, therefore, been made to link wash load with a specific range of particle sizes. As yet there is no concencus as to whether this can be achieved within the general 'definitions' of wash load given above although most writers assume that wash load largely comprises the silt and clay fractions (all particles less than, say 63µm). The only reliable method of providing a continuous record of wash load sediment discharge is by a continuous programme of sampling since wash load is supply dependent and, therefore, cannot be correlated with other hydraulic parameters such as river stage. For this reason various automatic sampling systems have been developed which are capable of obtaining samples at specified intervals. Such systems require ready access to laboratory facilities capable of analysing large numbers of samples.

The use of turbidity monitors provides an indirect method of measuring wash load which is of particular benefit in remote areas where access to laboratory facilities is difficult. In addition, since the output can be recorded in digital form by a data logging device, continuous automatic operation is possible. Thus, provided that adequate precautions are taken in the calibration and operation of such monitors, a continuous record of sediment concentrations can be obtained. The principal difficulty in the use of turbidity monitors is that the calibration is sensitive to particle size. In practice this is advantageous for recording wash load by itself because, as Fish (1983) has shown, turbidity monitors are virtually insensitive to sand particles unless their concentration is very high. Thus, provided that the monitors are located in a part of the flow where suspended sand concentrations are low, an indication of wash load concentration may be obtained. Fish (1983) provides practical details of the calibration and use of turbidity monitors.

Suspended bed material load 1.3

In contrast to wash load particles, suspended bed material particles are not uniformly distributed across a given cross-section of the flow: variations in sediment concentrations occur in both the vertical and horizontal directions. In the vertical direction concentration profiles occur which show maximum values close to the bed falling to small or negligible values at the water surface (see Figure 2a). The difference between the maximum and minimum concentration in a given profile depends, amongst other factors, on the particle sizes present. For this reason, it is generally preferable to record the concentration of separate size fractions rather than the total concentration of suspended bed material. However, to do this would require a sampling method which could provide a sufficiently large sample, from a selected point on the crosssection, for accurate particle size analysis to be undertaken. Moreover, samples would be required at a sufficient number of points to enable concentration profiles to be drawn in both the horizontal and vertical directions. The difficulties of undertaking such a comprehensive programme of sampling on a regular basis and of undertaking the laboratory analysis of the samples obtained are considerable. Few programmes have, in practice, achieved these objectives.

The different types of sampling device which have been developed for measuring suspended bed material transport rates are described in various references; see, for example, Graf (1971), p 368-379.

The simplest category of sampler is the instantaneous sampler. A device of this type encloses a volume of water at a selected location and allows it to be withdrawn from the river without contamination or loss for subsequent analysis. Such samples can give reliable values of sediment concentration if the sampler has been carefully designed. The sediment discharge can be calculated from velocity data obtained by using a current meter at the same location. The principal difficulty in using instantaneous samplers is that the sample size is generally small (typically 1-2 litres). Since the concentrations of sand particles in various size fractions are, in most cases, relatively small, accurate particle size analysis based on such samples is difficult to achieve. Also, the values of sediment concentration obtained will show fluctuations due to the effects of turbulence in the river. Multiple sampling would be necessary if a representative mean value were required.

The alternative category of sampler is the integrating sampler. The principle of such samplers is that the flow enters in a controlled manner through a restricted opening or nozzle. The sample is, therefore, taken over a period which typically varies from a few seconds to several minutes depending on sampler characteristics and flow conditions. In the majority of cases the sampler is designed to ensure that its intake velocity is equal to that of the river flow at the selected location. Such samples may be used in one of two ways. A point-integrated sample is one which is obtained by operating an integrating sampler at a single point in a cross-section. The sampler has a valve system to enable it to be lowered to the required position before sampling begins and to be sealed, once sampling has ceased, before being raised to the surface. Provided that the intake velocity is equal to the stream velocity the sample will provide a direct measure of the mean sediment discharge at that point during the sampling period without the need to measure stream velocity. A minimum sampling period of about a minute would be necessary to eliminate the effect of turbulent fluctuations, see Sub-Committee on Sedimentation (1963), p 50. A depth-integrated sample is one which is obtained by lowering an integrating sampler at a constant rate through the flow. The sampler may be immediately raised once the bed is reached, again at a constant rate, thus avoiding the need for the provision of a valve system in the sampler. The sample obtained comprises the sediment discharged during equal time intervals at each level in the flow. It therefore provides a measure of the total sediment discharge through the vertical section during the period of sampling. The mean discharge rate through the vertical may be calculated from the mass of sediment collected and the mean sampling time. However, since the intake velocity may not equal the stream velocity, due to the vertical component provided by the motion of the sampler, it is usual to determine the mean flow velocity in the vertical by current meter and to multiply it by the concentration of sediment in the sample to obtain the sediment discharge rate. A depth-integrating sampling procedure reduces the number of samples to be analysed since only one sample per vertical is required. On the other hand the sampling interval at a given elevation on the vertical is short. As a result, concentration fluctuations due to turbulence in the river are not eliminated and repeat samples may be necessary. Moreover, the results do not allow concentration profiles for different particle size-fractions to be obtained.

As with the majority of instantaneous samplers the principal disadvantage of integrating samplers is the small size of sample obtained. In addition, the limitations of various types of sampler, particularly in respect of the flow conditions and depths in which they will operate, together with certain practical considerations of their operation restrict the sites in which they can be used. A variation of the typical integrating sampler has been developed to overcome the first of these problems. In such samplers, of which the Delft bottle is an example, the sample passes from the intake nozzle into a wide

4

chamber where the reduction in velocity causes sediment particles to settle out allowing sediment-free water to be discharged. In this way sediment from a much larger sample of water can be collected. In general the water does not remain sufficiently long in the sampler for wash load particles to settle out and it is, therefore, not necessary to make a separate calculation of wash load if suspended bed material load by itself is required. However, as with other integrating samplers, the accuracy of the result relies on several important assumptions about its mode of operation and extensive laboratory tests are required to validate any results obtained. In the case of the Delft bottle it has been found that its efficiency in trapping suspended sediment is a function of both particle size and hydraulic conditions. It is, therefore, necessary to apply suitable correction factors to the results obtained.

Pumped sampling can be regarded as a variation on the technique of integrated sampling. In a pumped sampler an intake nozzle extracts a sample from the flow at a known location and in a controlled manner. A pump draws the sample from the nozzle to a container in which it is collected for analysis or to a filter unit through which it is passed. The system is, therefore, far more versatile than other integrating samplers and, in particular, samples of almost any size can be collected if required. It is for this reason that Hydraulics Research, Wallingford, has employed pumped sampling techniques in many of its investigations of suspended bed material transport rates in rivers and estuaries over the last decade. Further details of the technique are presented in Sections 2.2 and 2.3. The procedure for calculating suspended bed material flux from the results of a sampling programme is described in Sections 3.1-3.6.

Since the rate of transport of suspended bed material is governed by hydraulic processes the results of a sampling programme over a limited period may be used to investigate the form of the relationship between sediment discharge and other known variables so that estimates of sediment discharge over longer periods can be made from records of those variables. Such a procedure is described in Section 3.9

Bed load 1.4

Of the three categories of sediment transport under consideration the measurement of bed load presents the greatest difficulties. The problems arise partly from ambiguities in the definition of bed load and partly from the practical difficulty of investigating processes which are occurring within a few particle diameters of the river bed. A number of practical difficulties, related to these basic problems, are likely to be significant in any programme of field measurements. Firstly, it is very difficult to assess the degree to which the presence of a sampler disturbs the bed load transport processes. Secondly, many samplers trap not only bed load but also some suspended bed material load or stationary particles scooped from the channel bed. Thirdly, the presence of bed forms affects certain types of sampler by preventing them from lying in a horizontal position in contact with the bed. Forthly, where

bed forms are present the rate of bed load transport varies in a longitudinal direction across the profile of the bed form and, therefore, care must be taken to ensure that samples taken represent the mean rate of transport. Fifthly, the position of the bed may undergo dramatic changes during the passage of a flood, either in a lateral or vertical direction, which complicate bed load measurements. Sixthly in bed load transport the velocity of particles is likely to be smaller than that of the surrounding fluid. For this reason it is incorrect to determine the transport rate from the product of sediment concentration and flow velocity. Finally, bed load transport need not be limited to the top layer of particles on the bed; there may be a slow downstream movement of other particles lying deeper within the bed. Descriptions of different types of bed load sampler and discussions of their specific limitations may be found elsewhere; see, for example, Graf (1971), p 358-368.

