SLOPE-AREA DISCHARGE GAUGING IN STEEP WADIS: REPORT ON A VISIT TO THE YEMEN ARAB REPUBLIC JULY-AUGUST 1983

VOLUME 2

James C. Bathurst

October 1983

SLOPE-AREA DISCHARGE GAUGING IN STEEP WADIS

REPORT ON AN ADVISORY VISIT TO THE
TIHAMA DEVELOPMENT AUTHORITY
YEMEN ARAB REPUBLIC
JULY - AUGUST 1983

VOLUME 2

By

James C. Bathurst

Institute of Hydrology
Wallingford, Oxon, UK

October 1983

SUMMARY

This advisory visit by the Institute of Hydrology to the Tihama Development Authority concentrated on the estimation of flood discharge in steep wadis, with the aims of training staff in the slope-area gauging method and modifying the method to suit the conditions of the Yemen Arab Republic.

Volume 2 of the report is essentially a manual for the slope-area method. It begins with description of the mathematical equations, field technique, office procedure and associated problems, presented in a step by step manner to aid application. Following that, simplifications for reducing the amount of work are discussed. These consist of flood marker posts to minimize the fieldwork and charts of channel cross-sectional details and a computer program for calculating discharge to reduce the office work. Again the procedures are introduced in a step by step manner.

Several appendices enlarge upon aspects of the method and present the results of the training exercises carried out during the visit. These can be used as examples for familiarisation with the office procedures.

Volume 1, which has its own summary, provides a more general discussion of technical and non-technical problems, along with recommendations on ways of overcoming them.

The visit was funded by the UK Overseas Development Administration.

CONTENTS

INTRODUCTION

Aims of this Report

Although this volume is written as the second part of the report on my visit to the Tihama Development Authority (TDA), it has been designed to be used separately. Its aim is to describe the basic slope-area technique of discharge gauging, the modifications adopted to cope with the conditions of the Yemen Arab Republic (YAR) and the results of the training exercises carried out during my visit. With the theory, practical details and examples included, the report should be able to form the basis of a guide for future work by TDA. The only major assumption made is that a competent surveyor is available to carry out the fieldwork and it is therefore recommended that, before beginning slope-area operations, members of the TDA Hydrology Section be thoroughly trained in surveying techniques and analysis.

It is stressed that the slope-area method provides only an estimate of the discharge, not an accurate value. Generally it is used for the peak discharge of a flood, although it can be used for lesser flows if a measure of the water surface level is available.

1.2 Guide to this Report

The first sections of the report form a revised and updated version of the description of the slope-area method given in Appendix F of the report on my last visit to TDA (Bathurst, 1980). They cover the mathematical equations, field techniques and office procedures, information which is well described in the published literature (Barnes and Davidian (1978); Benson (1968); Dalrymple and Benson (1967)). They are followed by a brief analysis of some of the problems which hamper application of the method in the YAR. The main body of the report then concludes with a detailed description of the simplifications made to the method for ease of application under the conditions of the YAR. Finally various aspects of the procedure are enlarged upon in the appendices, which also contain the results of the training exercises. These results should be useful as examples with which to familiarize TDA staff with the office procedures. However, with the exception of the example in Appendix D, the exercises are not based on observed floods, so the way in which the flood levels are determined in the examples of Appendix E is not that which would be used for an observed flood.

Sections 6 and 7 can be used for simplifying the field and office procedures. However, Section 6, describing the flood marker posts, is not worth following unless the slope-area method is to be applied frequently at the same site.

THE EQUATIONS

2.1 Discharge Equation

The method assumes that flow depth and velocity are determined by channel cross-sectional shape, channel slope and bed roughness and uses theoretical or empirical relationships between these terms to calculate discharge. In order to allow for nonuniform flow effects, caused by variations in cross-sectional shape, measurements of the various quantities should be made at three cross sections along the chosen reach. Representing cross-sectional area by A, the energy loss coefficient by c, conveyance by K (defined below) and denoting the three sections by subscripts 1, 2, 3 (moving in the downstream direction) then discharge is calculated as:

$$Q = K_3 \sqrt{\frac{\Delta h}{\frac{K_3}{K_2}\left(\frac{K_3}{K_1} L_{1.2} + L_{2.3}\right) + \frac{K_3^2}{2g\, A_3^2}\left[(1 - c_{2.3}) + \left(\frac{A_3}{A_2}\right)^2 (c_{2.3} \quad c_{1.2}) \quad - c_{1.2}\left(\frac{A_3}{A_1}\right)^2\right]}} \qquad (2.1)$$

Here Δh the difference in water surface elevation between sections 1 and 3 (the fall, not the slope)

$L_{1.2}$ = the distance between sections 1 and 2

$L_{2.3}$ = the distance between sections 2 and 3

$c_{1.2}$ = 0 if $A_1 \quad A_2$

= 0.5 if $A_1 < A_2$

$c_{2.3}$ = 0 if $A_2 > A_3$

= 0.5 if $A_2 < A_3$

acceleration due to gravity.

The conveyance K is calculated as

$$K = A \cdot (g R)^{1/2} \left(\frac{8}{f}\right)^{1/2} \tag{2.2}$$

where

R = hydraulic radius (which can be replaced by mean depth, with little error)

= the Darcy-Weisbach resistance coefficient (see below).

Further details of the theory are given in Appendix A.

2.2 Flow Resistance Equation

Estimation of the resistance coefficient remains the principal source of error in the method. Relatively little work has been carried out on equations suitable for steep wadis with coarse bed material and high sediment discharge but, based on the little that has been done, the following equation is suggested:

$$\left(\frac{8}{f}\right)^{\frac{1}{2}} = 5.62 \log\left(\frac{d}{D_{84}}\right) + \tag{2.3}$$

where d = mean depth; D_{84} = the size of median axis of the bed material which is bigger than 84% of the material in a sample; and log is logarithm to the base of ten.

This equation is by no means perfect and is likely to be in error by 25 - 30%. As it is based on data from boulder-bed channels it may be even more in error if the relative quantities of sand and coarse material (gravel and boulders) are similar, as is the case at some of the TDA wadi sites. Nevertheless it seems to be the equation which is simplest and fits the available data best.

If it is obvious that the bed is largely sand (as for example at Wadi Harad), a set of equations reported by Simons and Şentürk (1977, pp. 334-335) can be used. Considering the likely range of conditions in steep wadis, the relevant equations are those for bedforms comprising either a plane bed with sediment movement or antidunes.

For the plane bed:

$$\left(\frac{8}{f}\right)^{\frac{1}{2}} = 7.4 \quad \log\left(\frac{d}{D_{85}}\right) \tag{2.4}$$

and for the antidunes:

$$\left(\frac{8}{f}\right)^{\frac{1}{2}} = 7.4 \quad \log\left(\varepsilon \frac{d}{D_{85}}\right) \tag{2.5}$$

ε is a correction term which is not well defined for steep flows but is likely to have a value between 0.1 and 1. D_{85} is the sand size and may typically be 2 mm for coarse sand.

FIELD PROCEDURE

This section describes the procedure to be followed in the field, from choice of site to measurements. It should be read carefully before going into the field and a checklist should be taken to the field site.

3.1 Choice of Site

1) The site should be as close as possible to the stage recorder. There should be no major tributaries between the slope-area reach and the recorder.

2) The reach should have well defined banks which can exhibit reliable high-water marks such as trash lines or mud lines.

3) The channel should be approximately straight and uniform, preferably contracting rather than widening in the downstream direction.

4) The total flow should be confined to one channel at all stages with no flow bypassing the site as subsurface flow. Check that at high flow there is no overflow channel behind rock outcrops. Banks should be permanent and free of vegetation.

5) The wadi bed should not be subject to scour and fill and should be free of vegetation. Scour is most likely to occur at narrow, constricted reaches and is least likely to occur in wide sections with stable alluvial banks. At the latter sites changes in the bed level during a flood are probably related more to the passage of bed-forms such as antidunes than to any overall lowering of the bed profile (Foley, 1975). Note that evidence of scour is difficult to find since scour holes developed during a flood are usually filled during the flood recession. Scouring to depths of over 1 metre has been measured in Wadi Rima by staff of the Hydraulics Research Station.

6) The longstream bed profile should be even with no sharp changes and no pools or bars. If the bed is uneven, the assumption that depth and velocity depend on channel shape, slope and roughness only, may not be satisfied.

7) The fall in the water surface along the reach should be greater than the range of error in measuring the high-water profile. Ideally the fall should exceed 0.15 m, which for slopes of 0.5% or so means that the reach length should be at least 30 m. However, the length should also be at least two times the channel width and preferably five times the width. This suggests reaches of at least 100 m length.

8) The wadi bed should be covered with gravel and boulders, although occasional sand bars can be included.

9) If the site is to be used on a regular basis, it should be relatively accessible.

3.2 Survey of Cross Sections

1) Once the slope-area reach has been selected, mark out three cross sections at the upstream and downstream ends and the centre of the reach. The centre section does not have to be exactly at the centre but should be near it.

2) Draw a sketch map of the reach, noting the position of the sections and any special features such as rock banks, sand bars and vegetation.

3) Measure the distances between the sections using a tape measure along the centre of the channel. Do not measure the distances by pacing.

4) Set up the surveying level somewhere near but not exactly on the centre section. If possible site the level so that it can view the surveying staff at all points of each section, including high-water marks and the lowest point of the channel. Make sure that the level views horizontally in all directions. If the level has to be adjusted or moved during the surveying, a temporary datum point should be established. This procedure requires a fully trained surveyor.

5) If the site is to be used several times, set up a reference datum, such as a convenient rock on the bank. Choose a permanent feature, not a boulder which can be washed away, and one which is easy to find. Mark the datum point with paint and survey its elevation. Use of the datum to relate surveys carried out on different occasions requires a fully trained surveyor.

6) Note the length of the survey staff and whether it reads from bottom to top (zero at the bottom) or from top to bottom (zero at the top).

7) Survey each cross section in turn, noting pairs of distances and elevations. The distances across the section should be measured on a tape measure with zero being at any convenient point on the left bank (looking downstream). The tape should be anchored or fixed to a stake so that the zero point does not change. To prevent the tape from flapping in the wind and being stretched, wrap it tightly but without too many spirals around a rope stretched across the section. Using the surveying staff, elevations should be noted at every break of slope (such as the top and foot of the bank). A less accurate but sometimes more convenient method is to take elevations at fixed intervals of distance, such as every 5 metres, across the section (Fig 1).

8) If the survey is being carried out for a particular flood, the elevation measurements should begin and end at the high-water marks on the left and right banks respectively. (These two measurements should have similar values). Make sure that the high-water elevations are marked as such on the note pad being used, in order to distinguish them from the other surveyed elevations. (See example in Appendix D.) If the survey is being carried out for more general purposes it should be continued sufficiently far up the banks to cover all expected flows. This may entail moving the surveying level (see point 4).

9) The high-water mark may be indicated by a trash line of drift-wood, vegetation, plastic bags and other rubbish. On rock faces it may be a line below which the rock is covered with a film of mud. On sandy ground the area below the mark may seem fresh and undisturbed, or perhaps covered with ripples, while the area above may seem more dusty and covered with footprints. If several trashlines are evident, the one for the most recent flood is the lowest. There can be no lower ones because they will have been washed away, while higher ones will not have been reached. Higher

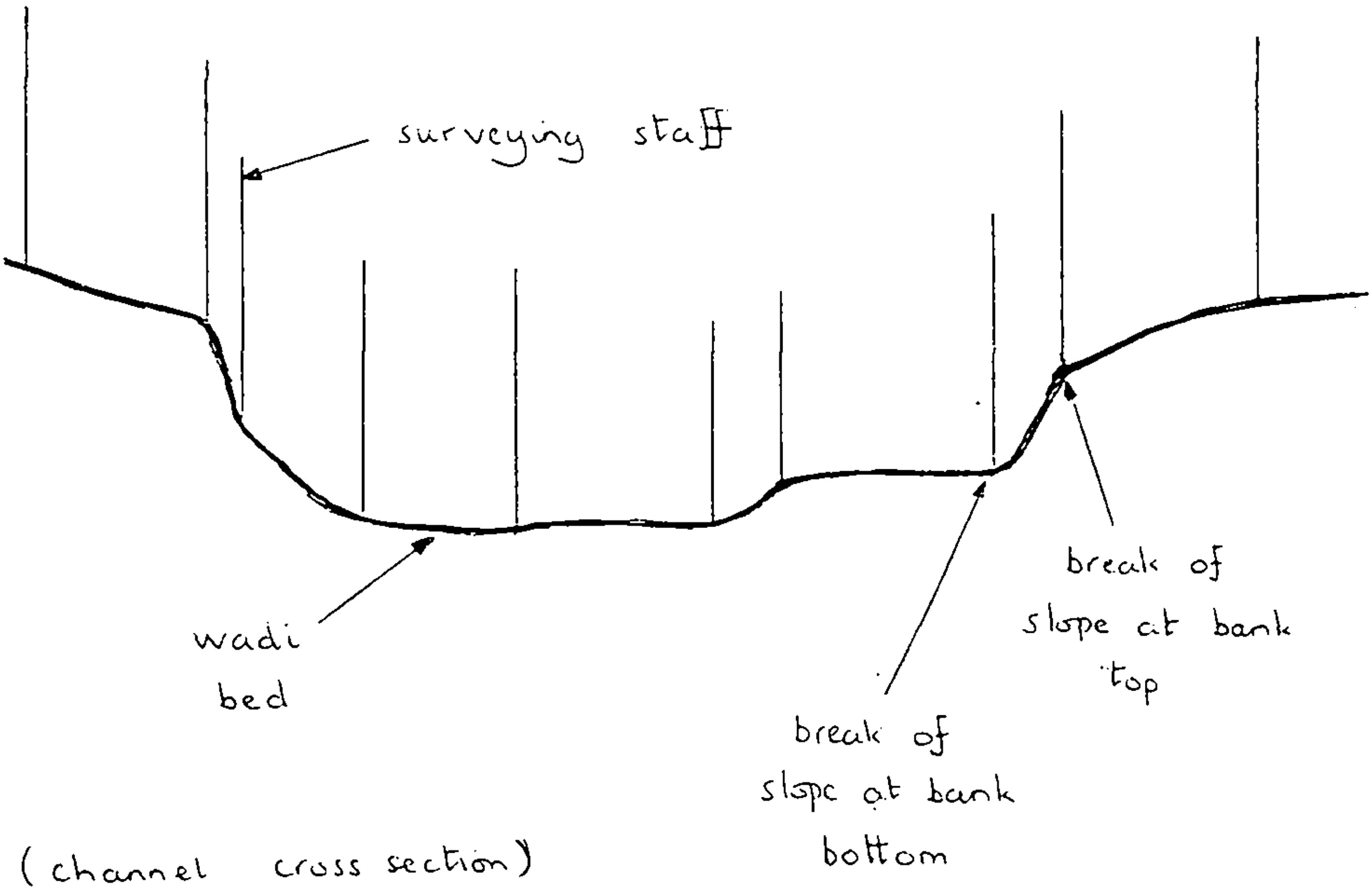


Fig 1. Illustration of the positioning of the surveying staff at breaks of slope when surveying a channel cross section.

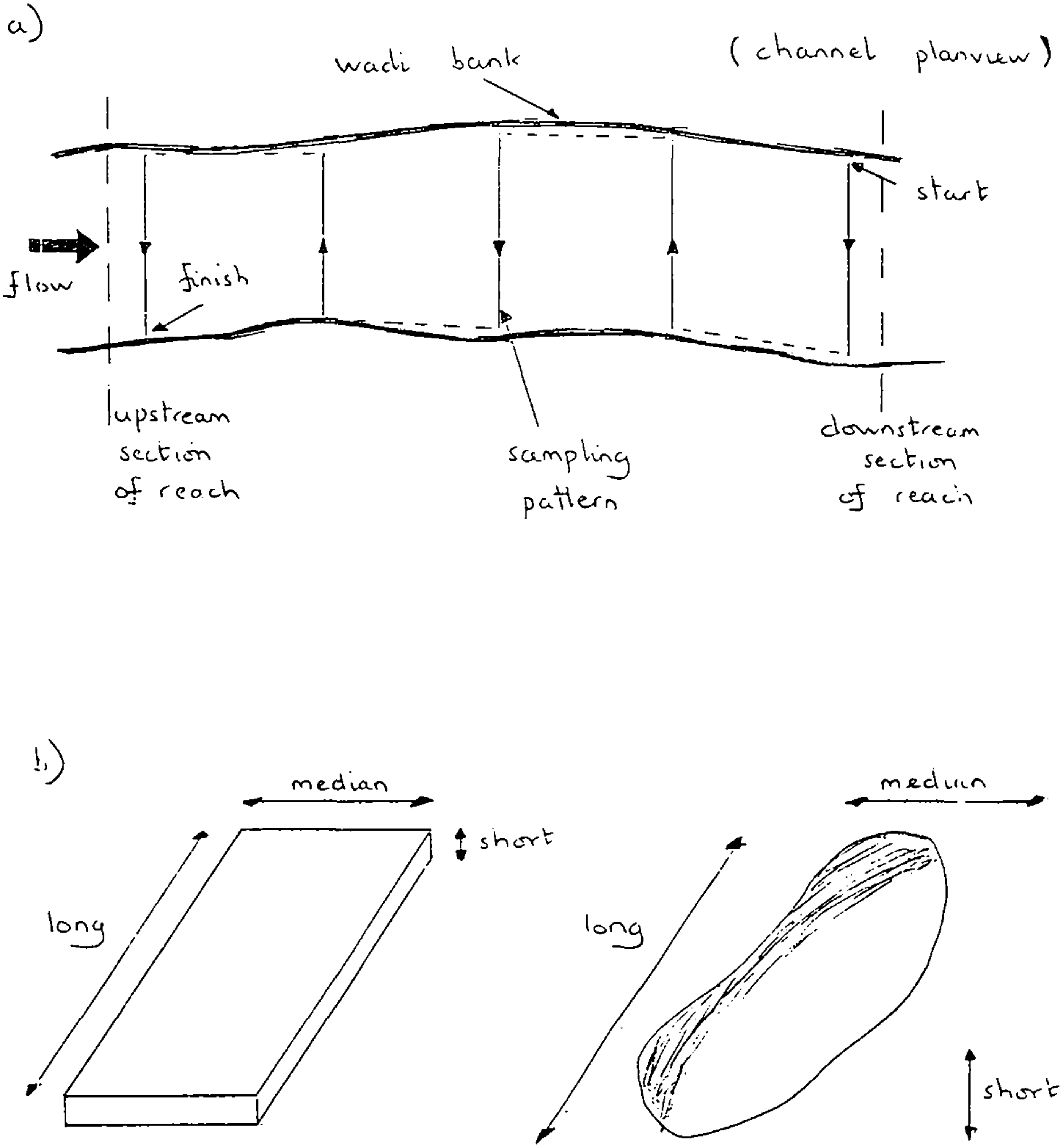


Fig 2. a) Example of sampling pattern. Measurements are made along each of the channel crossings.

b) *Definition diagram for the median axis of a bed material element.*

trash lines should be ignored.

The current level of the water surface at the time of the survey is irrelevant since it is not connected with the flood conditions. It is the high-water mark which is important and should be thought of as the water level.

