Guidelines on field measurement procedures for quantifying catchment sediment yields

(TDR Project R5836)

P Lawrence

Report OD/TN 77
June 1996

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Summary

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Methods for quantifying sediment yield from drainage basins ranging in size from small fields to the catchments of large dams are presented. The emphasis is on techniques that have proved to be suitable for use in developing countries, where restricted resources are available for setting up and sustaining measurement programmes.

For very small catchments, fractions of a hectare, catch pits or tanks provide a cheap and accurate means of measuring both water and sediment run off. Flow divisors can be used to divert a small fraction of the water and sediment run off when the storm run off is too large to be stored in a collection tank.

In larger catchments, with areas up to tens of hectares, run off flows can be measured with a purpose built measuring structure, ("H" flume or similar), and frequent sediment samples collected through storm events to quantify sediment yields. Sediment sampling is simplified if the sediments leaving a measuring flume are well mixed by the turbulent flows produced in a settling basin, so that single point sediment sampling can be adopted. In most cases automatic water level recording and sediment sampling is essential to ensure that run off events are monitored. The equipment developed by HR Wallingford to meet these requirements in developing country conditions for catchments of around 10 ha is described.

Sediment yields from larger catchments are usually quantified by measurements of the flow and sediment loads in rivers, or from the quantities of sediment trapped in water storage reservoirs. River measurements will not have a very high accuracy unless a large effort is devoted to sediment monitoring, particularly in flood flows. Sediment concentrations have to be measured frequently during flood events, implying round the clock manning at gauging sites in flashy rivers, or the use of automatic sediment sampling equipment.

Where this is not feasible a "sediment rating curve" approach can be adopted, with a significant reduction in the accuracy in the estimate of the annual sediment yield that can be achieved.

If manual measurements are chosen a measurement programme that combines frequent dip sampling, a simple technique that can be carried out by local staff with minimal training, with "calibration" derived from occasional measurements using a more complex pump sampling technique is suggested. In most circumstances this will provide the best compromise between accuracy in the determination of sediment yield, and the cost and complexity of maintaining a measurement programme.

Summary continued

Most of the logistical problems associated with river sediment sampling can be avoided when data derived from reservoir surveys are used to estimate sediment yields. However there are some difficulties in deriving sediment yields from reservoir volume changes: estimating the reservoir sediment trap efficiency, and the density of the sediment deposits. Means of determining these parameters, and recommended procedures for establishing reservoir volume changes from survey data are described.

Contents

Contents continued

1 Introduction

1.1 Background

Rising rates of soil erosion in many developing countries has highlighted the need for reliable field measurements of sediment yields from catchments. While large data sets describing sediment yields exist, (Reference 20), the information they contain is heavily biased to the developed world. Also much of the existing data base is fairly old, and does not reflect the impacts of the expansion of agricultural activities into steep and fragile upland areas that occurred as populations in many developing countries increased over the last few decades. Reliable data, reflecting changing conditions in catchments, is needed by agriculturists and planners concerned with sustainable agricultural development, engineers involved with downstream sedimentation problems, and researchers studying erosion and sediment delivery processes.

In agricultural studies replicated trials on small plots are used to account for uncontrollable variations in hydrology, soils etc, when erosion rates for different crops, cropping patterns and conservation measures are being evaluated. While most developing countries have collected many years of plot data, their value has been questioned. A recent review published by FAO, (Reference 1), concluded that erosion plot studies are expensive, have often failed to produce practical usable data, and should only be considered if there are specific questions that can only be answered by experiments carried out under controlled conditions at the plot scale. Plot data provides little useful information on catchment sediment yields, as sediment arriving from upslope is excluded at the upstream plot boundary, while sediment deposition downstream from the plot is not accounted for.

The information and references cited in Reference 1 provide advice on planning and carrying out plot studies, which are not considered in these guidelines.

Here we are concerned with monitoring programmes designed to quantify sediment delivery from land areas ranging in size from small fields to the catchments of large dams. Data collected at the catchment scale provides information on the down stream impacts of actual land use practices, including non agricultural erosion, land slips, gullies, and scour from stream banks etc, which are not represented in the artificial environments found in plot experiments.

1.2 This report

The guidelines were prepared for a Workshop held in collaboration with the Royal Irrigation Department in Bangkok, Thailand, in May 1995. They provide advice on methods for the measurement of sediment yields from catchments. The emphasis is on techniques that have proved to be suitable for use in developing countries, where restricted resources are available for setting up and then sustaining measurement programmes.

Advice, supported where possible by estimates of the accuracy that is likely to be achievable, are presented for measurements at the field, small and large catchment scales in Chapters 2 to 6. Where information is already available, (Reference 1) a summary of the important recommendations is presented. (Chapters 2, 3 and 4). More detailed information is presented on measurement procedures for rivers and reservoirs, (Chapters 5 and 6). These are largely based on the experience gained in developing country studies carried out by HR Wallingford. A preliminary check list for those involved in planning monitoring programmes is included in Chapter 7.

2 Reconnaissance methods

These provide a means of identifying catchments, or parts of catchments, with high erosion rates, which may need to be targeted for more detailed measurements. They involve visual observations, or very simple measurements, that provide a qualitative assessment of relative erosion rates.

Visual assessments can be made using easily identifiable indicators such as:

- The height of soil pedestals where soil has been protected by stones or vegetation.
- Stem or root exposure.
- Comparison of the soil height above or below fixed obstacles such as tree stems or boulders on a slope.
- Sampling of "armour layers", where comparison of the proportion of coarse particles on the surface with their proportion in the soil, can be used to estimate the amount of the finer particles that have been eroded from the surface layer.

The advantages of these methods are that they are cheap and simple, and that large numbers of observations can be carried out quickly, enabling a rapid assessment of relative erosion rates over large areas. At a point they indicate the net soil loss, that is the balance between the soil eroded locally, and the soil deposited from up slope erosion. The disadvantages are that the results are qualitative, and cannot be used to estimate actual erosion rates without time calibration. There is also evidence that suggests that the high soil levels observed at the base of trees, or under clumps of grass, can be the result of soil being trapped, and are thus the result of a local <u>increase</u> in soil level, rather than lowering of the surrounding ground.

Visual observation of the sediment quantities that have settled in drainage channels at the bottom of slopes can also be used to provide a qualitative indication of relative sediment yields.

3 Field scale measurements

3.1 Measurement of land level changes

Estimates of local erosion rates can be made by measuring changes in land surface level where erosion rates are high, for example in steep areas where cover has been removed, or from tracks or gullies etc. These methods are not usually appropriate in arable lands, where surface levels are effected by cultivation. Measurements taken at single points will vary widely, but if a large number of points are sampled and averaged useful estimates can be obtained.

Erosion pins have been widely used. These consist of a pin or stake that is pushed in to the soil. Pins are often made from a metal rod, for example off-cuts from steel reinforcing bar, typically 300 mm. long by about 5 mm. in diameter. Measurements from the top of the pin to the local soil surface indicate the depth of soil removed by erosion. Some workers place a small metal washer over the pin to provide a better base from which to measure the local soil level, Figure 1.

This has the advantage that if there are cycles of erosion and deposition, such as in a gully floor, the washer provides additional information by falling to the lowest erosion level, and then being covered by later deposition. Experience in the use of the erosion pin method is reviewed in Reference 2.

The accuracy of soil loss estimates provided by erosion pin measurements is not high. Changes in level cannot be measured more accurately than to about 1 mm, a change of this magnitude being equivalent to a soil loss of about 15 t/ha.

Other methods of measuring lowering of the soil surface include painting collars just above soil level around rocks, trees, or fence posts etc. Erosion can be estimated by distance from the eroded level to the bottom of the paint line. However local scour effects must be considered when such measurements are interpreted.

Changes in level can also be used to estimate erosion volumes. To estimate erosion from rills or roads, the length of the eroding section and the changes in cross section are measured. For gullies the change in gully length as the gully cuts back also has to be measured.

3.2 Run off measurements using catch pits

The procedures described above provide a measurement of net changes in the land surface elevation, resulting from the balance between erosion and the deposition of sediment supplied from upslope. The quantity of sediment transported from a small land area can be measured by trapping the water and sediment run off in a catch pit, which could be a tank constructed from oil drums, brick or concrete etc, or a excavated pit lined with a plastic sheet. If all the run off from a single event, or with a larger catch pit over a longer time periods, is trapped the method provides a very precise measurement of sediment and water yield. For example if the mass of sediment collected from a field with an area of 1 hectare is measured to a precision of 1 kg, then an estimate of soil loss will be accurate to 0.001 t/ha, many times more precise than estimates derived from erosion pins.

Catch pits obviously have to be designed with a capacity to store the runoff from the largest expected storms if data is not to be missed for the most important sediment run off events. Run off volumes can be estimated from catchment area, the maximum probable run off ratio for saturated soil, and the rainfall for the specified extreme event. The maximum flow rate can be estimated from the maximum expected short period rainfall intensity assuming a 100 % run off ratio.

Measurements are made easier if small containers, that have the capacity to store run off from typical run off events, are placed inside larger tanks, with the capacity for the largest expected event.

Catch pits are only feasible when the area being monitored is very small. For larger land areas the size of the collector required becomes too large to be practical, and either flow splitters have to be used, so that only a proportion of the run off is collected, or methods described in the next chapter involving a measurement flume and sediment sampling arrangement have to be adopted.

3.3 Flow splitters

Advice on the design of collector tanks and flow splitters is given in Reference 1. Many of the flow splitting devices illustrated in this publication were developed for plot studies, and most will not provide a correct division of sediment loads. Flow splitters consisting of a series of flumes with one or more vertical splitter plates, used to successively divide the flow, have the best chance of providing a correct division of both water and sediment, provided the precautions mentioned in Reference 1 are observed.

4 Small catchment measurements

The run off from small catchments is generally too large to be collected in tanks even when divisors are used. The usual practice is to divert run off flows through a flow measuring structure, and to take samples of the sediment concentrations in the run off water at frequent intervals. In most cases it will not be feasible to maintain measurement teams in the field on a continuous basis, and automated data collection is necessary to ensure that run off events are monitored.

4.1 Discharge measurement structures

A wide range of measurement structures are available which enable discharges to be determined from a measured water level. Some examples are given in Reference 1, a wider range of flow measuring structures are described in Reference 3. Structures with a "V" type control, providing a wide opening at high flows to minimises backwater effects, and an acceptable sensitivity at low flows, are recommended. The "H" flume series of special purpose flumes designed by the US Soil Conservation service for measuring run off from plots or small catchments are able to pass high sediment loads, and have been used successfully in studies carried out by HR Wallingford.

"H" Flumes are available in the range of sizes shown in Table 1, with the dimensions given in Figures 2, 3 and 4, from Reference 3. They are usually constructed from sheet steel, following exactly the dimensions given. The three types of flume should be located downstream of a rectangular approach channel, which has the same bottom width as the flume. Sediment deposition in the region upstream from the flume can be avoided by steepening the slope of the approach channel.

Water levels are measured in a stilling well connected to a tapping point located as specified in Figures 2 to 4. A float operated water level recorder is used to obtain a continuous record of the water level variations during run of events. Water levels are converted to discharges using either calibration tables presented in Reference 3, or the rating equation shown under Table 1, with the coefficients listed in the table. Provided flumes are constructed correctly, discharges can be measured to an accuracy of about 3%.

"H" flumes can be operated partially submerged, however Reference 3 recommends an upper limit on submergence of ratio of 0.25, to restrict non modular flow errors to less than 1 %. In HR Wallingford studies flow leaving the flume is dropped into a stilling basin so as to generate turbulence to mix sediments, and thus are always operated in the modular range, see Figure 6.

Flume selection often presents problems as it is necessary to compromise between sizing the flume to ensure that the discharge capacity is sufficiently large to cope with peak flows from the largest expected run off events, while maintaining an acceptable measurement accuracy for more frequent smaller events. For a small catchment it is often assumed that rainfall with a uniform intensity falls over the whole catchment for a time period at least equal to the time of concentration, ie all parts of the catchment contribute equally to the run off. In larger catchments it is necessary to consider the time of concentration, that is the longest time taken by surface run-off to travel from any point in the catchment to the outlet.

Several methods for estimating a maximum expected storm discharge are presented in Reference 1.

4.2 Sediment measurement

Sediment loads are measured by sampling the storm run off to determine the variation in sediment concentrations with time. The sediment sampling procedure should account for variations in sediment concentration through the flow from the channel bed to the free surface. (Larger sediments are transported at, or close, to the channel bed, while the finest sediment are well mixed through the flow). The methods used to account for these factors in streams and rivers is discussed in the next chapter. For the relatively small discharges leaving small catchments it is possible to simplify the sediment sampling procedure by mixing sediment in the flow at the sampling location, so that a representative sample can be obtained by sampling at a point.

This has been achieved in the small catchment studies carried out by HR Wallingford by providing a small basin at the flume outlet. Flow leaving the "H" flume is dropped into the basin, which is designed so that the turbulence that is generated thoroughly mixes the sediment. A representative sample can then be obtained by sampling from a point close to the basin floor, see Figures 5, 6 and 7. The sediment flux over a run off event is calculated by integrating the product of the sediment concentration and discharge, and event totals are summed to provide the annual sediment yield. Information of the sediment sizes in the sediment mixture leaving a catchment can be obtained from size analysis of the sediment samples, although in practice this is only feasible for individual samples when the sediment concentrations are large enough to provide a sufficient mass of sample.

4.3 Automatic sediment samplers

The pump sampling system shown in Figures 6 and 7 was developed to collect sediment samples automatically at remote sites. A long shaft pump, which can be seen mounted at the stilling basin exit in Figure 7, is used to draw samples from the sampling point and pass them to a bottle rack system which contains 24, 0.5 litre sample bottles, Figure 6. Sampling is initiated at a pre set flume discharge, using a float switch mounted in the "H" flume stilling well, Figure 7, and continued at pre set time intervals until the discharge falls below the trigger level. The time interval between samples can be adjusted so that samples are collected more frequently during the early part of run off events, when both the discharge and sediment concentrations are largest.

In the early version of the equipment shown in Figure 6 the chart on the water level recorder shown on the right hand side of the picture was marked automatically each time a sample was collected. Thus the flume discharge at the time each samples was collected was known. In later versions the pump sampler was controlled using an "intelligent" data logger, which also logged the output from a solid state water level recorder and autographic rain gauges placed in the catchment.

More detailed descriptions of applications of this equipment in small catchment studies can be found in References 4 and 5.

(Sediment samplers and data loggers suitable for this application are available commercially, see Reference 1)

4.4 Accuracy of sediment load estimates

The accuracy of annual sediment load estimates made using this technique depends on the accuracy of the discharge measurement, the number of sediment samples collected during run off events, the systematic error that may be introduced by assuming that samples are perfectly mixed, and the measurement errors discussed in Appendix 2 and the next chapter in the context of river measurements. Use of an "H" flume provides relatively precise estimates of discharge, and errors in sediment yields are mostly due to sediment sampling and measurement errors. Provided that the sediment mixture is relatively fine, so that representative samples are obtained by sampling at a point in the mixing zone, that a minimum of five sediment samples are collected during run off events, and that no data is missed, errors in estimates of annual sediment discharge will normally have a standard error of less than 25 %.

5 River measurements

The factors that influence the planning of sediment measurement programmes in rivers are similar to those for small catchments. However the flows are usually too large for a purpose built discharge measurement structure to be feasible, and it will rarely be possible to mix sediments in order to simplify sediment sampling procedures. Sediment yield measurements are often carried out at an existing river discharge gauging station.

In most rivers a major portion of the annual sediment load is transported in a few large discharge events, and thus it is vital that measurement programmes are set up to ensure that sediment sampling is carried out during flood flows. Unfortunately high flow periods are often not sampled, due to difficult access to remote sites in the wet season, floods occurring at night, and the problems of deploying conventional bottle sediment sampling equipment in high flows.

5.1 Use of Hydraulic Structures to measure discharge

The maximum discharge that can be measured with a standard "H" flume is about 3 m^3/s. While measuring structures are available for larger discharges, provision of a purpose built discharge measurement structure for sediment yield measurements in a large river is likely to be prohibitively expensive. However there may be existing structures in a river that is to be monitored, for example weirs constructed at irrigation or water supply offtakes, that can be utilised to estimate river discharges from measured water levels. Where suitable structures exist they should be used, as in general, discharge measurements will be both greatly simplified and more accurate than methods based on current metering. Discharge rating equations for a wide range of hydraulic structures, with an indication of the accuracy that can be expected, are presented in Reference 3.

5.2 Discharge by current metering

In many cases it will be necessary to set up a river flow and sediment gauging station. Criteria for selecting a discharge gauging site are given in International standards, References 6 and 7, and these should be followed to the extent that it is feasible. Generally, gauging sites should be located at the end of a relatively straight river reach, where the river flows in a single channel, between well defined banks. Additional criteria have to be considered when catchment sediment yield is to be measured, for example the location of tributaries draining sub catchments, that are to be either included in or excluded from the monitoring programme, ease of access at night, and when the river is flowing at flood discharges.

Procedures for carrying out discharge measurements, and analysing the results are specified in Reference 6. They consist of measuring water velocities at specified points with a current meter, together with the river cross section, to establish the discharge for a known water level, (stage). A stage - discharge relationship is built up by carrying out measurements for a range of flows, and then used to convert water level records derived from an automatic water level recorder, or possibly frequent manual measurements, to a discharge - time series.

It will often not be feasible to comply with all the ISO recommendations in a study set up with the primary objective of quantifying the sediment yield from a catchment. For example the large number of velocity measurements needed to provide a relatively precise measurement of discharge gives problems in rivers where the flow changes rapidly, and sediment measurements have to be carried out at the same time as current metering.

Discharge measurements in steep flashy rivers present particular problems. These include placing a current meter at the recommended locations in the flow when very high velocities are encountered, the trash that collects around the current meter and supporting cable, bed scour and fill during and after floods that results in frequent shifts in the rating relationship. A simple discharge measurement procedure for flashy rivers utilising surface floats described in Reference 8 can be used as an altemative to current metering.

A combined discharge measurement and sediment sampling procedure is used in the river measurements carried out by HR Wallingford.

5.3 River sediment measurements

Methods of measuring the sediment loads in rivers and canals have been reviewed in References 9 and 10, (see Appendix 2). In rivers with sand beds, or coarser beds, where the suspended sediment load dominates the total load in transport ie. in many Developing Country rivers, pump sampling is the most accurate of the available methods. Pump sampling has several other advantages over conventional bottle sampling methods, including:

- A large quantity of sediment can be collected at each sampling location, enabling individual sediment samples to be size graded.
- The method can be adapted for use in high velocity flows, enabling data to be collected when bottle samplers could not be used.
- Pump sampling can be automated, allowing unattended event or time based sampling at remote sites.

The pump sampling method is described in these guidelines.

The method is relatively simple. A pump is used to draw a sample of water and sediment through a nozzle mounted in the flow, and convey the sample via a plastic pipe to the channel bank or other convenient location. A single nozzle can be suspended from a winch or cableway, Figure 8, an array of nozzles mounted at fixed points in the flow on a streamlined mast, or secured to an weir or other hydraulic structure. A cable way, Figure 9, or winch system Figure 10, would be used in most circumstances.

A current meter is usually mounted close to and at the same elevation as the sediment sampling nozzle. Velocity measurements are taken during sediment sampling.

The pump discharge is passed on to a sieve to separate the very fine sediments, wash load, from the suspended bed material. (These terms are defined in Appendix 1). The weight of sediment recovered from the sieve, and the volume of water pumped over the sampling interval, usually measured in a large bucket, gives the sediment concentration at the nozzle location. By sampling at a number of locations in the flow sediment concentration profiles can be determined, and the mean sediment concentration established. A typical pump sampling operation is shown in Figure 11.

A description of the procedure developed in HR Wallingford studies is presented in Appendix 1. Methods for estimating the accuracy of individual sediment load measurements made by pump sampling are presented in Appendix 2.

5.4 Accuracy of measurements - implications for planning a measurement programme.

The utility of sediment transport measurements is directly related to their accuracy. Two factors have to be considered, the accuracy required in an estimate of the annual sediment yield, and the duration of the measurement programme needed to achieve a reliable estimate of a long term mean sediment yield from an annual series of measured sediment loads.

5.4.1 Choice of method and sediment sampling frequency

A relatively precise value for an annual sediment load can be obtained by continuously monitoring river sediment concentration and water discharge. Integration of the product of water discharge and sediment concentration over a year then provides the annual sediment yield. Errors in this estimate will be mostly due to measurement errors, which are discussed in more detail in Appendix 2. However, the difficulty and expense of setting up, and then maintaining, a continuous sediment monitoring programme usually results in intermittent sediment sampling being adopted. (Discharges are usually estimated from a continuous record of water level.)