It is beyond the scope of the present paper to discuss the methods of bed load measurement in any further detail. It is intended that the methods of sediment discharge measurement described in this paper should be applied only where the bed load transport rate is small relative to the total load. In qualitative terms, significant values of bed load discharge are likely to be associated with the following factors: low values of suspended bed material discharge; large sizes of bed material, say, mean diameter greater than 2mm; uniform discharges in which flood surges do not carry a significant proportion of the annual total; and flow in wide shallow channels in which turbulence is low. In quantitative terms, estimates of the rate of bed load discharge may be widely varying and, in many cases, meaningless. The calculation of order of magnitude values from 'total load' estimates based on two well known sediment transport formulae is described in Sections 3.7 and 3.8, but such results require careful interpretation.

Practical considerations in the selection of methods for sediment discharge measurement 1.5

In view of the difficulties involved in measuring sediment transport rates in natural channels and the considerable expense involved in undertaking elaborate programmes of sediment transport measurement it is important that careful consideration be given to the objectives of any field investigation before its implementation. Ideally, one might first wish to determine what level of accuracy would be tolerable in the results if they are to be used for a given purpose and to select a sampling procedure which would meet this requirement. Unfortunately, sediment sampling methods have not been studied in sufficient detail to provide a quantitative assessment of their accuracy. The sampling efficiency of many different types of sampler have been tested in laboratory flumes but the results of such tests may not be applicable under the more

varied conditions found in natural rivers. In addition, the problems of using a finite number of measurements to predict the sediment discharge across an entire cross-section, including the region close to the bed, and to predict sediment discharge over a continuous period prevent reliable estimates of the level of error from being made. Compared with other hydrological and hydraulic parameters the level of error in measuring and estimating sediment transport rates is, in any case, likely to be high. For example, in comparing the use of sediment transport formulae for the estimation of sediment transport rates from hydraulic parameters, against measured sediment transport rates over a variety of flow conditions, White, Milli and Crabbe (1973) found that, even with the most reliable formula tested, the ratio of calculated to observed values lay outside the range 0.5 to 2.0 for over 30% of their data.

Although optimization of sediment discharge measurement and calculation procedures based on quantitative assessments of error may not, at present, be possible, various qualitative factors could have a considerable influence over the choice of sampling method depending on the purposes for which the data are required. Practical reasons for which sediment discharge data may be required include the following:

a) To predict rates of reservoir sedimentation

Loss of capacity due to sediment accumulation may pose a significant hazard to the future operation of a reservoir project. In order to assess the hydrological changes caused by sedimentation and to evaluate the economic costs of resulting changes in the output of a project, it is necessary to determine the mean rate at which such loss of capacity is occurring. Measurements of sediment transport rates in tributary rivers, undertaken for this purpose, should provide information on sedimentation rates and also identify the principal sediment source areas. Measurements can be restricted to those particle sizes which would be deposited in the reservoir. Thus, in certain cases where the trap efficiency of the reservoir is low, it is adequate to monitor the suspended bed material and bed load transport rates. In other cases, where the large capacity of the reservoir ensures that a high proportion of sediment particles are trapped, measurement of wash load is also required. Indeed, if initial investigations indicate that bed load and suspended bed material load together represent only a small proportion of the wash load, even at high flows, the accurate determination of wash load becomes paramount. Under whatever conditions, the accuracy required of the sampling programme will depend on the rate at which sediment accumulation is occurring in the reservoir and the magitude of the economic cost which such loss of capacity represents.

b) To determine rates of catchment erosion

Detailed information about rates of soil erosion from specific catchments is required in order to assess the factors which

influence agricultural productivity and environmental conservation and to identify areas of particular erosion hazard. For this purpose it is desirable to monitor the total sediment discharge from a given catchment using techniques similar to those applied to the measurement of sediment inflow to reservoirs with high trap efficiencies. Thus, as indicated above, it is sufficient, in certain cases, simply to measure the wash load if this is known to constitute the bulk of the discharge. In other cases bed load and suspended bed material load must also be measured. Unfortunately, it is rarely possible to relate rates of catchment erosion directly to economic factors and it is, therefore, difficult to provide economic justification for undertaking an elaborate sampling programme for a catchment investigation. Nevertheless, the results of such work may be of far-reaching importance in regions in which accelerated erosion would threaten the future livelihood of large populations.

c) To provide information about channel morphology

Knowledge of the morphological behaviour of alluvial rivers is required when river regulation for flood control or navigation is undertaken or in the design of engineering structures such as bridges. For these purposes, measurement of wash load will be unnecessary but accurate measurements of bed load and suspended bed material load should be made. Field investigations will be designed, primarily, to obtain sufficient information to provide a reliable basis for calibrating any numerical or physical models of the channel behaviour which may be undertaken. The cost of such investigations can frequently be included within the budget of a specific project.

2 The measurement of suspended bed material load using pumped samplers

Selection of suitable gauging stations 2.1

In any programme of sediment sampling in a river the choice of gauging station has an important effect on the results obtained. Since in the measurement of sediment discharge the distribution of flow velocity is important, guidelines for the selection of liquid discharge gauging stations are relevant, see ISO 748 (1979). However, because sediment concentration profiles are very sensitive to unsteady flow conditions, even greater care must be taken in the selection of the site than for a liquid discharge gauging station. The principal factors to take into consideration in the selection of a suitable gauging station are as follows:

a) The gauging station should be located at a point where the flow is uniform and unidirectional, that is, in a straight section of the river. For liquid discharge gauging stations it has been suggested that the channel should be straight for a distance of at least five channel widths upstream of the station and two widths downstream, see USDA (1979) p 171. For sediment gauging these distances should probably be increased by a factor of two or three to ensure that stable concentration profiles have been fully developed. Thus, ideally, in a river 10m wide, a straight channel reach over 150m long would be required. In practice this may be difficult to achieve.

b) A straight channel reach is required not only to enable accurate current metering to take place and to ensure that the concentration profiles are fully developed but also to enable accurate measurements to be made of the water surface gradient. This parameter is important in defining the hydraulic characteristics of the channel for theoretical analysis. A realistic value of water surface gradient can only be obtained if the channel is straight, free from constrictions such as bridge piers and free from rapids, jumps or sills. Water surface gradient is measured either directly using an engineer's level and staff or by recording the difference in elevation of two accurately levelled gauge posts positioned a known distance apart along such a reach. Since, by these methods, elevation can only be read to the nearest 5mm, a difference between upstream and downstream levels of over 50mm would be required to give an error of under 10%. Thus, if the mean gradient is, say 500 x 10^{-6} (0.05%), the horizontal distance between the measuring sites must be at least 100m to provide this level of accuracy.

c) The sediment sampling site should not be immediately downstream of a major tributary or of an area of bank erosion since in either case large inputs of sediment may occur which, for a considerable distance downstream, would be unevenly distributed in the flow.

d) The cross-section at which sampling takes place should have a uniform shape and should not contain excessive growths of vegetation either at the banks or in the channel.

e) In the past it has been recommended that natural reaches of turbulent flow or artificially created turbulent flumes be used for sediment measurements because the turbulence throws bed load particles into suspension thereby making it unnecessary to determine separately bed load discharge and suspended bed material discharge. This procedure has a number of disadvantages and cannot be generally recommended for present purposes. Firstly, although bed material particles will be in suspension they will not be uniformly distributed so that the labour of sampling at various levels in the vertical and of computing the total discharge is not reduced. Secondly, because the flow is very turbulent, sampling times must be increased to obtain mean values of concentration. Moreover, the possibility of introducing significant errors by calculating sediment flux as the product of mean velocity and mean concentration at a given point is increased. Thirdly, there may be a significant concentration gradient along the principal direction of flow in which case it would no longer be correct to ignore this factor in the general equation of sediment continuity which forms the basis of sediment discharge calculations, see Section 3.1. Finally, it is unlikely that a reliable value of the water surface gradient can be obtained for a short turbulent reach of channel.

f) Although all the above considerations are important in the selection of sediment sampling sites, it is likely that two practical considerations will overshaddow these in the final choice of location. Firstly, it is of considerable advantage to use an established river gauging station not only because various items of equipment will already be deployed and the discharge relationships will have been studied but also because the hydrological records which have been collected will be used in the interpretation of the results of the sediment monitoring programme. Secondly, whether or not an existing station is used, accessibility will be an important factor to consider especially if large numbers of samples have to be transported from the station to a laboratory elsewhere.