10) If a particular flood is to be surveyed, the work should be done as soon as possible after the passage of the flood, preferably on the following day. This is to ensure a clearly marked trashline.

3.3 Sample of Bed Material

Once the surveying is completed, the bed material size should be measured as follows:

1) A sample of 100 elements is required, collected from the full width of the channel between the trash lines.

2) To cover the area representatively, sampling should be carried out by walking across the channel several times, measuring approximately the same number of elements on each crossing. For example, if five crossings are made, about twenty elements should be measured on each crossing. Ensure that successive crossings are upstream of each other so that the material to be sampled is undisturbed (Fig 2a).

3) During each crossing an element should be picked up every one or two paces. The sampler must not look at what is to be picked up but should pick up the first element which is touched by his or her fingers in the vicinity of his or her foot.

4) Measure the median axis in millimetres with a ruler (Fig 2b). Note the value in one of the boxes on the special data sheet, examples of which are shown in Appendix E. There are 100 boxes on each sheet.

3.4 Stage

Check that the stage recorder measured the flood hydrograph. The peak stage, ie the hydrograph peak, should be noted so that it can be paired with the estimated discharge for later use in constructing the stage-discharge rating curve. If the stage was not measured, the estimated discharge will be of no use for the rating curve and merely provides information on the magnitude of the flood in question.

3.5 Résumé

The data to be brought back from the field are:

A sketch map of the reach

2) Pairs of tape distances and elevations across each of the three sections the high-water points should be carefully noted.

3) Longstream tape distances between sections.

4) Elevation of the surveying reference datum, if used.

5) Bed material sizes.

6) Details of the surveying staff.

Peak stage if recorded.

Finally, all problems which may have occurred during the survey should be noted.

Examples of collected data are given in Appendices D and E.

OFFICE PROCEDURE

Once the field data have been collected, the peak discharge is calculated as follows.

) For each section, plot the surveying data to show the cross-sectional shape. Plot the tape distance on the horizontal axis with zero at the left hand side. Plot the surveyed elevations on the vertical axis. If the surveying staff used in the field read from top to bottom, with zero at the top, then the vertical axis of the plot should read upwards with zero at the bottom (Fig 3a). If the surveying staff read from bottom to top, with zero at the bottom, then the vertical axis of the plot should read downwards with zero at the top (Fig 3b).

2) If the survey at each section includes high-water marks on both sides of the channel, join the two levels with a straight line. If marks were observed on only one side of the channel, draw a horizontal line across the channel at the level of the mark. The line indicates the water surface elevation at the peak flow. Note this elevation for each section.

If no marks were observed, the mean bed elevation at each section is used instead. See point 6 and Appendix C.

3) Calculate the cross-sectional area A of each section. This may be done graphically (counting squares) or mathematically by the trapezoidal rule. See Appendix B.

) Calculate the surface width w for each section. This is the distance between the high-water marks at each section or the distance along the line of the water surface (Fig 4).

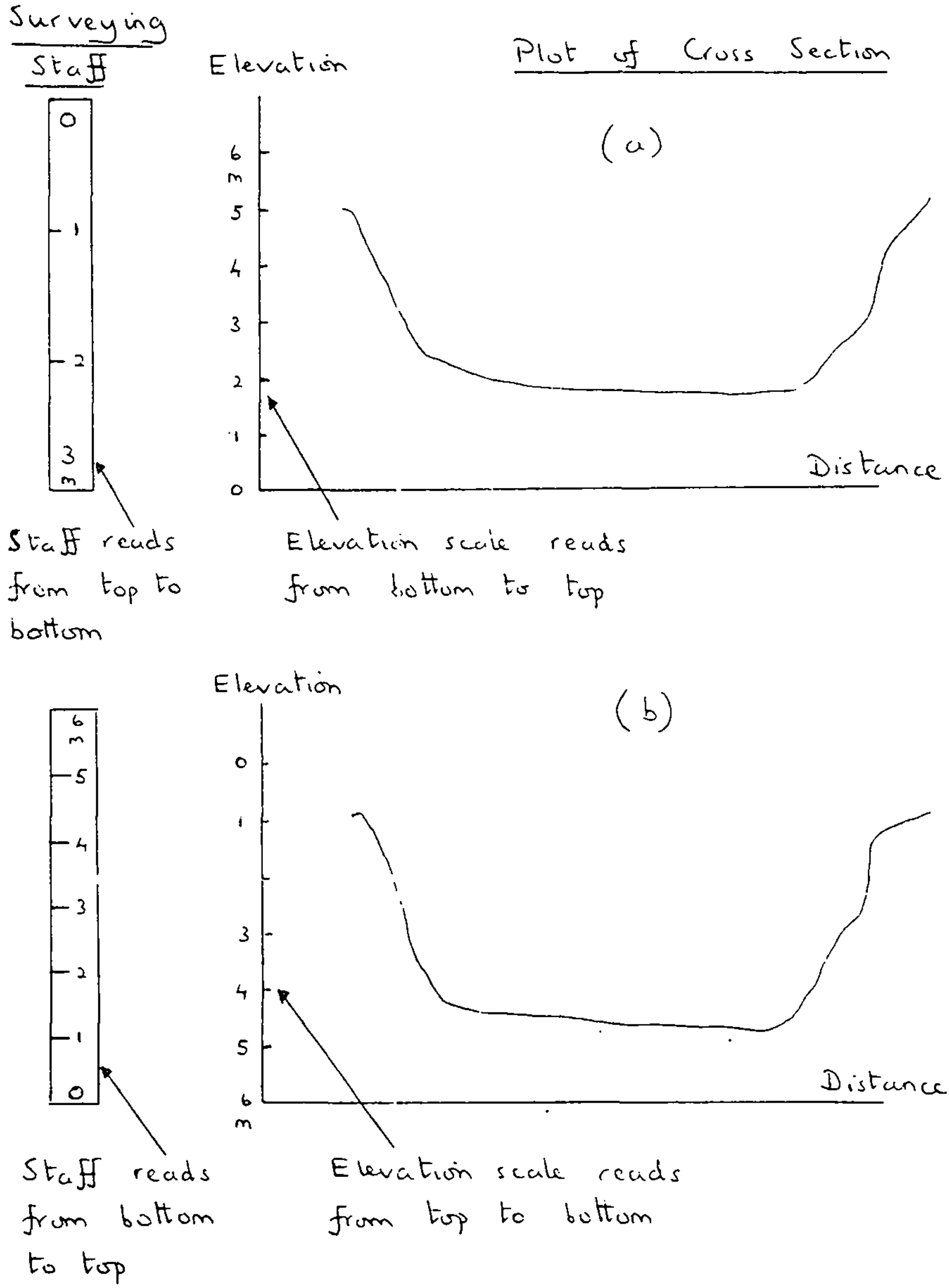


Fig 3. Illustration of how to plot the cross-sectional data according to the convention of the scale on the surveying staff.

a) Staff reads from top to bottom;

b) Staff reads from bottom to top.

5) Calculate mean depth d = A/w for each section. This is assumed to be similar to the hydraulic radius.

6) Calculate the overall fall in the water surface level from the upstream section (section 1) to the downstream section (section 3). The fall is the difference between the respective high-water levels. If the surveying staff used in the field read from top to bottom, with zero at the top, the fall is the upstream level minus the downstream level. If the surveying staff read from bottom to top, with zero at the bottom, the fall is the downstream level minus the upstream level. The final figure should be positive. If a negative value is calculated, there is a mistake in either the field measurements or the calculations.

If no high-water levels are available, use average bed levels instead and calculate the fall in the bed level. See Appendix C.

The slope of the water surface (or bed) is then the fall divided by the total length of the reach, from section 1 to section 3.

Using the bed material data sheet, obtain the cumulative size distribution and thence the D_{84} size of the bed material. For each element size put a tick or mark against the appropriate size range in the column headed "NUMBER IN RANGE". For example, if the element size is 32 mm put a tick against the range 30-35 mm. If the size is equal to one of the boundary values, eg 30 or 35 mm, the tick should be placed against the range for which that value is the upper limit. Thus for 35 mm tick the range 30-35 mm and for 30 mm tick the range 25-30 mm.

Add up the number of ticks for each range. Then in the column headed "CUMULATIVE TOTAL" add these figures to give the cumulative total at each size. The final figure should be 100. Plot a graph of cumulative total against size, using the upper limit of each size range as the size. For example, use 35 mm for the range 30-35 mm. Extract the size corresponding to 84 on the axis for cumulative total. This size is D_{84}. See Appendix E for examples.

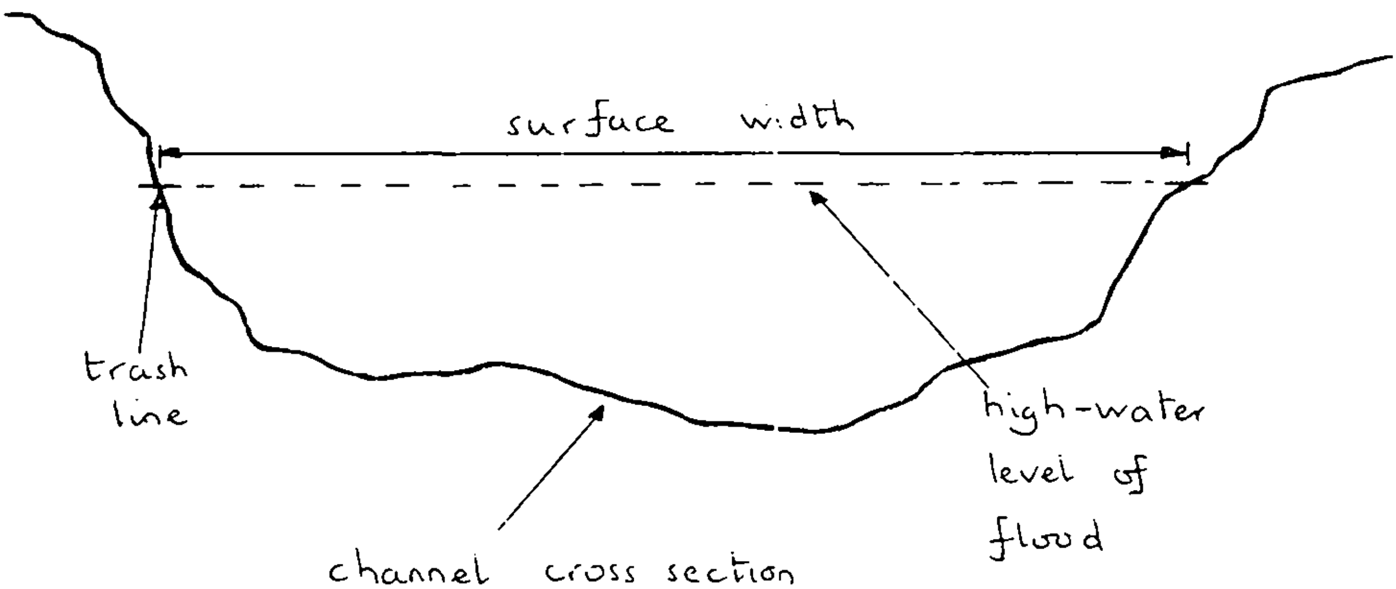


Fig 4. Definition diagram for the surface width of the peak flow.

8) At this stage, the following information should be available:

cross-sectional area	A	for each section;
width	w	for each section;
depth	d	for each section;
the fall	Δh	for the whole reach;
distance	$L_{1.2}$	from section 1 to section 2;
distance	$L_{2.3}$	from section 2 to section 3;
median axis size	D_{84}	for the bed material.

Distances and D_{84} should be in metres and areas should be in square metres. Section 1 is the upstream section, section 2 is the centre section and section 3 is the downstream section.

9) Calculate $(8/f)^{\frac{1}{2}}$ *for each section* using Eq 2.3 for a gravel bed and Eq 2.4 or 2.5 for a sand bed.

10) Calculate conveyance K for each section using Eq 2.2 with hydraulic radius R replaced by depth d.

11) Calculate the peak flood discharge using Eq 2.1. This value should be paired with the peak stage measured by the stage recorder and used in constructing the stage-discharge rating curve.

12) Examples of the calculation are given in Appendices D and E.

PROBLEMS WITH THE SLOPE-AREA METHOD IN THE YAR

It must be stressed that the slope-area method of estimating discharge is approximate and can be in error by 30%. However, if direct gauging cannot be carried out, it is the best that can be done. Particular problems with the method which I noted during my visit include:

1) Poor sites. The wadi morphology does not seem to provide very good slope-area sites. The Wadi Zabid site at Kolah suffers from overbank flow at high flows, the Wadi Rasyan site is rather nonuniform and the Wadi Siham site widens in the downstream direction. Only the Wadi Harad site came near to being ideal.

2) Lateral variation in the water surface level. The method assumes that the high-water mark is the level of the water surface right across the section. However, because of projecting rocks and channel bends which may cause piling up of water at the banks, this assumption may not hold in the steep wadis.

3) Scour. The degree to which this occurs is unknown but, if it occurs, the flow cross-sectional area at peak discharge will be greater than that measured on the basis of a survey made at low flow.

4) Lack of surveying practice. TDA hydrologists carrying out this method should be properly trained in the technique of surveying and in the analysis of the results. A surveying level, staff, tripod and tape measure should be bought for use with the method.

5) Inflexible response. In order to use the method successfully it will be necessary to carry out the surveying as soon as possible after a flood, before the high-water marks are destroyed. This means that a surveying team should be sent out the morning after a flood has been reported. During the flood season it may therefore be necessary to change plans at short notice.

6) Unmeasured stage levels. Unless the stage recorder is working properly the effort of estimating discharge will be wasted as far as development of the stage-discharge curve is concerned.

A more detailed discussion of the technical and nontechnical problems of slope-area gauging in the YAR is provided in Volume 1 of this visit report.

SIMPLIFIED FIELD PROCEDURE

6.1 Simplified System

If the slope-area method is to be used several times at one site, there is no need to repeat the field measurements at each visit. Once the initial survey has been made, the only field measurements required at subsequent visits are the peak flood levels or high-water marks at each section. These can be obtained using a system of flood marker posts installed at the reach during the initial survey. Office work, too, can be minimised by the use of specially prepared charts which give cross-sectional details for each flood level and by the use of a pocket computer for calculating the discharge.

Tests of the twin simplifications (flood marker posts and computer calculations) are currently being carried out for the Kolah gauging station in Wadi Zabid. The aim is to reduce the work involved, minimize the many possibilities for error inherent in the field and office procedures, overcome the deficiency in surveying and mathematical expertise at TDA and generally increase the reliability of the method in the context of the problems typically encountered in the YAR.

The system installed during my visit is experimental and its performance over a flood season must be checked. However, if it performs satisfactorily, the same approach could be applied at other wadi sites. This Section describes the simplifications in the field procedure while the office procedure is dealt with in Section 7.

6.2 Installation of Flood Marker Posts

The purpose of the posts is to record peak water surface levels more reliably than does a trash line and without having to resort to surveying. Posts should be installed at the banks of each of the three cross-sections in the slope-area reach as follows:

- The flood posts should be able to record the likely range of moderate to high floods. At the Kolah site in Wadi Zabid, a range of flood levels of 5 to 6 m is covered. The posts themselves are erected in sets of three at each section, each post being only about 2 m high so that there is no difficulty

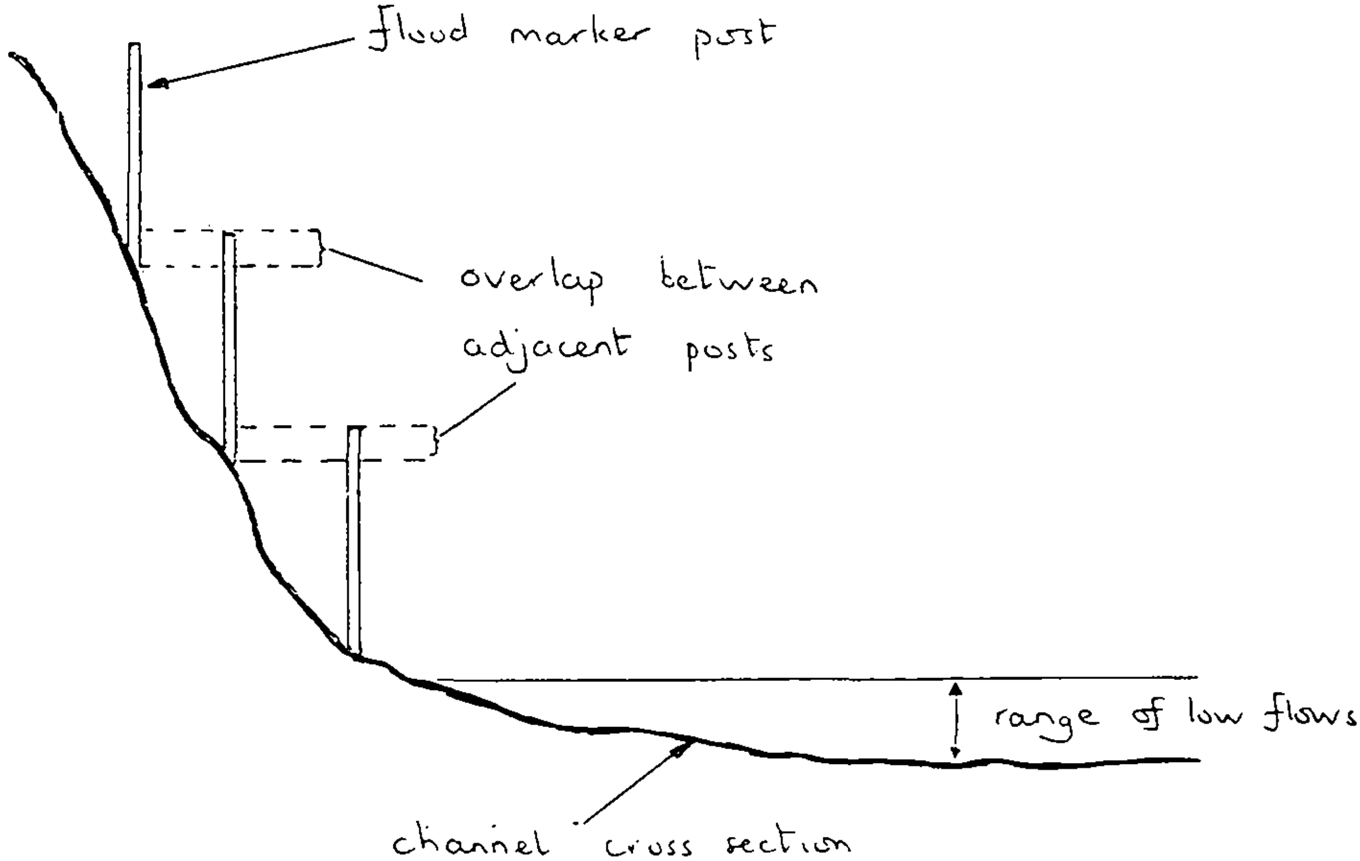
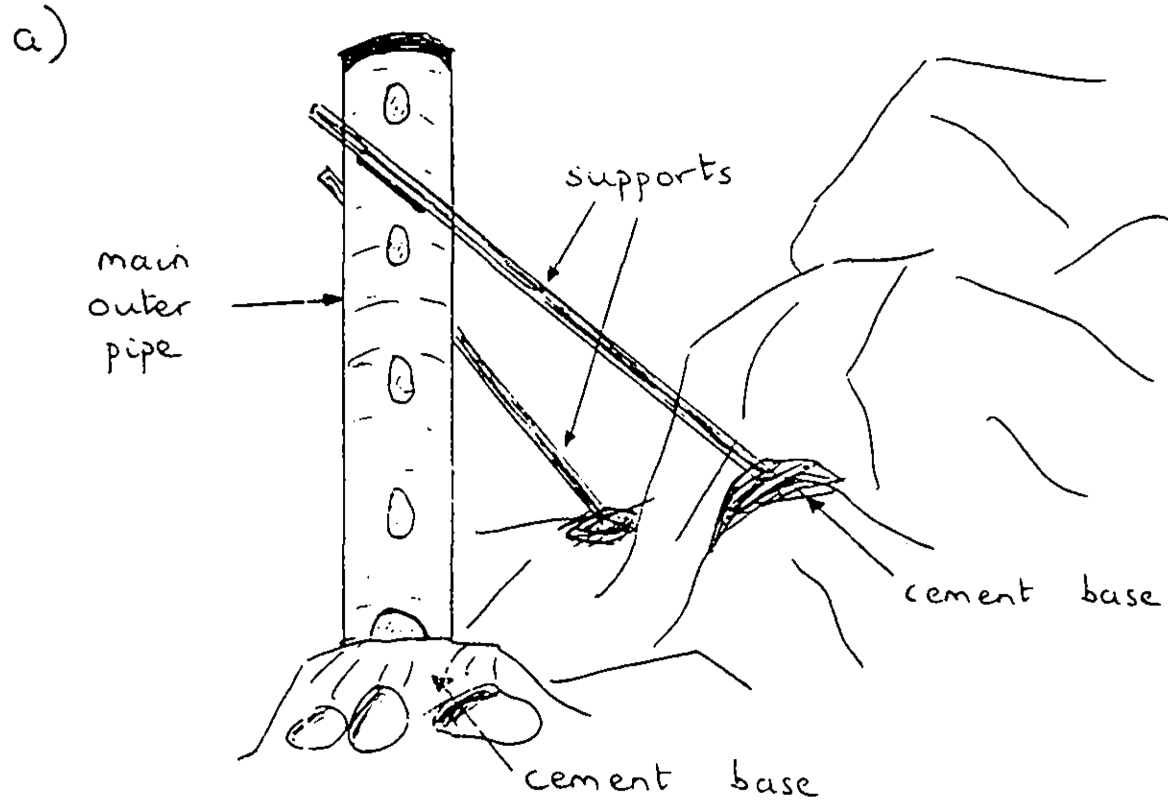


Fig 5. Layout of the flood marker posts at a cross section.