When infrequent sediment samples are collected, or there are significant gaps in the data, the integration approach is invalid. In this case measurements, ideally covering the full range of river discharges, are used to generate a sediment rating relationship to estimate sediment loads in unmeasured events. A sediment rating curve is derived by measuring sediment concentrations for a range of flows, and plotting the sediment load as a function of discharge or river stage. Rating relationships are then usually obtained by fitting a straight line on a graph of logarithm of the sediment load, plotted against the logarithm of the river discharge. As the sediment load is proportional to concentration * discharge, discharge appears on both axis, and the plotted relationship usually appears to indicate a correlation, albeit with a large scatter of points around the fitted line.

The concentrations of the larger sediment sizes are related to hydraulic parameters, such as discharge. However a large proportion of the sediment in transport usually consists of finer "washload" sediments, whose concentration is controlled by supply rather than the local transporting capacity of the river. This, and hysteresis effects in flood flows, leads to a very large scatter in the points used to assemble rating curves, and potentially large errors, often a significant underestimation, in estimates of annual sediment loads.

Reference 11 compares sediment load estimates derived from rating curves, and after correction to remove the bias inherent in log transformed relationships used to derive the rating relationships, for a number of sampling strategies. It concludes that the most important source of error is associated with the varying relationship between sediment concentration and discharge. It also concludes that methods to remove the bias introduced in log transformed relationships did not always improve the accuracy of the estimate of sediment load.

The sediment rating curve method is thus not recommended, particularly for rivers where a large proportion of the annual discharge, and hence sediment transport, occurs in a few flood events, as it can lead to very large errors. A further disadvantage of the rating curve method is that it is impossible to identify trends in sediment yield over time unless new rating curves are to be generated each year. In this case the large measurement effort devoted to collecting sufficient data to generate a reliable rating curve would be better directed at frequent monitoring during flood events.

However it is recognised that the cost and logistical requirements of high frequency monitoring programmes may make use of the rating curve approach inevitable in some situations. If this is the case, then the most accurate procedure to develop a rating relationship is to use measured data to calculate mean concentrations for about 20 discharge ranges, covering the full range of discharges that are expected. Interpolation between mean values provides a relationship that does not rely on an assumed form for the function relating sediment load to discharge.

When "continuous" measurements are adopted it is necessary to consider the sampling frequency required to provide a given level of accuracy in the measurement of an annual sediment yield. Numerical simulations have shown that a sediment sampling schedule should be specified so that at least five sediment samples are collected during typical flood events. For the circumstances that apply in typical measurement situation this will ensure that the standard random error in an estimate of annual sediment yield is below about 30%. (See Reference 12 for more detailed information). In flashy rivers this implies either that measurement stations are continuously manned and provision is made to carry out sediment sampling at night, or that automatic sediment sampling equipment is used.

Quantitative estimates of the accuracy that will be obtained depends on many site specific factors, and no general guidance can be given. Achieving a sufficiently frequent sampling programme is important, but once this is achieved, the expense of obtaining a greater sampling frequency is not likely to be justified in terms of improvements in accuracy. The highest accuracy will be obtained using pump sampling, with a sampling interval meeting the criteria that at least five samples should be collected during large run off events. However useful savings in the costs and complexity of sediment sampling can be achieved, with only a small reduction in accuracy, by basing measurement programmes on frequent dip sampling with occasional calibration measurements using the pump sampling technique. Dip samples can collected in bottles from the water surface, possibly by local observers living on site. Results have to be "corrected" for concentration profile effects using data collected using the pump sampling method. Pump sampling could be carried out by a specialist team who would visit the measurement site at regular intervals during periods when high flows are expected, to ensure that some high discharge flows are monitored.

In summary the broad conclusions derived from HR Wallingford experience, (Reference 12), are:

> The accuracy of an estimate of annual sediment yield is dominated by the effects related to frequency of sediment sampling. While measurement errors can be substantial, see Appendix 2, they will in most circumstances be insignificant when compared with the errors due to an inadequate sediment sampling frequency in flood flows.
>
> When frequent observations are made in flood flows then integration of the observed sediment loads will give the greatest accuracy. When observations are infrequent, so that for example only one or two samples are collected in a typical flood, then application of a sediment rating curve will provide greater accuracy. The crossover between the two conditions is when the ratio of sampling interval to flood duration is about 0.3.
>
> The rating curve method is the most suitable technique for estimating sediment loads during periods without observations, although errors will often be large. Rating curves should be derived using the group averaging procedure described earlier.
>
> If insufficient data is available to carry out group averaging then a rating curve should be fitted to the observed data using non linear regression assuming a power law relationship. Linear regression on data transformed to logarithmic axes introduces a systematic error, and is not recommended.

5.4.2 Duration of measurement programme

Long term records of annual sediment loads are characterised by a high degree of variability, some examples from rivers in Kenya are shown in Figure 12. The coefficient of variation (Cv) of a sequence annual sediment loads, (standard deviation divided by the mean), can be used to estimate the standard error of an estimate of the mean for records of different length using Figure 13, from Reference 13. For a typical values of Cv, say 0.75, data should be available for about 5 years if the standard error in the estimate of the mean catchment sediment yield is to be reduced to less than 50%. (This takes no account of the errors in the estimates of individual annual sediment loads, however if these are dominated by random errors, see Appendix 2, then they will cancel over the long term.) Longer data records are required when the coefficient of variation is larger, as will be case in semi arid regions. This implies that measurement programmes with long durations are needed to reliably quantify mean sediment yields at the catchment scale, particularly when sediment yields from catchments with different rainfall patterns are to be compared.

Figure 13 is useful for assessing the required duration of measurement programmes where data already exists for the river being studied, or for similar rivers in the same region. This will rarely be the case. An approximate estimate of the measurement duration required can be derived from annual rainfall statistics, if it is assumed that annual sediment loads are approximately proportional to annual run off, and the run off coefficient does not vary too much.

6 Reservoir surveys

Reservoir survey techniques and a recommended method for analyzing the results are described in this chapter. More detailed information on survey methods is presented in Appendix 3. The emphasis is on simple procedures that can be carried out without the use of sophisticated equipment.

Many of the problems associated with river sediment sampling can be avoided when data derived from reservoir surveys are used to estimate sediment yield. Provided that the reservoir is large enough to have a fairly high sediment trapping efficiency, most of the incoming sediment, including that transported in flood flows, will be trapped. The differences in sediment volumes derived from surveys integrates sediment supply over the period between surveys, which is typically five to ten years. However there are some difficulties in deriving sediment yields from reservoir volume changes, estimating a reservoir sediment trap efficiency, and the density of the sediment deposits.

Estimating reservoir trapping efficiency

A proportion of the sediment entering a reservoir, particularly the finest sediment fractions, is not trapped. Thus a reservoirs sediment trap efficiency must be known so that a correction can be applied to measured sediment volumes to allow for sediments that have passed through the dam. The simplest method, and the most commonly used, is that of Brune (Reference 14).

Brune's results are derived from studies of reservoirs in the USA, and are expressed as curves relating trap efficiency to the ratio of reservoir capacity, C to annual inflow, I. The curves are shown in Figure 14. The two outer curves represent the envelope containing all Brune's results. The curve that is most often used is the middle one, but in cases where information on the size of sediment in the inflowing material is available, the upper curve is used if the material is coarse, or the lower one if it is fine. (Brune did not define "coarse" and "fine")

As Figure 14 shows, very large reservoirs ($C/I > 1.0$) are expected to retain all the incoming sediment, medium-sized reservoirs ($0.1 < C/I < 1.0$) to retain all but a few per cent, small reservoirs ($C/I < 0.002$) to retain none at all. The accuracy of the prediction of trap efficiency is thus only important for reservoirs that are of small to medium size in relation to the rivers from which they are supplied, with C/I somewhere in the range 0.01 to 0.1. A great many Developing Country reservoirs fall in this range.

Although Brune's curves are now rather old, and, being empirical, can only be presumed to apply in conditions broadly similar to those where they were derived (the Southwestern United States), they have remarkably few competitors in the literature. Brunes curves are often used as alternative methods require more information than is generally available.

Estimating the density of reservoir sediment deposits

The density of the sediment deposits trapped in a reservoir is used to convert sediment volumes derived from a survey to an equivalent sediment mass to calculate a catchment sediment yield. Settled densities of reservoir sediments can vary between quite wide limits, and depends on the size range of the deposits, the age of the deposit and the manner in which the reservoir is operated. (Reference 15). Data from Indian reservoirs indicates that although measured densities ranged between 0.46 to 1.8 Tonnes/m^3, the average sediment density in each of eight impoundments was close to 1 Tonne/m^3.

If density data derived from coring is not available, the density of sediment deposits can be estimated using one the methods in the literature. Lane and Koezlers method, described in Reference 16, is often used when information on the size range of the sediment deposits is available. If no data is available an approximate figure of 1 Tonne/m^3 can be adopted.

6.1 Survey techniques

6.1.1 Dry surveys

When a reservoir is dry for part of the year standard land surveying procedures can be used to produce a contoured map of the reservoir area, and the volumes of sediment deposits derived from a comparison with a pre - impoundment survey. In cases where surveys are being carried out with the reservoir drawn down, but not empty, a dry survey will be used in conjunction with a hydrographic survey. Combined surveys require careful attention to ensure continuity in the shallow water zone, particularly if significant water level changes occur between the two surveys.

Drawdown provides an opportunity to inspect the distribution and pattern of sedimentation within a reservoir, and take sample corings to directly determine sediment depth and sediment density.

For very small impoundments, which are dry for a long enough period to allow inspection pits to be excavated, the volume of sediment deposits can be estimated by coring or digging pits to the original land surface, so as to determine the depth of sediment deposits. This method is useful when there is no pre-impoundment map and the sediment thickness is relatively small.

The number of sediment cores required will depend largely on the topography and the survey accuracy required. These site specific factors have to evaluated on a case by case basis.

6.1.2 Wet surveys

Hydrographic surveys are the most commonly used method to survey reservoirs, and are based on either range line or grid surveys. A range line survey requires that beacon's are established along each bank to mark the end of range lines. The position in space of the beacons is established by triangulation, which can be relatively expensive and time consuming. However range line surveys do not require particularly sophisticated equipment, and are often most suited to resources and skills that will be available in Developing Countries.

A uniform grid survey provides data suitable for use by Digital Terrain Model (DTM), but can miss significant features. A non-uniform grid allows for surveyors to select significant points to survey, but requires an experienced surveyor. Grid surveys are usually carried out using sophisticated position fixing and depth sounding equipment linked to a computer to produce plots, cross-sections and sediment volumes. This method is not discussed further here.

6.2 Range line surveys

This is the method that will usually be adopted, and consists of the following activities:

Initial triangulation of range line beacons: On either bank of the reservoir, permanent beacons are established to act as datums for position and level. This, and the initial triangulation to obtain accurate beacon positions and levels, constitutes by far the most time-consuming parts of the reservoir survey. However, once established, beacons enable later surveys to carried out rapidly.

Depth measurement : The depth of water along a range line is normally measured using an echo sounder mounted on a boat, with continuous chart readout or, in shallower water, with a measuring rod. Measured depths are related to a datum elevation by measurements of water surface elevation.

Position fixing : Position fixing equipment is required to guide the survey vessel along the range line, and to locate its position at the times when depth is measured.

Position fixing methods can be divided into two groups, where position fixing equipment is on board the survey vessel or on shore. With a shore position fixing systems, radio communication is required, a complication that can lead to additional operational problems. There many position fixing methods, with varying degrees of sophistication, some are described in Appendix 3.

6.3 Volume calculations

The method adopted for computing sediment volumes from survey data depends on mostly on the survey method that has been used. Here we are concerned with range line surveys, for which the constant factor method, (Reference 17) has been widely adopted. One problem associated with this method is its reliance on the availability of contour areas between measured cross sections, which are derived from pre-impoundment survey data. If the contour interval is large, or contour area data are missing, the accuracy of the method suffers severely.

The Stage width modification method, described in Reference 18, is a development of the constant factor method, and exploits the close relationship between stage width and stage area curves. Its performance is substantially better than the constant factor method when pre impoundment data is sparse. The method makes better use of sparse input data both in calculating the original reservoir volume and in coping with an erratic sediment distribution. However it shares some of the defects of the constant factor method, in that it hypothesises that the vertical distribution of sediment throughout a reach between cross sections is closely related to its distribution at the end cross sections. This is a reasonable assumption in most cases, but the more irregular the reservoir, and the larger the distance between sections, the less likely it is to be true. It is thus essential that range lines are placed initially so that the survey reaches are as uniform as possible, and are representative of the situation along the reservoir. (See Appendix 3)

It is recommended that the stage width modification method is used to compute sediment volumes. As hand calculations using the procedure would be very time consuming, calculations are best carried out using the "SWIMM" software package, developed by HR Wallingford. Computations are based on the data collected from a range line survey, with cross sections and contour areas derived from pre-impoundment maps or surveys. The software computes the storage volume for a range of water levels at the time of pre impoundment and first or later surveys, and estimates the volume of sediment deposits from the differences in water volumes.

The program includes an interactive cross section editor which can be used to view, correct and verify the surveyed sections. Comprehensive graphics are provided making it easy to locate data errors. (The software and detailed guidance on its use are available from HR Wallingford.)

6.4 Calculation of catchment sediment yield

An average annual sediment yield from the catchment supplying a reservoir is calculated from the volume of sediment derived from the survey divided by the number of years between impoundment and the data of the survey, or between later surveys. This figure must then be adjusted to account for the reservoir trap efficiency, and converted to an equivalent mass using an estimate of the density of the reservoir deposits.

In most cases the accuracy of the volume changes derived from surveys is dependant mostly on the reliability of the pre impoundment information, which often has to be derived from old maps, possibly at different scales and contour intervals, and the range line spacing. The accuracy of survey results thus has to be evaluated on a case by case basis.

7 Planning a measurement programme

Many of the parameters that effect rates of soil erosion and sediment yield exhibit large variations in time and space. Also most of the methods of quantifying sediment yield have a low accuracy. Measurement programmes thus have to be carefully planned if meaningful and reliable results are to be obtained.

7.1 Measurement planners check list

Some important points to be considered at the planning stage of a measurement programme are:

- What purposes is the data be used for?, and hence what has to be measured, and what is the minium accuracy that will be needed in estimates of run off and sediment yield to ensure that the objectives of the study can be met?

- What is the length of time over which measurements should be carried out?

- Have <u>all</u> the parameters and supporting information needed to analyse and interpret the results been included in the data acquisition programme?

- Has the data collection programme been set up to <u>ensure</u> that data is collected during relatively infrequent extreme events that are so important in the sediment erosion transport and deposition cycle?

- Are sufficient resources available both to sustain the measurement programme and, importantly, to process and interpret the large quantities of data that may be collected?

- If comparisons are to be made between different land types or agricultural treatments, does the experimental design follow the recommendations concerning controls, pre treatment catchment calibration etc presented in

Reference 1, and have the effects of sediment delivery processes on the results been considered?

To ensure that a sustainable programme can be set up it is recommended that ambitious measurement programmes involving sophisticated equipment, which usually requires specialist skills for maintenance, are avoided unless they are essential to meet the project objectives, and the support required can be guaranteed over the expected life of the study. It is usually better to initiate projects with a pilot phase, which will highlight the difficulties to be overcome, before launching into a large and expensive measurement programme.

7.2 Sediment delivery effects

The quantity of sediment that is transported from a catchment is dominated by the effects of sediment delivery. Generally only a small proportion of the sediments eroded from the land surface appears at catchment outlets. This is due to the deposition of sediment eroded upslope on the land surface, at the base of slopes, and on the bed and banks of drainage channels. The effect is quantified by a sediment delivery ratio, the ratio of the quantity of sediment delivered to a catchment outlet, to that derived by summing erosion rates measured or estimated from small plots of a defined area. Sediment delivery ratios generally reduce as the size of catchment increases, and the opportunities for sediment deposition increase. Figure 15 compares sediment delivery relationships derived from regional data.

The large variations shown in this figure demonstrate that simple sediment delivery predictors should not be applied outside the region for which they were developed without verification. Thus it is usually not possible to predict sediment yield from a catchment by applying a sediment delivery ratio to measured or estimated erosion rates. A direct measurement of sediment yield at the catchment outlet is recommended if the quantities of sediment supplied to river systems are to quantified.

Catchment degradation is often reflected in a fairly rapid increase in sediment loads measured at catchment outlets, particularly when the sediments eroded from the land surface are fine, and can be transported easily through the drainage system. However reductions in erosion rates, resulting for example from catchment conservation programmes, may not be reflected in the sediment yield at catchment outlets for decades, or even centuries in large catchments. The store of easily erodible sediments within catchments and river systems continue to be reworked and contribute to sediment yields, even if "source erosion" is completely cut off. Sediment delivery effects are thus central to the analysis and interpretation of sediment yield data and must be considered carefully when measurement programmes are being planned. The "sediment delivery problem" is reviewed in Reference 19.

8 Summary and Conclusions

Methods for quantifying sediment yield appropriate for use in Developing Countries have been described. The choice of measurement method depends mostly on catchment scale. The principal conclusions from the study are listed below:

Chapters 3 and 4

For very small catchments, fractions of a hectare, catch pits or tanks provide a cheap and accurate means of measuring both water and sediment run off. However, the size of pit required becomes prohibitively large for larger catchments with appreciable storm run off volumes. Flow divisors can be used to divert a small fraction of the water and sediment run off to a tank, but it is essential that divisors are designed to ensure an equal division of sediments. Devices based on flumes with repeated division by vertical baffles are most likely to provide this.

In larger catchments, discharges can be measured with a hydraulic structure, and frequent sediment samples collected through storm events to quantify water and sediment yields. The "H" flume enables an accurate measurement of a wide range of discharges and can pass high sediment loads. Sediment sampling is simplified if the sediments leaving a flume are well mixed by the turbulent flows produced in a settling basin, and single point sediment sampling is adopted. In most cases automatic water level recording and sediment sampling is essential to ensure that run off events are monitored. The equipment developed by HR Wallingford to meet these requirements in developing country conditions for catchments of around 10 ha is described in Chapter 4.

Chapter 5

Sediment yields from larger catchments are usually quantified by measurements of the flow and sediment loads in rivers or from the quantities of sediment trapped in reservoirs. River measurements will not have a very high accuracy unless a large effort is devoted to sediment monitoring, particularly in flood flows. Recommendations based on HR Wallingford experience are summarised in Chapter 5. The most important of these are:

- Pump sampling provides the most accurate means of measuring river sediment loads.

- The accuracy of an estimate of annual sediment yield is dominated by the effects related to frequency of sediment sampling. While measurement errors can be substantial, see Appendix 2, they will in most circumstances be insignificant when compared to errors associated with an inadequate sediment sampling frequency or application of sediment rating relationships.

- When frequent observations are made in flood flows then integration of the observed sediment loads will give the greatest accuracy. When observations are infrequent, so that for example only one or two samples are collected in typical floods, then application of a sediment rating curve will give greater accuracy. The crossover between the two conditions is when the ratio of sampling interval to flood duration is about 0.3.

- The rating curve method is the most suitable technique for estimating sediment loads during periods without observations, although errors will often be large even when the recommended methods for developing sediment rating curves are used.

The principal implications of these conclusions is that sediment monitoring sites in flashy rivers either have to manned on a continuous basis during the flood season, or automatic sampling equipment used. If manual measurements are to be used a measurement technique which combines frequent dip sampling, a simple technique that can be carried out by relatively untrained local staff, with calibration measurements derived from less frequent pump sampling during flood flows, is suggested.

Chapter 6

Many of the problems associated with river sediment sampling can be avoided when data derived from reservoir surveys are used to estimate sediment yield. Provided that the reservoir is large enough to have a fairly high sediment trapping efficiency, most of the incoming sediment, including that transported in flood flows, will be trapped. The differences in sediment volumes derived from surveys integrates sediment supply over the period between surveys, which is typically five to ten years. However there are some difficulties in deriving sediment yields from reservoir volume changes, estimating a reservoir sediment trap efficiency, and the density of the sediment deposits. Means of estimating these parameters and recommended procedures for establishing reservoir volume changes are discussed in Chapter 6.

Chapter 7

A realistic appreciation of what can be achieved in monitoring programmes, and the resource implications for both sustaining a field programme, and analyzing and interpreting and reporting the results, is essential when measurements are planned. Methods using simple robust equipment are recommended, and large monitoring programmes should be preceded with a pilot phase to identify problems and constraints. If comparisons are to be made between catchments with different land use or agricultural treatments, the experimental design should follow the recommendations concerning controls, pre treatment catchment calibration, etc. presented in Reference 1. The effects of sediment delivery on the results obtained should be carefully considered.