The principle of pumped sampling is straight forward. A nozzle is introduced into the river flow at a predetermined position. This nozzle is connected by a pipe to a suction pump which, when operated, draws water through the nozzle at a constant rate. The required volume of the sample is collected at the outlet of the pump. To sample at different points on a cross-section a single nozzle may be moved between the points or, alternatively, a number of nozzles may be used each in a fixed location. Pumped samples have been used to provide small bottle samples at regular intervals using an automated system. The chief advantage of pumped samplers, however, is their ability to provide large samples from which reliable values of sediment flux for different sand sized particles can be obtained. Since large samples are difficult to transport it is preferable to filter the sample in the field or, at least, to allow the sample to stand long enough for the sand to settle out of suspension in order that the bulk of the water can be decanted back into the river.

The following outline illustrates a possible sampling procedure using a filter, comprising a large container whose base is formed by 60μ m nylon mesh* suitably supported from below:

- a) Attach the pump to the tube leading from the nozzle and begin pumping. If the pump being used is not self-priming or the lift is too great for self-priming to occur an alternative method of priming may be required, see Section 2.3.
- b) Allow the pump to run for a minute or so to flush traces of previous samples from the system and to establish uniform flow in the pipe. During this time the sample runs to waste.
- c) Introduce the filter into the sample stream to collect the sediments and, at the same time, start timing with stop watch A.

Sediment sampling using pumped samplers 2.2

^{*}Strictly speaking 63μ m mesh should be used but nylon mesh of this gauge is not commercially produced in the UK.

- d) Continue to collect the sediment until a sufficient quantity has been obtained. The time for this will depend on the mean sediment concentration in the stream as well as the depth of sampling — samples taken closer to the bed having higher concentrations than those near the surface. Sampling is likely to continue for at least five minutes.
- e) While the sediment collection is proceeding, measure the rate of pumping using a container of known capacity and a second stop watch, B. A discharge measurement should be made in this way two or three times during sampling and the mean value obtained. Together with the total sampling time, from stop watch A, this mean pumping rate will provide a value of the total volume of water passing through the filter. This, in turn, provides values of sediment concentration from the mass of different particle sizes collected on the filter.
- f) Also while the sediment collection is taking place collect bottle samples of the filtered water for subsequent analysis in a laboratory to determine the wash load concentration.
- g) If possible, a current meter should be positioned in the flow adjacent to the intake nozzle in order that the mean stream velocity during the period of sampling can be measured. If this is not possible, an estimate of velocity can be obtained by other means, see Section 3.3.
- h) Carefully transfer the collected sediment from the filter to a sample container for transport to the laboratory. If necessary the particles should be flushed with clear water from the filter to the container to ensure that none are left on the filter. The sample containers, together with the bottles containing filtered water for wash load analysis, must be clearly labelled and adequately sealed to ensure that the results can be identified correctly and that no part of the sample is lost in transit.

Technical and practical considerations in pumped sampling 2.3

Although in outline the above pumped sampling procedure is straight forward a number of technical and practical difficulties arise which must be fully considered if such a programme is to provide useful results:

a) The velocity of flow in the pipe should be sufficiently high to prevent particles from falling out of suspension along horizontal sections of the pipe. For a given size of pipe the velocity required depends on the concentration of sediment and, to a lesser extent, on the size of particles being transported. Experimental work reported by Crickmore and Aked (1975) suggests that with 13mm diameter pipe, provided the line velocity exceeds 1m/s, no sediment deposition will occur. Their tests were, however, limited to particle sizes below 0.3mm and concentrations below 600ppm by weight. If larger particle sizes or, more importantly, higher concentrations than these are being sampled it may be necessary to consider whether higher line velocities should be used. Similarly, if larger pipe diameters are to be used a higher line velocity may be required.

b) The filter should be sufficiently large to pass the sample volume at the pumping rate selected even when the filter has collected an appreciable quantity of sediment. If this is not possible it will be necessary either to introduce a pressure filtration system or to store the whole sample in a barrel for subsequent filtration or until particles have settled out of suspension.

Care may be necessary in choosing the type and position C) of the pump to be used. For a given pipe diameter the pumping rate needed to produce a line speed of over 1m/s is readily calculated. For example, using pipe of internal diameter 13mm a pumping rate of just under 150 x 10^{-6} m³/s, that is 9 1/min, gives a line speed of over 1m/s. From pump characteristics data supplied by the pump manufacturer the maximum head over which a given pump can produce this discharge can be found. In most cases, however, the pump will be capable of operating over a greater head as a force pump than as a suction pump since, in suction, the pump is limited to a maximum pressure of one atmosphere. This limitation, rather than the pump capacity, generally provides the principal constraint in the design of a pumped sampling system. Thus, in any system, the maximum suction head which can be provided is less than 10m. This includes both the static head, the difference in elevation between the lowest river level and the pump, as well as the head loss due to friction in the pipe. For PVC pipes of about 20mm internal diameter the friction head loss is likely to be over 0.1m/m at line speeds above lm/s. If calculations indicate that a pump working in suction cannot provide the necessary lift and flow rate it will be necessary to use submerged pumps located near the nozzle. These also overcome another problem which arises with suction pumps, that of priming the pumps at the start of each sampling period. Even with self-priming equipment it is sometimes necessary to provide an auxillary hand-operated vacuum pump to fill the sampling pipe with water when the total head to be overcome is large.

d) It has always been considered that an important factor in the design and operation of depth and point integrating samplers is to ensure that the intake velocity of the sample through the nozzle is equal to the stream velocity. If this is achieved it eliminates the need to provide a separate measurement of stream velocity since this can be calculated from the sample volume, nozzle diameter and sampling time. It has also been suggested, see Nelson and Benedict (1951), that unless the two velocities are similar the samplers will not provide reliable values of sediment concentration. The reason for this is that sampling at a velocity other than the stream velocity causes streamlines to curve either inwards or outwards in the vicinity of the nozzle. Larger particles fail to

follow these streamlines with the result that if the intake velocity is lower than the stream velocity the concentration of larger particles in the sample is greater than in the stream and if the intake velocity is higher their concentration is lower than in the stream. In respect of pumped sampling, Crickmore and Aked (1975) found that even with large differences between the intake and stream velocities the effects of sediment concentration are insignificant. On this basis they concluded that neither intake velocity nor nozzle orientation are critical for accurate pumped sampling. This conclusion enabled them to adopt a relatively simple sampling procedure without the need to match the sampling rate to the measured stream velocity at each location. However, the results on which this conclusion was based were obtained from flume tests performed on sediment with a maximum particle size of 0.25mm. It is unlikely to be true for particle sizes significantly larger. On the other hand, the sampling characteristics of a given nozzle can be assumed to be consistent so that, provided the sampling efficiency for different particles sizes has been examined in the laboratory under different stream and intake velocities, it would be possible to derive a set of coefficients which could be applied to measured concentrations of given particle sizes in order to obtain their true concentration.