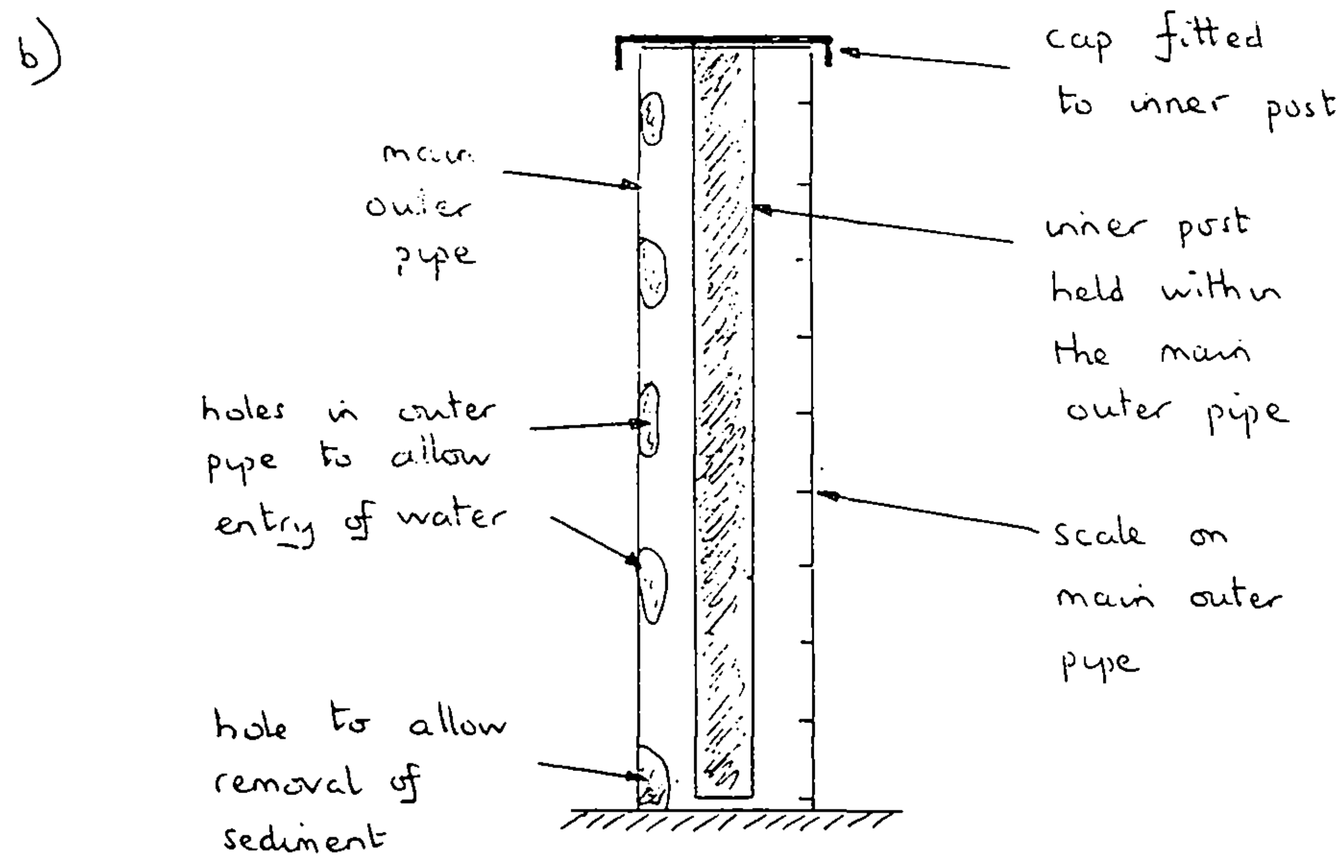


Fig 6. Design of the flood marker posts.

a) Support system.

b) Inner and outer posts.

in reading the flood level. There is a small overlap between posts (Fig 5). The base of the system is high enough that low flows cannot be measured. (At low flows, a water level measured at the bank may not be representative of the section because of lateral nonuniformities introduced by bed features such as bars.)

2) The posts record the flood level by the film of mud deposited on them during the flood. The top of the film, which could be on any of the three posts, marks the peak level. To ensure that the mark is not washed away by rain, the actual record is made on an inner post protected inside the main outer post. This main post is a pipe with holes to let water in and out and a large hole at the bottom to aid removal of sediment. It is planted in a cement foundation and is held against the force of the flow by two side supports (Fig 6a). Whether such a system is strong enough is being studied as part of the experiment.

   The inner post is held in place by a small plate at its top end which also effectively caps the main pipe and prevents rain from entering (Fig 6b). It should be locked or clipped to the main pipe so that it cannot be stolen or pulled out when submerged during a flood.

   At present the scale is marked on the outside of the main pipe, so the inner post must be taken out and laid against it to measure the flood level.

3) Once the main pipes have been erected at each section, a surveying level is used to mark a common benchmark on one of the pipes at each section (Fig 7). This benchmark is the basis of the scale to be marked on the pipes and ensures that the scales at each section have the same datum level. The value given to this elevation can be quite arbitrary: at Kolah, for example, it was convenient to set it at 2.1 m. After the benchmark value has been assigned, the scale can be completed at each section, marked in tens of centimetres. The scale should be carefully transferred between successive posts at each section using a level.

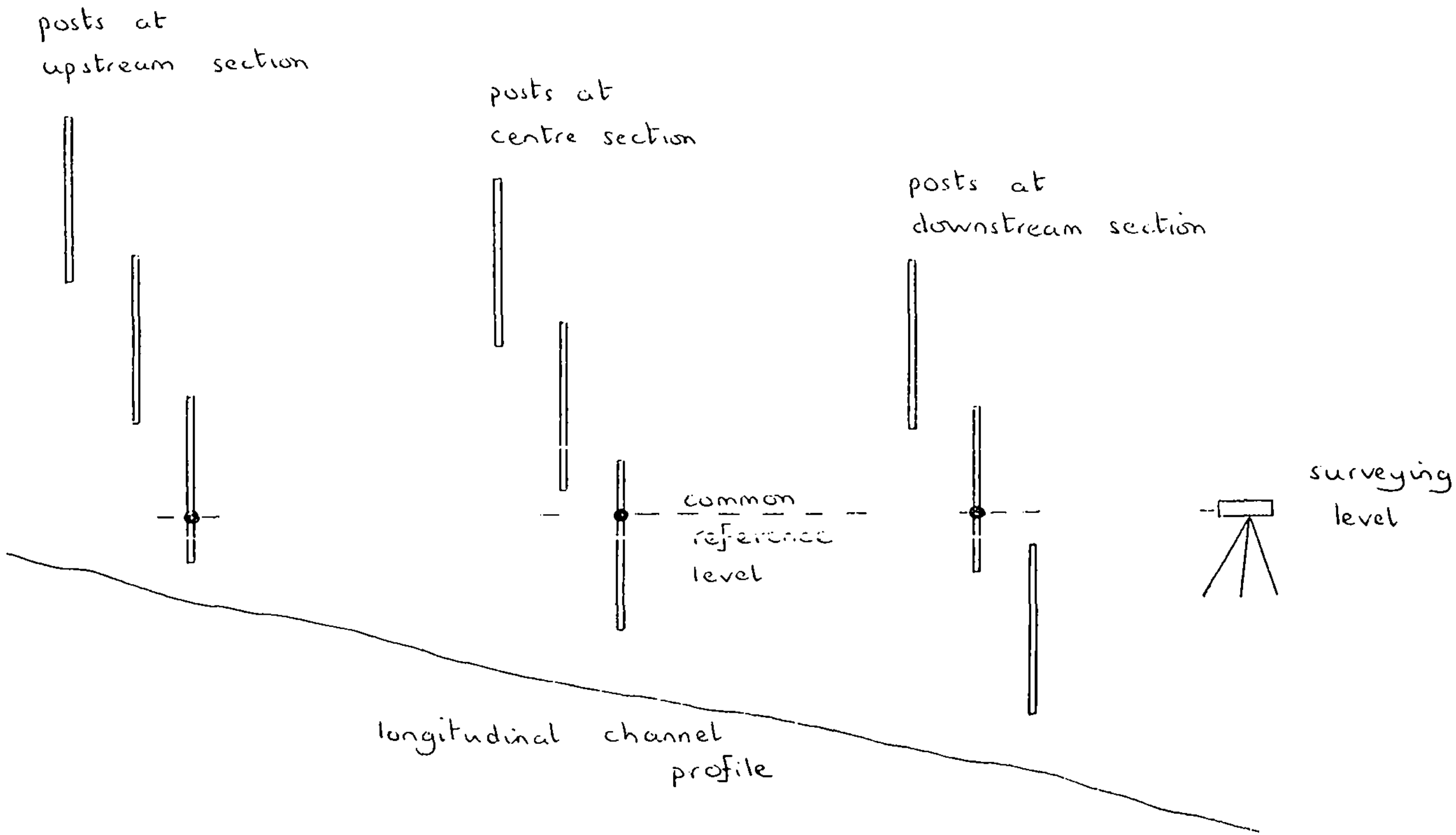


Fig 7. Surveying the common reference level or benchmark for the marker post scales at each section. This level is the basis of the scale at each section and ensures that water levels measured at each section are directly comparable with each other.

4) The exact details of the scales at each section at Kolah are shown in Fig 8. Note that the levels increase upwards. Each 10 cm mark is indicated by a hacksaw cut and a figure written with a magic marker. These figures should be replaced as they fade but if they are lost altogether they can be rewritten using Fig 8 as a guide.

5) The initial survey of each cross section (Section 3.2) and the survey of the posts should be carried out in such a way that the elevations of the flood marker posts and the elevations of the section can be reduced to the same reference datum level. Then a level measured on a marker post corresponds to the same level on the surveyed cross section. The way to ensure this is to use a surveying datum, such as a convenient rock projection. At Kolah the datum is a rock about 2 m above the wadi bed level on the left hand bank just downstream of the centre section. It was marked by spray paint at the end of my visit.

6) The initial survey should provide all the data mentioned in Section 3.5. Use of these data is discussed in Section 7.

The system is now ready for operation.

6.3 Operation of Flood Marker Post System

1) After a flood has passed, only three simple measurements need to be made, namely the peak flood elevations at each section.

2) Find which of the three posts at each section shows the high-water mark. If there has been recent rain, the mark may have washed off the main post but should be retained by the inner. Check that the level corresponds roughly with a trash line of litter and vegetation: If a high-water mark is not immediately obvious check to see whether the mark is at the overlap between posts, ie at the very top of one and the very bottom of its higher neighbour. If that is the case, small pieces of vegetation may also be lodged at the respective ends of the posts.

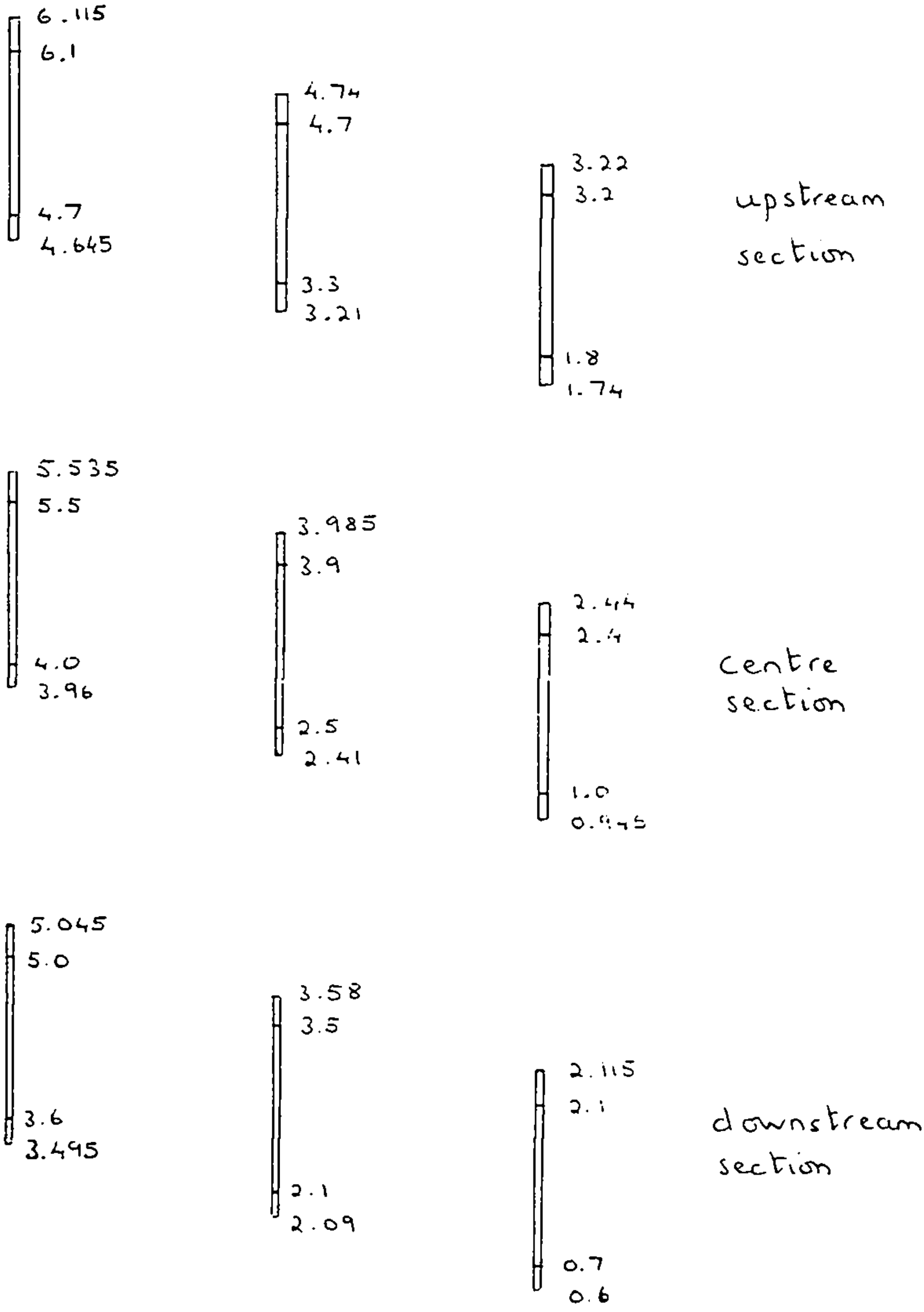


Fig 8. Details of the scale markings on the flood marker posts at the Kolah site. For each post the levels refer to, from top to bottom : the top of the post; the highest hacksaw cut; the lowest hacksaw cut; and the bottom of the post.

3) Pull out the relevant inner post and suspend it against the outside of the main pipe with its end plate resting on the top of the main pipe (Fig 9). In this way it should be at the same elevation as it was inside the main pipe. Make sure that any projection or flange on the end plate does not intrude. Measure the elevation of the flood mark on the scale of the main pipe. Use a ruler or tape measure to measure values between the 10 cm cuts on the scale. Note the level and note to which section it refers. Do not yet clean off the mud.

4) Compare the three measured flood elevations. The upstream value should be higher than the centre value which in turn should be higher than the downstream value. At the Kolah site the difference in each case should be about 0.4 m. If the comparison does not agree with these requirements, check the measurements. If the relative values of the levels are still unsatisfactory (for example, if the downstream value is higher than the upstream value), it is likely that some confusion of flood levels has occurred. If this cannot be resolved, the data should be abandoned.

5) Clean out any sediment which may be silting up the main pipe above its cement base.

6) After the flood levels have been satisfactorily dealt with, clean the mud film off both the inner and main posts, including any lower posts of the system which were fully submerged. This is very important since, if the mud is not removed, it will be very difficult to find the level of any later flood.

) Replace the inner pipe, remembering to lock or clip it into place.