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Tables

Table 1 "H" Flume Data

TYPE	FLUME DEPTH "D" (metres)	CALIBRATION FACTORS (see equation below)			MAXIMUM CAPACITY $m^3/s * 10^3$
		A	B	C	
HS	0.122	-0.4361	2.5151	0.1379	2.27
HS	0.183	-0.4430	2.4908	0.1657	6.14
HS	0.244	-0.4410	2.4571	0.1762	12.7
HS	0.305	-0.4382	2.4193	0.1790	22.3
H	0.152	0.0372	2.6629	0.1954	9.17
H	0.229	0.0351	2.6334	0.2243	26.9
H	0.305	0.0206	2.5902	0.2281	53.5
H	0.457	0.0238	2.4573	0.2540	150
H	0.610	0.0237	2.4918	0.2605	309
H	0.762	0.0268	2.4402	0.2600	542
H	0.914	0.0329	2.3977	0.2588	857
H	1.370	0.0588	2.3032	0.2547	2366
HL	1.070	0.3142	2.3417	0.2568	2369
HL	1.220	0.3240	2.3083	0.2527	3326

The following equation, from Reference 3, relates the discharge (Q) in m^3/s, to the measured head (h) in metres, with the values of the constants tabulated above for each flume type.

$$\log Q = A + B * \log h + c * (\log h)^2$$

Figures

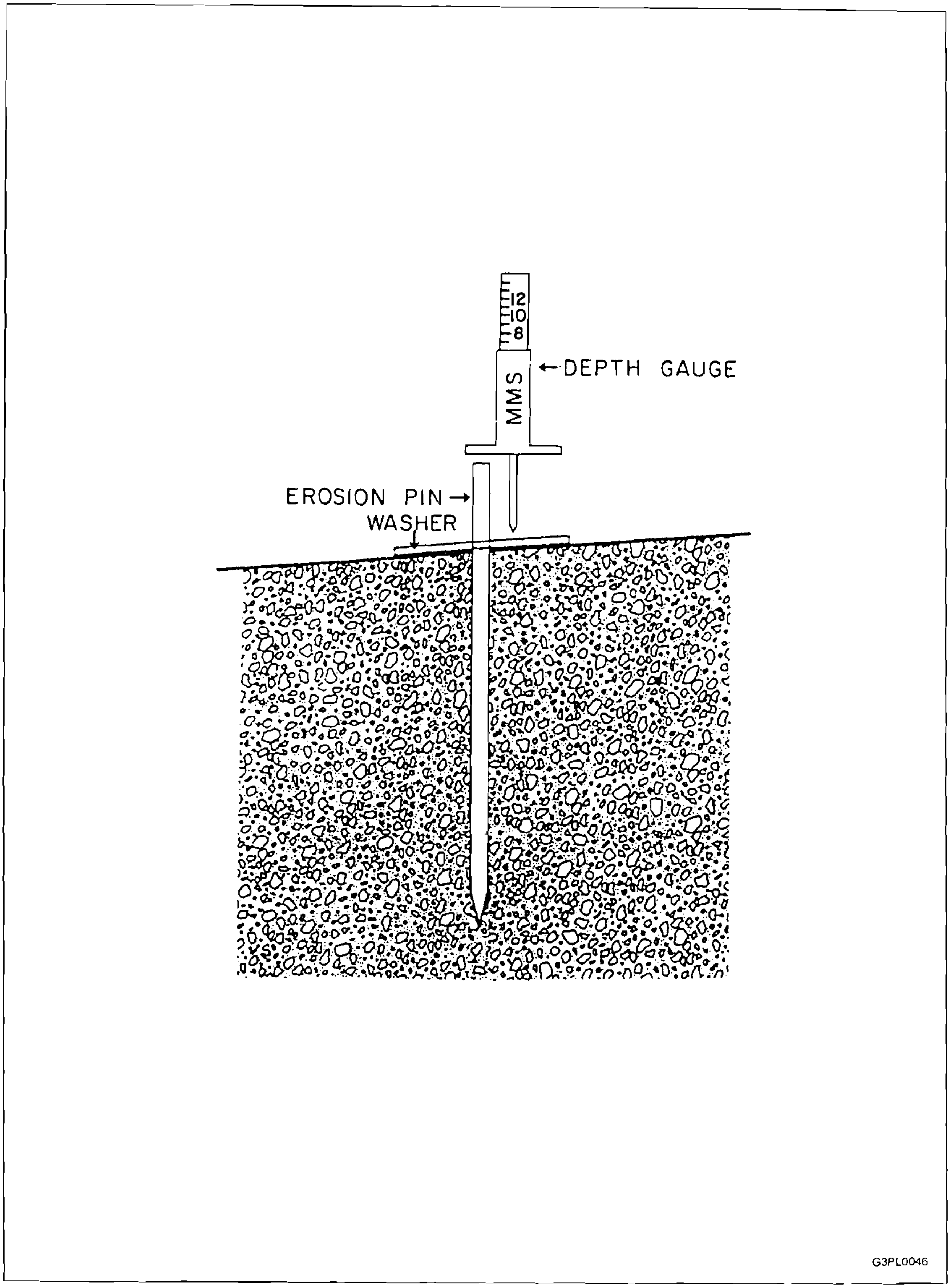

Figure 1 Erosion Pin

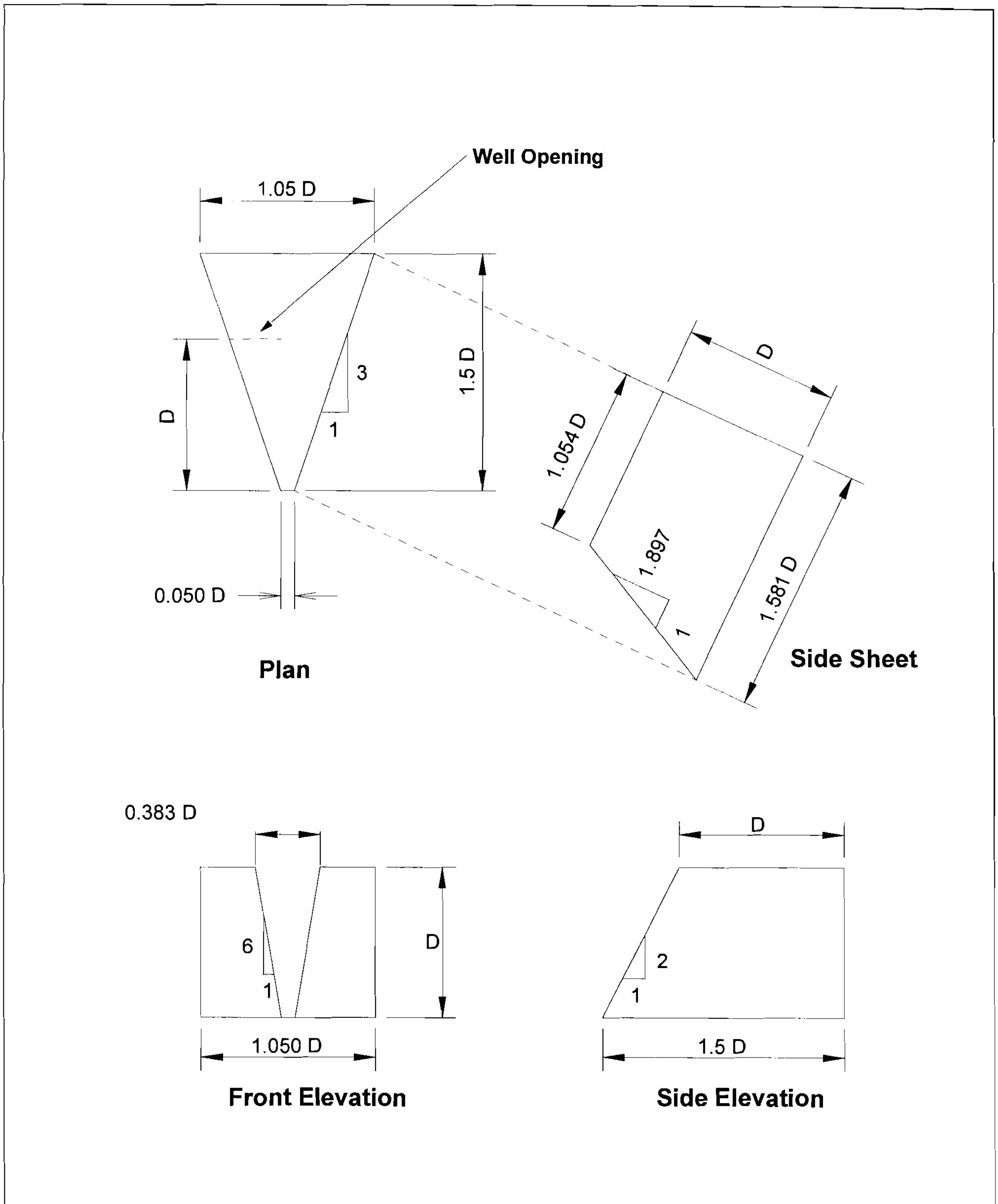

Figure 2 Dimensions of HS-Flume

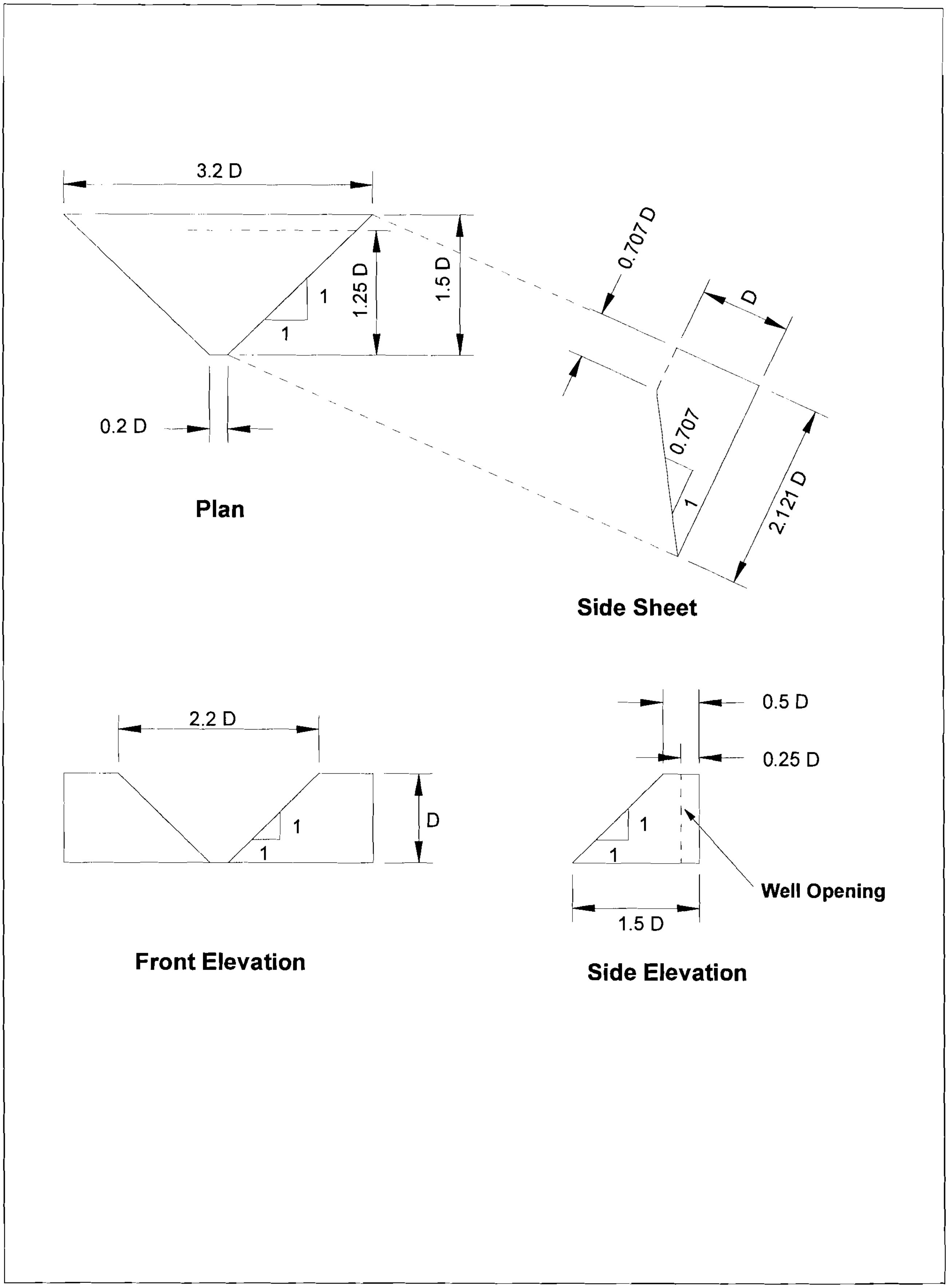

Figure 3 Dimensions of HL-Flume

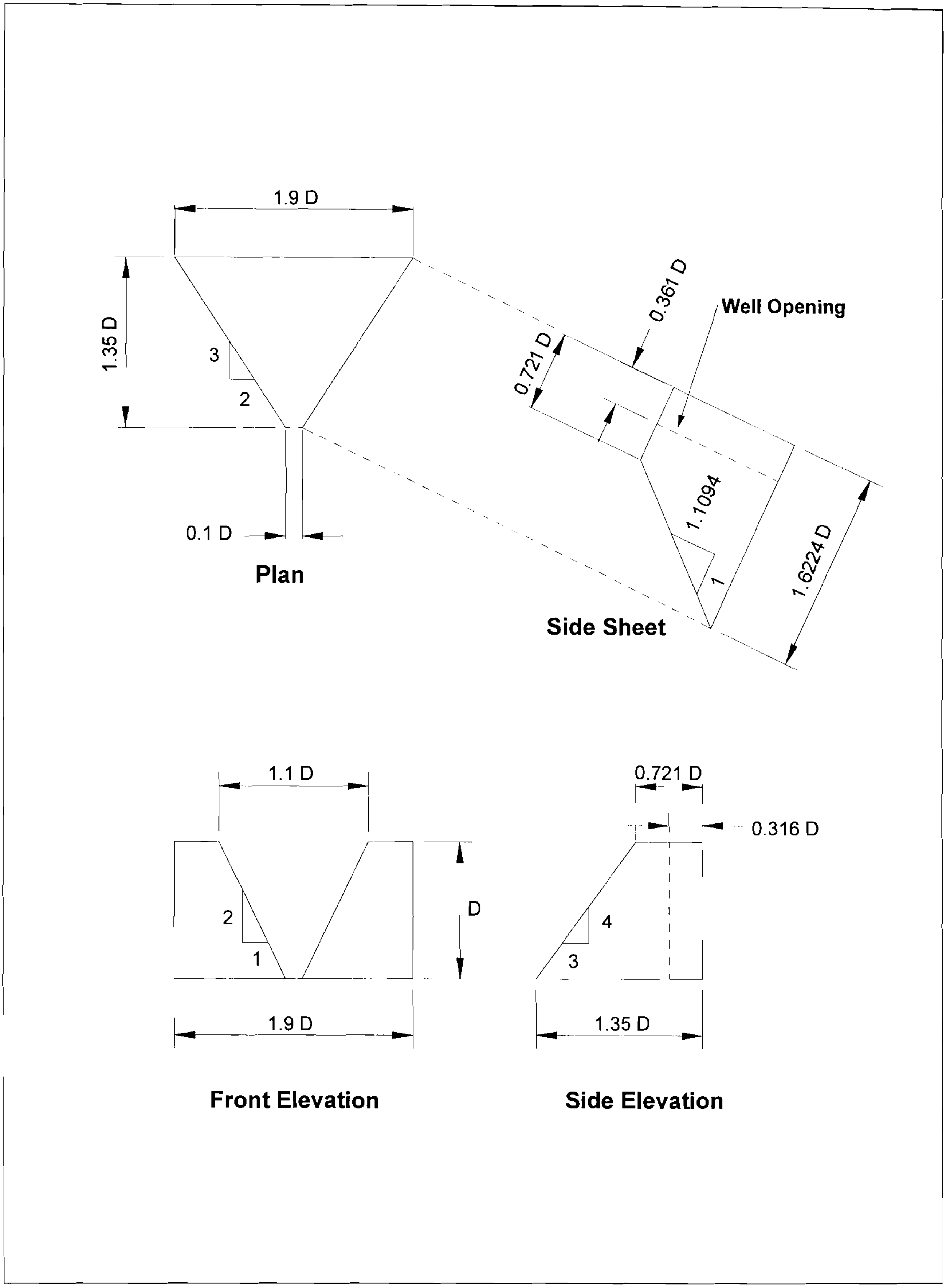

Figure 4 Dimensions of H-Flume

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Figure 5 HR Wallingford "H" Flume

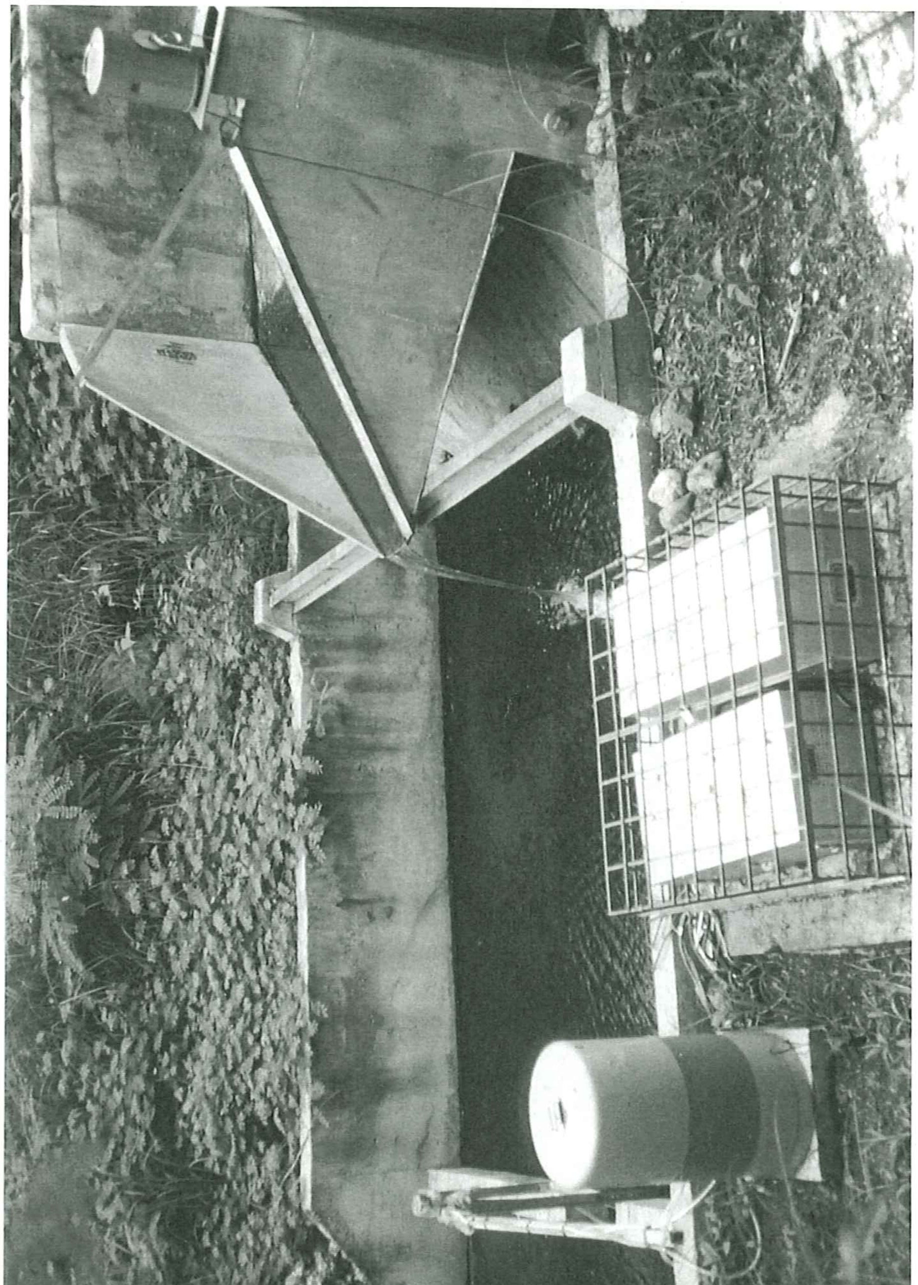

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Figure 6 Automatic Sediment Sampler, Bottle Rack