In many cases the principal difficulties in undertaking e) sediment discharge measurements by pumped sampler arise in the design of apparatus for introducing the nozzles into the river flow. Standard apparatus for current metering based on wading rods, cableways or boats, as appropriate, can be adapted for such work. However, the need for a shore-based pump, when using hand-held wading rods or cableways, calls for long pipe runs and carefully co-ordinated operation. In this respect the use of a boat may be preferable provided that onboard pumping and filtration can be achieved. In deep fastflowing rivers, where current metering would normally be undertaken by cableway or boat, the size of ballast weight to use with a pumped sampling nozzle would be rather larger than that used with a current meter by itself. The reasons for this are that the pipe from the nozzle increases the stream's drag on the apparatus and that with pumped sampling it is even more important than with current metering that the suspension cable should be as near as possible to the vertical in order that the height of the nozzle above the bed can be accurately determined. To overcome the difficulty of accurately positioning a nozzle and current meter within a few centimetres of a river bed different designs of 'bed frame' have been developed. These are open structures, resting on the bed and positioned using a boat mounted winch. Nozzles may be rigidly attached to the frame or to a motor driven carriage which can be raised and lowered between the bed and the top of the frame. The principal disadvantages of such frames are their weight, the difficulty of manipulating them from a boat and the possibility that, unless carefully designed, the frame will disturb the flow pattern in its vicinity. For sediment discharge measurements at a single site a further possibility

is to use a permanent structure fixed in the bed of the river. Such structures may be used in rivers which experience marked seasonal differences between low flow and high flow conditions; the installation could take place in the dry season and, provided that the structure has been adequately designed, samples could be obtained even in peak flood conditions when sampling from a boat would be hazardous if not impossible. The disadvantages of fixed structures are that nozzles can only be located in a relatively small number of predetermined positions, most probably in a single vertical section, and that there are considerable problems in designing a structure which can withstand the forces of drag and debris impact which arise in peak floods without modifying the nature of the river bed during construction or causing local regions of scour to occur in floods. As with bed frames, the influence of the structure on the hydraulic behaviour of the river must be considered.

A more fundamental difficulty arises in the use of fixed f) structures for the measurement of sediment discharge. In laterally constricted alluvial channels dramatic changes may occur in the elevation of the bed during the course of a flood. Leopold, Wolman and Miller (1964), p 228-230, recorded bed scour of the order of 2m in the Colorado and San Juan rivers as a result of flood discharges and indicated that far higher values occur in some rivers. However, there is no theoretical method currently available of estimating what the extent of the scour might be at a particular site. For this reason, previous records of channel behaviour in floods would be of considerable value in designing a sediment sampling structure. Consideration of the effects of scour and deposition is necessary not only in the design of the structure but also in the interpretation of the results obtained since the calculation methods described below require that the distance of the sampling nozzle above the bed be accurately known. In such circumstances it may be necessary to install an echosounder on the structure to record the local elevation of the bed. This would also provide information about the movement of bed forms (ripples, dunes and antidunes) along the channel if a sufficiently accurate system were used.

3 Procedures for calculating sediment discharge values from the results of a pumped sampling programme

Theoretical considerations 3.1

In all standard procedures for calculating sediment discharge values from field data it is customary to apply two important simplifications to the general equation of sediment continuity in the channel. Firstly, it is assumed that a steady state condition has been reached; that is, that at the selected cross-section concentration and sediment flux values are not varying with time. Clearly, these values do vary with time but the rate of change is generally considered to be small and to have a negligible effect on sediment discharge calculations. This assumption will be invalid in rivers which carry heavy sediment loads in short duration floods but even in such cases the errors introduced by neglecting temporal variations may be small compared with those which arise because of the difficulties involved in undertaking any form of sampling under such conditions. Secondly, it is assumed that the concentration gradient in the direction of flow is negligible. As indicated above, this assumption depends in part on the selection of the sampling station. In situations in which steady state conditions cannot be assumed to apply there may also be a significant concentration gradient along the stream.

The motion of sediment particles in a river is generally described by a single equation of continuity in the direction of the flow. Particles will, in reality, be continuously settling to the bed. However, under the two foregoing assumptions, the removal of particles should be exactly matched by their replacement as a result of turbulent eddies which carry fresh material from the bed into the flow. Yet even in 'steady state' conditions, the flow velocity and sediment concentration at a specific location will show short term fluctuations due to turbulence. These fluctuations add further complications in the computation of sediment flux. The effects are shown algebraicly below.

Consider the water and sediment passing through a small element, on the cross-section under study, and having instantaneous velocity v and instantaneous sediment concentration, c (mass per unit volume). It is assumed that the water and sediment particles travel at the same velocity, an assumption which is unlikely to be valid close to the bed. The instantaneous sediment flux, s, per unit area, passing through the element is given by:

s = v.c

Writing velocity_and concentration as their time averaged mean values, v and c, together with a varying turbulent component, v' and c', the instantaneous sediment flux is given by:

$s = (\overline{v} + v')(\overline{c} + c')$

Integrating this expression over time to obtain the mean sediment flux through the element gives:

$\overline{s} = \overline{v} \cdot \overline{c} + \int (v' \cdot c') dt + \overline{c} \cdot \int v' dt + \overline{v} \cdot \int c' dt$

By definition the last two integrals both equal zero. However, the integral of $v' \cdot c'$ with respect to time is likely to have a non-zero value unless the fluctuations in velocity and concentration are exactly in phase with each other. Unfortunately, it is not at present possible to measure the fluctuations which occur in a natural river with sufficient accuracy to quantify the integral although, in many cases, it is thought to be relatively small. For this reason, most writers consider it to be sufficiently accurate to calculate the steady state, time averaged, sediment flux through a small element as:

 $\overline{s} = \overline{v} \cdot \overline{c}$

This expression, which is widely used as the basis for sediment flux calculation procedures, depends on the various assumptions indicated above whose effects cannot, at present, be quantified. In the absence of further information it will also be used in the present paper.

Consider, next, a vertical element in the chosen crosssection of unit width and of height, d, (the flow depth). Within this element the value of \overline{s} varies with the distance, y, from the bed of the channel. The total sediment load, \overline{S} , passing through this element, on the same assumptions as above, is given by:

$\overline{S} = \int_{y_{min}}^{d} \overline{v} \cdot \overline{c} \, dy$

It should be stressed that it is the product of velocity and concentration which is integrated. The mean velocity, obtained by integration of velocity over depth, is readily calculated from the results of current meter measurements but to attempt to use this value to calculate sediment load by multiplying it by the mean concentration and depth is incorrect*. Procedures by which S can be calculated are described in Sections 3.3-3.5. Using pumped sampler measurements it is preferable, although not essential, to consider the sediment load in different particle size fractions. The manipulation of field data to separate the particle sizes is, therefore, described in Section 3.2.

So far the calculation procedures described have been applicable only to the calculation of the sediment load per unit width through a single vertical on the chosen cross-section. In an initial pumped sampling programme it may be necessary only to sample in a single vertical in order to provide information about the relative magnitudes of the different modes of transport. However, if a more precise evaluation of the total load is required measurements will be required in several verticals since significant changes in sediment flux are likely to occur across the cross-section. It is beyond the scope of the present paper to discuss the number and location of additional sampling verticals since this will depend on the specific characteristics of the cross-section under study and the degree of accuracy required in the result. Further work is required before such recommendations can be made. Where a single vertical is used the value of its results for predicting the total sediment load in the cross-section will be enhanced if the section is of fairly uniform depth with steep banks and if the chosen vertical is located within the middle third of the section.

*Such a procedure would be correct if the mean concentration were obtained by using a depth-integrating sampler as described above. The reason for this is that such devices produce a sample with a "discharge weighted" mean concentration as opposed to the "spatially weighted" mean concentration which is obtained by integrating concentration over depth.