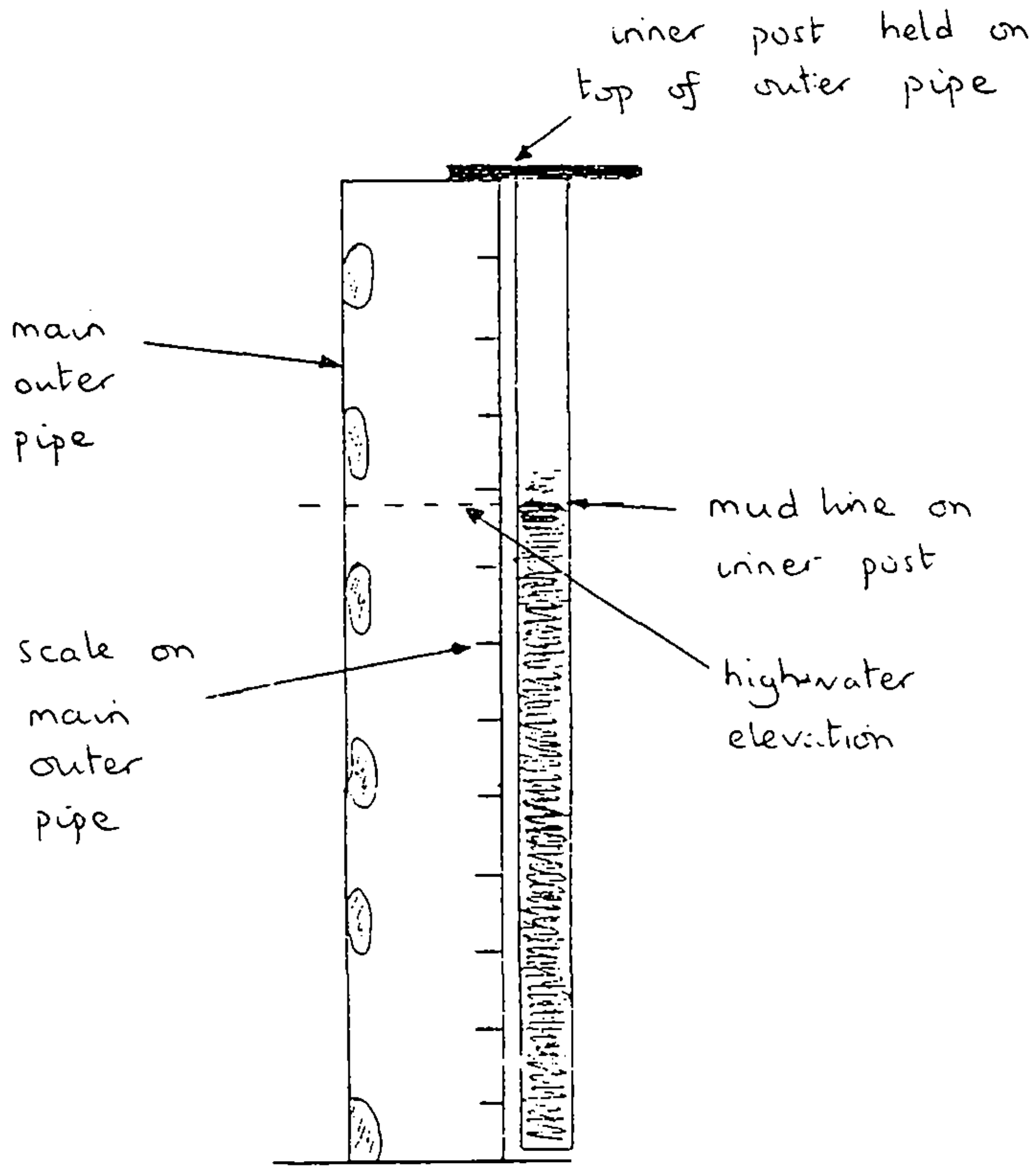


Fig 9. Illustration of how the elevation of the high-water mark on the inner post is measured against the scale on the outer post.

8) Periodically resurvey the cross sections and resample the bed material. This does not have to be done after each flood but, say, at the beginning and end of the flood season or after a major flood. Small changes in bed geometry will not greatly affect the flow cross section but an accumulation of changes over a long period could be important.

6.4 Résumé

Once a system of flood marker posts has been installed and a survey of the slope-area reach has been carried out, the only field measurements needed in connection with a subsequent flood gauging are the peak water surface levels at each of the three sections.

SIMPLIFIED OFFICE PROCEDURE

7.1 Preparation of Data

As with the full slope-area method, the basic quantities needed to calculate discharge are:

cross-sectional area at each section;
surface width at each section;
bed material size D_{84} for the reach;
distance between each section;
flood levels at each section.

The difference in the simplified method is the way in which some of these terms are derived from the field data.

The flood levels are the only quantities actually measured in connection with a gauging, using the system of flood marker posts.

The distances between sections and the bed material size D_{84} are measured during the initial survey and are assumed to be the same at subsequent visits.

Area and width are obtained from charts which show those terms as functions of flood level, based on the initial survey data.

The charts are prepared and used as follows.

1) For each cross section, use the survey data to calculate the cross-sectional area and surface width for a series of specified flood levels. The levels might be separated by intervals of, say, 0.5 m, so that area and width would be calculated for levels of, for example, 1, 1.5, 2, 2.5 and 3 m.

2) For each section, use these values to plot two graphs, one of area against flood level and one of width against flood level. As an example, the completed chart for Kolah, containing the information on area and width, is shown in Fig 10.

) When a flood level has been measured on a flood marker post, the area and width for that section are obtained simply by reading the values corresponding to the flood level on the chart. In other words it is no longer necessary to calculate them from the surveying data each time.

Once the data have been assembled, discharge can be calculated using a specially designed computer program. The program applies to reaches with or without a system of flood marker posts but requires that the data be presented as for reaches with marker posts. In particular, the upstream section flood level shoild be higher than the centre section level which should in turn be higher than the lower section value. This ought to be the case if the levels were measured using flood posts or a surveying staff reading from top to bottom, with zero at the top. However, if measurements were made with a surveying staff reading from bottom to top, with zero at the bottom, the following correction should be made.

) Calculate the difference between the centre and upstream level $= \Delta_1$ (a positive value in metres).

2) Calculate the difference between the downstream and upstream levels $= \Delta_2$ (a positive value in metres).

3) Set a new upstream level with an arbitrary value, say 5 m.

4) The new centre level is then $5 - \Delta_1$.

5) The new downstream level is then $5 - \Delta_2$.

6) Use these new values with the program. It is the difference between levels and their signs (positive or negative) which are important to the program, not the values themselves.

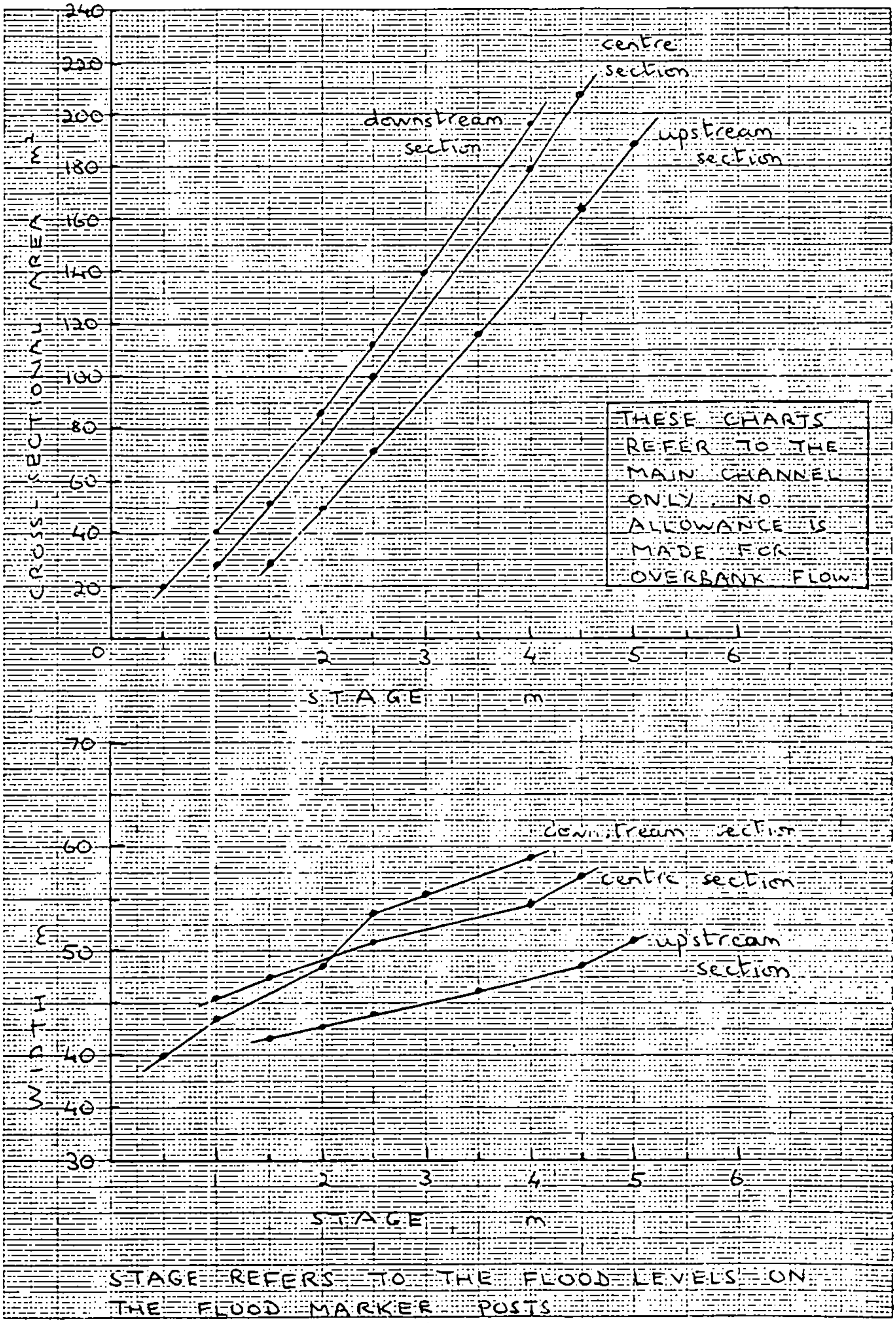


Fig 10. **Relationships between cross-sectional area and stage and between width and stage for the Kolah site. These charts enable values of area and width to be obtained for given stage levels on the marker posts.**

7.2 Discharge Calculation by Program SLOPE-AREA

The program "SLOPE-AREA" confines the calculation of discharge to the SHARP PC-1500 pocket computer loaned to TDA by IH, so avoiding the complexities of hand calculation of discharge. It follows the slope-area procedure exactly as described in Sections 2 and 4 and according to the listing in Table 1. However, it applies only to reaches with gravel beds and data for three cross sections.

The program should be run as follows:

) Switch the computer on and connect it to the tape recorder as indicated in the SHARP manual or the guide by Dr. Green (1983).

2) Transfer the program "SLOPE-AREA" from its tape to the computer using the CLOAD function as indicated in the SHARP manual or the guide by Dr. Green.

3) Disconnect the tape recorder.

) Make sure that the computer is in RUN mode and type "RUN". The program is now in operation and the computer will begin to ask for data and information.

5) To the question "YOUR NAME?" enter your name eg BATHURST.

6) To the question "NAME OF SITE?" enter name of site eg KOLAH.

) To the question "DATE OF FLOOD?" enter date of flood eg 28/7/83 or AUG 1983.

8) To the question "UPSTREAM STAGE?" enter the flood level at the upstream section in metres.

9) To the question "CENTRE STAGE?" enter the flood level at the centre section in metres.

10) To the question "DOWNSTREAM STAGE?" enter the flood level at the downstream section in metres.

11) The computer then checks to make sure that the flood levels decrease in the downstream direction. If there is an error, for example if the centre level is higher than the upstream level, the computer will indicate this with a message on the screen and ask for the data to be re-entered, beginning at step 8. If subsequently the check continues to show an error, the computer will eventually stop the program. If not the program continues with step 12.

12) To the question "UPSTREAM AREA?" enter the cross-sectional area at the upstream section in square metres. For the Kolah site this is the area which corresponds to the upstream flood level in Fig 10.

13) To the question "CENTRE AREA?" enter the cross-sectional area for the centre section as in step 12.

14) To the question "DOWNSTREAM AREA?" enter the cross-sectional area for the downstream section as in step 12.

15) To the question "UPSTREAM WIDTH?" enter the surface width at the upstream section in metres. For the Kolah site this is the width which corresponds to the upstream flood level in Fig 10.

16) To the question "CENTRE WIDTH?" enter the surface width at the centre section as in step 15.

17) To the question "DOWNSTREAM WIDTH?" enter the surface width at the downstream section as in step 15.

18) To the question "DISTANCE 1?" enter the distance between the upstream and centre sections in metres. At Kolah this is 59 m.

19) To the question "DISTANCE 2?" enter the distance between the centre and downstream sections in metres. At Kolah this is 44 m.

20) To the question "GRAVEL D84 IN M?" enter the D_{84} size of the bed material in metres. At Kolah this was 0.113 m at the last check.

21) The screen will now go blank and the discharge calculation begins. If there are no serious mistakes in the data the results will appear on the printer. If, however, the screen flashes an error message it is likely that a mistake was made while entering the data. In that case press the button BREAK/ON and begin again at step 4.

22) The computer prints the original data which were entered, various parameters calculated for the slope-area method and finally the estimated discharge. Examples are shown in Appendices D and E. Check all these data carefully. In particular check that the original data were entered correctly. Check that the slopes are reasonable (between about 0.002 and 0.02). Note that if the slopes in the upper and lower reaches differ by a factor of two or more, the computer will print a warning. This does not necessarily mean that there is an error but it means that the flow is apparently not very uniform and that there could be a mistake in the flood levels or distances between sections.

Finally check that the discharge seems reasonable. Was it a high or a moderate flood and does the estimated discharge tally? At the Kolah site it is likely that a flood which stays within bank and does not flow over the fields on the right hand bank has a discharge of less than 300 m^3/s.

23) The program ends with a short "beep".

24) If you have no more discharges to calculate, turn the computer off or plug it onto the adapter to recharge as required. The program "SLOPE-AREA" will be retained until the command "NEW" is typed in. Thus it can be used at a subsequent time simply by switching on the computer and beginning at step 4.

Finally, the data assembled for the Kolah site, including Fig 10, refer to the main channel only. No allowance has been made for overbank flow. If the flood level is such that overbank flow would have occurred, the program will still calculate only that discharge which flowed along the channel. The estimated discharge will therefore underestimate the total discharge. A separate slope-area calculation can be carried out for the overbank flow with a resistance coefficient appropriate to vegetation. However, training in this aspect was not carried out during my visit.

7.3 Résumé

Once a flood marker post system has been installed, discharge may be estimated with a minimum of work.

In the field, measure the flood levels at each of the three sections as indicated in Section 6.3.

Table 1. Listing for the program "SLOPE-AREA" in Basic Language

```
  10:CLEAR :WAIT 10
     0
  20:DIM H(2),A(2),
     D(2),W(2),FF(2
     ),K(2),L(1),DD
     (2)
  30:REM H IS STAGE
  40:REM A IS AREA
  50:REM D IS DEPTH
  60:REM W IS WIDTH
  70:REM FF IS √8/F
  80:REM K IS CONVE
     YANCE
  90:REM L IS DISTA
     NCE
 100:REM DD IS D/D8
     4
 140:IC=0:ID=0
 150:INPUT "YOUR NA
     ME?";NA$
 160:INPUT "NAME OF
      SITE?";SI$
 170:INPUT "DATE OF
      FLOOD?";DT$
 180:INPUT "UPSTREA
     M STAGE?";H(0)
 190:INPUT "CENTRE
     STAGE?";H(1)
 200:INPUT "DOWNSTR
     EAM STAGE";H(2
     )
 210:IF H(0)<H(1)
     THEN GOTO 240
 220:IF H(1)<H(2)
     THEN GOTO 300
 230:GOTO 390
 240:IC=IC+1
 250:IF IC>2THEN
     GOTO 360
 260:PRINT "UPSTREA
     M STAGE ";H(0)
 270:PRINT "LESS TH
     AN CENTRE ";H(
     1)
 280:PRINT "REENTER
      DATA"
 290:GOTO 180
 300:ID=ID+1
 310:IF ID>2THEN
     GOTO 360
 320:PRINT "CENTRE
     STAGE ";H(1)
 330:PRINT "LESS TH
     AN DOWNSTREAM
     ";H(2)
 340:PRINT "REENTER
      DATA"
 350:GOTO 180
 360:PRINT "INCOMPA
     TIBLE STAGE DA
     TA"
 370:PRINT "PROGRAM
      WILL END"
 380:GOTO 2000
 390:INPUT "UPSTREA
     M AREA?";A(0)
 400:INPUT "CENTRE
     AREA?";A(1)
 410:INPUT "DOWNSTR
     EAM AREA?";A(2
     )
 420:INPUT "UPSTREA
     M WIDTH?";W(0)
 430:INPUT "CENTRE
     WIDTH?";W(1)
 440:INPUT "DOWNSTR
     EAM WIDTH";W(2
     )
 450:INPUT "DISTANC
     E 1?";L(0)
 460:INPUT "DISTANC
     E 2?";L(1)
 470:REM LT IS TOTA
     L LENGTH
 480:LT=L(0)+L(1)
 490:INPUT "GRAVEL
     D84 IN M?";D8
 491:CLS
 500:REM CALCULATIO
     NS
 510:REM SLOPES
 520:S1=(H(0)-H(1))
     /L(0)
 530:S2=(H(1)-H(2))
     /L(1)
 540:S=(H(0)-H(2))/
     LT
 550:REM TOTAL FALL
      DH
 560:DH=H(0)-H(2)
 570:FOR I=0TO 2
 580:REM SECTION DE
     PTHS
 650:D(I)=A(I)/W(I)
 660:REM D/D84 AND
     √8/F
 670:DD(I)=D(I)/D8
 680:XX=LOG DD(I)
 690:FF(I)=(5.62*XX
     )+4
 700:XX=9.81*D(I)
 710:K(I)=A(I)*(√XX
     )*FF(I)
 720:NEXT I
 730:REM SLOPE-AREA
      METHOD
 732:X2=A(2)/A(1)
 734:K2=0
 736:IF X2>1THEN
     LET K2=0.5
 738:X1=A(1)/A(0)
 740:K1=0
 742:IF X1>1THEN
     LET K1=0.5
 744:XY=A(2)/A(0)
 746:XX=(XY^2)*(1-K
     1)
 748:XZ=(X2^2)*(K2-
     K1)
 750:XY=1-K2+XZ-XX
 780:XZ=(K(2)/A(2))
     ^2
 790:XX=XZ*XY/19.62
 800:XY=(L(0)*K(2)/
     K(0))+L(1)
 810:XZ=(K(2)/K(1))
     *XY
 820:XY=DH/(XZ+XX)
 830:Q=K(2)*√XY
 840:REM PRINT RESU
     LTS
 850:COLOR 0
 860:CSIZE 2
 870:LPRINT TAB 6;S
     I$
 880:LPRINT TAB 1;"
     GAUGING STATIO
     N":LF 1
 890:LPRINT TAB 5;"
     FLOOD OF"
 900:LPRINT TAB 5;D
     T$:LF 1
 910:LPRINT TAB 1;"
     PEAK DISCHARGE
      BY"
 920:LPRINT TAB 1;"
     SLOPE-AREA MET
     HOD":LF 1
 930:LPRINT TAB 1;"
     DATA ENTERED B
     Y"
 940:LPRINT TAB 1;N
     A$:LF 2
 950:COLOR 1
 960:LPRINT TAB 6;"
     RESULTS"
 970:LF 1:LPRINT
     TAB 3;"FLOOD L
     EVELS"
 990:FOR I=0TO 2
 991:USING "##"
 992:J=I+1
1000:LPRINT TAB 1
     ;"SECT ";J;"
      ";USING "##
     #.##";H(I);"
     M"
1010:NEXT I
1020:LF 1:LPRINT
     TAB 3;"DISTA
     NCES"
1040:FOR I=0TO 1
1041:USING "##"
1042:J=I+1
```