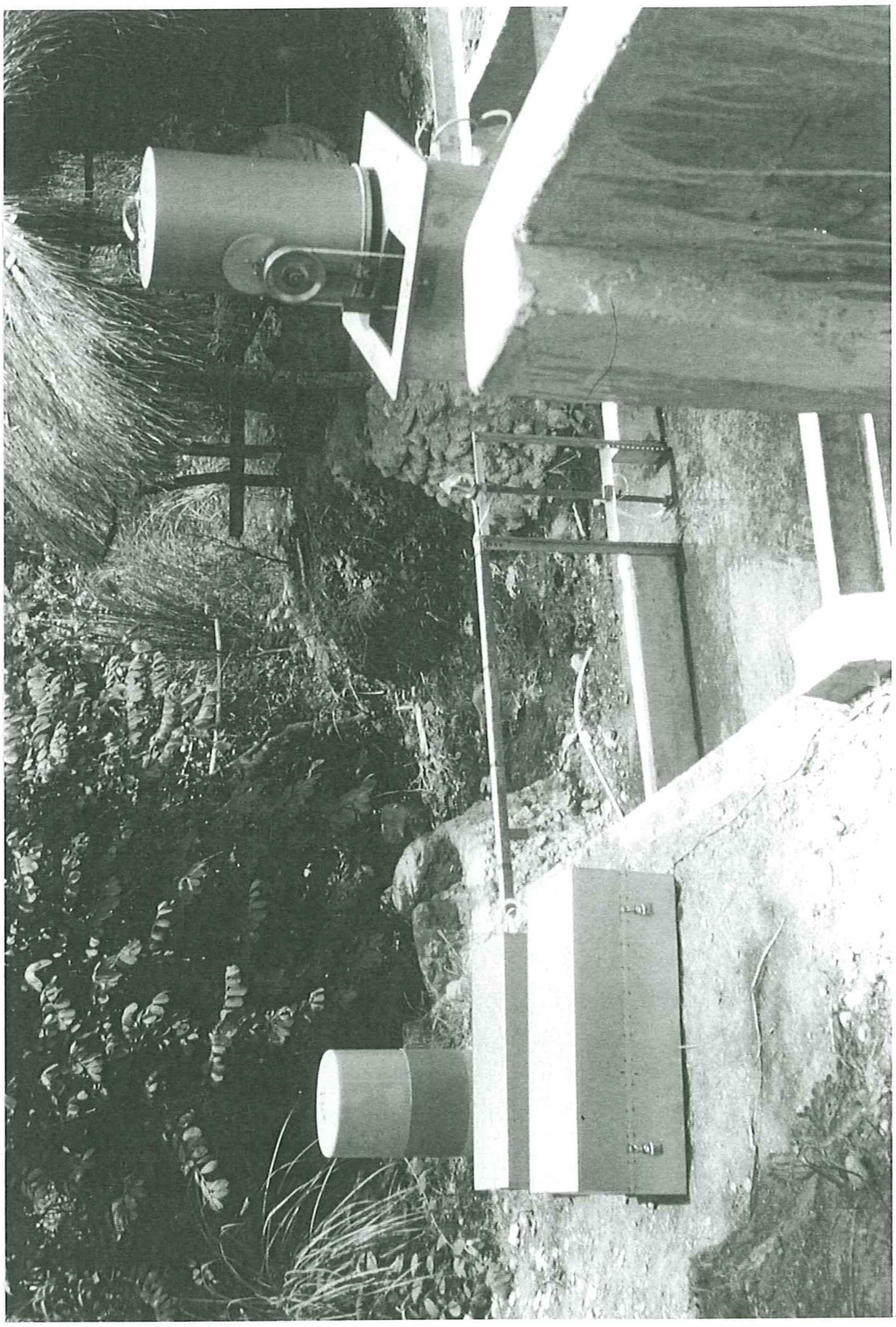

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Figure 7 Automatic Sediment Sampler, Pump and Mixing Basin

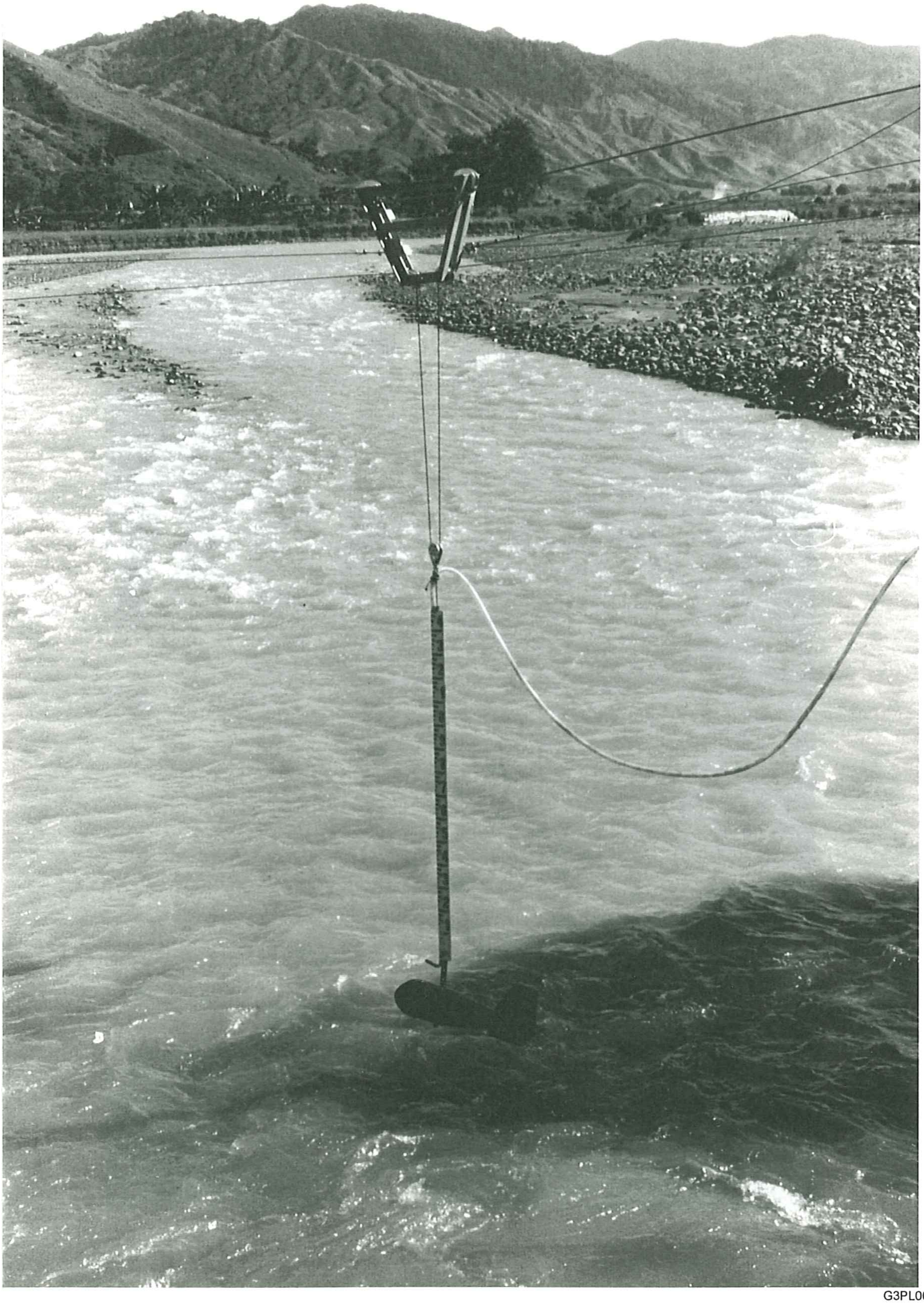

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Figure 8 Sampling Nozzle and Sinker Weight Mounted on Stream - Lined Mast

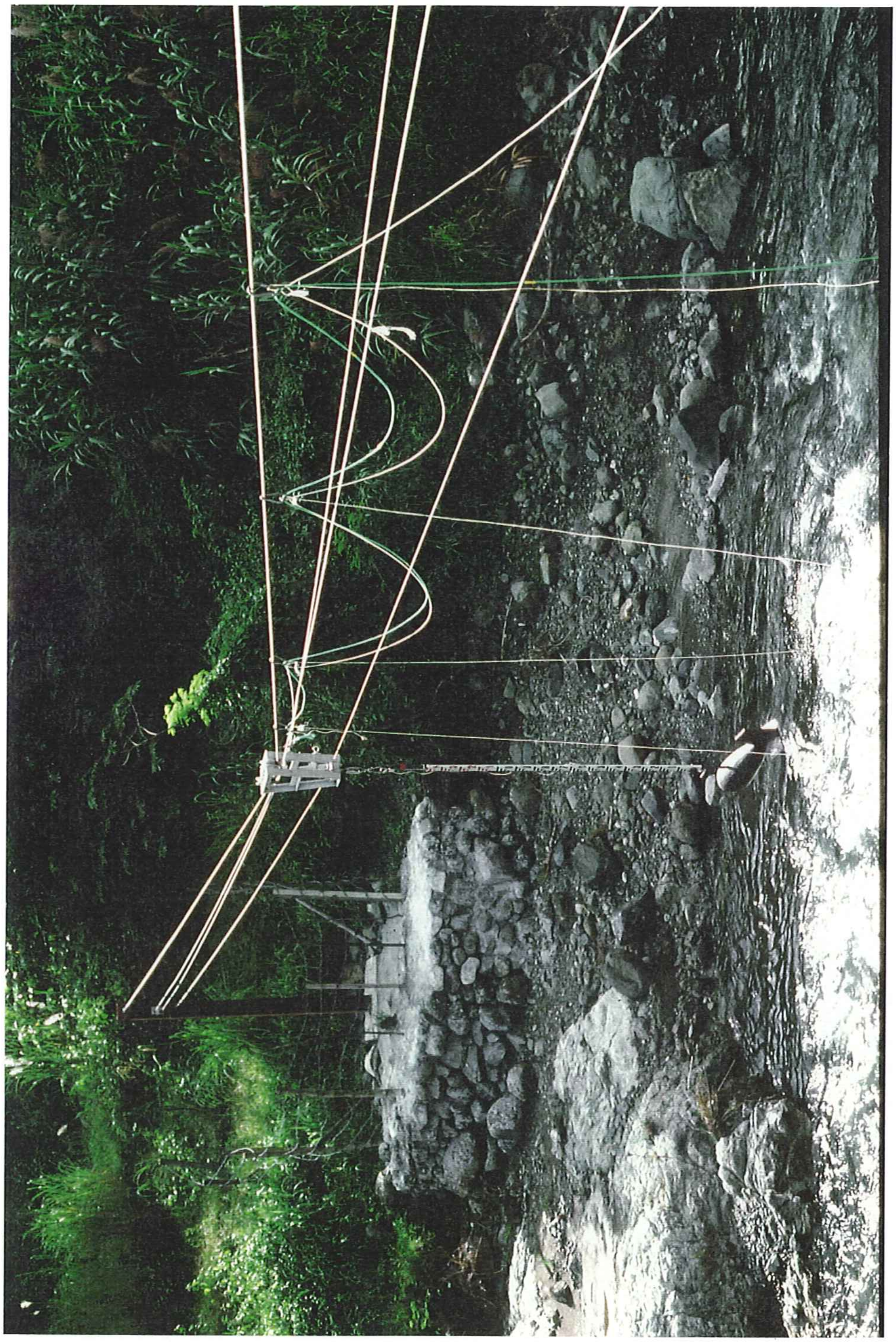

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Figure 9 Low Cost Cableway

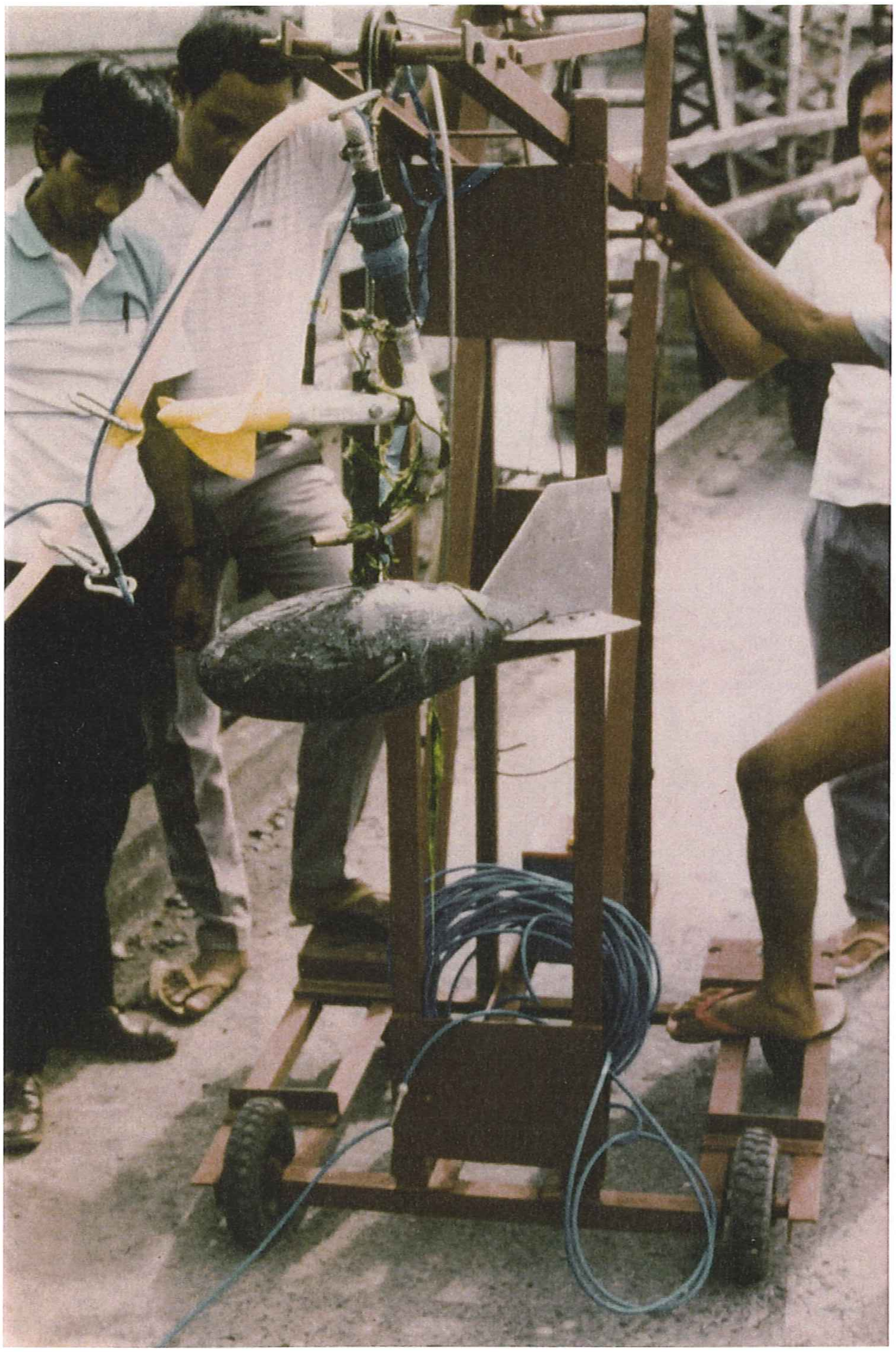

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Figure 10 Lifting Frame for Sediment Sampling from Bridges

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Figure 11 Pump Sampling

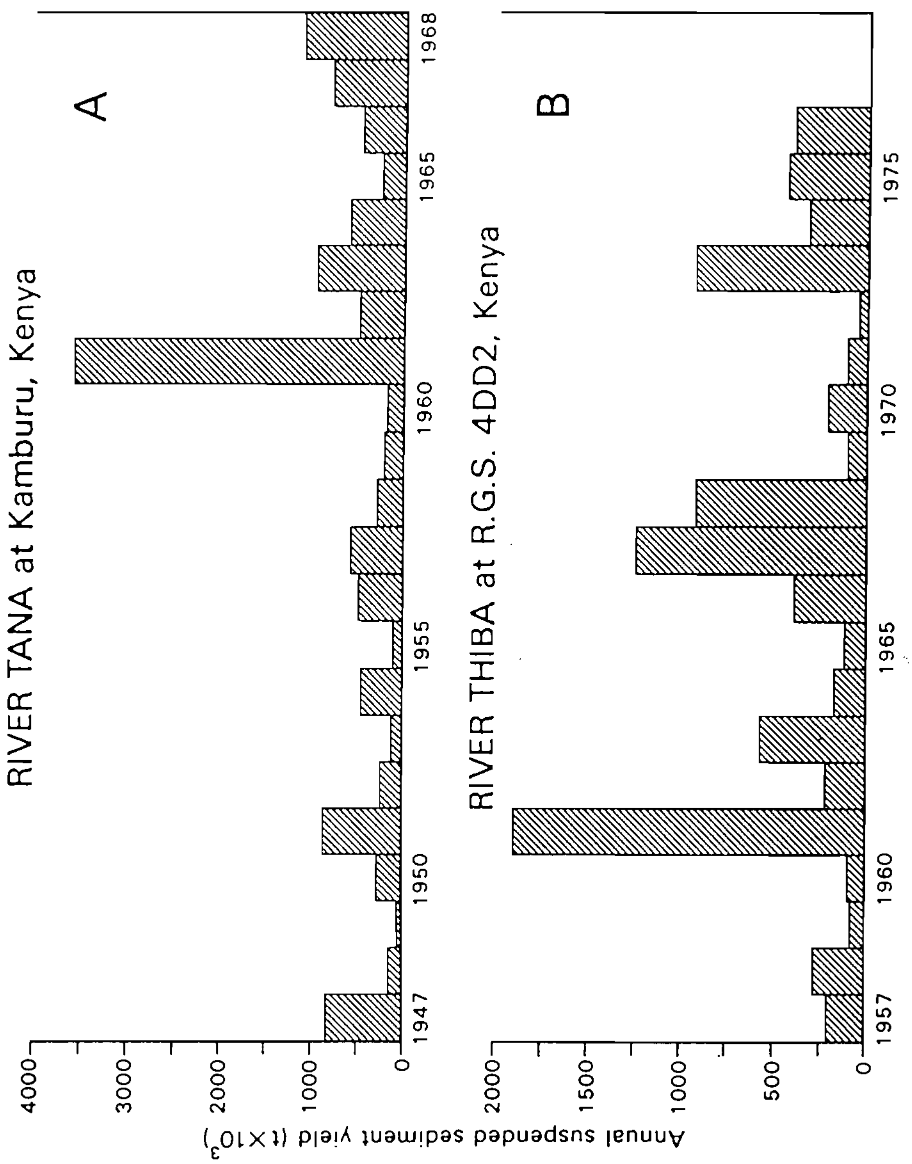

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Figure 12 Variations in Annual Sediment Loads, Kenyan Rivers

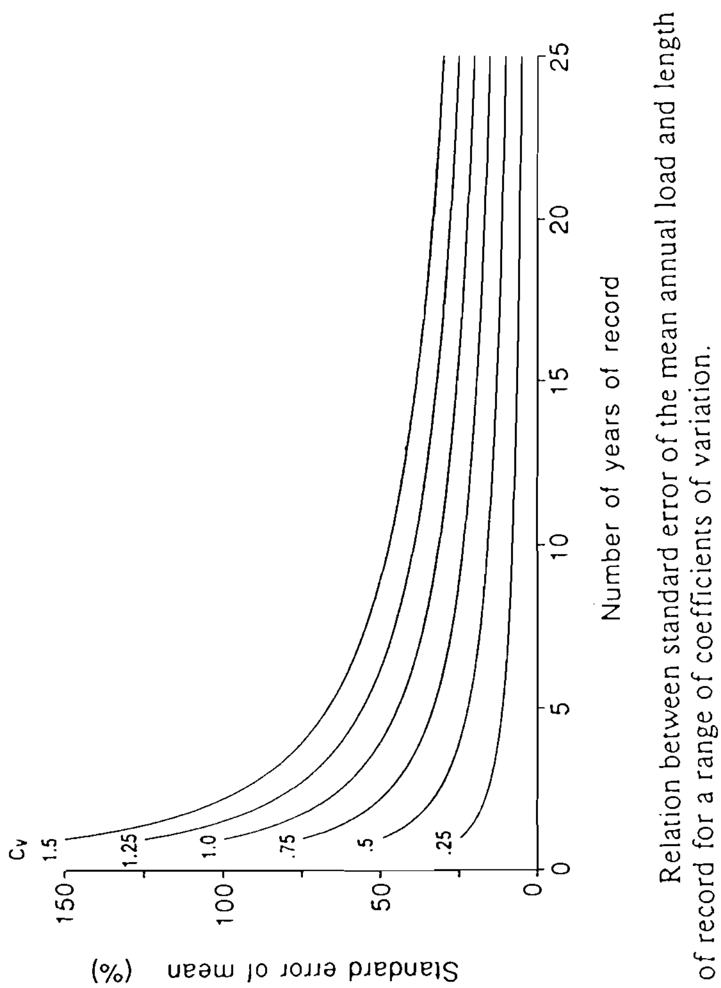

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Figure 13 Standard Error of Mean Annual Sediment Loads as a Function of Record Length, (Olive and Rieger, 1992)