Separation of particle size fractions 3.2

The proposed sampling procedure requires consideration to be given to separate particle size fractions. The principal division to be made is between sand particles (> 63μ m) and silt and clay particles ($< 63\mu$ m). Samples of the material passing through a 63μ m sieve are analysed to give the silt and clay concentration. It has been assumed that this represents wash load and is uniform across the flow. The assumption may be verified by comparing the concentrations obtained at different nozzle locations and, if found to be valid, a single mean value of silt and clay concentration may be calculated from all the bottle samples obtained on each sampling occasion, see Form Pl. This value should be used to verify simultaneous turbidity measurements in order that future discharges of wash load can be based on a continuous turbidity record and a continuous record of liquid discharges. To calculate the daily discharge of wash load, mean concentration readings are obtained from the turbidity record at, say, hourly intervals. Mean river gauge levels at the same intervals are obtained, using an automatic chart recorder, and from these the liquid discharges may be calculated using a previously determined stage-discharge relationship. The discharge of wash load, in a given interval, is then calculated as the product of corresponding values of mean concentration and mean liquid discharge. The results are integrated over a twenty-four hour period to provide a value of the daily discharge of wash load. It should be noted that the choice of time interval has a major influence on the accuracy of the final result. Where concentrations and discharges are rapidly fluctuating it may be necessary to adopt an interval shorter than an hour whereas in more stable conditions longer intervals may be adequate. Trial calculations will assist in choosing the appropriate interval in a given situation.

The proposed procedure also requires the separation of different sand fractions, see Forms P2 and P3. For each position of the sampling nozzle in a given vertical the concentrations of separate sand fractions are calculated by dividing the dry mass of particles of each size fraction by the total volume of the sample. These values are used to produce concentration profiles for the calculation of sediment flux values in a given vertical as described below. However, in order to obtain these sediment flux values a velocity profile in the vertical is also required.

Determination of velocity profiles 3.3

When pumped sampling is being undertaken from a boat or cableway it is relatively simple to fix a current meter close to each nozzle intake position and thereby obtain a direct measurement of the time averaged velocity at each depth sampled. Such values may be used directly to calculate the sediment flux at each depth, see Form P3, or may be plotted as a velocity profile for graphical analysis as described below. However, in strong flow where it has been decided to locate sampling nozzles on fixed structures which remain submerged for long periods it would not be practicable to attach current meters since access for inspection and maintenance, especially during the highest floods, would be impossible. In such cases it might be possible to measure velocity head by using the sampling nozzles as Pitot tubes although care would be needed to ensure that misalignment of the nozzles or increased fluid densities caused by high sediment concentrations did not lead to spurious results. Alternatively, velocity profiles can be derived from theoretical considerations. The velocity distribution generally adopted is a log-normal relationship based on the Karman-Prandtl equation for velocity distribution in a vertical for steady flow in a broad straight channel over a rough bed. This gives the time averaged velocity, \overline{v} , at distance y above the bed, as:

$$\overline{v} = \overline{v}_{mean} + \frac{v_{\star}}{k} [\ln (y/d) + 1]$$

where

 $\overline{v_{mean}}$ is the mean of \overline{v} over the depth;

 v_* is the 'shear velocity' = $(g.d.i)^{\frac{1}{2}}$;

i is the water surface gradient; and

k is the Von Karman constant = 0.4.

This equation has been found to provide good correlations with observed velocity distributions in relatively clear flow under a wide variety of conditions although significant differences have occurred in certain cases*. Furthermore, the equation cannot be applied close to the bed since it gives $\overline{v} =$ 0 at a finite distance, y_o, above the bed and increasing negative values of \overline{v} if y values less than y_o are used. Nevertheless, for the purposes of the present calculations the introduction of more complicated functions would not be justifiable.

The procedure by which a velocity profile is obtained from the Karman-Prandtl equation is as follows.

- a) From the stage-discharge relationship for the gauging station the total discharge, Q, corresponding to the observed gauge reading, is calculated.
- b) From the cross-sectional profile of the station, see Figure 1, the cross-sectional area, A, of the flow at the observed gauge reading is measured.

*The presence of sediment is known to affect the proposed log-normal relationship, see Yalin and Finlayson (1972), but the extent to which such changes would affect the calculated sediment flux values for a given sediment concentration profile cannot at present be fully determined. It is, therefore, assumed that the effect can be ignored except close to the bed.

- c) The mean velocity, V, through the section is calculated as Q/A. It is assumed that this value may be used as the value of $\overline{v_{mean}}$ in a vertical located towards the centre of the river provided that the section is sufficiently wide and uniform.
- d) The value of v_* is computed from the depth and surface gradient of the flow.
- e) For selected values of y the corresponding values of \overline{v} can now be calculated using the equation above. If the values of y used are identical to those at which sampling nozzles are located the calculated velocities can be recorded on a single table alongside sediment concentration values, see Form P3.

Preparation of sediment flux profiles 3.4

The calculation of sediment discharge rates from the results of a pumped sampling programme is best undertaken by a combination of graphical and numerical methods as illustrated by Form P3, and Figures 2, 3 and 4. Figure 2c shows a typical profile of time averaged sediment flux values, \overline{s} , obtained by multiplying time averaged concentrations, \overline{c} , Figure 2a, with time averaged velocities, \overline{v} , Figure 2b, at each depth. In general it is not necessary to draw the concentration and velocity profiles since the sediment flux profile can be derived directly from data on Form P3. However, sediment flux profiles are required for each particle size fraction greater than $63\mu m$, see Figure 4.

A major problem in deriving total sediment discharge rates from sediment flux profiles is the difficulty of estimating sediment flux values below the lowest level at which sampling has occurred. Sediment concentrations increase very rapidly with decreasing values of y and reach the limiting value corresponding to loose-packed sand grains at the bed itself. At the same time, decreasing values of y produce decreasing velocities which fall to zero when the bed is reached. The product of the two parameters gives rise to a sediment flux profile which has a maximum value close to the bed but falls to zero within the bed itself. Whether sediment flux is zero at y = 0, however, depends on the chosen definition of the datum for the y axis. The choice of a suitable datum is complicated both by the bedforms which are present and by the movement of particles beneath the top layer of the bed. Thus, if sediment flux has been measured to within 0.3m of the bed, as in Figure 4, there are considerable problems in predicting its form between this level and the bed. Because of the rapid changes which occur in sediment flux in this region it would be most unwise to attempt to extrapolate the curves of Figure 4 by eye. The following analytical approach is offered as a sounder basis for extrapolation despite its significant shortcomings.

a) It is assumed that the velocity profile adheres to the Karman-Prandtl equation in the region of extrapolation. Thus, if velocities have been measured directly, the available data may be plotted on log-linear axes, see Figure 3b. On these axes the Karman-Prandtl equation results in a linear plot so that a straight line fitted to the measured data can be used for extrapolation. Where velocities were not measured directly but were computed following the procedure in Section 3.3. that same procedure may be used to obtain addition values closer to the bed. There are limits to how close to the bed the Karman-Prandtl equation may be applied. Firstly, as mentioned above, the equation is physically unrealistic close to the bed since it gives negative velocities below a certain level, y. $(y_{o} = 0.5 \text{mm} \text{ in the case of the data given in Figure 3b}).$ Secondly, the equation is valid only for clear water. Significant deviations from predicted velocities are likely to occur in the heavy sediment concentrations close to the bed. Thirdly, close to the bed sediment particles will not be travelling at the same horizontal velocity as the water with the result that the sediment flux cannot be calculated using the stream velocity. (The point at which significant differences become apparent between horizontal velocities of sediment and water provides a possible boundary condition to distinguish bed load from suspended bed material load but it is not clear how this might relate to other 'definitions' of bed load. Moreover, the condition cannot be clearly defined, except in probabalistic terms. nor can it be readily measured in actual flow conditions). Finally, if bed forms are present the value of y at which this boundary occurs would vary with time as the bed forms move through the section.

b) Of the various empirical and theoretical formulae proposed to describe concentration profiles the most widely used is that based on diffusion theory. Unfortunately this theory does not enable absolute values of concentration to be computed but gives concentrations of particles of a given size relative to their known concentration $\overline{c_a}$, at a distance y = a from the bed, as:

$$\overline{c} = \overline{c_a} \left(\frac{d-y}{y} \cdot \frac{a}{d-a} \right)^Z$$

where

 $z = w/k u_*$ depends on flow conditions and particle size; and

w is the fall velocity of the sediment particles.