continued

Table 1 continued

```
1050:LPRINT TAB 1
     ;"DIST ";J;"
      ";USING "##
     ##.#";L(I);"
      M"
1060:NEXT I
1070:LF 1:LCURSOR
     3
1080:LPRINT USING
     "##.#####";"
     SLOPE ";S
1090:LPRINT "(UPP
     ER = ";S1;")
     "
1100:LPRINT "(LOW
     ER = ";S2;")
     ";LF 1
1110:IF S1>2*S2
     THEN GOTO 11
     40
1120:IF S2>2*S1
     THEN GOTO 11
     40
1130:GOTO 1200
1140:COLOR 3
1150:LF 1:LPRINT
     TAB 1;"WARNI
     NG"
1160:LPRINT TAB 1
     ;"SLOPES IN
     UPPER"
1170:LPRINT TAB 1
     ;"AND LOWER
     REACHES"
1180:LPRINT TAB 1
     ;"ARE NOT SI
     MILAR."
1190:LPRINT TAB 1
     ;"CHECK ABOV
     E DATA."
1200:COLOR 1
1210:USING "##.##
     #"
1220:LF 1:LPRINT
     "GRAVEL D84"
     ;D8;  M":LF
     1
1231:LPRINT TAB 3
     ;"SECTION AR
     EAS"
1240:FOR I=0TO 2
1241:USING "##"
1242:J=I+1
1250:LPRINT TAB 1
     ;"SECT ";J;"
      ";USING "##
     ##.#";A(I);"
      M2"
1260:NEXT I
1270:LF 1
1281:LPRINT TAB 3
     ;"SECTION DE
     PTHS"
1290:FOR I=0TO 2
1291:USING "##"
1292:J=I+1
1300:LPRINT TAB 1
     ;"SECT ";J;"
      ";USING "##
     #.##";D(I);"
      M"
1310:NEXT I
1320:LF 1
1340:LPRINT TAB 3
     ;"SECTION WI
     DTHS"
1350:FOR I=0TO 2
1351:USING "##"
1352:J=I+1
1360:LPRINT TAB 1
     ;"SECT ";J;"
      ";USING "##
     ##.#";W(I);
      M"
1370:NEXT I
1380:LF 1
1400:LPRINT TAB 3
     ;"SECTION D/
     D84"
1410:FOR I=0TO 2
1411:USING "##"
1412:J=I+1
1420:LPRINT TAB 1
     ;"SECT ";J;"
      ";USING "##
     ##.##";DD(I)
1430:NEXT I
1440:LF 1
1450:LPRINT TAB 3
     ;"SECTION √8
     /F"
1460:FOR I=0TO 2
1461:USING "##"
1462:J=I+1
1470:LPRINT TAB 1
     ;"SECT ";J;"
      ";USING "##
     #.##";FF(I)
1480:NEXT I
1490:LF 2
1500:COLOR 2
1510:EN$="+++++++
     ++++++++"
1520:LPRINT TAB 1
     ;EN$:LF 1
1530:COLOR 3
1540:USING "#####
     "
1550:LPRINT TAB 6
     ;"DISCHARGE"
1560:LPRINT TAB 5
     ;Q;  M3/S"
1570:COLOR 2
1580:LF 1:LPRINT
     TAB 1;EN$
2000:BEEP 1,150,1
     000
2010:END
```

2) In the office, obtain the values of cross-sectional area and surface width which correspond to the measured levels at each section, using a diagram such as Fig 10.

3) Run the program "SLOPE-AREA" to calculate discharge as indicated in Section 7.2.

4) Check that the data were entered properly and that the results are reasonable.

REFERENCES

Barnes, H.H., and Davidian, J. 1978. Indirect Methods. In Hydrometry, R.W. Herschy (ed), John Wiley, Chichester, 149-204.

Bathurst, J.C. 1980. Stage and Discharge Measurements in Steep Wadis. Visit Report No. 8, Institute of Hydrology, Wallingford.

Benson, M.A. 1968. Measurement of Peak Discharge by Indirect Methods. WMO No. 225. TP.119, Technical Note No. 90, Geneva, Switzerland.

Dalrymple, T., and Benson, M.A. 1967. Measurement of Peak Discharge by the Slope-Area Method, United States Geological Survey Techniques of Water - Resources Investigations, Book 3, Chap. A2.

Foley, M.G. 1975. Scour and Fill in Ephemeral Streams. Report No. KH-R-33, W.M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Pasadena, California, pp.189.

Green, C.S. 1983. Yemen Arab Republic Visit Report (November 1981 and October 1982). Visit Report, Institute of Hydrology, Wallingford.

Simons, D.B., and Şentürk, F. 1977. Sediment Transport Technology, Water Resources Publications, Fort Collins, Colorado, pp.807.

APPENDIX A THEORY OF SLOPE-AREA METHOD

A.1 Uniform Flow Equation

The central assumption of the method is that the flow depth and velocity are determined by channel cross-sectional shape, channel slope and bed roughness. Calculation of discharge can then be based on a uniform-flow equation such as the Manning, Chézy or Darcy-Weisbach equation. Here the Darcy-Weisbach equation is used since it is dimensionless:

$$Q = A \, (g \, R \, S_f)^{\frac{1}{2}} \quad \left(\frac{8}{f}\right)^{\frac{1}{2}} \qquad (A.1)$$

where Q = discharge; A = flow cross-sectional area; g = acceleration due to gravity (9.81 m/s² or 32 ft/s²); R = hydraulic radius; S_f = friction slope: and f = the Darcy-Weisbach resistance coefficient which is calculated as shown in Section 2.2. Hydraulic radius can be replaced by mean depth d (calculated as A/w where w = flow surface width) if w/d exceeds about 15.

If the flow were uniform, with friction slope equal to bed slope and with no longstream changes in cross-sectional geometry, data from just one cross section would be sufficient for the calculation of discharge via Eq A.1. However, uniform conditions are rarely attained in natural rivers and the method must be modified to incorporate data from several cross sections and to include the change in velocity head in the friction slope. These modifications are described here in conjunction with Fig A1 which is a definition diagram of a river reach between two sections.

A.2 Friction Slope

In order to calculate the friction slope, it is necessary to consider the longstream change in the total energy of the flow. A flow possesses potential energy by virtue of the elevation of the bed and the depth of flow and kinetic energy by virtue of the flow velocity. Total energy H at a section is therefore (see also Fig A1)

$$H = z + d + h_v \qquad (A.2)$$

where z = bed elevation; d = depth; h_v = velocity head defined as $\alpha V^2/2g$; V = mean velocity; and α = the velocity head coefficient, a

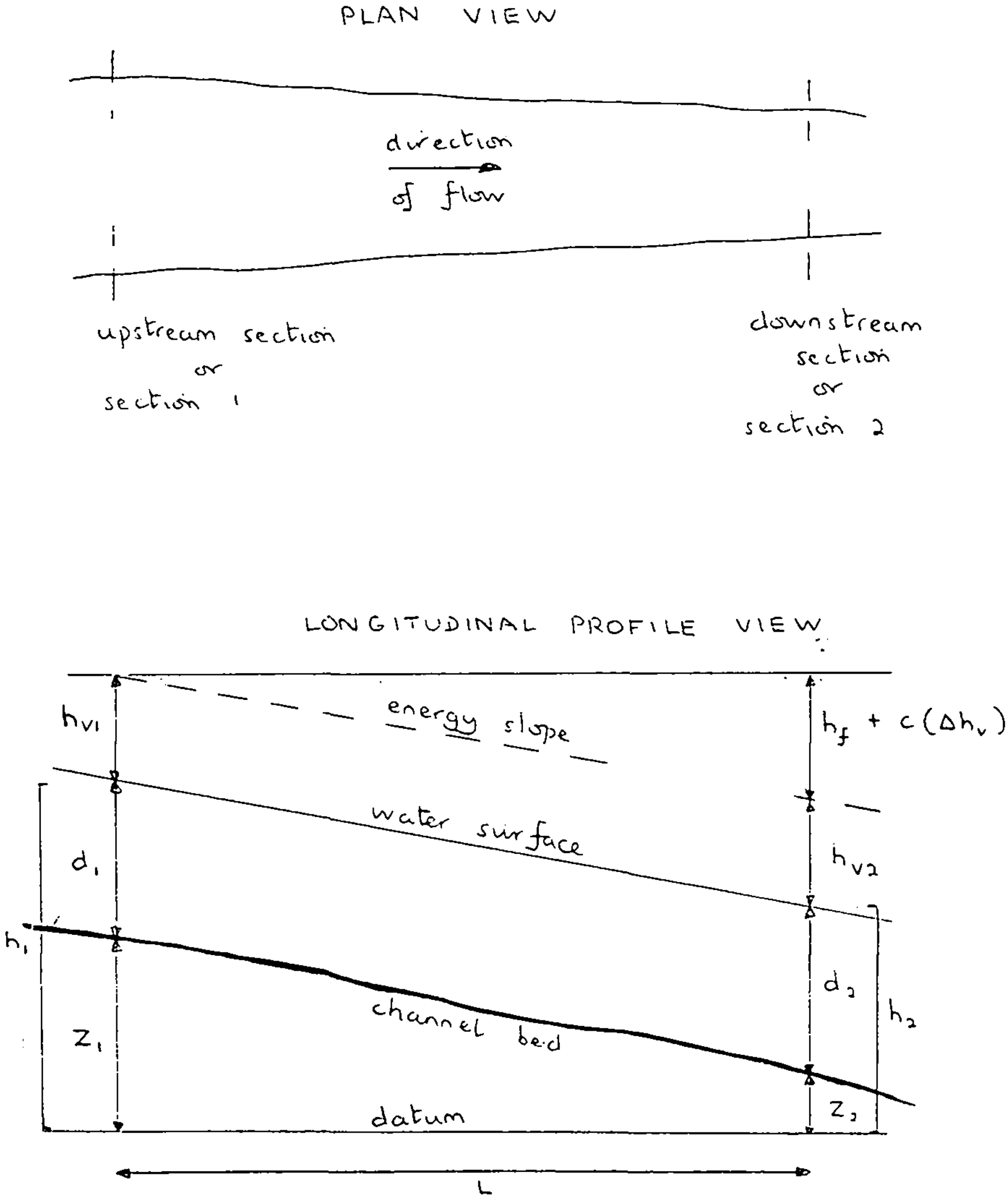


Fig A1. Definition diagram for a slope-area reach between two sections.

mathematical term approximately equal to 1. The quantity (z+d) can be replaced by h which is the elevation of the water surface or stage. Then

$$H = h + h_v \tag{A.3}$$

As the flow moves along the channel it loses energy in overcoming the friction of the bed, through expansion and contraction of the flow area and through other processes. The loss in energy between two sections is obtained from the energy equation (see also Fig A1)

$$h_1 + h_{v1} = h_2 + h_{v2} + h_f + c\,(\Delta h_v) \tag{A.4}$$

where subscript 1 refers to the upstream section; subscript 2 refers to the downstream section; h_f = the energy loss caused by boundary friction; Δh_v = the upstream velocity head minus the downstream velocity head (ie $h_{v1} - h_{v2}$) and is used as a criterion of expanding or contracting flow; c = the energy loss coefficient; and $c\,(\Delta h_v)$ = the energy loss due to acceleration or deceleration in a contracting or expanding reach respectively. It is from this equation that the friction slope is defined, being the gradient of the energy loss due to friction between the sections.

$$S_f = \frac{h_f}{L} = \frac{\Delta h + \Delta h_v - c\,(\Delta h_v)}{L} \tag{A.5}$$

where $\Delta h = h_1 - h_2$; $\Delta h_v = h_{v1} - h_{v2}$; and L = distance between sections. The terms involving the change in velocity head, Δh_v, distinguish the friction slope from the water surface slope, which is simply $\Delta h/L$.

In order that this definition of friction slope can be easily incorporated into Eq A.1, the following modifications are carried out. By continuity the discharge Q is related to velocity V by cross-sectional area A

$$Q = A\,V \tag{A.6}$$

Therefore the velocity head can be given as

$$\frac{\alpha V^2}{2g} = \frac{\alpha}{2g}\left(\frac{Q}{A}\right)^2 \tag{A.7}$$

Making the assumption that the velocity head coefficient α is 1, the change in velocity head is

$$\Delta h_v = \frac{Q^2}{2g}\left(\frac{1}{A_1^2} \quad \frac{1}{A_2^2}\right) = \frac{1}{2g}\left(\frac{Q}{A_2}\right)^2 \left[\left(\frac{A_2}{A_1}\right)^2 \quad 1\right] \qquad (A.8)$$

The friction slope is then

$$S_f = \frac{\Delta h + \left(\frac{1 - c}{2g}\right)\left(\frac{Q}{A_2}\right)^2 \left[\left(\frac{A_2}{A_1}\right)^2 \quad 1\right]}{L} \qquad (A.9)$$

If A_2 exceeds A_1, the reach is expanding and c takes the value 0.5. If A_2 is less than A_1, the reach is contracting and c is zero.

A.3 Average Cross-Sectional Values

As a simplification, all the terms on the right hand side of Eq A.1, apart from S_f, may be considered together as the conveyance K. Thus

$$K = A\,(g\,R)^{\frac{1}{2}}\,\left(\frac{8}{f}\right)^{\frac{1}{2}} \qquad (A.10)$$

and

$$Q = K\,S_f^{\frac{1}{2}} \qquad (A.11)$$

For a nonuniform reach, K is not constant so an average value, based on data from the two sections, must be used. Discharge is then

$$Q = (K_1 K_2\,S_f)^{\frac{1}{2}} \qquad (A.12)$$

A.4 Discharge Calculation

Final calculation of discharge involves the solution of Eq A.12 (which is a modified form of the basic Eq A.1) incorporating the definition of friction slope in Eq A.9. Solution is complicated because the discharge term is also contained in the friction slope. For a reach with two cross sections it is

$$Q = K_2 \sqrt{\frac{\Delta h}{\frac{K_2^2}{K_1} L + \frac{K_2^2}{2g\, A_2^2} \left[1 - \left(\frac{A_2}{A_1} \right)^2 \right] (1 - c)}} \qquad (A.13)$$

For a reach with three cross sections, the solution is

$$Q = K_3 \sqrt{\frac{\Delta h}{\frac{K_3}{K_2} \left(\frac{K_3}{K_1} L_{1.2} + L_{2.3} \right) + \frac{K_3^2}{2g\, A_3^2} \left[(1 - c_{2.3}) + \left(\frac{A_3}{A_2} \right)^2 (c_{2.3} \quad c_{1.2}) \quad (1 - c_{1.2}) \left(\frac{A_3}{A_1} \right)^2 \right]}} \qquad (A.14)$$

Here Δh = the difference in water surface elevation between sections 1 and 3 (the fall, not the slope)

$L_{1.2}$ = the distance between sections 1 and 2

$L_{2.3}$ = the distance between sections 2 and 3

$c_{1.2}$ = 0 if $A_1 > A_2$

= 0.5 if $A_1 < A_2$

$c_{2.3}$ = 0 if $A_2 > A_3$

= 0.5 if $A_2 < A_3$

Further information on the slope-area method can be obtained from Barnes and Davidian (1978), Benson (1968) and Dalrymple and Benson (1967).

APPENDIX B CALCULATION OF CROSS-SECTIONAL AREA

This appendix shows how to calculate the cross-sectional area of a flow from surveying data, as required for Section 4.

B.1 Data Requirements

The necessary surveying data (Section 3.2) are:

Corresponding pairs of:

tape distance across the channel;
surveying staff elevation.

2) Water surface elevation for the flood in question. This *must have the same surveying reference datum as do the staff* elevations.

The data can be plotted as described in Section 4 to show the shape of the cross section. This provides a convenient illustration but is not in fact necessary for the calculation.

B.2 Distance at Water Edge

If the tape distance at the edge of the flood flow at one or both banks is not known (ie it was not measured), it must be obtained by interpolation. This can be done either graphically from the plotted cross section or mathematically as follows.

Let the water surface level be e_o.

Let the staff elevation readings be e_1, e_2, e_3 e_i.

Let the corresponding tape distances be z_1, z_2, z_3 z_i measured from the left hand side.

For the bank in question find the two staff readings which straddle the water surface level. Suppose for example that e_o lies between e_i and e_{i+1}. Then the tape distance of the water edge z' is given by

$$= z_i + (z_{i+1} \quad z_i) \frac{(e_i - e_o)}{(e_i - e_{i+1})} \qquad (B.1)$$

and is a distance from the left hand side of the section.

B.3 Calculation Procedure

1) Prepare a table of corresponding tape distances and staff readings, beginning at the left hand water edge and finishing at the right hand water edge. Thus

Tape Distance	Staff Elevation	
z_1	e_1	left hand edge
z_2	e_2	
z_3	e_3	
z_r	e_r	right hand edge

Note the water surface elevation e_o. If the banks are gently shelving, this should equal e_1 and e_r.

2) The total area is to be calculated by dividing the section into the segments between each set of distances z_i and z_{i+i}, obtaining the area of each segment by the trapezoidal rule and then summing the segment areas (Fig. B1).

3) The area of each segment is

$$\left[\frac{(e_o - e_{i+1}) + (e_o - e_i)}{2}\right] (z_{i+1} - z_i) \qquad (B.2)$$

Make sure that the difference between e_o and the staff reading is positive. If the surveying staff read from top to bottom (with zero at the top) use $(e_o - e_1)$, $(e_o - e_2)$, etc. If the surveying staff read from bottom to top (with zero at the bottom) use $(e_1 - e_o)$, $(e_2 - e_o)$, etc.