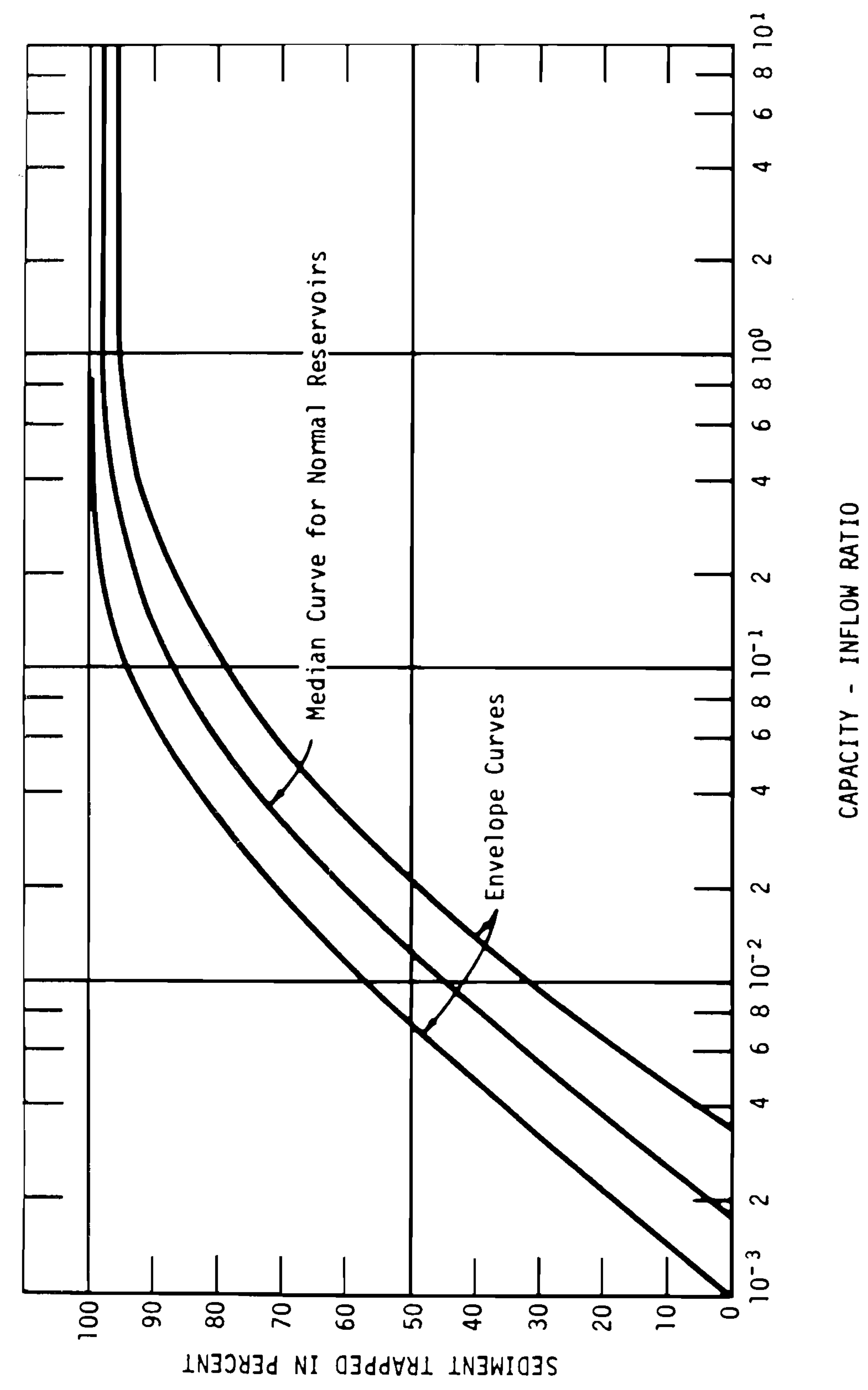

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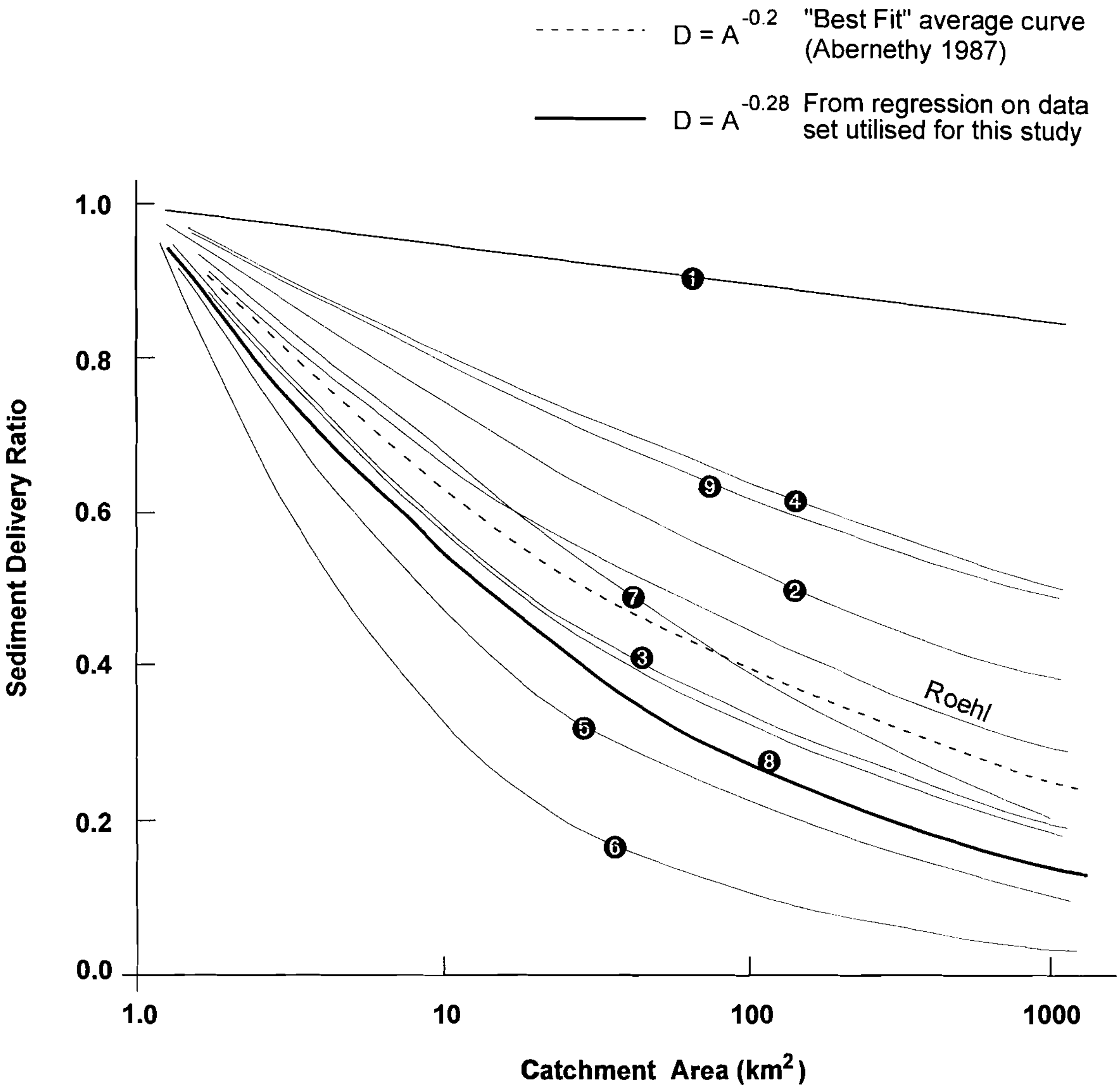
Figure 14 "Brunes" Curves



Sources:

❶	North Shaanxi	❻	West Iowa: Corn
❷	Blackland Prairie (Texas)	❼	Central + East USA
❸	Texas	❽	Missouri
❹	USSR	❾	West Iowa: Pasture
❺	Southernt Piedmont		

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Figure 15 Sediment Delivery Ratios as a Function of Catchment Area

Appendices

Appendix 1

Procedures for carrying out pump sampling

Appendix 1 Procedures for carrying out pump sampling

CONTENTS

A1.1 INTRODUCTION

A1.1.1 Background

This Appendix describes the procedures developed in studies carried out by HR Wallingford for measurements of sediment transport using pump sampling. The techniques have been used to collect sediment samples in a wide variety of measurement situations in many Developing Countries.

A1.1.2 Definition of terms

We follow the definitions of the various sediment transport mechanisms given in ISO 1977. In summary these are:

Total Load - All the sediment in transport.

Bed Load - The sediment transported in almost continuous transport with the bed, carried forward by rolling, sliding or hopping.

Suspended Load - Sediment maintained in suspension by turbulence in the flowing water for considerable periods of time without contact with the stream bed.

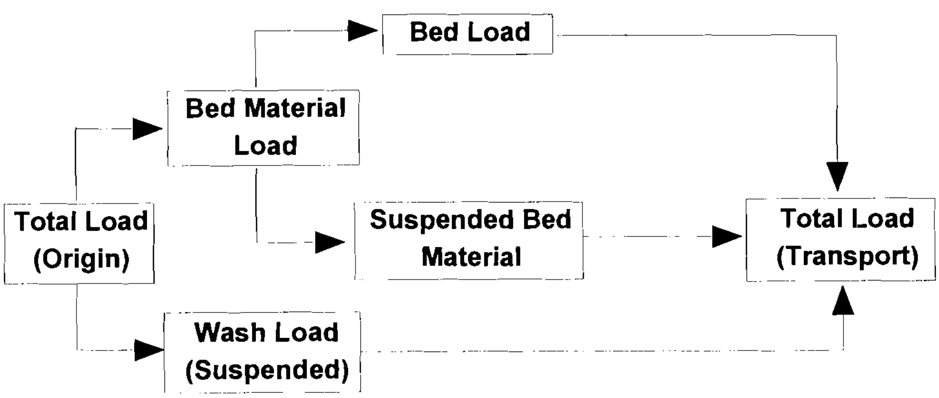
Wash Load - That part of the suspended load which is composed of particles smaller than those found in appreciable quantities in the bed material. The discharge of wash load through a reach depends on the rate at which these particles become available in the catchment, and not on the transport capacity of the flow.

To these definitions we add:

Suspended bed material load - That part of the suspended load which is composed of particle sizes present in the channel bed. The concentration of suspended bed material load is governed by the hydraulic parameters in the channel reach.

Total bed material load - The sum of the suspended bed material load and bed load.

These link between the various components of the total load can be illustrated as shown below:



In practice the point at which bed load becomes suspended bed material, and suspended bed material becomes wash load, are not well defined, and for a particular sediment size will vary with flow parameters. In engineering studies in rivers we "define" as wash load all particles smaller than sixty three microns, as sediments smaller than this are not usually found in significant quantities in the river bed material. However this definition is arbitory. For example in very steep rivers sediments very much larger than 63 microns can behave as wash load, ie the concentrations in transport are supply controlled, and may not be related to local hydraulic parameters such as river discharge.

A1.1.3 Measurement of the components of total load

Wash load is relatively uniformly distributed in the flow, and wash load sediment concentrations can be measured with simple dip sampling equipment. However the pump sampling procedures described later are also used to measure washload.

Suspended bed load concentrations are largest near the channel bed, reduce towards the free surface, and can also vary across the channel width. By sampling sediment concentrations at a number of locations in the flow the mean concentration can be determined. The pump sampling method described in the report is designed primarily to measure suspended bed load concentrations.

Bed load is difficult to measure reliably, partially because of uncertainties over its definition, and hence uncertainty over what exactly is being measured with conventional bed load samplers. However in channels with sand beds, which includes most rivers, bed load usually represents less than ten percent of the total bed material load, and errors in its estimation will not have a large impact on the accuracy of total load measurements. The method used to analyse pump sample data, described in Appendix 2, partially accounts for unmeasured bed load.

A1.2 PUMP SAMPLING

The method is relatively simple. A pump is used to draw a sample of water and sediment through a nozzle mounted in the flow, and convey the sample via a plastic pipe to the channel bank or other convenient location. A single nozzle can be suspended from a winch or cableway, or an array of nozzles mounted at fixed points in the flow on a streamlined mast, or secured to an existing structure.

The pump discharge is passed through a sieve to separate the very fine sediments (wash load) from the suspended bed material. The weight of sediment and water pumped over the sampling interval gives the sediment concentration at the nozzle location. By sampling at a number of locations in the flow concentration profiles can be determined, and the mean sediment concentration established.

A1.3 EQUIPMENT

A1.3.1 Suspension Gear

There are several methods of suspending a sediment sampling nozzle and current meter in the flow. A single nozzle can be suspended from a winch or cableway, an array of nozzles mounted at fixed points in the flow on a streamlined mast, or secured to an weir or other flow measuring structure. In most cases a cableway or suspension derrick mounted on a bridge have proved to be the most successful systems. Fixed nozzles mounted on a mast have advantages but have suffered from blocked nozzles, which are difficult or impossible to clear when the river is flowing, and mast failures due to the build up of trash. Cableways and suspension derricks are available commercially, however in HR studies it has often proved far cheaper to manufacture simple cableways and suspension systems using the winches and blocks and cables etc that are readily available from ships chandlers. (An example of a low cost cable way is shown in Figure 9).

If the expected flow velocities are larger than say 1.5 m/s it is necessary to reduce the drag forces on the suspension gear by using a streamlined mast section (Figure 8) with the sampling hose and current meter cables running inside. Use of a mast section enables the size of the sinker weight to be reduced. With a large sinker weight, or a vane set to produce downforce, measurements have been carried out in flows with velocities up to 3.5 m/s. (Bottle sampling equipment could not be used in such high velocity flows)

The basic items required to carry out pump sampling are described below:

A1.3.2 Pump

The pump used for most studies is a 24 volt positive displacement pump with a helical steel rotor and a resilient stator, capable of pumping high sediment concentrations. The pump can be operated with a vertical lift of up to about 4 metres, the limit depending on the length and diameter of suction hose that is used. The pump is powered by two car batteries, wired in series, and controlled by a heavy duty switch. Typically about thirty samples can be pumped before the batteries need recharging, this figure depending on the sampling time used, the pumping duty, and the capacity and condition of the batteries.

A1.3.3 Sampling Nozzle and sinker weight

A sampling nozzle, (internal diameter typically 15 mm), is attached to the sinker weight by a suspension bar, or mounted at the base of a streamlined mast section. The sinker weight is required to maintain the nozzle at a fixed location above the river bed. A 14 Kg weight is suitable for use in velocities up to about 1 metre/ second, with larger weights required for higher velocities.

A1.3.4 Hose, sieve, and bucket.

Water and sediment are drawn up from the river by the pump through a reinforced plastic hose. The pump discharge is passed through a sixty three micron sieve, which retains sand sized sediments, the water passing the sieve is collected in a bucket.

A1.3.5 Wash bottle and sample bottles

Sediment retained by the sieve is washed into a numbered sample bottle using a Wash Bottle. Sample bottles are also used to collect and store a wash load sample from the bucket.

A1.3.6 Current meter and counter

Any standard current meter could be used. In HR studies one of the Braystoke range of current meters are used as they have impellers which can easily be replaced in the field and a group calibration is available. The counter unit is supplied in a rugged waterproof box and can be set to integrate the current meter count over the 100 seconds that is recommended.

A1.4 PROCEDURE FOR PUMP SAMPLING

The field procedures that are followed will depend on the purpose of the measurements, and on how the sampling nozzle and current meter are mounted in the flow. Here we assume that measurements are being made using a cableway, or a lifting frame located on a bridge.

At least three people are required, one to operate the lifting frame or cableway, one to operate the pump and carry out sieving and current metering etc, the third to direct operations, operate a stop watch, and record the data on to a field data sheet.

Before the measurements start the number of verticals to be measured, and the non dimensional sampling locations on each vertical should be established using the information presented in Appendix 2.

The procedure is:

- Position the equipment at the location chosen for the first vertical. Measure the distance between the base of the sinker weight and the centre of the sampling nozzle and current meter. Determine the depth of flow at the measurement location.

- Set the sampling nozzle and current meter nozzle at the first of the pre-determined sampling positions, (see Appendix 2)

- Switch on the pump, allow between ten and twenty seconds for the pump to prime, and for a steady flow to be established.

- Direct the flow from the pump outlet into the sieve held over the bucket, starting the stop watch at the same time. When the bucket is full the pump outlet pipe and sieve are moved away from the bucket, the "lap time " button on the stop watch is pressed, and pumping and sieving are continued. The time over which the sample is collected depends on several parameters, a minimum of two minutes is recommended, but longer sampling times may be required if the sediment concentration is low. In general at least one gramme of sediment is needed to minimise weighing errors, preferably about ten grammes of sediment should be collected. When two minutes has elapsed, and enough sediment has been collected, the pump discharge can be directed away from the sieve, the stop watch stopped and the pump switched off.

- Measure the water velocity over a time period of 100 seconds while the sediment sample is being collected.

- Wash the sediment trapped on the sieve into a numbered sample bottle. Note the sample location and bottle number, the time to fill the bucket, and the time over which the sample was collected on the field data sheet.

- Stir the water and fine sediment in the bucket until the sediment is well mixed, collect a wash load sample in a second numbered sample bottle.

- Repeat the procedure at the remaining sampling position on the vertical and at the other verticals.

The velocity measurements made in the procedure set out above are used in the analysis to derive a mean sediment concentration. They can also be used to compute the river discharge. However in a typical measurement sediment data may at be collected at two or three verticals. To obtain a more accurate discharge measurement velocity measurements will have to carried out at additional verticals. The number of verticals required can be selected using information presented in the International Standards for stream gauging listed in the references.

If velocities are not measured then the mean sediment concentration can still be computed, with a possible reduction in accuracy, provided that the discharge passing the measuring location is known, and the water surface slope in the river reach upstream from the measurement location is known or can be estimated. The method is described in Appendix 2.

A1.5 SEDIMENT ANALYSIS

Sediment samples should be sent to a suitably equipped analysis laboratory. The dry weight of suspended bed material and washload samples should be determined using standard procedures. In some cases the suspended bed material load samples will also be sieved to provide a cumulative size grading curve for the suspended bed material load.

A1.6 CALCULATION OF SEDIMENT LOADS

The quantity of sediment passing a point in a channel is proportional to the product of the local velocity and the local sediment concentration. In general the highest velocities occur near the surface, while the highest sediment concentrations occur near the bed. Multiplying the velocity and sediment concentration profiles together yields a sediment flux profile, which has to be integrated to find the mean sediment concentration for a vertical.

Appendix 2 describes the methods that are used to compute sediment loads from field data collected using the pump sampling procedure described above. The calculations can be carried out using the HR Software DSAS, details of which are available from HR Wallingford.

Appendix 2

Accuracy of sediment load measurements in rivers

The material in this Appendix is derived from the paper, "Accuracy of sediment load measurement in rivers and canals" by E Atkinson and P Bolton, first presented at a Workshop on Sediment Measurement and Control, and Design of Irrigation Canals, IPD, Lahore, Pakistan, in October 1989. Reprints of the original paper are available from HR Wallingford.

Appendix 2   Accuracy of sediment load measurements in rivers

CONTENTS

FIGURES

TABLES

A2.1 INTRODUCTION

Sediment load measurements in rivers and canals are required for many engineering, agricultural and environmental purposes. However the difficulty and cost of maintaining a regular programme of sediment discharge measurements prevents the authorities in many countries from obtaining adequate sediment transport records. Much of the data that is available is of dubious reliability due to the methods used to collect and analyse sediment samples.
In this appendix theoretical principles are applied to the measurement of sediment loads, in order to maximise the accuracy which can be obtained from practical measurement techniques using relatively simple equipment. It is recognised that increased precision requires increased effort in both the field and laboratory. It is thus important to assess errors due to measurement methods, and arising from simplifications if optimum use is to be made of available resources. The various components of the term sediment load are defined in Appendix 1.

The advantages and disadvantages of four methods of bed material load measurement commonly used in routine data collection programmes, and two methods of wash load measurement are discussed. Errors associated with the pump sampling method for bed material measurements and bottle sampling for wash load measurement are quantified, and recommended measurement procedures to minimise errors are presented.

A distinction between wash load and bed material load based on sediment size, for example sediment sizes that are not found in appreciable quantities in the river bed are regarded as wash load, does not constitute a rigorous definition. Nevertheless, for the majority of rivers, large errors are unlikely to be introduced if wash load is "defined" as the movement of particles of less than 63 microns and bed material load "defined" as the movement of all larger particles. These "definitions" have the advantages of being clear and simple to apply.

Emphasis is sometimes placed on a further distinction; that between "suspended bed material load" (also referred to as "saltation load") and "bed load". This distinction is based more on the practical consideration of what particles can and cannot be trapped in sediment samplers than on a conceptual separation based on hydraulic principles. Except in situations where the supply of bed material becomes exhausted or where significant "armouring" occurs, the two transport mechanisms depend on the same hydraulic forces acting on the same heterogeneous supply of sediment particles. The measured (suspended bed material) load can, therefore, be extrapolated to provide an estimate of the unmeasured (bed) load if the measurement procedure adequately defines the variation of sediment discharge with depth.

A2.2 METHODS USED TO MEASURE SEDIMENT CONCENTRATIONS

Bottles or sediment traps

The simplest sediment concentration measurements are obtained using a bottle or sediment trap which removes a small volume of water from the flow, usually through a nozzle, for subsequent analysis. The main sources of error in using this technique are as follows:

Variations of concentration with depth. Only in the case of wash load or where the sediment is fully mixed in the flow can it be assumed that sediment concentrations are uniform across the river section. In all other cases, larger sediment particles are present in greater concentrations close to the bed than at the surface of the flow. Sampling devices must be capable of extracting samples from known locations in the flow so that concentration variations can be recorded.

Distortion of flow patterns by the sampling device. If the velocity of the water entering the sampling device is different from that in the surrounding flow the sample obtained will not contain representative concentrations of all the particle sizes present.