This relation gives a linear plot, on log-log axes, of (d-y)/y against \overline{c} , see Figure 3a. Again, the equation is not valid close to the bed since fall velocity is no longer independent of concentration at high concentrations and the differential equation for diffusion also becomes invalid close to a boundary. The equation has been compared with empirical data, for a minimum value of a = 0.05d, and has been found to give reasonably accurate results. This is generally taken as

the limiting value at which the theoretical relationship can safely be applied (for the data in Figures 2, 3 and 4, 0.05 d = 0.15m). To apply the relationship to field data a straight line is fitted to the data on a log-log plot and values of \overline{c} extrapolated for the required values of y. Since the theoretical curve is being used to extrapolate measured values it may be worthwhile studying alternative distributions to determine whether they would provide curves which fit the data as well or better than the one given above. In particular, there might be some merit in using the simpler relationship proposed by Lane and Kalinske (1942) which reduces to the form

 $\ln \left(\overline{C/C_a}\right) = -6z \left[(y/d) + a \right]$

The advantage of this formula, if it is found to fill measured values sufficiently closely, is that it gives a linear relationship when $\overline{c/c_a}$ (or simply \overline{c}) is plotted against y/d on log-normal axes. This is easier to plot than the previous expression. However, for illustrative purposes the previous expression is used in the diagrams and discussion within this paper.

c) If direct evidence is available on the mean height of ripples or dunes on the bed this may be used to define the safe limit to which velocity and concentration profiles be extrapolated. In all other circumstances the limit y = 0.05 d should be used initially. The sediment flux profile should be extended from the lowest measured level to this limit by extrapolation as described above. Values are obtained from graphs similar to those in Figure 3, recorded in the lower part of Form P3 and the calculated sediment flux values included on the profiles, see Figures 2c and 4.

Calculation of total sediment discharge in a vertical 3.5

The sediment flux profiles for different particle sizes should be integrated over y from the chosen minimum level, y_{min} , to y = d to provide the total discharge per unit width of each particle size within the vertical. These values, together with the previously calculated value for wash load discharge, are recorded at the foot of Form P3. The integration may be performed either by use of a planimeter or by numerical integration. A suitable method of numerical integration for the data of Figure 2c is as follows:

a) The depth over which the integration is to be performed is split into an even number of equal elements; for example, eight.

Integration depth = $d - y_{min} = 3.05 - 0.15$ = 2.90m

Height of one element, $\delta = 2.90 \div 8 = 0.3625m$

b) The points marking the boundaries between these elements are marked on the sediment flux profile and corresponding values of s are noted.

y(m): 0.15; 0.51; 0.88; 1.24; 1.60; 1.96; 2.33; 2.69; 3.05. s̄(kg/m²/s): 1.94; 1.03; 0.75; 0.55; 0.38; 0.27; 0.19; 0.14; 0.12 c) The integration is performed using Simpson's rule. If the values of \overline{s} are referred to as $\overline{s_1}$, $\overline{s_2}$ $\overline{s_n}$, the integral is calculated as:

$$\int_{y_{min}}^{d} \overline{s} \, dy = \frac{1}{3} \cdot \delta \left[(\overline{s}_1 + \overline{s}_n) + 4(\overline{s}_2 + \overline{s}_4 + \dots + \overline{s}_{n-1}) + 2(\overline{s}_3 + \overline{s}_5 + \dots + \overline{s}_{n-2}) \right]$$

= $\frac{0.3625}{3} \left[(1.94 + 0.12) + 4(1.03 + 0.55 + 0.27 + 0.14) + 2(0.75 + 0.38 + 0.19) \right]$

= 1.53 kg/m/s

Thus, the sediment discharge per unit width between y = 0.15m and the surface in the vertical represented in Figure 2c is 1.53 kg/m/s.

Integrations performed as the profiles shown in Figure 4 demonstrate the important influence which the unmeasured zone has on the total sediment discharge. This influence is most pronounced with the largest particle sizes. For example, the integral between y = 0.15m and y = 0.30m as a percentage of the total integral from y = 0.15m to the surface for the various particle size ranges were as follows:

0.067 — 0.074mm, 12%; 0.074 — 0.105mm, 14%; 0.105 — 0.145mm, 22%; 0.145 — 0.201mm, 39%; 0.201 — 0.297mm, 62%.

Such figures indicate that, for large particle sizes, values based on extrapolation into the unmeasured zone may be very unreliable. This is related to the fact that bed load transport is of increasing significance as particle size increases. Clearly, if the sediment discharge below the chosen lower limit of integration is large relative to that calculated in the integration itself the sampling and calculation procedures proposed in this paper would be of limited value. It is, therefore necessary to develop some means of judging the relative magnitude of the bed load discharge.

Determination of bed load discharge 3.6

The problem of determining what, exactly, constitutes the bed load has been discussed in Sections 1.1 and 1.4. For the present purposes the value required is not that corresponding to any theoretical or empirical definition of bed load but rather the fraction of the total load which has not been included in the measurements of wash load and suspended bed material load described above. It is likely that this value will be higher than the 'true bed load', however defined, because the arbitrary lower limit of integration adopted in Section 3.4 will, in most cases, exclude part of the suspended bed material load from the calculation of \overline{S} .

No method of estimating bed load has proved sufficiently reliable even for order of magnitude calculations, to be advocated for general use. It is, therefore, advisable to apply a number of different methods and to compare the results. Suitable methods may be categorised into three major groups. The first group includes various methods which do not provide quantitative values of the bed load transport and are, therefore, referred to as qualitative methods. The second group includes 'bed load' formulae which purport to provide values of bed load directly. The third group uses 'total load' formulae to provide values of bed load as the difference between calculated 'total load'* and measured suspended bed material load.

A number of qualitative approaches to estimating the importance of bed load are described below:

- a) An indication of whether bed load discharge is likely to be important may be obtained from the general characteristics of the river at the section under study. Relevant features are listed in Section 1.4.
- b) A number of such characteristics have been incorporated into empirical tables for estimating the importance of bed load; see, for example, the classification prepared by Maddock which is presented by Vanoni (1975) p 348.
- c) Measurements on the sediment flux profiles of Figure 4 may indicate the conditions under which bed load becomes significant. For example, if the area of the rectangle in the unmeasured zone, formed by the coordinates of the lowest extrapolated point on each curve and the two axes, is expressed as a percentage of the integral of \overline{s} from y_{min} to the surface the following values are found for given particle sizes.

0.067 — 0.074mm, 17%; 0.074 — 0.105mm, 20%; 0.105 — 0.145mm, 31%; 0.145 — 0.210mm, 49%; 0.210 — 0.297mm, 102%.

Although this approach requires further investigation it is clear that with larger particle sizes, where the area of the rectangle is comparable with that of the integral, 'bed load' discharge will be significant. Whether the total 'bed load' discharge is significant will then depend on the relative contribution of the larger particle sizes to the total sediment load.

*The term 'total load' is misleading since it does not, in the context of such formulae, include the wash load.

d) Criteria have been proposed for determining the hydraulic conditions under which particles of a given size will begin to move as bed load and suspended load. The presentation of various criteria in graphical form by White, Milli and Crabbe (1973), Vol 2, based on the work of Engelund, is shown in Figure 5. In this figure two criteria for initial particle movement in the bed (indicated by Y_e) and two criteria for the initiation of suspension (based on the dimensionless fall velocity, F, of the Rubey equation) are shown on a plot of mobility number, Y, against dimensionless grain size, D_{gr}, where:

 $Y = v_{\star}^2 / [g D (\gamma_s - 1)];$

 $D_{sr} = D[g(\gamma_s - 1)/\nu^2]^{\frac{1}{3}}$; and

D is a representative grain size,

 γ_s is the specific gravity of the particles, and

 ν is the kinematic viscosity.

Values of ν may be obtained using the Poiseuille expression:

 ν (in m²/s) = 1.79 x 10⁶/(1 + 0.03368T_c + 0.000221T_c²)

where T_e is temperature in °C.