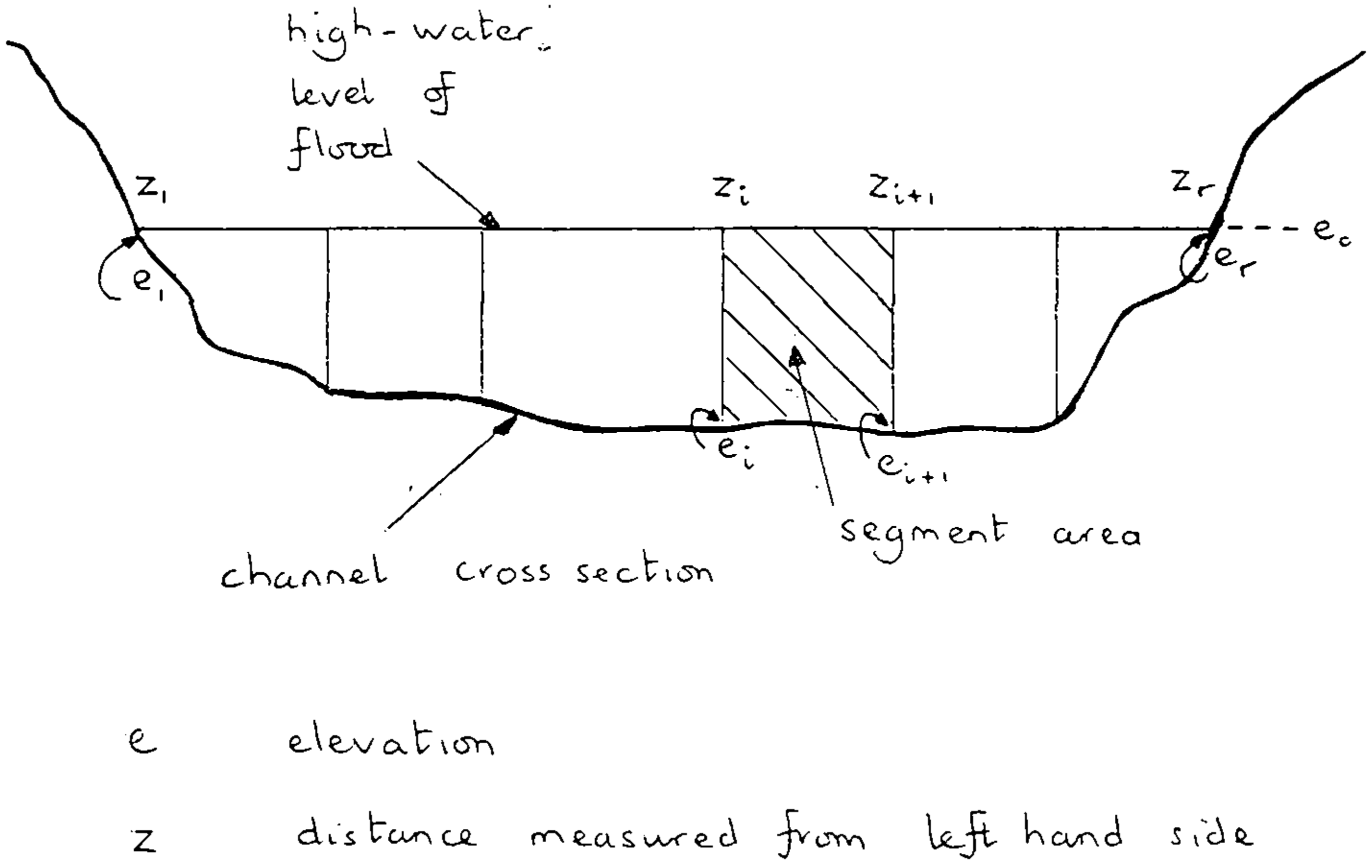


Fig B1. Definition diagram for the calculation of flow cross-sectional area by summation of segment areas.

4) The total area is the sum of these areas

$$A = \frac{1}{2}\ [\ (e_o - e_1) + (e_o - e_2)]\ \ (z_2 - z_1)$$

$$+ \frac{1}{2}\ [\ (e_o - e_2) + (e_o - e_3)\ ]\ \ (z_3 - z_2)$$

$$+ \frac{1}{2}\ [\ (e_o - e_3) + (e_o - e_4)\ ]\ \ (z_4 - z_3)$$

$$+ \frac{1}{2}\ [\ (e_o - e_{r-1}) + (e_o - e_r)]\ \ (z_r - z_{r-1}) \qquad \text{(B.3)}$$

5) Surface width is $(z_r - z_1)$ and mean depth is total area/surface width.

B.4 Example

The following data were surveyed at a section at the Kolah site, Wadi Zabid.

Tape Distance m	Staff Elevation m	
0	2.415	left hand side
1	1.738	... high-water level
1.7	0.823	
3	0.903	
5	0.825	
10	0.583	
15	0.739	
20	0.700	
25	0.515	
30	0.308	
35	0.289	
40	0.592	
41.5	0.730	
43.6	1.361	
44.0	2.052	
46.0	2.162	right hand side

The water surface elevation of the flood was estimated to be 1.738 m. The surveying staff read from top to bottom (with zero at the top).

1) The tape distance for the water edge at the left bank was measured (1 m). However, the distance at the right bank must be calculated.

For water surface elevation = 1.738 m, the two straddling staff readings at the right bank are 1.361 m at a distance of 43.6 m and 2.052 m at a distance of 44 m. Thus for Eq B.1

e_i = 1.361 m e_{i+1} = 2.052 m e_o = 1.738 m

z_i = 43.6 m z_{i+1} = 44 m

and the distance at the water edge is then

$$= 43.6 + (44 - 43.6)\ \frac{(1.361 - 1.738)}{(1.361 - 2.052)}$$

43.8 m.

2) The table of data for the area calculations should therefore be rewritten as

Tape Distance m	Staff Elevation m
1	1.738 .. left hand edge
1.7	0.823
3	0.903
41.5	0.730
43.6	1.361
43.8	1.738 .... right hand edge

3) By Eq B.3 the total area is

$$A = \frac{1}{2} [(1.738 \quad 1.738) \quad (1.738 \quad 0.823)] \quad (1.7 - 1)$$

$$+ \frac{1}{2} [(1.738 - 0.823) \quad (1.738 \quad 0.903)] \quad (3 \quad 1.7)$$

$$+ \frac{1}{2} [(1.738 - 0.730) \quad (1.738 \quad 1.361)] \quad (43.6 - 41.5)$$

$$+ \frac{1}{2} [(1.738 - 1.361) \quad (1.738 \quad 1.738)] \quad (43.8 - 43.6)$$

$$= 47.9 \ m^2.$$

4) Surface width is (43.8 - 1) = 42.8 m

Therefore mean depth = 47.9/42.8

1.12 m .

APPENDIX C CALCULATION OF BED SLOPE

This appendix shows how to calculate the bed slope along a reach from surveying data. Bed slope may be needed where there is no means of measuring water surface slope, for example from a trash line or the actual water surface.

C.1 Data Requirements

The necessary surveying data are:

1) For each of the cross sections in the reach, corresponding pairs of:

   tape distance across the channel;
   surveying staff elevations.

   The surveying elevations must all have the same reference datum.

2) Distance between sections.

C.2 Calculation Procedure

1) Plot the surveying data to show the shape of each cross section and use the result to define the width of the channel bed. This is effectively defined by the base of the bank on each side of the section (Fig. C1).

2) For each cross section prepare a table of corresponding tape distances and staff readings, beginning at the base of the left hand bank and ending at the base of the right hand bank. Thus for each section

Tape Distance	Staff Elevation	
z_1	e_1	left hand bank
z_2	e_2	
z_3	e_3	
z_r	e_r	right hand bank

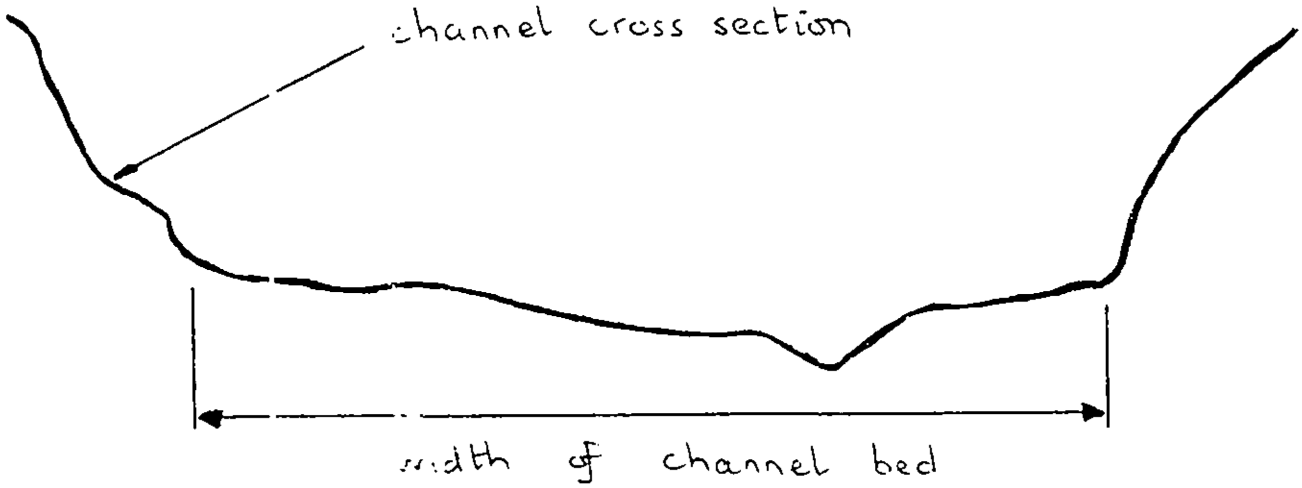


Fig C1. Definition diagram for width of channel bed, determined empirically.

3) Calculate the mean bed level $\bar{e}$ of each section as

$$\bar{e} = \frac{1}{(z_r - z_1)} \left[\frac{(e_1 + e_2)}{2} (z_2 - z_1) \right.$$

$$\frac{(e_2 + e_3)}{2} (z_3 - z_2)$$

$$\left. + \frac{(e_{r-1} + e_r)}{2} (z_r - z_{r-1}) \right] \quad (C.1)$$

4) The bed slope along the reach between two sections is then

$$\frac{\left| \bar{e}_u - \bar{e}_d \right|}{L} \quad (C.2)$$

where $\bar{e}_u$ is the mean bed level at the upstream section, $\bar{e}_d$ is the mean bed level at the downstream section and L is the distance between the two sections.

The difference between the two levels must be calculated as a positive figure. If the surveying staff read from top to bottom (with zero at the top) use $(\bar{e}_u - \bar{e}_d)$ If the surveying staff read from bottom to top (with zero at the bottom) use $(\bar{e}_d - \bar{e}_u)$.

C.3 EXAMPLE

The following data were surveyed at the Kolah site, Wadi Zabid.

UPSTREAM SECTION		CENTRE SECTION		DOWNSTREAM SECTION	
Tape distance m	Staff level m	Tape distance m	Staff level m	Tape distance m	Staff level m
0	0.59	0	0.41	0	1.10
1	1.26	1	1.55	1	2.07
1.7	2.18	3.5	3.12	3.5	3.3
3	2.1	6	2.87	10	3.15
5	2.18	10	2.49	15	2.94
10	2.42	15	2.49	20	3.02
15	2.26	20	2.61	25	3.13
20	2.30	25	2.88	30	3.05
25	2.49	30	2.92	35	3.02
30	2.69	35	3.04	40	3.2
35	2.71	40	2.92	43.9	2.81
40	2.41	45	2.8	47	2.02
41.5	2.27	46.2	2.67	49.4	1.16
43.6	1.64	47.9	2.18		
44	0.95	50.5	1.00		
46	0.84				

The surveying staff read from bottom to top (with zero at the bottom)

Distance from upstream to centre section 50 m

Distance from centre to downstream section = 42 m

Total reach length = 92 m

1) From the plotted data (see Fig D1), the bed of the channel is defined roughly as follows.

At the upstream section z_1 1.7 m

z_r = 41.5 m

At the centre section z_1 3.5 m

z_r = 46.2 m

At the downstream section z_1 3.5 m

z_r = 43.9 m

Data values for distances outside these ranges are ignored as far as the bed slope calculations are concerned.

2) For the upstream section the mean bed level, by Eq C.1, is

$$\bar{e}_u = \frac{1}{(41.5 - 1.7)} \left[\frac{(2.18 + 2.1)}{2} (3 - 1.7) + \frac{(2.1 + 2.18)}{2} (5 - 3) \;\vdots\; + \frac{(2.71 + 2.41)}{2} (40 - 35) + \frac{(2.41 + 2.27)}{2} (41.5 - 40) \right]$$

2.42 m.

For the centre section the mean bed level, by Eq C.1, is

$$\bar{e}_c = \frac{1}{(46.2 - 3.5)} \left[\frac{(3.12 + 2.87)}{2} (6 - 3.5) + \frac{(2.87 + 2.49)}{2} (10 - 6) + \frac{(2.92 + 2.8)}{2} (45 - 40) + \frac{(2.8 + 2.67)}{2} (46.2 - 45) \right]$$

2.79 m.

4) For the downstream section the mean bed level, by Eq C.1, is

$$\bar{e}_d = \frac{1}{(43.9 - 3.5)} \left[\frac{(3.3 + 3.15)}{2} (10 - 3.5) \quad \frac{(3.15 + 2.94)}{2} (15 - 10) \;\vdots\; + \frac{(3.02 + 3.2)}{2} (40 - 35) \quad \frac{(3.2 + 2.81)}{2} (43.9 - 40) \right]$$

3.08 m.

5) Slope is based on the difference ($\bar{e}_d - \bar{e}_u$) since the surveying staff read from bottom to top.

For the reach from upstream to centre section

$$\text{slope} = \frac{(2.79 - 2.42)}{50} \qquad 0.0074.$$

For the reach from centre to downstream section

$$\text{slope} = \frac{(3.08 - 2.79)}{42} \qquad 0.0069.$$

For the overall reach

$$\text{slope} = \frac{(3.08 - 2.42)}{92} \qquad 0.0072.$$

APPENDIX D EXAMPLE OF SLOPE-AREA GAUGING

This appendix presents the results of the only slope-area exercise based on real flood level observations. The flood occurred on the night of 27-28 July 1983 in Wadi Zabid and the measurements were made at the Kolah slope-area reach, upstream of the stage recorder. The choice of sections differs slightly from that finally adopted for the installation of flood marker posts (Appendix E).

D.1 Surveying Data

The high-water mark consisted of a mudline along the rock bank on the left hand side of the wadi. (No high-water mark was noted on the right hand bank.) On the day after the flood, the marks at each of the three sections were reinforced with spray paint, so that they would not be lost, and surveying was carried out on July 29 and again on August 10. The data from the latter occasion are used here.

All surveying measurements were made with a Wild automatic level and a metric surveying staff 3 metres long, reading from top to bottom (with zero at the top). Distances were measured with a tape measure.

Cross-sectional data for the three sections are as follows.

Upstream Section		Centre Section		Downstream Section	
Tape distance m	Staff level m	Tape distance m	Staff level m	Tape distance m	Staff level m
0	2.42	0	2.59	0	1.90
1	1.74*	1	1.45*	1	0.94*
1.7	0.82	3.5	-0.12	3.5	-0.3
3	0.90	6	0.13	10	-0.15
5	0.83	10	0.51	15	0.06
10	0.58	15	0.51	20	-0.02
15	0.74	20	0.40	25	-0.13
20	0.70	25	0.13	30	-0.05
25	0.52	30	0.09	35	-0.02
30	0.31	35	-0.04	40	-0.2
35	0.29	40	0.09	43.9	0.19
40	0.59	45	0.20	47	0.98
41.5	0.73	46.2	0.34	49.4	1.84
43.6	1.36	47.9	0.88		
44	2.05	50.5	2.00		
46	2.16				

* Observed peak flood level or high-water elevation

Elevation at datum point on left hand bank	=	2.83 m
Distance from upstream to centre section	=	50 m
Distance from centre to downstream section	=	42 m
Total reach length	=	92 m

The data are plotted in Fig D1. Also shown in that figure are the bed widths referred to in Appendix C.

D.2 Bed Material Data

The bed material sample and size distribution are as shown in Appendix E.1. The bed consisted mainly of gravel and boulders but also contained some sand.

$$D_{84} = 0.113 \text{ m}$$

D.3 Flow Data

Cross-sectional area, width and depth calculated for each section (Appendix B or Fig 10) are as follows.

Section	Cross-sectional Area m^2	Surface Width m	Mean Depth m
Upstream	47.9	42.8	1.12
Centre	56.3	48.0	1.17
Downstream	43.6	45.8	0.95

From the surveying data:

Upstream flood level	1.74 m
Centre flood level	1.45 m
Downstream flood level	0.94 m

The water surface fall and slope are therefore calculated as:

Fall in Water Surface Level

From upstream to centre section	1.74 - 1.45	= 0.29 m
From centre to downstream section	1.45 - 0.94	= 0.51 m
Total Δh	1.74 - 0.94	= 0.80 m

Water Surface Slope

From upstream to centre section	0.29/50	0.0058
From centre to downstream section	0.51/42	0.0121
Overall	0.80/92	0.0087

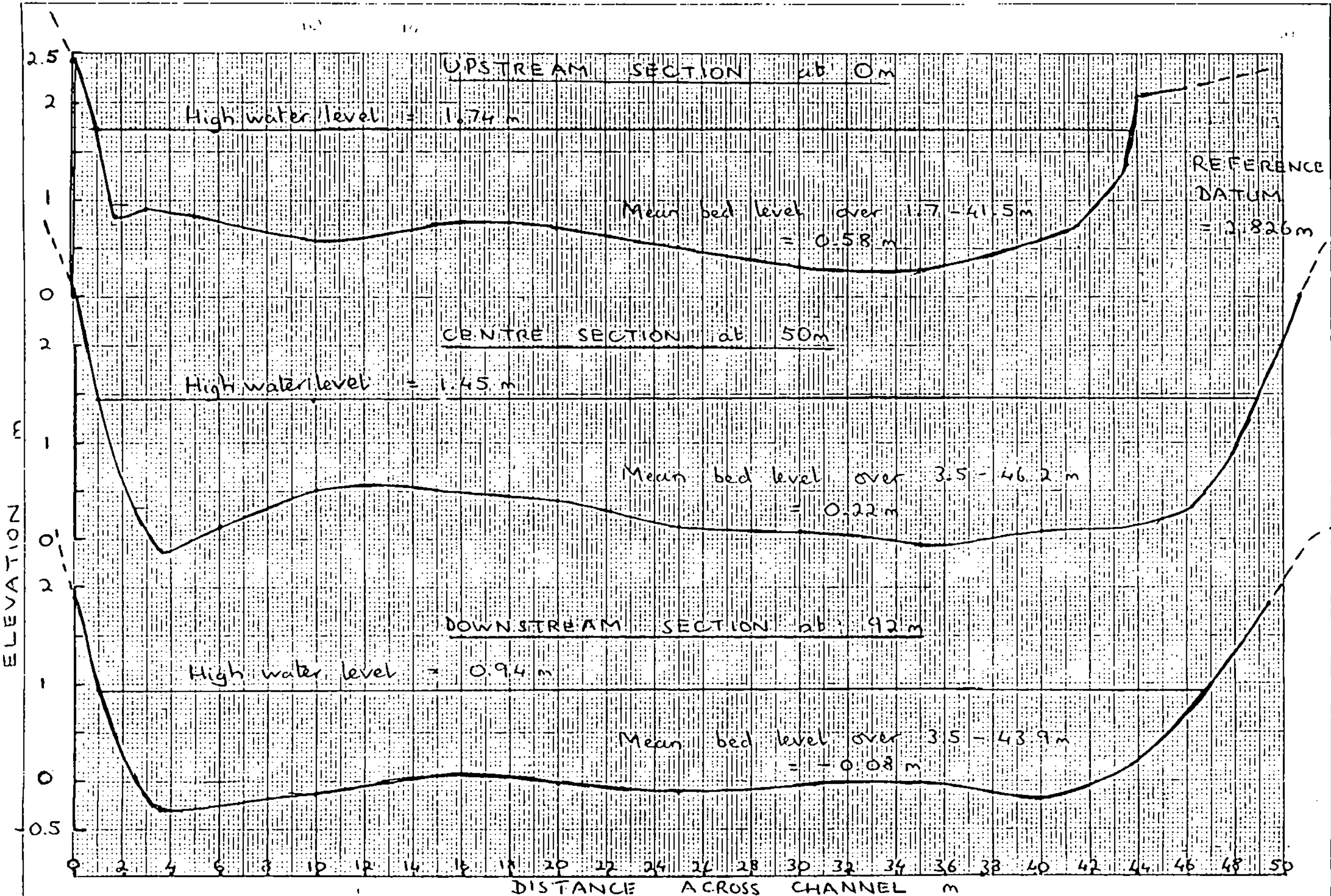


Fig D1. Plots of flow cross sections for the flood of 27-28 July 1983 at the Kolah site in Wadi Zabid.