Small sample size. The principal disadvantage of bottles and sediment traps is the size of sample which is obtained; generally less than one litre. With samples of this size it is difficult to separate sediment of different sizes during the laboratory analysis, and this will introduce errors into the sediment discharge calculation. At the very least, samples must be large enough for the wash load particles to be separated from those of the bed material load. Where there are low sediment concentrations, or where the concentration is fluctuating greatly due to turbulence, the use of small samples will lead to potentially large random errors.

Depth integrated samplers

Depth integrated samplers were produced in the USA following extensive field and laboratory studies aimed at standardising sediment sampling techniques (Nelson & Benedict, 1951). They were designed to remove the need for multiple sampling, whilst taking account of variations in sediment concentration with depth. To achieve this a sample is collected as the sampler is lowered from the surface to the bed. The rate at which water enters the sampler is proportional to the water velocity at the sampling point, so that the total sediment discharge can be obtained simply by multiplying the concentration of sediment in the sample by the total water discharge through the section or sub-section. Despite the speed and simplicity offered by depth integrated samplers they have a number of important disadvantages:

The sample obtained is relatively small (½ litre), which introduces errors as described in the previous section.

Since sediment transported close to the bed cannot be sampled a rather complex correction calculation to account for sediment transported in the unsampled zone must be undertaken. The correction often accounts for a significant proportion of the final "measured" sediment concentration.

The operation of the sampler requires some skill in order to achieve uniform sampling through the depth.

The standard model of depth integrated sampler (US D-49) cannot be operated in depths greater than 5m.

The nozzle size must be kept small to prevent the sample bottle from overfilling, but use of a small nozzle introduces sampling errors when coarse sand particles are in transport.

Delft Bottles

Delft Bottles were developed to overcome the problem of small sample size, one of the principal drawbacks of depth integrated samplers. A sample drawn in through a nozzle passes through a chamber designed so that sediment particles settle out of suspension, allowing the sample to be trapped and water to be released back to the river. In this way sediment from a large volume of water can be collected. Unfortunately the Delft Bottle cannot measure wash load, since it traps only the larger sediment particles. Careful calibration is required to make allowance for the proportion of the smaller sand particles which pass through the sampler with the ejected water. Delft Bottles can be used either to sample at a single location, or to collect depth integrated samples.

Pump sampling

For pump sampling a nozzle is positioned in the flow and connected by a plastic pipe to a pump placed on the river bank/boat or bridge. Water and sediment are pumped through the nozzle and passed onto a 63 micron sieve, to separate washload. The dry weight of the sediment retained on the sieve, the sampling period, and the pump discharge (measured using a bucket or graduated oil drum and stopwatch) provide a time averaged concentration of sediments larger than 63 microns at the nozzle position. Sediment concentrations are measured at a number of depths, and fitted to a theoretical concentration profile. The resulting concentration profile is used in combination with a velocity profile to calculate the sediment discharge.

Pump sampling has the following advantages over other sampling methods:

There is almost no limit to the volume of the sample taken. A 50 litre sample is collected in about 2 minutes of sampling using the portable equipment currently employed by HR Wallingford. This avoids the errors associated with small sediment sample weights, and short sampling durations.

Extrapolation of the fitted velocity and concentration profiles provides a reliable method of predicting sediment discharge in the unsampled region close to the bed.

The technique may be adapted for use in extreme conditions of fast flow in floods. A nozzle attached to a sinker weight suspended from a cable will perform at least as well as bottle-type samplers particularly if the hose is mounted inside a streamlined mast section. Nozzles can readily be attached to moveable or permanent structures located in the river.

Comparison of sampling methods

Van Rijn and Schaafsma (1986) report a comparison of the USP-61 bottle sampler, the Delft Bottle and pump sampling. Measurements were carried out in the Danube river near Ilok, Yugoslavia. The samplers were positioned within a few metres of each other at the same distance above the bed. The USP-61 had a sampling period of about 30 seconds, this caused fluctuations in measured sediment concentration of up to 50% during repeat sampling. The Delft Bottle avoided these temporal fluctuations but suffered from a loss of sample due to finer sediment passing through the device, as well as a probable loss of sample during hoisting of the instrument. Pump sampling gave relatively small fluctuations in measured concentration, fluctuations were over the range ± 6% of the mean value for 300+ samples. Van Rijn and Schaafsma recommended pump sampling as the most suitable method for sand sized sediment transport measurements.

A2.3 ANALYSIS OF PUMP SAMPLE DATA

The following calculation procedure is used to compute the total sediment discharge at a vertical from a set of measured sediment concentrations and velocities at known heights above a channel bed. Firstly a theoretical concentration profile is fitted to the sediment data. The exponential profile due to Lane and Kalinske (1942) is recommended for ease of computation, also it has consistently performed well when compared to data measured in HR studies.

$$C = C_a e^{-ky/d} \qquad (1)$$

where

C	=	sediment concentration at height y above the bed
C_s	=	reference concentration
k	=	a constant, related to the steepness of the concentration profile
y	=	height above the bed
d	=	flow depth.

Similarly velocity data are fitted (by adjusting u*) to the Karman-Prandl logarithmic velocity profile

$$u = \bar{u} + \frac{u_*}{\kappa} (\ln(y/d) + 1) \qquad (2)$$

where

u	=	velocity at height y above the bed
$\bar{u}$	=	mean velocity
u.	=	shear velocity
κ	=	Von Karman's constant which is taken to be 0.4.

The gravimetric sediment flux at a point (sediment discharge per unit area) is the product of sediment concentration and flow velocity. The total discharge in the vertical section is the integral of sediment flux from the bed to the surface. This value divided by the mean velocity in the vertical gives the velocity weighted mean sediment concentration hereafter referred to as the mean concentration. An additional allowance for bed load can be included in the analysis using the conceptual model of Einstein (1950) which relates bed load to the reference concentration, Ca, two grain diameters above the bed.

A2.4 ACCURACY OF PUMP SAMPLING

The benefits of knowing the magnitude of the error in sediment discharge measurements are:

> Optimisation of the field and laboratory resources. For most sources of error an increase in effort will reduce the error; for example, sampling at a greater number of points in each vertical. By comparing the effectiveness of the various means of reducing error, the best use of field and laboratory resources can be made.

> Assessing required frequency of sediment load measurement. Some measurement errors are random in nature, so repeated measurements give a greater accuracy. By quantifying errors the required frequency of measurements can be estimated.

Compensation of errors. If a systematic error can be predicted then a compensation factor can be applied and a more accurate result obtained.

In the rest of this section the sources of error in bed material load measurement using the pump sampling technique are listed, and the errors involved are assessed. The pump sampling technique is subject to both random and systematic errors; the latter can be reduced in many cases by applying a suitable correction procedure. Both types of error as well as correction procedures are discussed below.

In every case the magnitude of the error is related to the parameter k, defining the steepness of the sediment concentration profile. Values of k at a particular location are related to the slope of the river channel, and the composition of the bed material. In addition, values vary with the flow conditions. For example in a typical river measurement situation, the Mae Tang river in Northern Thailand, k values derived from measurements ranged between 1.8 and 3.2.

Bed load

A direct measurement of bed load presents great difficulties. The problem arises 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. There are number of bed load samplers, but their use often interferes with the processes of sediment transport which they are trying to measure.

By following the measurement procedure described in this appendix, data for the suspended bed material flux at various depths in the vertical is obtained. A sediment flux profile can be drawn through these data, and the profile extrapolated to the bed to provide an estimate of the total load. The bed load is included since it is governed by the same hydraulic forces as the suspended bed material load. However in practice there may be residual systematic errors as the extrapolation procedure cannot adequately account for the near-bed particle movements.

Two approaches can be used to judge the magnitude of the error. An estimate of the upper bound for the error can be obtained by predicting the bed load using a bed load formula, such as the Bagnold (1980) formula. Experience has shown that, for canals and rivers where the bed material consists of sediments in the sand size range, this usually gives a value of bed load of less than 10% of the total bed material load. An indication of the likely importance of the bed load can also be derived from the suspended sediment concentration measurements. If the predicted sediment flux in the bottom 5% of the flow profile is less than about 10% of the total sediment flux then the bed load is likely to be unimportant. Figure A2.1 shows predictions of this near-bed sediment flux for differing values of u/u^* and k. The figure was obtained using Equation 1 with the near bed load enhanced using the Einstein (1950) bed load formula as described in Section 4.

The effect of bed forms

The presence of bed form will affect the accuracy of bed material load measurement. Field data from the Middle Loup river, Dunning, Nebraska, highlights the effect of dunes (Guy, 1970). Consecutive measurements of suspended bed material load at a vertical when the river had a plane bed form gave a standard deviation of 3% of the mean, while a dune bed form gave 10%.

Antidunes are likely to present a rather worse situation, but they constitute a special case not covered in the sediment measurement procedure.

When using theoretical profiles in the measurement procedure as described above in a situation where bed forms are present, it is assumed that the profiles apply over the flow depth from the mean bed level to mean water surface level. When single depth measurements are made a range of values could be recorded, a minimum depth being measured when the point of contact with the bed is at the crest of a bed form. This source of error is discussed below.

A dune passing the measuring point represents a transfer of material which might be thought to introduce further errors when the suggested measurement procedure is adopted. However, the argument of continuity persuades us that this "error" cannot be greater than the magnitude of the bed load itself.

Measurement of bed level

An inaccurate determination of bed level position relative to the sampling positions will cause an error in the measured sediment load. It can be shown using the exponential sediment concentration profile that the error in mean concentration due to an uncertainty in bed level of magnitude b is:

$$\text{Error} = \left[\frac{e^{kb} - e^{-k}}{(b+1)\ (1-e^{-k})} - 1\right] \times 100\% \tag{3}$$

Dunes are the principal source of uncertainty in bed level, their effect is quantified in Figure A2.2, which shows maximum possible errors in sediment load measurement as a function of relative grain size D_{50}/d, and concentration profile steepness, k. The errors were calculated using Equation 3 and the Van Rijn (1984) bed form height predictor. These are maximum possible errors because both the worst case for the transport parameter and bed level (half dune height) is chosen. The figure shows that quite large errors could be produced due to the presence of dunes, perhaps up to 10% for deep rivers carrying fine sand, 10% to 20% in shallower rivers and greater errors in more extreme conditions. These will be random errors, which can be minimised by carrying out repeat measurements.

Choice of theoretical sediment concentration profile

A measured sediment concentration profile will not have a shape which perfectly fits theory, and this will introduce a systematic error. Two theoretical concentration profiles are commonly used in the literature, the exponential profile proposed by Lane and Kalinske (1942) as used in this appendix, and the Rouse (1937) profile. Laboratory research (Coleman, 1970, & McTigue, 1981) has suggested that a two layer model may be the most accurate, with the exponential profile applying to the upper half of the flow and the Rouse or a power law profile near the bed. Thus a measured profile might be expected to lie somewhere between the two theoretical profiles.

Errors produced by an inaccurate representation of sediment concentration profile have been quantified by comparing the exponential profile and the Rouse profile. The difference in results obtained by fitting data to the two profiles was tested analytically, and was found to be sensitive to the sampling positions used in the calculation. Heights of sampling position were obtained which minimise the difference between the two profiles; they are given in Table A2.1. Table A2.1 lists the differences between the profiles found for each value of exponential profile steepness, k.

A separate set of sampling positions could have been chosen for each value of k, and this would have reduced the differences between the profiles, but obtaining a value of k before the measurements are made is not feasible. If it is possible to change the position of the sampling points once values of k have been measured then the following heights above the bed are recommended:

Value of "k"	Height of sampling point as a proportion of river depth			
1	0.09	0.30	0.55	0.85
2	0.07	0.20	0.45	0.80
3	0.06	0.13	0.35	0.70
4	0.05	0.09	0.30	0.60
5	0.04	0.06	0.27	0.55

If standard sampling heights are used, (Table A2.1), the difference between the profiles increases as k increases, and also as the height of the lowest sampling point is raised above its optimum value of 0.04 of the depth. The expected error could be approximated as the difference in sediment loads predicted by the use of the two profiles. The table highlights the importance of using equipment which can sample close to the bed.

The conclusion is that errors due to an inappropriate choice of theoretical sediment concentration profile could be large. However, if the recommended sampling positions are chosen, errors will be reduced to well below 10% except in the most extreme cases.

Variation of concentration with time

The temporal variations of sediment concentration at a point introduce a random error into pump sampling measurements. Table A2.2 contains empirical data which give an indication of the size of this error. It appears that random errors are likely to be less than 10% for a sample time of one minute. This would be reduced by increasing the sampling period. It is recommended that the sampling period be determined by the size of sample required for laboratory analysis, with a minimum sampling time of one minute.

Position and number of sampling points on a vertical

Random errors in a vertical section are reduced as the number of points on the vertical are increased. This effect was investigated using numerical experiments. In the experiments a series of sediment concentration profiles was produced assuming a set of random errors at each data point. The profiles were then analysed to give a mean sediment concentration. The standard errors in mean concentration predicted by these experiments are shown in Table A2.3. The standard error at a point was taken conservatively at 20%, this value was chosen because it produced concentration profiles which appeared to be similar to, or less regular than, profiles observed in the field (see Figure A2.3).

The results of the numerical experiments (Table A2.3) show that as the number of sampling points increases, the accuracy improves dramatically, but that beyond four measurement points the improvement in accuracy will rarely justify the additional effort required. Therefore, four sampling locations in a vertical are recommended. The sampling positions which were recommended earlier produce smaller errors than when the same number of sampling points are equally spaced.

Table A2.3 shows that, for the case with the recommended sampling positions, the random error in the measurement of mean sediment concentration due to random variations in the individual data points is less than 10%.

Measurement of velocity profile

Velocity measurements are used for two purposes. Firstly to obtain the river discharge, and secondly to establish the velocity profile needed to calculate a mean sediment concentration. Here only the second purpose is considered. (Methods for assessing the accuracy of discharge gauging are presented in references 6 and 7 of the main report.)

If the effect of the velocity profile is ignored and the concentration taken as the integral of the sediment concentration profile from the bed to the water surface (the spacial mean concentration), then an error is introduced. The mean concentration obtained in this way is overestimated by about 10% or 20% at a typical site, because the largest sediment concentrations are moving in the slowest part of the flow.

As the maximum error caused by totally ignoring the velocity profile is only of the order of 20% there appears to be scope for reducing the number of velocity measurements on a vertical used for sediment sampling. This was tested by comparing values of the factor u/u* obtained from two points on the vertical with that obtained by using five or more points. The two points are located at approximately mid depth and close to the bed. Table A2.4 shows that the standard error in u/u* due to the use of only two measurements points was about 20% for the four cases tested, but the resulting errors in measured mean sediment concentration were only 2% or 3%.

The following recommendation for velocity measurement is made. Measure velocity by the most appropriate method for determining the mean velocity (usually the one-point or two-point method) and, in addition, measure the velocity as close to the bed as possible. This will provide sufficient data points to minimise errors due to an inaccurate representation of the velocity profile in the calculation of the mean sediment concentration.

Mismatch of sampling nozzle velocity and stream velocity

The sample collected by pumping sediment and water through a sampling nozzle will not be representative if the water accelerates or decelerates as it enters the nozzle. It would be difficult and time consuming to minimise this source of error when pump sampling, as the pump discharge would have to be carefully adjusted match the sampling velocity to the stream velocity at each sampling location. A further constraint is the need to keep line velocities above about lm/s to avoid sediment deposition in the sampling line. The following empirically based equation developed by Atkinson (1989) can be used to predict the error caused by velocity mismatch, and hence compensate for it:

$$\text{Error} = 0.305\left[1 - e^{-13V_s/\sqrt{rg}}\right]\left[u/u_n - 1\right] \times 100\% \qquad (4)$$

where

V_s = settling velocity
r = sampling nozzle radius
u = stream velocity upstream of nozzle
u_n = velocity through nozzle.

The performance of the correction method is shown in Figure A2.4, which compares observed and predicted errors derived from a data set not used in developing the correction function. The close agreement between prediction and observation suggests that sampling errors due to a velocity mismatch can be successfully corrected by using Equation 4.

Laboratory sieving of suspended samples

When a theoretical concentration profile is fitted to a set of measured sediment concentrations an error is introduced because the use of a single profile implies that the suspended sediment has a single grain size. However the errors involved are generally small, so the increased work involved in sieving sediment samples is rarely justified on the grounds of improving the accuracy of a sediment load measurement. In cases where it is appropriate the size of the error can be predicted by using the following procedure.

Firstly, predict the relative proportion in transport for each of the size fractions found in the bed material (a method is outlined in Atkinson, 1987). Secondly, use Equation 1 to calculate the concentration of each size fraction at each sampling position, taking $k = 15Vs/u^*$ after Lane and Kalinske (1942). Thirdly, sum the concentrations at each sampling position. Finally, compare the mean concentrations obtained by the analysis with that obtained using the total concentrations. Repeating this calculation for a range of flow conditions at a given sampling site provides suitable correction factors to compensate the error.

The method has been tested using data collected at a sand and gravel bed river in Thailand, where samples were sieved, and the errors resulting from not sieving could be compared with the procedure outlined above. The error produced by not sieving was -4%, while error predicted using the method outlined above was -3%, verifying the correction procedure.

Lateral variations in sediment concentration

The variation in sediment concentration across the width of a channel is generally less than the variation through the depth. However large errors are possible if insufficient verticals are used for sediment measurements. The principal cause of lateral variations of sediment load in rivers is the effect of bends and meanders; it is rare to find a convenient location for a sediment load measurement which is not influenced by a river bend.

Generalised advice can not be provided for the size of the errors associated with an inadequate number and location of measurement verticals, as this will site specific. It is recommended that detailed measurement at many verticals are made when a sediment gauging is set up. This data can then be used to assess the number of verticals required. However measurements at least two verticals is recommended unless the data clearly shows that it is not necessary.

The effect of turbulence

A further source of error is that arising from variations in velocity and sediment concentration due to stream turbulence. Since these are unlikely to be in phase with each other the mean sediment flux will not be the same as the product of mean velocity and concentration. However the systematic error introduced by neglecting this effect will be small when compared to the other sources of error. Values of 5% and 1% are reported by Mulder et al (1985) and Soulsby et al (1985) respectively.

A2.5 WASH LOAD

Wash load comprises those particles which are not present in appreciable quantities in the material of the river bed, and is normally defined as those suspended particles less than 63 microns in size. There are two important characteristics of wash load which influence the method of measurement. Firstly, 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. Secondly, wash load concentrations do not, in general, correlate closely with the water discharges in the river. Variability in wash load concentrations are caused by: the supply of sediment being exhausted in the early part of a storm; the variation in cover provided by vegetation at different times of the year; and the rainfall and hence run off occurring at different locations within a catchment.

The implications for measurement of wash load noted are that single measurements of wash load discharge can be obtained relatively simply from a dip sample collected near the surface of the river, but continuous monitoring is needed to determine wash load discharges. Since peaks in wash load discharge often occur for a short duration in floods the monitoring programme must ensure that measurements to be made at sufficiently frequent intervals.

The factors which affect the accuracy of wash load measurements have not been studied in sufficient detail to allow quantitative prediction of the magnitude of measurement errors. Errors associated with two common measurement techniques are discussed below, but further work on this subject is required.

Turbidity monitors

A continuously recording turbidity monitor immersed in the flow can be used to obtain wash load data. This method has been used successfully by HR Wallingford in Kenya and Indonesia. As the response of turbidity monitors is sensitive to the size, shape and colour of sediment particles, the equipment must be calibrated for use at each location (Fish, 1983). Turbidity monitors have a very low sensitivity to sand particles and can, therefore, be used to measure wash load even where appreciable concentrations of bed material load are present. The two main disadvantages of most turbidity monitors are their relatively high electrical power consumption, and the rapid growth of algae on the sensor lenses. Both these factors give rise to the need for frequent site visits to maintain the equipment: batteries must be changed every five to seven days, and in some cases lenses must be cleaned daily. These disadvantages are now being overcome to some extent by the development of dual path infra-red sensors with much lower power requirements.

A further disadvantage of turbidity monitors is the effect that organic matter in the river may have on an instrument"s calibration.

Bottle sampling

Bottle sampling is a simpler alternative method to measure wash load. In the pump sampling method described earlier wash load samples are collected in a bottle from the container used to measure the pump volume, after stirring to ensure that sediments are well mixed. The method of sampling is unimportant as wash load concentration is relatively uniform across a river section. However the frequency of sampling has an appreciable effect on the accuracy of the result obtained.

In a study of sampling frequency based on the continuous record of the turbidity monitor used in a study in Kenya, Bolton (1985), found the following errors in the calculated total wash load relative to the value obtained from samples taken every hour.

Sampling Interval hours	Mean absolute error in seasonal sediment load %
1	0
2	2
3	3
4	5
6	9
8	13
12	20
24	42

A typical duration of a flood event duration in the river was two days.