The criteria in Figure 5 may be applied by determining the values of Y and D_{gr} under observed flow conditions at a particular site using various bed material sizes. In this way a series of points is obtained. These form a line, gradient = -1.0, across the graph. From this line it is possible to estimate the particle sizes at which bed load transport and suspended bed material transport would begin, for the given flow conditions, and by comparing these sizes with the results of analyses of bed material samples an indication of the relative importance of bed load and suspended bed material load is obtained. The calculation should then be repeated for different flow conditions.

e) Another possible criterion for establishing whether bed load is likely to predominate for a given particle size is to consider the curvature of its concentration profile as defined by the parameter $z = w/kv_{\star}$. If w is expressed in terms of the Rubey equation $w = F[gD(\gamma_s - 1)]^{\frac{1}{2}}$ then

 $z = F/kY^{\frac{1}{2}}$

This criterion can then be related to the expressions shown in Figure 5. In particular, the upper criteria defining the initiation of suspended bed material load given by $Y = 1.0F^2$ and $Y = 0.7225F^2$ correspond to z = 2.50 and z = 2.94 respectively. From this it can be seen that a smaller value of z, say $z \le 1.0$, may be used to indicate the point at which suspended load is likely to predominate over bed load. Further study of the transport processes would be required before such a value could be used with confidence. Even then some means of applying it to sediments of mixed size would be necessary.

The use of 'bed load' formulae to provide quantitative results is not, in general, recommended. At first sight such formulae appear to offer advantages over the use of 'total load' formulae because they provide values of bed load directly rather than as the difference between the two numbers which may be considerably larger than the result. However, they have two major disadvantages. Firstly, since there is no generally accepted definition of what constitutes bed load the quantity calculated is unlikely to correspond to the 'definition' of bed load which is adopted in a given study. This will be especially true with the method of sediment measurement proposed in this paper since 'bed load' has been rather arbitrarily defined as the part of the load which has not been included as wash load or suspended bed material load. Secondly, the bed load formulae in common use have been shown, by White, Milli and Crabbe (1973), to give results which appear unrealistic when compared against measured sediment transport rates. The report referred to compared computed sediment transport rates with measured values of 'total load'. Thus, with formulae which are intended only for use in predicting bed load transport it would be expected that calculated and observed values show close agreement only for data in which particle sizes are large; where 'total load' will largely comprise bed load. For smaller particle sizes the calculated 'bed load' should be less than the observed 'total load'. Of the large number of specifically 'bed load' formulae tested by White, Milli and Crabbe only the original Einstein bed load formula of 1950 performed in this way. If a 'bed load' formula is to be used, therefore, this appears to be the one likely to give the most sensible results. However, in view of the problems arising from the difficulty of defining bed load, the inclusion of details of this formula in this report was not considered worthwhile. Details may be seen in numerous references (see, for example, Graf (1971) p 139-150). Care should be taken to avoid confusion with the Einstein total load formula, the Modified Einstein formula and the Einstein-Brown formula.

The use of 'total load' formulae as a means of estimating bed load, for a measured suspended bed material load, offers some improvement over the use of 'bed load' formulae. Nevertheless, this approach should be applied with extreme care since the most reliable 'total load' formulae are likely to give results which differ from the true values over the range +100% to -50%. Where the suspended bed material load is larger than the bed load then the bed load is determined from the difference between two larger numbers. Computed values may then differ by several orders of magnitude from the true values, or may even be negative, as a result of errors in the 'total load'. Where the bed load is larger than the suspended bed material load the use of 'total load' formulae is likely to give more dependable results provided that the total load formulae are applicable in such conditions. Details of two 'total load' formulae are given below.

The 'total load' formula of Ackers and White 3.7

Of the formulae tested by White, Milli and Crabbe (1973) the one which gave predicted sediment transport rates which agreed closest with empirical data was that of Ackers and White. This formula relates a non-dimensional sediment transport parameter, G_{gr} , to a non-dimensional 'sediment mobility' parameter, F_{gr} , as follows:

$$G_{er} = C(F_{er}/A'-1)^m$$

The formula is based on physical considerations but includes coefficients which are chosen to provide correlation with empirical results. For full details of the formula and its application see Ackers and White (1973). A brief description of the relevant parameters is provided below within a structured calculation procedure.

a) Determine the value of D_{sr} for a 'typical' sample of bed material such that:

 $D_{gr} = D[g(\gamma_s - 1)/\nu^2]^{\frac{1}{3}}$

D, the representative grain size is based on the results of a particle size analysis and is generally taken to be D_{35} ; that is, the diameter below which 35% of the sample, by weight, lies.

b) For $D_{gr} > 60$ take the values of the following coefficients as:

 $\begin{array}{ll} n &= 0.0 \\ A' &= 0.17 \\ m &= 1.5 \\ C &= 0.025 \end{array}$ For 60 $\geq D_{gr} \geq 1$

The coefficients n and A' have physical meaning, n relating to the position within the transition zone between very large ($D_{gr} > 60$) and very small ($D_{gr} < 1$) particle sizes and A' being the Froude number at initial motion.

c) The mobility number is calculated as

$$F_{gr} = \frac{V_{\star}^{n}}{[\sigma D(\gamma - 1)]^{\frac{1}{2}}} \left[\frac{V}{5.657 \log_{10} (10d/D)}\right]^{1-n}$$

where V is the mean velocity through the cross-section.

Other parameters are defined elsewhere in this paper.

d) G_{gr} is calculated using the formula given at the beginning of Section 3.7.

e) The mean sediment concentration by weight in the crosssection is given as:

$$X = \frac{G_{gr} \cdot \gamma_s \cdot D}{d} \left(\frac{V}{V_{\star}}\right)^n$$

From this the total sediment discharge rate through the crosssection is given as:

 $Q_s = X \cdot V \cdot A \cdot \varrho$

where ρ is the density of water.

The 'total load' formula of Engelund and Hansen 3.8

In view of the complexity of the Ackers and White formula preference is sometimes expressed for the formula of Engelund and Hansen which performed only marginally less well in the tests undertaken by White, Milli and Crabbe. The Engelund and Hansen formula may be expressed as

 $X = \frac{0.05 \cdot \gamma_s \cdot V \cdot v_{\star}^3}{d \cdot g^2 \cdot D (\gamma_s - 1)^2}$

In this case it is specified that the value to use for D is D_{50} , the median particle diameter. The principal weakness of the formula, according to White, Milli and Crabbe, is that it overestimates transport rates when discharges are low.

Estimating sediment discharges over long periods 3.9

The methods proposed in this paper for calculating the discharges of suspended bed material load and bed load on the basis of field measurements are intended for use in an intensive programme conducted over a relatively short period. It is intended that the results of this programme be used for estimating bed material discharges over a long period on the basis of available data, principally recorded gauge board levels. For this purpose a correlation should be sought between discharges calculated from the intensive programme and gauge board levels. In investigating this relationship it is essential to specify whether instantaneous values or daily/hourly mean values are to be used. If it is found that the correlation is poor alternative methods of prediction could be tried. These might be based on various total load formulae. Strict application of such formulae would not normally be possible since one of the parameters usually required, water surface gradient, is not widely available unless levels from two gauge boards, located close to each other, have been recorded. However, it may be possible to estimate suitable values on the basis of the field measurements undertaken. The degree of accuracy which should be sought in estimating discharge rates will depend on the relative importance of bed material discharge against wash load and on the purposes for which the data are required.

4 Summary of proposed sediment sampling programme

The following summary lists the principal components of the proposed methodology and indicates the sections in this paper, or other references, in which further details are to be found.