D.4 Discharge Calculations

The calculations are completed as indicated in Section 4 or else using the computer program "SLOPE-AREA" (Section 7.2) to give a peak discharge of 135 m^3/s. Details of the calculation are shown on the computer printout in Table D1. A warning is given after the slope values because the slopes in the upper and lower halves of the reach differ by more than a factor of two.

Table D1. Computer printout of the discharge calculations for the slope-area exercise at the Kolah site, Wadi Zabid.

```
KOLAH
GAUGING STATION

FLOOD OF
28/7/83

PEAK DISCHARGE BY
SLOPE-AREA METHOD

DATA ENTERED BY
JCB

RESULTS

FLOOD LEVELS
SECT  1   1.74 M
SECT  2   1.45 M
SECT  3   0.94 M

DISTANCES
DIST  1   50.0 M
DIST  2   42.0 M

SLOPE  0.00865
(UPPER =  0.00580)
(LOWER =  0.01214)

WARNING
SLOPES IN UPPER
AND LOWER REACHES
ARE NOT SIMILAR.
CHECK ABOVE DATA.

GRAVEL D84 0.113 M

SECTION AREAS
SECT  1   47.9 M2
SECT  2   56.3 M2
SECT  3   43.6 M2

SECTION DEPTHS
SECT  1   1.11 M
SECT  2   1.17 M
SECT  3   0.95 M

SECTION WIDTHS
SECT  1   42.8 M
SECT  2   48.0 M
SECT  3   45.8 M

SECTION D/D84
SECT  1    9.90
SECT  2   10.37
SECT  3    8.42

SECTION √8/F
SECT  1   9.59
SECT  2   9.71
SECT  3   9.20

+++++++++++++

DISCHARGE
135 M3/S

+++++++++++++
```

APPENDIX E SLOPE-AREA EXERCISES AT WADI SITES

This appendix presents the results of the slope-area exercises carried out at the various wadi sites. Because they are not based on real flood level observations, the calculations involve a characteristic discharge defined by either the bankfull geometry or the boundary of the vegetation along the channel. (See Section 5 in Volume 1 for further details.) Some modifications to the method, relative to Sections 3 and 4 and the example in Appendix D, are therefore apparent. In particular the lack of high-water marks means that the bed slope has to be used instead of the water surface slope (see Appendix C). This would not of course be necessary in the gauging of an observed flood with well defined high-water marks. The exercises are therefore presented to enable TDA staff to familiarise themselves with the various mathematical analyses, while Appendix D is a better guide to actual flood discharge estimations.

For the six examples a uniform style of presentation is adopted, consisting of:

A sketch map of the site.

2) The cross-sectional surveying data, all corrected to the same reference datum at each site and with distances reading from left to right.

3) Graphs of the cross sections.

4) The bed material sample.

5) A graph of the bed material size distribution.

6) Calculated flow data (using the methods of Appendices B and C).

7) Calculated discharge.

8) A printout of the calculation by the program "SLOPE-AREA".

The relevant diagrams and tables are given at the end of the section on each wadi.

All surveying measurements were made with a Wild automatic level and a metric surveying staff 3 metres long, reading from top to bottom (with zero at the top). Distances were measured with a tape measure.

E.1 WADI ZABID AT KOLAH EXPERIMENTAL SLOPE-AREA SITE

E.1.1 Slope-Area Site

This is the site at which the experimental flood marker posts were installed. The reach is 103 m long and is just upstream of the Kolah stage recorder (Fig E1). It is not ideal since it is quite short and the flow is likely to be affected by the sharp bends immediately upstream and downstream. Also there is a small tributary wadi between the stage recorder and the slope-area reach, although this is normally dry. However, the site is the best available in the vicinity of the existing gauging station. The survey was made on 17 and 18 August.

E.1.2 Surveying Data

Upstream Section		Centre Section		Downstream Section	
Tape distance m	Staff level m	Tape distance m	Staff level m	Tape distance m	Staff level m
- 4.5	5.20	4.7	4.41	- 8.8	3.65
- 4	4.49	- 4.2	4.16	- 8.2	3.47[a]
- 2.8	4.66[a]	- 3	4.01[a]	- 6.5	1.97
- 1.4	3.19[b]	2.2	2.42[b]	- 5	1.94
0	1.74[c]	0	0.94[c]	- 3.25	2.07[b]
1	0.96	0.6	-0.11	- 1	1.10
3	1.11	2.3	0.21	0	0.60[c]
5	0.93	3.5	-0.02	1.5	-0.74
10	0.83	5	0.45	2.5	-0.61
15	0.95	10	0.69	5	-0.14
20	0.84	15	0.63	10	-0.26
25	0.70	20	0.39	15	0.16
30	0.53	25	0.26	20	0.14
35	0.52	30	0.26	25	0.14
39.8	0.92	35	0.19	30	0.13
41.2	1.31	40	0,25	35	0.0
42.3	1.79	42.7	0.51	39.2	0.34
42.6	2.27	44.8	0.70	40.5	0.59
44.5	2.35	45.9	1.24	42	0.84
		47	1.74	44.6	1.50
		49	2.75		

[a] base of upper flood marker post

[b] base of middle flood marker post

[c] base of lower flood marker post

All surveying levels have been corrected so that at the reference datum point the equivalent level is zero.

Distance from upstream to centre section	59 m
Distance from centre to downstream section	44 m
Total reach length	103 m

The data are plotted in Fig E2.

E.1.3 Bed Material Data

The bed material sample is shown in Table E1 and the size distribution is plotted in Fig E3.

D_{84} 0.113 m

E.1.4 Characteristic Flow Data

Mean Bed Level

Upstream section over	1	to	39.8 m	0.78 m
Centre section over	0.6	to	44.8 m	0.37 m
Downstream section over	1.5	to	39.2 m	0.01 m

Fall in Bed Level

From upstream to centre section	0.78 - 0.37	0.41 m
From centre to downstream section	0.37 - 0.01	0.36 m
Total	0.78 - 0.01	0.77 m

Bed Slope

From upstream to centre section	0.41/59	0.00695
From centre to downstream section	0.36/44	0.00818
Overall	0.77/103	0.00748

The characteristic flow is chosen to be the natural bankfull flow. The right hand banks at the centre and downstream sections are affected by field bunds and all the left hand banks are rock cliffs. The only more or less natural bank level is at the right hand bank of the upstream section. Using this bank top to give the bankfull level at the upstream section, the corresponding levels at the other two sections are found by subtracting the fall in bed level from the upstream level. Thus

Upstream bankfull level		2.27 m	
Centre bankfull level	=	2.27 - 0.41	1.86 m
Downstream bankfull level	-	2.27 - 0.77	1.50 m

For these levels the corresponding cross-sectional areas and widths for each section are as follows.

Section	Cross-sectional Area m^2	Surface Width m
Upstream	60.5	43.3
Centre	68	48.5
Downstream	63.5	46

E1.5 Characteristic Flow Discharge

Using the above data the bankfull discharge is calculated to be 209 m^3/s. Details of the calculation are shown on the computer printout in Table E2.

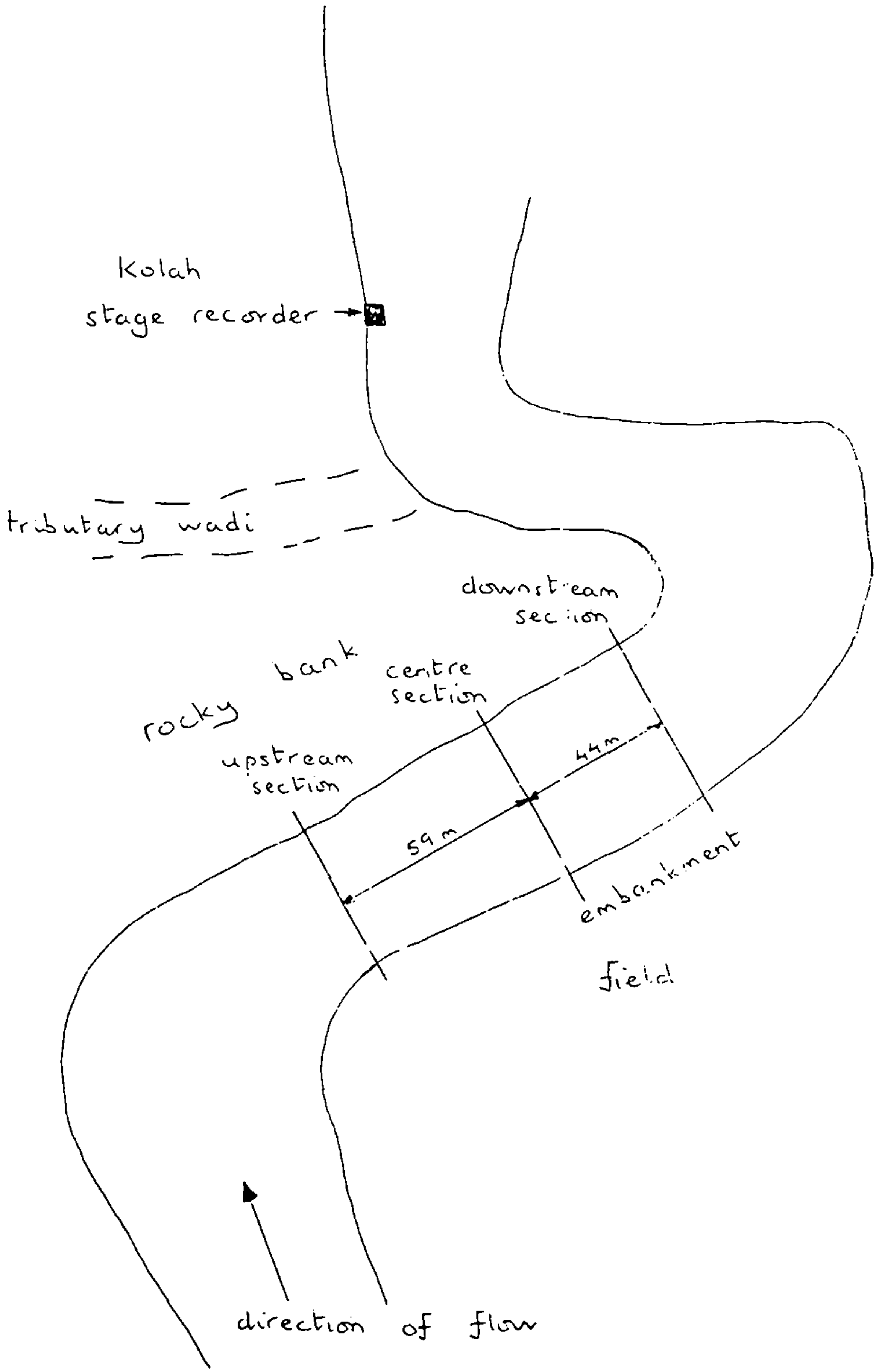


Fig E1. Sketch map showing the position of the Kolah experimental slope-area reach, Wadi Zabid.

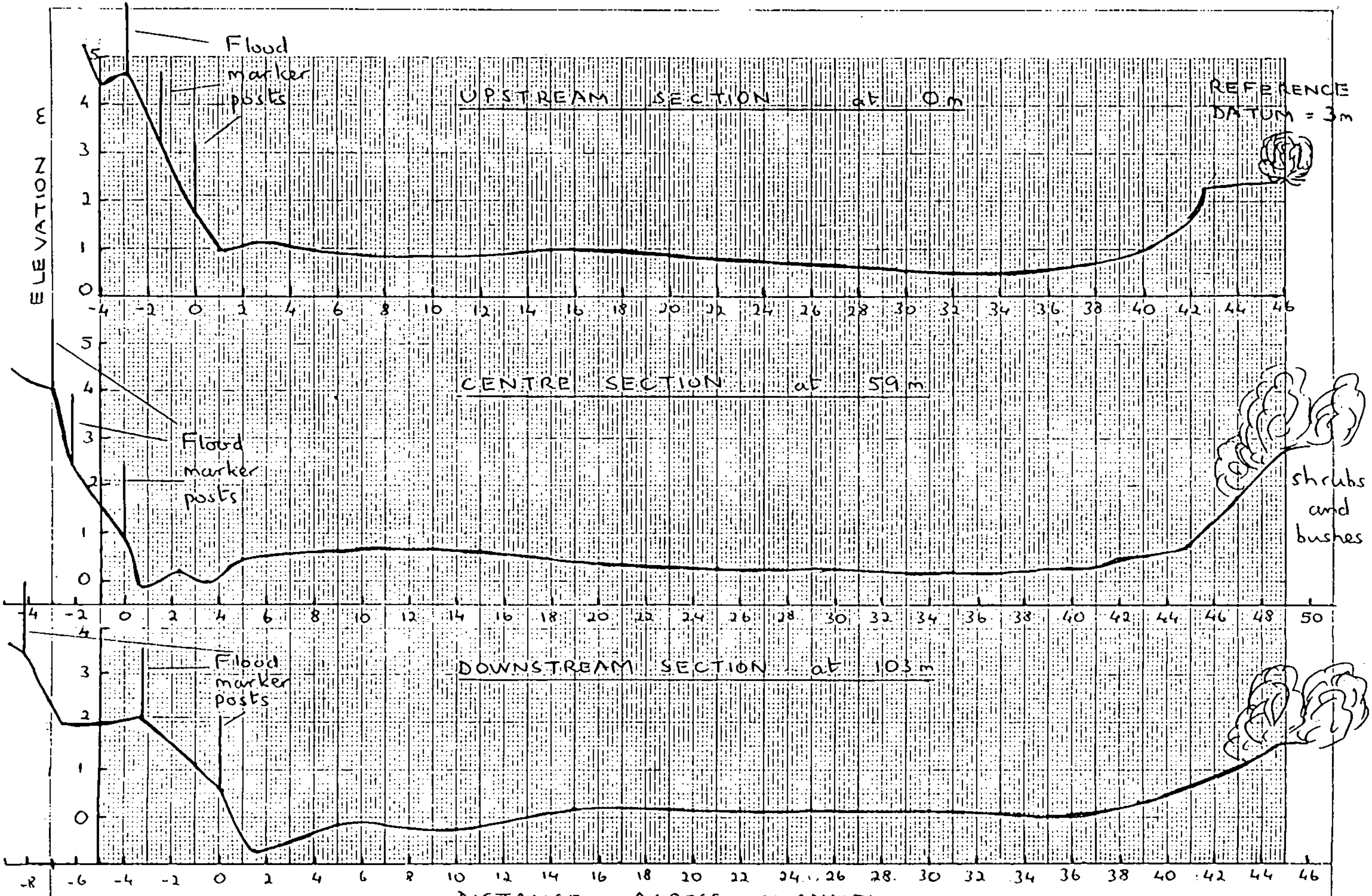


Fig. E2 Channel cross sections at the Kolah experimental slope-area site in Wadi Zabid.

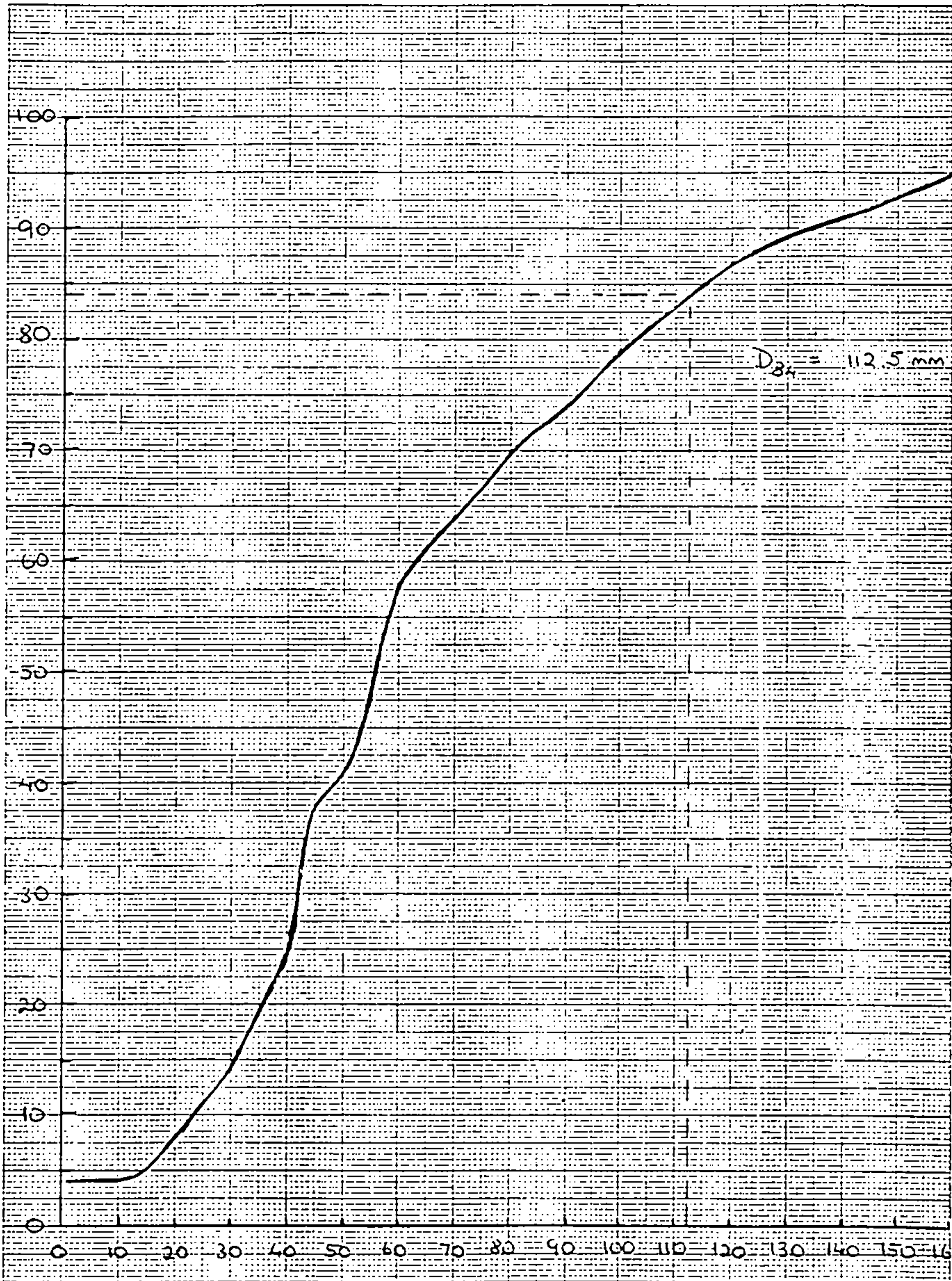


Fig E3. Size distribution curve for the bed material at Kolah experimental slope-area reach, Wadi Zabid.