Appreciable differences between the errors arising in different locations are expected. The errors are of a random nature but where sampling is undertaken only during daylight hours a systematic error will also be introduced if the rainfall, and hence periods of higher river flow occurs more frequently at certain times of day. As a broad guideline it can be recommended that the sampling interval must be set at so that four or five samples are collected during flood events.

In the case just quoted this would have produced a 20% error in the measured total wash load for a season.

A2.6 CONCLUSIONS

For the measurement of suspended bed material load the pump sampling method has been shown to be the most accurate. Measurement and analysis methods have been described and errors quantified. Table A2.5 summaries the results. For a fairly high value of sediment concentration profile steepness (k=3), the overall standard error in mean concentration on a vertical is approximately 17% when the recommended measurements and analysis methods are applied. This comprises of an uncorrected systematic error of 9%, and a random error of 14.6%. The random error can be reduced by repeat sampling, with errors due to dunes likely to be the most significant.

Quantifying the errors has enabled recommendations on the number and position of sampling points to be made, and has enabled some methods for error correction to be developed.

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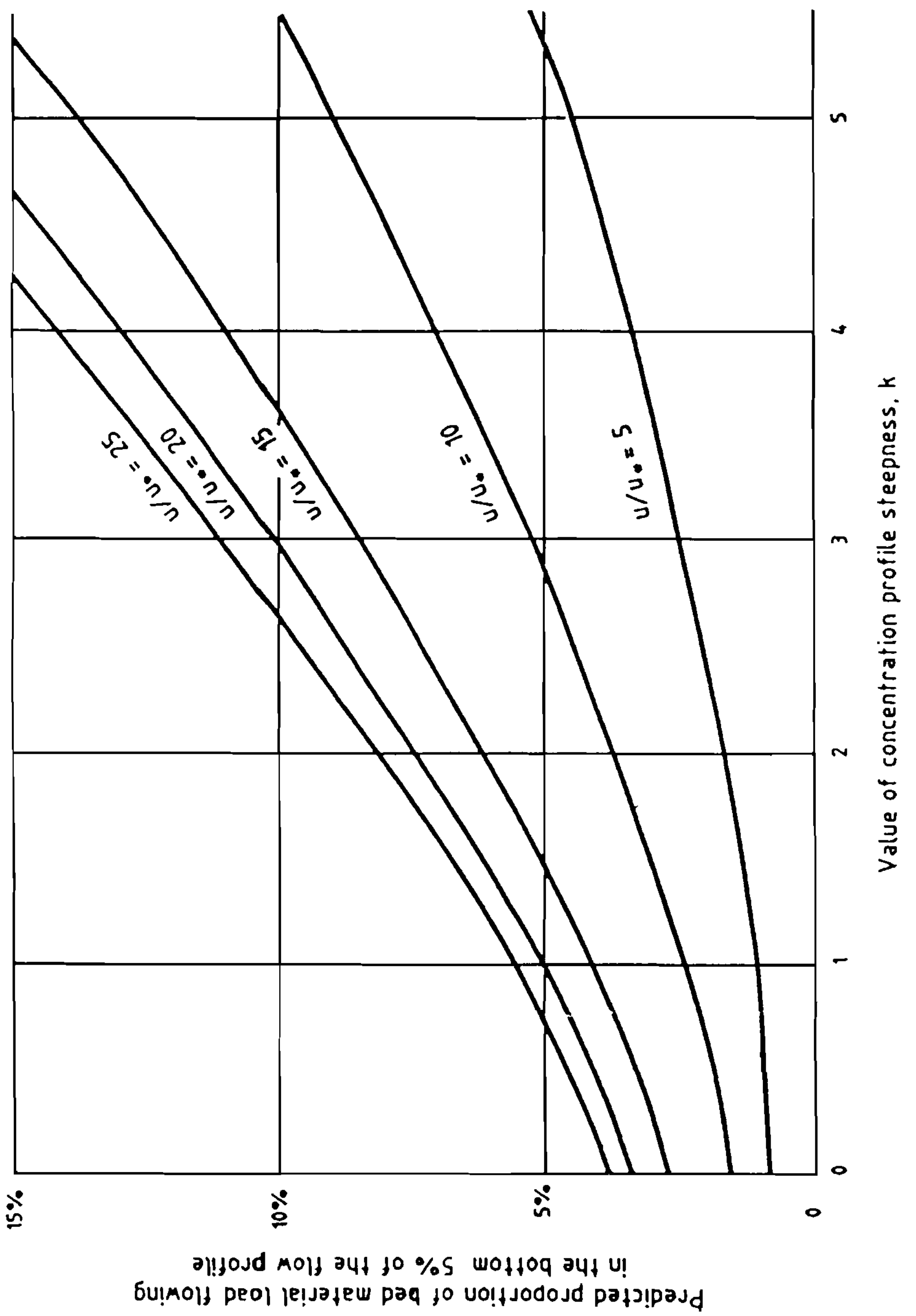

G3PL0045

Figure A2.1 **The Proportion of the Sediment Load Flowing Near the Bed**

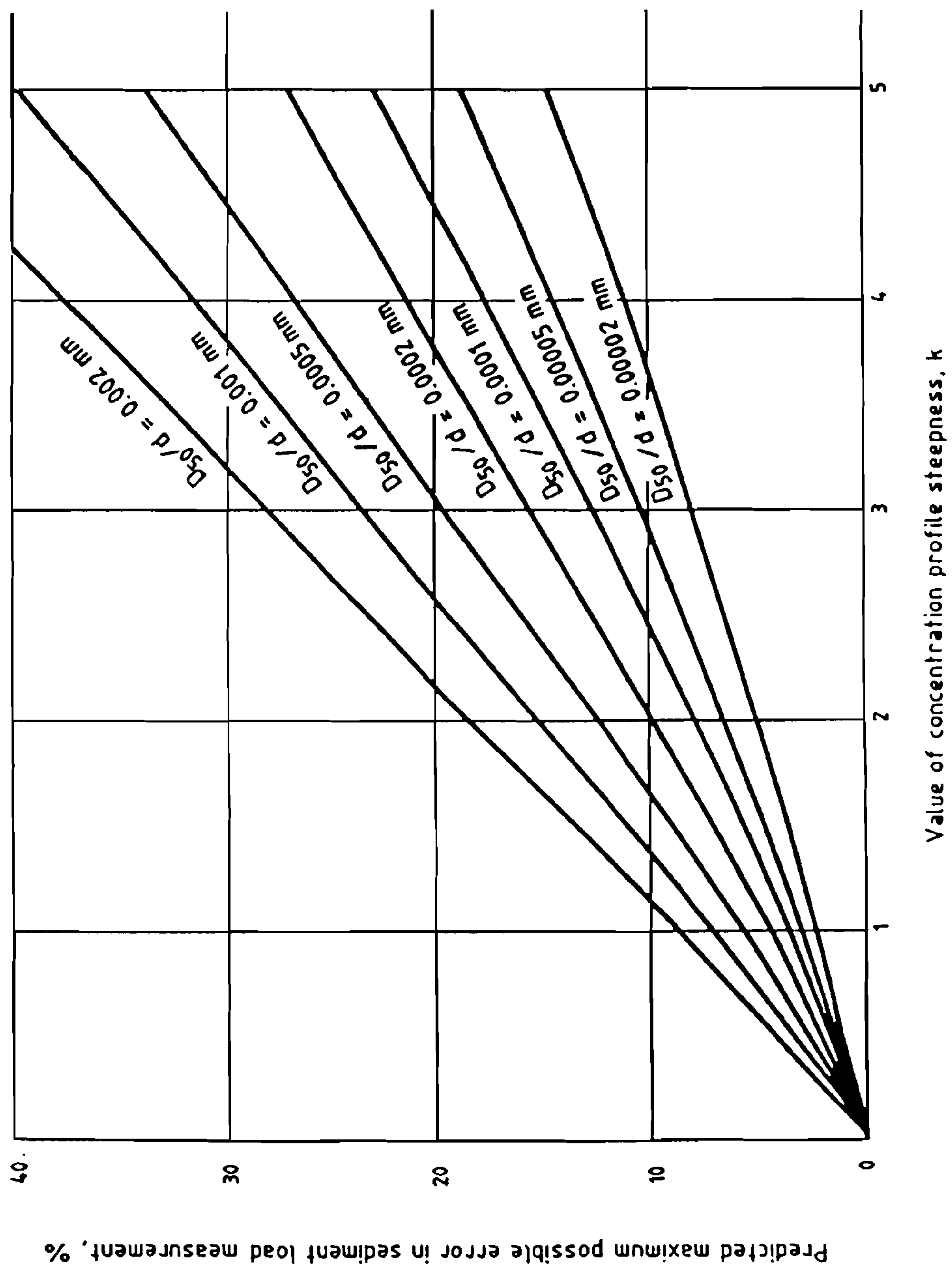

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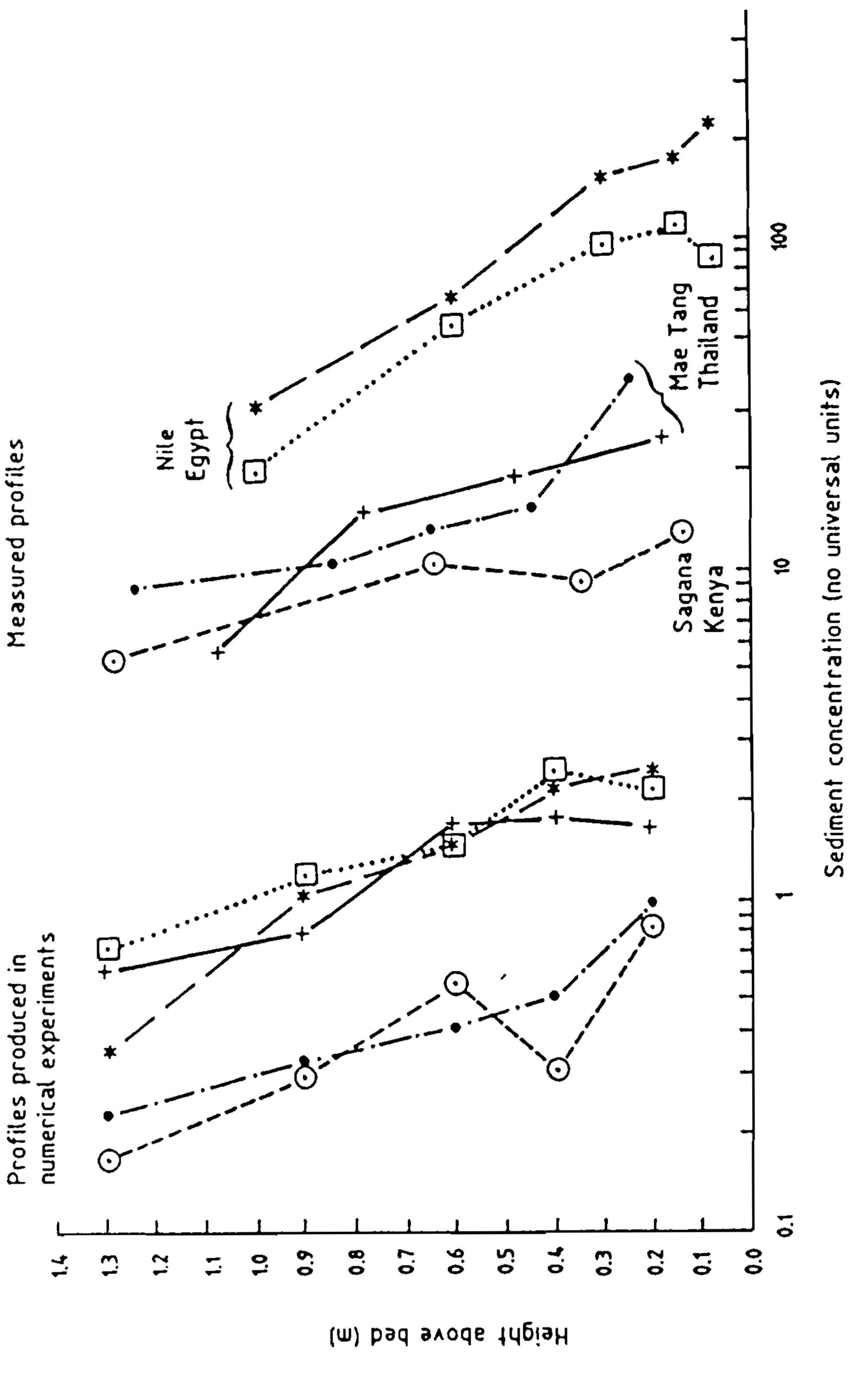
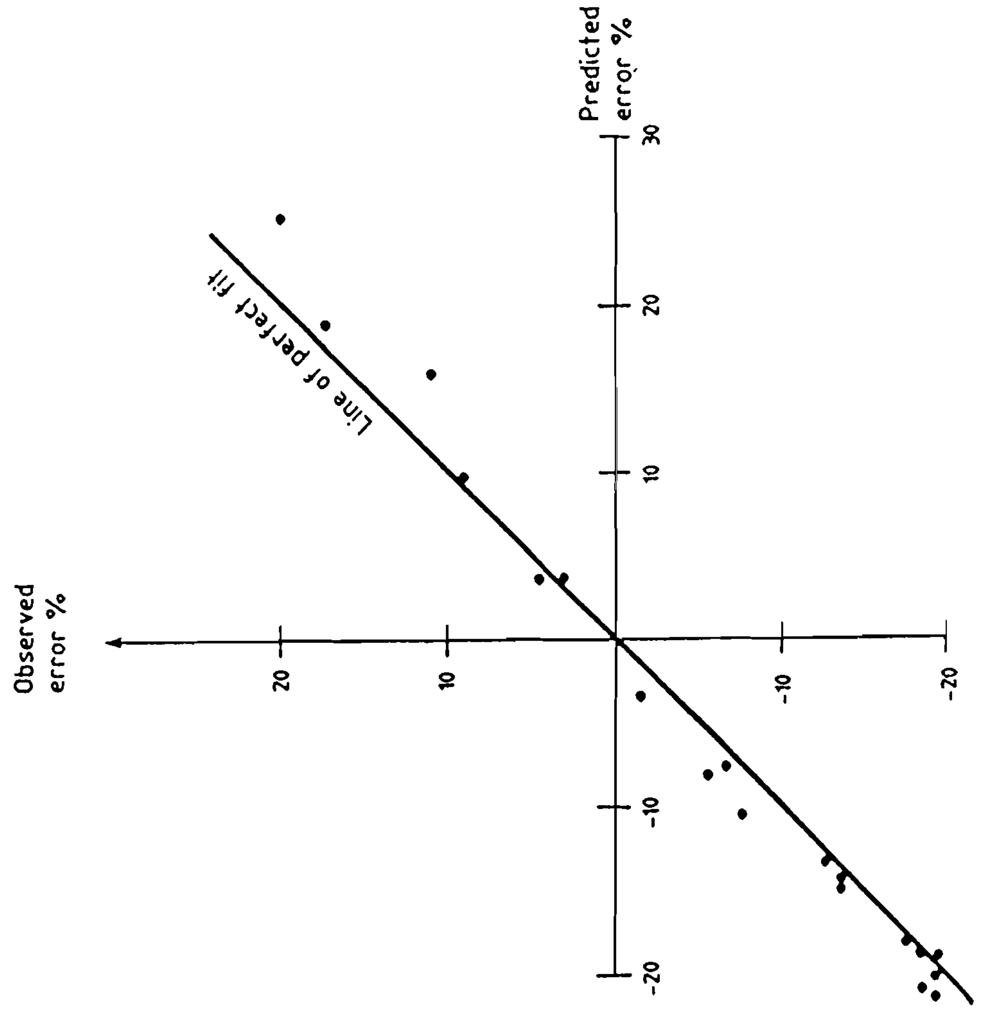
Figure A2.2 Maximum Possible Errors in Sediment Load Measurement Produced by Dunes



G3PL0045

Figure A2.3 **Comparison of Measured Sediment Concentration Profiles with those Produced in the Numerical Experiments**



G3PL0045

Figure A2.4 Predicted and Observed Errors due to Incorrect Sampling Velocity (Bosman et al data)

Table A2.1 Recommended heights of sampling positions

As a proportion of total depth					Resulting percentage difference between profiles* for k				
Minimum height of bottom sampling point	Recommended height above bed of sampling points				1	2	3	4	5
up to 0.04	0.04	0.06	0.27	0.55	2	2	2	5	11
0.06	0.06	0.06	0.35	0.55	1	1	3	8	18
0.08	0.08	0.08	0.35	0.55	1	3	7	17	35
0.1	0.1	0.1	0.35	0.55	1	4	12	26	50

* This is the maximum difference between the exponential and Rouse profiles over the range $5 \leq \bar{u}/u_* \leq 25$

Table A2.2 Variation of measured sediment concentration at a sampling point

Source	Description	Time of Samples (secs)	Coefficient of variation of measured sediment concentration
Crickmore & Aked (1975)	Flume: depth - 0.4m velocity - 0.62m/s bed material: 0.15mm	12 240	17% 7%
Bennett & Nordin (1973)	Flume: depth - 0.37m velocity - 0.91m/s bed material: 0.25mm	14 54	9% 6%
Van Rijn & Schaafsma (1986) Figure 5	Danube River, Yugoslavia, 0.55m above bed flow velocity = 0.9 m/s	300	about 5%
Unpublished data collected by HR Wallingford	Agno River, Philippines, depth = 1.8m velocity = 2.5m/s	72	5%

Table A2.3 Errors in calculated mean sediment concentration produced by a 20% error at each sampling point

Number of sampling points	Overall standard error in mean sediment concentration (%)					
	Uniform spacing of sampling points			Spacings derived from work in Section 5.4		
	Value of k			Value of k		
	1	3	5	1	3	5
2	14	19	23	14	14	14
3	12	14	16	12	12	13
4	10	13	15	10	10	10
5	9	12	14	9	9	9
6	8	10	12	8	8	8
7	7	9	11	7	7	7

Table A2.4 Effect of a 2-point method to measure friction factor

Site	Measured friction factor with		Mean error	Resulting error in measured sediment concentration
	2 points on vertical	Full number of points (Number)		
Lower Nile River	20.8	18.0 (7)	+12%	+1.6%
Mae Tang River, Thailand	7.4	8.1 (5)	-9%	-1.9%
Sagana River, Kenya	7.7	8.7 (6)	-12%	-3.4%
Rajastan Canal, India	34.4	26.3 (6)	+31%	+1.3%*

NOTE: Each value is the mean of five separate measurements.

* An estimated value based on a predicted value of k (k = 2.7).

Table A2.5 Estimated errors in a bed material load measurement on a vertical

	Source of error	Standard error (%)				
		Value of k				
		1	2	3	4	5
1	Ignoring bed load (Fig 1, bed load is half of near-bed portion of suspended load, $\bar{u}/u_* = 15$)	4	6	8	11	14
2	Dunes causing unknown bed level (Fig 2, standard error is taken as half maximum possible error, $D_{50}/d = 0.0005$)	3	6	10	13	17
3	Inaccuracy in theoretical sediment concentration profile (Table 2, error is taken as difference between "bound" profiles)	2	2	2	5	11
4	Random errors produced by variations in sediment concentrations at a point (Table 3, four sampling points)	10	10	10	10	10
5	Two-point measurement of velocity profile (Section 5.7)	3	3	3	3	3
6	Miss-match of stream and sampling velocity. Correction applied (Section 5.8)	3	3	3	3	3
7	Suspended samples not sieved. Correction applied (Section 5.9)	2	2	2	2	2
8	Effect of turbulence (Section 5.11)	3	3	3	3	3
	Overall standard error, systematic only (Items 1, 3, 5 and 8)	6	8	9	13	18
	Overall standard error	12	14	17	21	27

Appendix 3

Notes on reservoir surveys by the range line method

Appendix 3 Notes on reservoir surveys by the range line method

CONTENTS

A3.1 INTRODUCTION

Reservoir surveys are usually carried out to determine the rate at which storage is being lost due to sedimentation, and provide information on changes in the storage volume curves. The data derived from surveys can also be used to estimate catchment sediment yields. This Appendix presents more detailed information on reservoir survey techniques than was presented in the main text. The emphasis is on relatively simple survey methods that can be carried without the use of sophisticated equipment.

A3.1.1 Dry surveys

If the reservoir is dry for part of the year, then standard land surveying procedures can be used to produce a contoured map of the reservoir area, and the volumes of sediment deposits derived from a comparison with a pre - impoundment survey. In some cases, when surveys are being carried out with the reservoir drawn down but not empty, a dry survey will be used in conjunction with a hydrographic survey. Combined surveys require careful attention to ensure continuity in the shallow water zone, particularly if significant water level changes occur between the two surveys.

Drawdown provides an opportunity to inspect the distribution and pattern of sedimentation within a reservoir, and take sample corings to directly determine sediment depth and sediment density.

For very small impoundments (< 1km^2), which are dry for a long enough period to allow holes to be dug, the volume of sediment deposits can be estimated by digging pits through sediment deposits to the original land surface, so as to determine the depth of sediment deposits. This method is useful when:

- there is no pre-impoundment map
- the sediment thickness is relatively small.