- i) Establish the objectives of the study and determine whether the total sediment discharge is required or whether one mode of transport, say bed load discharge, should be given priority. Also, if possible, determine the level of accuracy which would be required to fulfil the objectives (Section 1.5). The following procedure applies to situations in which the total sediment discharge is required and bed load discharges are relatively small.
- ii) Select a suitable site at or close to a river gauging station where a functioning water level recorder exists or could be installed (Section 2.1).
- iii) Survey the chosen cross-section using the gauge board zero as the datum for elevations (Figure 1).
- iv) Establish a reliable stage-discharge relationship for the cross-section by measuring the flow velocity at different river levels. Standard current metering techniques should be used for this although if high velocities are experienced, the use of current meters may be difficult and hazardous. In such situations other methods, such as float tracking, might be necessary. It should be noted that some sections show unstable stage-discharge relationships. If the changes are long-term it may be adequate to redetermine the relationship periodically but if significant short-term changes occur the site would not be suitable for the proposed sampling programme.
- Establish a continuous programme of wash load measurev) ment by installing a recording turbidity monitor preferably on a near-by structure such as a bridge. The monitor head should be located at a position in the flow such that it is as far from the bed as possible but will be submerged at all times. It should also be protected from light. From initial observations an estimate of the maximum concentration of wash load likely to occur in the river is made. Using this value as the upper limit of the working range, calibrate the monitor using samples of local silt obtained, for example, from downstream reservoir deposits. It is assumed that the sand concentration at the head is low and that it will, therefore, have no effect on the turbidity monitor. Thus, only wash load concentrations will be recorded. If subsequent results from the pumped sampling programme indicate the possibility of high sand concentrations around the head some adjustment to the calibration may be necessary. Similarly if the organic content of the wash load is high simple calibration procedures may be inadequate. The turbidity monitor must be regularly maintained; once a week the head

28

should be checked for algae growth, and if necessary cleaned, and the batteries should be re-charged. A recalibration should be undertaken once a month (Section 1.2 and Fish (1983)). From the turbidity monitor record, wash load discharges may be calculated (Section 3.2). The values obtained may be verified against the results of simultaneous pumped sampling results.

- vi) Select a suitable method for locating pumped sampling nozzles at several levels on one or more verticals in the chosen cross-section (Section 2.3). The nozzle positions relative to the bed should be accurately known; the nozzle positions should be more closely spaced near the bed where the concentration gradient is greatest. If possible, a method of measuring the flow velocity at each of the nozzle positions should be incorporated into the sampling programme. Pumped samples should be obtained through the nozzles at fairly regular intervals for a period of, say, three months (practical details are discussed in Sections 2.2 and 2.3). It is necessary, for the success of the proposed method, for sampling to be undertaken under the widest possible range of hydraulic conditions. During periods of relatively constant discharge it would not be worthwhile sampling more frequently than once a day but during flood peaks sampling should be undertaken more frequently. Using a single pump the sampling programme for a single vertical will take about ten minutes per nozzle, that is, about an hour for six nozzles. If the flow is changing rapidly significant changes may have occurred in this period. In such circumstances accurate sampling can only be achieved by using additional pumps to allow simultaneous sampling from several nozzles. Samples are passed through a 63μ m filter, the particles retained on the filter being analysed for particle size distribution and the material passing the filter being analysed to provide a value for the wash load concentration (Section 3.2).
- vii) From the results of the particle size analysis prepare concentration profile data for each selected particle size fraction in a given vertical. The profiles may be extended below the lowest measured level, if necessary, by fitting curves based on theoretical distributions (Section 3.4). A single velocity profile is also prepared for each vertical on each sampling occasion. These profiles are derived either from direct flow measurements or from a theoretical relationship using a value for the mean velocity obtained from the stage-discharge curve. The theoretical relationship is also used to provide values of velocity at levels below the lowest measured in cases where direct measurements have been taken (Section 3.3).
- viii) Sediment flux profiles are obtained by calculating the product of concentration and velocity at selected levels in the vertical (Section 3.4 the assumptions on which this calculation are based are discussed in Section 3.1). The

lowest level to which the concentration and velocity profiles may be extrapolated may be determined from knowledge of the bed forms or, as an initial limit, the value $y_{min} = 0.05d$ may be used. The sediment discharge rates of given particle sizes through a vertical are obtained by integrating their respective sediment flux profiles between y_{min} and the surface (Section 3.5). The sum of these rates, together with the wash load, provides a value for the total discharge rate, above the level y_{min} in a given vertical.

- ix) If nozzles are attached to fixed structures a study of the behaviour of the river bed under different hydraulic conditions should, if possible, be undertaken. This is because the presence of bed forms or the occurrence of largescale changes in bed elevation during the passage of floods would change the distance from the bed of the sampling nozzles which, in turn, would have a significant effect on the value obtained by integrating the sediment flux profile. In addition samples should be taken of the bed material on several occasions during the three month sampling programme to provide information on sediment sizes within the bed material.
- Apply various qualitative tests to determine whether the X) unmeasured sediment load (including bed load) is likely to be significant (Section 3.6). Attempt to estimate the magnitude of this unmeasured discharge by calculating the 'total load' using formulae such as those of Ackers and White (Section 3.7) or Engelund and Hansen (Section 3.8) and subtracting from this value the suspended bed material discharge calculated from the measured sediment flux profiles. (Wash load is not included in 'total load' formulae). If bed load and unmeasured suspended bed material load are found to comprise the bulk of the total, the sampling programme proposed in this paper should be abandoned and the use of alternative methods for measuring sediment transport rates, such as dune tracking, should be investigated.
- xi) Investigate the correlation between the measured suspended bed material discharges and river gauge levels in order to provide a basis for estimating sediment discharge values once the initial pumped sampling programme has been completed (Section 3.8). The accuracy required in the prediction of suspended bed material discharge rates will depend on their magnitude in relation to the measured wash load discharge rates and the purposes for which the data are required.

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30

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Data forms for use in the collection and analysis of pumped samples

GAUGE BOARD READING, at start:m at finish:m WATER TEMPERATURE:0C SIEVE MESH:..... at finish: TIME, at start: Slope Horizontal distance (m) HYDRAULICS RESEARCH - OVERSEAS DEVELOPMENT UNIT PUMPED SAMPLING FIELD DATA RECORD Downstream level (m) DATE: POSITION OF VERTICAL: SITE: Upstream level (m) (s/m) (sec) (m from bed) (min-sec) (ກ PUMP FLOW RATE MEASUREMENTS (sec) Flow velocity at nozzle Position of nozzle in RIVER: Water surface slope if available GENERAL REMARKS: Total time of sampling, T At Finish At Start Volume vertical Time Form Pl

Total volume of sample sieved = T x R (l) IDENTIFICATION NUMBERS ON SAMPLES COLLECTED

 (λ/sec)

Mean Rate, R

Rate

SAMPLES COLLECTED Particles on sieve Bottle samples of 1

3 2 1

material passing

sieve

Form P2

HYDRAULICS RESEARCH - OVERSEAS DEVELOPMENT UNIT PUMPED SAMPLING: SIZE ANALYSIS OF SAND PARTICLES

RIVER SITE D

DATE OF SAMPLING

DATE OF ANALYSIS

GENERAL REMARKS ON SAMPLES:

|--|

Form P3

HYDRAULICS RESEARCH - OVERSEAS DEVELOPMENT UNIT PUMPED SAMPLING: SUMMARY OF CALCULATIONS

RIVER SITE DATE OF SAMPLING POSITION OF VERTICAL TIME AT START OF SAMPLING FLOW DEPTH, d

GENERAL REMARKS:

		SEDIMENT TRANSPORT IN GIVEN PARTICLE SIZE RANGE (μm)										
У	v	>	 to	to	 to	 to	 to	 to	 to	 to	 to	wash load (<63)
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S per unit		.t										

width

TOTAL TRANSPORT OF PARTICLES>63µm PER UNIT WIDTH IN VERTICAL* = kg/m/s

y = position within vertical (m from bed)

 \overline{v} = velocity (m/s). Indicate whether measured or computed

 \overline{c} = concentration (kg/m³ = ppm ÷ 1000)

 \overline{s} = sediment flux (kg/m²/s) computed as $\overline{v} \times \overline{c}$

 \overline{S} = total discharge of given particle size $(kg/m/s)^*$

* Between lower reference level y = ... m and y = d

Figures

Y



Fig 1 Typical record of river cross-section

data



of a sediment flux Derivation profile

Fig 2



Fig 3 Linear representation of data from Fig 2a & 2b



Fig 4 Typical sediment flux profiles for different particle sizes

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This technical note is one of a series on topics related to water resources and irrigation, prepared by Hydraulics Research, Wallingford, and funded by the British Overseas Development Administration.

Others in the series include:

OD/TN 1 Partech turbidity monitors: calibration with silt and the effects of sand I L Fish, September 1983