(If a new stage-capacity curve is needed, either a pre-impoundment survey or an accurate new survey will be required.)

The options available depend on:

- Whether a pre-impoundment survey is available and/or a current topographic survey is required

- What density of coring is required

- Whether the excavation will be by hand-dug pit or auger, or by machine or mechanically powered auger.

The number of sediment cores required will depend largely on the topography and the survey accuracy required. These site specific factors have to evaluated on a case by case basis, and no simple guidelines can enunciated.

A3.1.2 Wet surveys

Hydrographic surveys are the most commonly used method to survey reservoirs, and are based on either range line or grid surveys. A range line survey requires that beacon's are established along each bank to mark the end of range lines. The position in space of the beacons is established by triangulation, which can be relatively expensive and time consuming. However range line surveys do not require particularly sophisticated equipment, and will often be the method most suited to rescouses and skills that will be available in Developing Countries.

A uniform grid survey provides data suitable for use by DTM, but can miss significant features. A non-uniform grid allows for surveyors to select significant points to survey, but requires an experienced surveyor. Grid surveys are usually carried out using sophisticated position fixing and depth sounding equipment linked to a computer to produce plots, cross-sections and sediment volumes. This method is not discussed further here.

A3.2 RANGE LINE SURVEYS

These require the following activities:

Initial triangulation of range line beacons: On either bank of the reservoir, permanent beacons should be established to act as datums for position and level. This, and the initial triangulation to obtain accurate beacon positions and levels, constitutes by far the most time-consuming parts of the reservoir survey. However, once established, beacons enable later surveys to carried out rapidly.

Depth measurement : The depth of water along a range line is normally measured using an echo sounder mounted on a boat, with continuous chart readout or, in shallower water, with a measuring rod. Measured depths are related to a datum by measurements of water surface elevation. Fluctuations in water levels in reservoirs are not usually very large, however water level readings should be taken at least daily.

Position fixing : Position fixing equipment is required guide the survey vessel along the range line, and to locate its position at the times when depth is measured.

The methods of position fixing can broadly be divided into two groups, those with position fixing equipment on board the survey vessel and those position fixing equipment on shore. With a shore position fixing systems, radio communication is required. This is an extra complication, and can lead to additional operational problems. There are numerous methods for position fixing, with varying degrees of sophistication, and these are described later.

A3.2.1 Range Lines and Survey beacons

For a range line survey the accuracy of the results and the time taken on the hydrographic survey will depend primarily on the number of range lines. The number of range lines is thus a key parameter and is related more to shape than overall size.

An indication of the number of range lines that may be required is given by the formula:

$$N = 14.3 \ A^{0.29}$$

where A is the surface area in Km^2

No allowance is made for topography in the above, developed by USBR, and in any case the number of cross sections that can be surveyed will often be controlled by the resources that are available. It is clear that a reservoir with a complex shape and a large number of tributaries will require a larger number of cross sections than an impoundment with a simpler shape.

For a typical reservoir plan shape a range line spacing of around 500 m has been used in HR studies, with range lines positioned so that:

- They define segments of water that are regular as possible.

- Are concentrated at areas with of irregular topography or high sedimentation

- Are set out normal to the main river channel.

The measurement of depth profiles requires that the survey boat is moving along a known line giving the operator a true position (easting and northing) or chainage to at worst +/-2 or 3m, depending on the plotting scale.

The horizontal and vertical control for the survey is established by land survey methods by installing, coordinating and heighting monuments or permanent ground marks (PGM's). For the purpose of the following methods the term PGM will be used to include survey monuments.

The location of sites for survey beacons can be decided by either:

(i) obtaining appropriate maps or aerial photographs of the area.

(ii) carrying out reconnaissance of the area to identify transects and PGM sites and the installation of marker pegs for future PGM's at easily accessible sites.

A reservoir bathometric survey will require a preliminary land survey to be carried out, if one does not already exist. This will establish the limits of the area to be investigated in detail by the bathometric survey. Available maps from National agencies at scales of 1:100000, 1:50000, or more detailed maps, should be obtained if possible. If no maps exist then it is recommended that for large reservoirs, ie greater than 20 to 30 km. length, a sketch aerial survey be carried out to obtain an appropriate true to scale photo mosaic or single large (30 x 30 cm) photograph.

If an aerial survey or published maps are not available then reconnaissance methods will be required to establish the transect locations.

It is advisable to establish a base-line for the survey area by installing a pair of PGM's near to or along the line of the crest of the dam. This pair will be the start of a subsequent triangulation, traverse and coordination of all the reservoir PGM's. All adjacent monuments should be visible from each other to facilitate coordination by one the methods given below. The ends of the transects should initially be marked by wooden pegs until all the reservoir perimeter has been visited and the transects are decided upon. Permanent ground marks set in concrete or concrete survey monuments should then be installed at the peg positions. Allowance must be made for the changing water level in the reservoir to ensure that the marks are always above water, and vegetation should be cleared to allow clear sight lines. For low lying areas where this is not possible it is suggested that long marker poles are erected over the PGM prior to any flooding to allow the installation of a prism array from a boat.

A survey monument is generally a concrete pillar or block set firmly into the ground, with a rustless central marker set in its top, such as a stainless steel or brass bolt. This is accurately punch-marked to give a position for the land surveyor to set up a tripod and theodolite.

The size of the PGM, especially if set in concrete above ground level, should be large or high enough to allow it to be found easily. In areas of dense vegetation a routine clearance scheme may be necessary throughout the year so that PGM's are not lost.

There are advantages in using marks flush with ground level in areas of possible vehicle traffic or human interference, but these must be identified relative to nearby hard detail such as fencelines or nails in rocks etc, on station description forms. These descriptions, to centimetre accuracy, should permit the surveyors to relocate the PGM's should they become buried, damaged or lost.

It is essential to coordinate and level all the control points by accepted self checking procedures, prior to any bathometric survey. That is, coordinates (easting and northing) and level (height above a datums) in metric units of all the PGM's established around the reservoir must be surveyed into the National mapping and height datums. Coordination can be achieved by the methods below, combined with subsequent heighting by standard levelling techniques:

- triangulation
- traversing
- Global Positioning System (GPS)

These three methods are described in detail by A.L. Allan and Banister and Raymond as well as many other standard textbooks, (see References) hence are not described further here.

For most small reservoirs (< 20km length), a single closed three tripod EDM traverse would be the preferred method for reasons of speed and economical use of manpower. For larger reservoirs it may be advisable to divide the area into two or more closed traverses, working away from the reservoir baseline, and to quantify any misclosure errors before continuing with the next traverse.

Software packages are available for the calculation of coordinates from both triangulation and more commonly traverses.

The vertical reference datums for a reservoir survey is of equal importance to the horizontal coordinate system. Heighting control for small reservoirs should be observed by standard levelling techniques.

The levelling of the reservoir must start at a firm/stable reference point or bench mark (BM) which is either based on a local reservoir datums ie the spillway, or preferably based on the country's national datums with respect to mean sea level. The use of the national datums will provide consistency between reservoirs surveys and other measurements.

Additional stable reference datum points should be established near to the reservoir to allow for damage to the primary mark. These should take the form of dome headed rustless long (eg.300mm) bolts, or steel bar/angle iron set in concrete at ground level. These may already be in existence as part of the reservoir construction control network.

As the measurement of water depth can usually be achieved to within +/- 50mm, the height control accuracy, in areas of clear and stable terrain, should be better than this ie +/-25mm.

Several short levelling closed traverses heighting the tops of all the PGM's are recommended, rather than one long traverse around the reservoir perimeter. This will allow for the calculation of closure errors for each short traverse and hopefully identify those which will require repeating.

Alternative methods such as transferring height by water level are often used in areas of difficult or inaccessible terrain. The surveyor must keep an open mind as to how it is best to overcome access problems to avoid unnecessarily time consuming activities such as extensive vegetation clearance.

A3.2.2 Position fixing systems

This section describes the basic equipment and methods required for fixing the position of a boat, fitted with echo sounder for depth recording, as it crosses the reservoir on a predetermined transect or range line.

Single range laser range-finder

The measurement of position along a single line can be achieved by a number of simple methods. There are however significant disadvantages to each, and the laser rangefinder method is usually considered to be the most cost effective. This enables the distance from the survey boat to the shore to be measured with a hand held electronic rangefinder, at a update interval of at least once per second or faster. All electronic range finders rely on a transmitted pulse of invisible light being returned by a retro-reflector such as a glass corner cube prism, or plastic reflector. A hand held range-finder can be used either from the boat or from the land.

A reflector is usually set up on a tripod over a previously coordinated position (beacon) that marks one end of a survey transect across the reservoir. multiple reflectors assist measurement of longer ranges, and if placed in the same plane and spaced out, eg two or four prisms separated by 50cm or 100cm on a frame or sighting board, also make pointing and receiving of distances easier for the range-finder operator. The survey boat will then cross the transect starting in the shallow water farthest from the reflectors, measuring distances which are also displayed on the distance repeater for the echo sounder operators use. The echo sounder chart will be marked as required with distance and time details as discussed later.

The boat is kept on the transect by either transit marks, or more usually by an operator with a radio who is set up on a beacon with a simple theodolite on the same transect.

When a rangefinder is handheld on a boat, it has been found that the maximum distance for easy operation is about 2 km. This is due to the difficulty of holding the unit steady and pointed directly at the reflector prisms on the land. Larger distances can generally be achieved with the rangefinder ashore on a tripod, pointing at a circular prism cluster on the boat. A circular prism cluster for use at maximum ranges could require up to 18 corner cube glass prisms in three layers to give a reflection from 3 prisms at any one time. However such a prism cluster is extremely vulnerable, expensive, and heavy for small boat use. (It is generally accepted that the most efficient operation of a bathometric survey is one where all the sensors and systems are installed on the survey vessel. However, in reservoir surveys in countries with minimal resources there may have to be compromises to meet local conditions and availability of equipment.)

It is important that prior to any work, and at regular intervals of at least three to six months, the rangefinder is calibrated over its typical working distances, by comparing its measurements to a higher order system as described in 9.5. This will ensure that the rangefinder is giving accurate distance measurement, and check whether any offsets need to be applied to the range data at the processing stage.

It must be remembered that the hand held laser rangefinder could be pointed at or close to the land survey operators and must meet the international eye safety standards. The manufacturer should be asked to provide a safety statement concerning the lasers use, especially with respect to the viewing of the laser from the land by a theodolite or telescope observer. It should be possible to fit safety filters if required for the rangefinder transmitting optics, which the manufacturer should be asked to recommend.

Other simple methods

Autolog The autolog consists of a small multi-bladed impeller carried on an outrigger to one side of the survey vessel. Output is in the form of a mark scribed on the echo sounder chart at a pre-determined distance interval which corresponds to a given number of revolutions of the impeller. This method is not very accurate, for example comparative tests between the autolog and double sextant angle method showed differences of up to 7m in position along a 600m rangeline, where the accuracy of the double sextant method was assessed at ± 2m.

Sextant The sextant has been used for many years for navigational position fixing at sea and for hydrographic surveying. It can be used to observe vertical or horizontal angles between objects on land, which will give a position offshore. It should be graduated from at least -3 to +120 degrees and have a minimum reading to 1 minute of arc by use of the vernier. A survey sextant is usually a lightweight version of a navigational sextant and as such should be cheaper.

The measurement of position by horizontal sextant angles can be achieved in a variety of ways, but only two are described here because of the long transect distances involved in reservoir surveys:

Single angles These are measured by one observer, who is seated over or next to the echo sounder transducer, to a pair of coordinated target boards erected near the waters edge (Figure 8). The distance between the boards should ideally subtend angles to the observer of between 30 and 120 degrees perpendicular to the measurement transect, as the index arm mirror will present a small reflected area at larger angles. For regular measurement of larger angles a pentaprism attachment is recommended.

The angles observed represent a number of position arcs across the transect, and their measurement locations will need to be fixed by a second line of position. This is achieved by either setting up another pair of marker boards called "transits" on the land on the same line as the transect at a distance apart of one-third the transect maximum width, or by the set up of a theodolite on the transect. The transits, or the theodolite operator with radio link, will then control the survey boats direction across the transect.

Sextant angles should be recorded at approximately 5, 10 or 20m. intervals, which is about every 5 seconds at a boat speed of 2 to 4m/sec. The fix interval depends on the scale of the final plotted chart or cross section. The echo sounder is marked at the same instant with fix number and time. The more often the angle measurement the better becomes the position accuracy of underwater features, but the plotting time increases accordingly.

The advantage of this method is the low cost of the equipment required, disadvantages include plotting of positions is time consuming, that distance off track is not recorded and extra marker boards are often required for sighting.

Double simultaneous angles These are measured by two observers standing next to or over the echo sounder transducer to avoid parallax errors. The method is similar to that for single angles except that both angles must be taken at the same time (ie within a second of each other).

Three targets are needed on the land. Track control from transits or a theodolite on the survey line will be necessary if "straight" lines of data are required. The advantage of this method is that good track information is provided, however an extra person is required, a specialist plotting aid needed (station pointers), and two sextants are required. Straight lines cannot be run without additional shore control eg. theodolite

The most efficient way to plot sextant angles is by station pointer, which is similar to a 360 degree metal protractor fitted with three arms. The central arm is fixed to the zero degree setting, and the other two are free moving with adjustable clamps and vernier scales for setting on angles in the range 0 to 180 degrees.

Cross section wire A wire or pre-stretched rope is tensioned across the transect. The wire is marked at 5 or 10m. intervals by tags that will not slip. The survey boat is pulled across the transect by the boats crew and a depth profile recorded on the echo sounder. The echo sounder is marked at the intervals on the wire. Minimal equipment required, the method is simple to install and use but cannot be used easily on transects wider than about 100m., or in fast flowing rivers.

More advanced electronic systems

There is a wide variety of sophisticated electronic systems for position fixing. These have mostly been developed for the offshore oil, hydrographic and oceanographic industries. Onshore electronic distance measurement relies on a shore-based EDM (Electronic Distance Meter) or laser theodolite to track the survey vessel and has many of the advantages of the more sophisticated automatic tracking and microwave systems. There are two modes of operation:

Range finder and Range/Azimuth. Rangefinder mode uses the EDM on shore over a known distance from the rangeline beacon. A survey prism mounted over the echo sounder transducer is tracked and depth and distance to EDM recorded simultaneously. A second theodolite is required to ensure the vessel is on-line. This method in effect uses the EDM as if it were a cheaper laser range finder, and the only advantage of this would appear to be if one is already available; in this case it can be used to speed up initial triangulation.

Range/Azimuth mode utilises the EDM theodolite or Total Station in conjunction with an on-board microcomputer to provide both navigation and position fixing information. The use of a computer requires a larger vessel with protection against the weather. Rangelines can be set out on the VDU screen, the initial triangulation survey is reduced to the establishment of control beacons to cover the reservoir typically at 2/3km intervals and there is a marked saving in equipment costs over the automatic tracking and microwave systems. A telemetry link between EDM and the vessel transmits position fixing data to the computer which displays the boats position along the required rangeline on the screen. While the EDM operator sights a target on the vessel, its position is recorded on the computer, and co-ordinates of the fixes are stored together with a reference number or the time of fix.

These and the other systems that are available may be too sophisticated and expensive for some applications, although they offer some major advantages in terms of speed of survey and the accuracy that can be achieved.

Appendix 4 gives a brief summary of a number of position fixing methods, and lists approximate (1992) costs. This shows that the accuracy of the end result is improved and the cost of preparatory work falls when more expensive equipment is used.

Choice of Position fixing system.

The factors to be considered prior to the purchase or hire of a positioning system are as follows:

- operational environment and system requirements
- price and sophistication
- technical standard of personnel
- training requirements
- service facilities available

The variety of electronic positioning equipment is extremely diverse, and for the unfamiliar, the selection and purchase of a system could be a time consuming and excessively costly exercise.

The measurement of a single range is probably the most cost effective, fastest and simplest method for reservoir transect surveys where transects do not exceed 4000m.

A3.2.3 Depth measurement

Water depths are measured using an echo sounder. The equipment should meet the specification given in Appendix 4.

The data output from an echo sounder can be on a chart or a digital readout. The paper chart should be considered an essential feature, as a permanent record of the depth is kept and any operator comments can be written on the paper during the survey.

If automation of the depth logging process is needed then it will require the use of a digitiser linked to the sounder. The output of depth data in digital form can be to simple LCD built in to the unit, or to an RS232 data port. It is desirable in any survey to have the raw depth data on a chart paper, and at the RS232 port. Most depth digitisers however, under operator control, will optionally reject unwanted echoes that it considers to be unrepresentative of the reservoir bed. These may be fish or tree branches. For this reason these sounders are efficient by logging only the "good" data for future analysis. However it equally applies that any isolated high spots may be not be recorded to the chart or as serial output.

Some sounders use a digitiser that will convert every depth "ping" to a digital value. The advantage of this approach is that the surveyor can analyze all the depth data stored on floppy disk on a PC and make his own choice of what should be used on the final chart or transect profile. This assumes that the reservoir survey system is provided with the necessary post-processing software.

The sounder is used to measure and record water depths across transects. Calibration procedures are necessary to allow the observers to measure off the paper chart correctly scaled depths so that the reservoir profile can then be adjusted for water level datums and a bed profile drawn or tabulated.

The preferred method is the "bar check" which will provide the observers with a "hard copy" on the paper chart of the calibration. In the case of a boat with an in-hull transducer this entails lowering a horizontal bar (of length equal to the width of the boat at the transducer location) beneath the transducer at several water depths until the full working depth is covered. The bar is attached to two graduated non-stretch wires or chains to allow its descent to be controlled at levels 1m, 2, 4, 6, 8, 10m etc. The maximum depth achievable could be 50m below the transducer if the wind and flow conditions permit. This method is of most use for echo sounders that have adjustments for transducer depth (tide and draught) and speed of sound as it allows the operator to set the unit to read correctly and true to any pre drawn chart recorder paper scales. For sounders without these controls the method will still provide a good indication for the correct measurement of depths from the paper chart.

For overside transducers a heavy (5-10kg) steel disc with a central lifting eye is lowered beneath the transducer. The discs weight could be increased for deeper water and faster rates of drift for the survey boat, to ensure it always stays beneath the transducer. A better reflection of the echo can be achieved by gluing a circle of air bubble material such as polystyrene or "bubble wrap" to the upper surface of the bar or disc. The zero of the calibration measurement chain or wire should be started at the first reflective surface, which will be the air bubble material surface or the upper edge of the steel plate. Bar checks should be repeated at least twice daily throughout the survey, and all echo sounder settings should be recorded on daily log sheets.

Appendix 4

Specification for echo sounder

Appendix 4 Specification for echo sounder

	Specification:
11-32v power supply circuit protection	usually 12v from one car battery for over voltage and reverse polarity
60m. depth maximum or greater	by selectable or auto depth ranging optional depths to 120m on x2 range.
selectable depth ranges (overlapping)	0-15,10-25,20-35 etc metres or 0-11, 10-21 etc with same chart scale per unit depth
selectable speed of sound	to give the correct calibration for water density in area of operation
selectable draught setting	to allow for depth of transducer face below water surface
wide paper	10mm per metre of depth scale in use ie 100mm wide for 10m. depth
fast sounding rate	at least 10 per second
accuracy	+/-0.5% +/-25mm of depth scale
frequency	approx. 200 kHz
portable and light weight	can be easily carried, fitted with handle(s), approx weight 15 to 30 kg. inc transducers
narrow beam width	3 to 8 deg. at half power points
selectable chart speeds	eg 25, 50, 75, 100 mm/min. or in the range 0 to 100mm/min or 0 to 200mm/min
overside transducer	can be fitted into tubes for overside use
long transducer cable	10m to 15m
hinged chart window	allows manual annotation while in operation
splash proof	case provides protection against spray and rain
standby switch *	unit kept in "warmed up" state but chart not operational to save paper
built in digitiser *	to convert analogue to digital depths
RS232 output *	for data output to logger or PC

RS232 input or similar *	for auto strobing and annotation of chart by external device
LCD depth display *	output to 2 decimals of a metre
dual frequency *	a second frequency of 30 to 40 kHz to investigate depth of soft sediment. Large transducer size will usually prohibit its use from small boats

Functions marked * are useful but not essential

Examples of shallow water survey echo sounders

For the echo sounders listed below it is recommended that the manufacturer or agent is contacted for information concerning the latest specification and a more detailed summary of particulars.

This should not to be considered a comprehensive list of all the available systems.

Name	**Manufacturer**
Thermal digital sounder TDS-1000	Ocean Data Corporation, Massachusetts, USA.
LAZ 4100	Honeywell-ELAC Nautik Gmbh Kiel, Germany
Raytheon DE-719C	Raytheon Ocean Systems Company, Rhode Island, USA
Echotrac 3100L	Odom Hydrographic Systems Inc., Louisiana, USA
RTS 40	Raymar Technical Services, London, England
EA 300 P	Simrad Subsea A/S, Horten, Norway
Navisound 10	Navitronic, Aarhus, Denmark
	Interspace Technology, Inc New Jersey, USA
	Atlas Elektronik, Bremen, Germany