Table E1. Bed material sample :

SITE WADI ZABID : KOLAH SLOPE-AREA SITE

DATE FRIDAY 29 JULY 1983

14	72	110	45	44	110	2.5	170	52	37
47	78	95	60	42	73	79	95	235	34
2.5	93	42	18	135	31	36	50	18	53
43	230	60	64	63	55	42	69	145	83
52	69	38	33	26	76	55	107	65	75
52	31	60	90	120	215	55	19	44	48
38	170	45	2.5	155	21	54	55	52	45
72	43	25	90	29	135	95	70	58	44
120	102	29	58	58	105	145	45	31	42
23	130	44	2.5	125	160	40	55	85	107

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
0 - 2.5	||||	4	4
2.5 - 5			4
5 - 7.5			4
7.5 - 10			4
10 - 15	|	1	5
15 - 20	|||	3	8
20 - 25	|||	3	11
25 - 30	|||	3	14
30 - 35	|||||	5	19
35 - 40	|||||	5	24
40 - 45	||||||||||||||	14	38
45 - 50	|||	3	41
50 - 60	|||||||||||||||||	17	58
60 - 70	||||||	6	64
70 - 80	||||||	6	70
80 - 90	||||	4	74
90 - 100	|||||	5	79
100 - 120	||||||||	8	87
120 - 140	||||	4	91
140 - 160	||||	4	95
160 - 180	||	2	97
180 - 200			97
200 - 240	|||	3	100
240 - 280			
280 - 320			

D_{16} = 32 mm

D_{50} = 55.3 mm

D_{84} = 112.5 mm

$\log\left(\frac{D_{84}}{D_{50}}\right) = 0.308$

Table E2. Computer printout of the discharge calculations for the slope-area exercise at the Kolah experimental slope-area reach, Wadi Zabid.

```
      KOLAH
 GAUGING STATION

     FLOOD OF
     AUG 1983

PEAK DISCHARGE BY
SLOPE-AREA METHOD

DATA ENTERED BY
JCB


     RESULTS

   FLOOD LEVELS
SECT  1    2.27 M
SECT  2    1.86 M
SECT  3    1.50 M

  DISTANCES
DIST  1    59.0 M
DIST  2    44.0 M

  SLOPE   0.00747
(UPPER =  0.00694)
(LOWER =  0.00818)


GRAVEL D84 0.113 M

  SECTION AREAS
SECT  1    60.5 M2
SECT  2    62.0 M2
SECT  3    63.5 M2

  SECTION DEPTHS
SECT  1    1.39 M
SECT  2    1.40 M
SECT  3    1.38 M

  SECTION WIDTHS
SECT  1    43.3 M
SECT  2    48.5 M
SECT  3    46.0 M

  SECTION D/D84
SECT  1  12.36
SECT  2  12.40
SECT  3  12.21

  SECTION J8/F
SECT  1  10.13
SECT  2  10.14
SECT  3  10.10


+++++++++++++++

      DISCHARGE
       209 M3/S

+++++++++++++++
```

E.2 WADI RASYAN

E.2.1 Slope-Area Site

Measurements were made along a 60 m reach at a narrow rock gorge section a few hundred metres downstream of the gauging station (Fig E4). The site is not a very good one since the lateral bed profile is uneven and a line of bamboo bushes runs down the middle of the gorge. However, it seems to be the best available in the vicinity of the gauging station. The survey was made on 9 August.

E.2.2 Surveying Data

The walls of the gorge are assumed to be vertical. The staff levels at the ends of each section therefore refer to the bed levels at the bases of the walls.

Upstream Section		Centre Section		Downstream Section	
Tape distance m	Staff level m	Tape distance m	Staff level m	Tape distance m	Staff level m
0	1.92	0	0.55	0	0.30
0.5	1.35	2	0.50	2.3	0.46
1.5	1.75	4	0.65	5.4	0.51
3	1.69	6	0.95	9	0.67
5	1.56	9	0.99	11.3	0.85
7	1.13	11	1.18	21	2.27
11	1.07	12.8	1.27	22.8	2.37
14	1.17	15.8	1.25	26.1	2.58
16	1.24	18.7	1.69	27.3	2.00
18	1.44	23.4	2.43	27.8	2.03
21	1.47	24.8	2.03	28.8	2.61
22.5	1.47	25.5	2.01	32.6	2.54
24	1.72	26.6	2.42	35.8	2.53
26	1.68	30.1	2.75		
27.8	1.58				

Distance from upstream to centre section = 30 m

Distance from centre to downstream section = 30 m

Total reach length = 60 m

The data are plotted in Fig E5.

E.2.3 Bed Material Data

The bed material sample is shown in Table E3 and the size distribution is plotted in Fig E6.

D_{84} 0.09 m

E.2.4 Characteristic Flow Data

Mean Bed Level

Upstream section over	5 to 22.5 m	=	1.26 m
Centre section over	0 to 14 m	=	0.98 m
Downstream section over	0 to 14 m	=	0.65 m

Fall in Bed Level

From upstream to centre section	1.26 - 0.98	=	0.28 m
From centre to downstream section	0.98 - 0.65	=	0.33 m
Total	1.26 - 0.65	=	0.61 m

Bed Slope

From upstream to centre section	0.28/30	0.00933
From centre to downstream section	0.33/30	0.011
Overall	0.61/60	0.0102

The characteristic flow is chosen to be contained by the channel within the flood deposits and the line of bamboo. The relevant flood level is defined most accurately at the downstream section so the corresponding levels at the other two sections are found by adding the rise in bed level from the downstream level. Thus

Downstream flood level = 1.25 m
Centre flood level = 1.25 + 0.33 = 1.58 m
Upstream flood level = 1.25 + 0.61 = 1.86 m

For these levels the corresponding cross-sectional areas and widths for each section are as follows.

Section	Cross-sectional Area m^2	Surface Width m
Upstream	12.7	27.8
Centre	10.4	18
Downstream	8.43	14

E.2.5 Characteristic Flow Discharge

Using the above data the flow within the vegetation level is calculated to be 18 m^3/s. Details of the calculation are shown on the computer printout in Table E4.

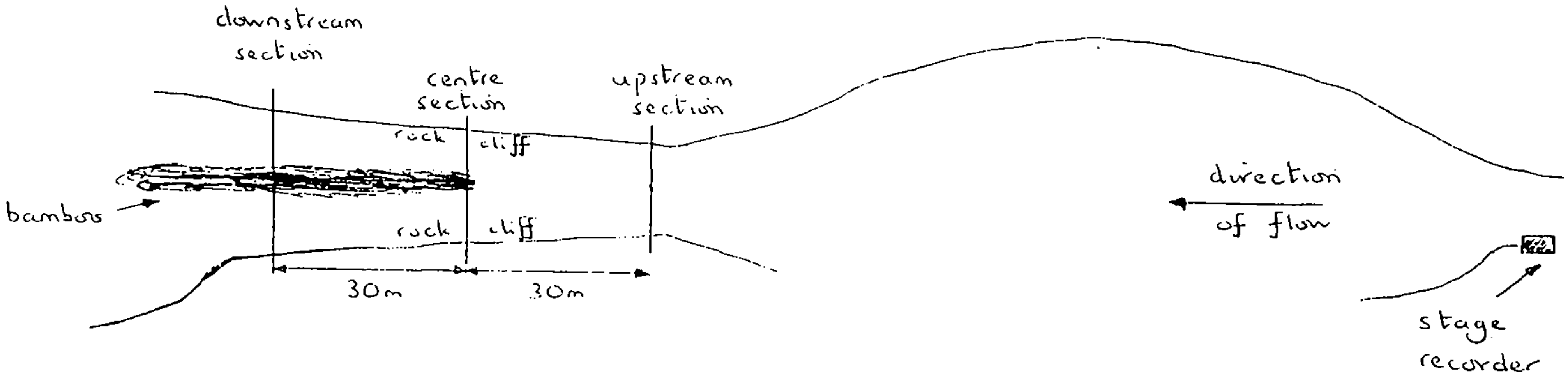


Fig E4. Sketch map showing the position of the slope-area reach in Wadi Rasyan.

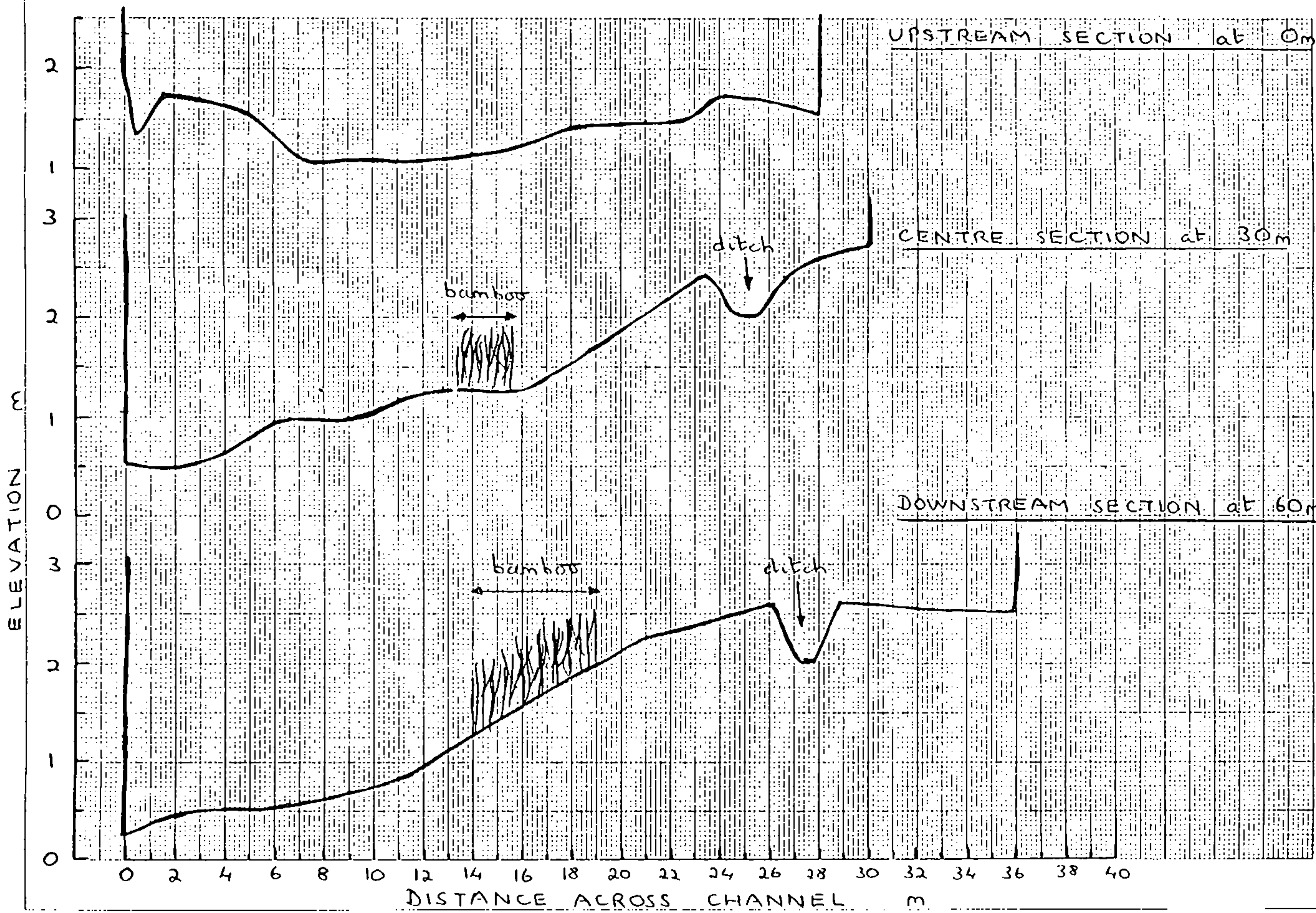


Fig E5. Channel cross sections at the slope-area site in Wadi Rasyan.

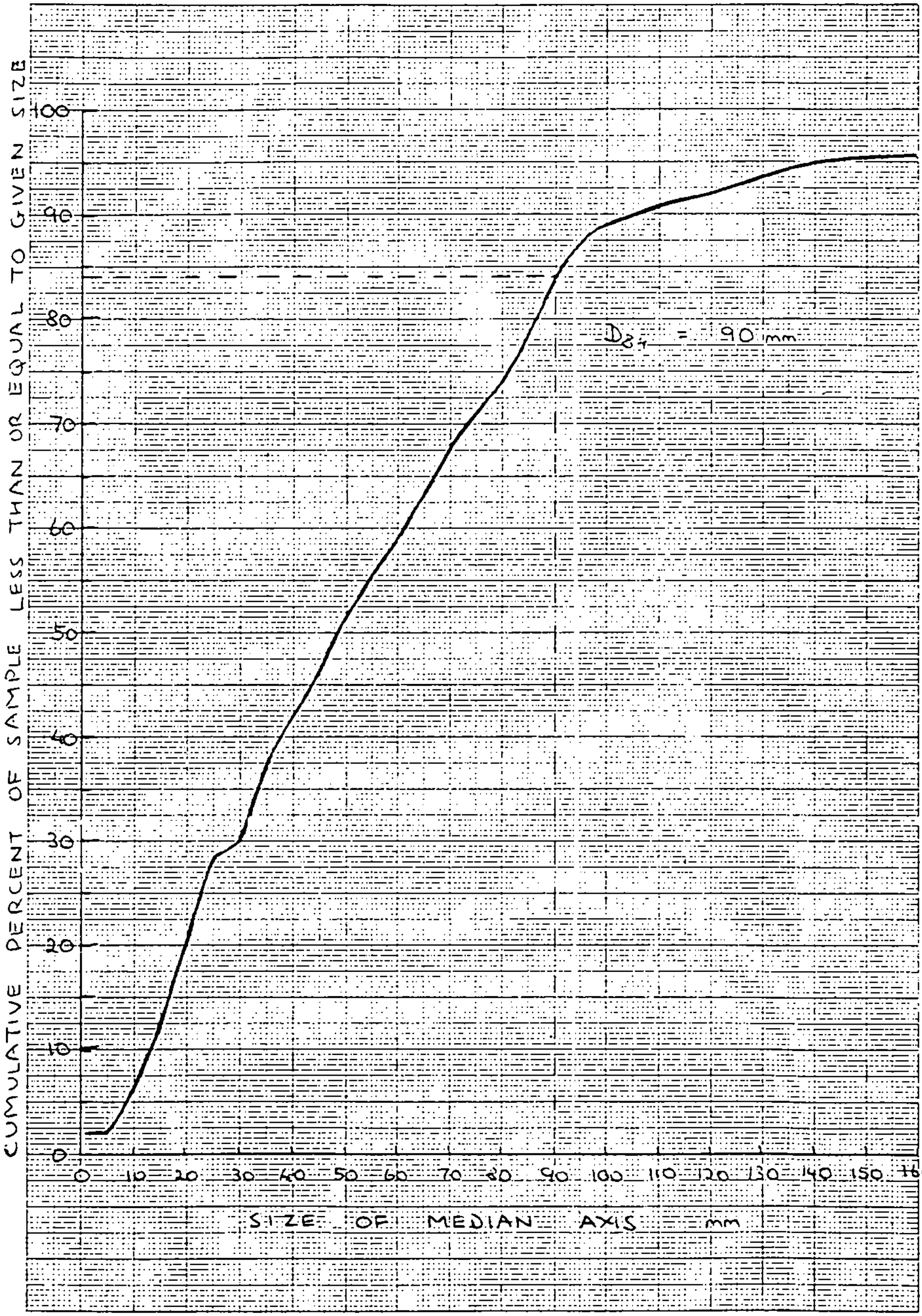


Fig E6. Size distribution curve for the bed material at the slope-area reach in Wadi Rasyan.

Table E3. Bed material sample :

SITE WADI RASYAN SLOPE-AREA SITE

DATE TUESDAY 9 AUGUST 1983

78	48	40	32	87	95	52	20	33	60
69	18	90	95	39	47	40	110	110	75
100	105	205	140	41	10	11	46	53	55
205	60	23	75	62	19	91	14	25	30
34	2.5	65	71	68	68	2.5	12	14	90
7	100	23	16	85	43	22	31	16	83
18	39	90	90	15	42	46	41	22	35
75	125	61	24	71	34	24	67	57	17
180	12	10	46	88	87	70	86	24	190
130	28	20	35	6	70	235	55	36	50

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
0 - 2.5	II	2	2
2.5 - 5			
5 - 7.5	II	2	4
7.5 - 10	II	2	6
10 - 15	IIIIII	6	12
15 - 20	IIIIIIII	8	20
20 - 25	IIIIIIII	8	28
25 - 30	II	2	30
30 - 35	IIIIIII	7	37
35 - 40	IIIII	5	42
40 - 45	IIII	4	46
45 - 50	IIIIII	6	52
50 - 60	IIIIIII	7	59
60 - 70	IIIIIIIII	9	68
70 - 80	IIIIII	6	74
80 - 90	IIIIIIIIII	10	84
90 - 100	IIIII	5	89
100 - 120	III	3	92
120 - 140	III	3	95
140 - 160			
160 - 180	I	1	96
180 - 200	I	1	97
200 - 240	III	3	100
240 - 280			
280 - 320			

D_{16} = 17.5 mm

D_{50} = 48.3 mm

D_{84} = 90 mm

$\log\left(\frac{D_{84}}{D_{50}}\right)$ = 0.270

Table E4. Computer printout of the discharge calculations for the slope-area exercise in Wadi Rasyan.

```
       RASYAN
   GAUGING STATION

       FLOOD OF
       AUG 1983

   PEAK DISCHARGE BY
   SLOPE-AREA METHOD

   DATA ENTERED BY
   JCB


       RESULTS

     FLOOD LEVELS
   SECT  1    1.85 M
   SECT  2    1.58 M
   SECT  3    1.25 M

     DISTANCES
   DIST  1   30.0 M
   DIST  2   30.0 M

     SLOPE  0.01016
  (UPPER =  0.00933)
  (LOWER =  0.01100)


  GRAVEL D84 0.090 M

     SECTION AREAS
   SECT  1    12.7 M2
   SECT  2    10.4 M2
   SECT  3     8.4 M2

     SECTION DEPTHS
   SECT  1    0.45 M
   SECT  2    0.57 M
   SECT  3    0.60 M

     SECTION WIDTHS
   SECT  1    27.8 M
   SECT  2    18.0 M
   SECT  3    14.0 M

     SECTION D/D84
   SECT  1    5.07
   SECT  2    6.41
   SECT  3    6.69

     SECTION J8/F
   SECT  1    7.96
   SECT  2    8.53
   SECT  3    8.63


   +++++++++++++++

        DISCHARGE
          18 M3/S

   +++++++++++++++
```

E.3 WADI SIHAM AT MAHAL AL SHAMIKI

E.3.1 Slope-Area Site

Measurements were made along a 100 m reach confined within the walls of the wadi (Fig E7). The left bank is a steeply rising cliff while the right bank is less steep and is vegetated with scrub and bushes. The reach widens slightly in the downstream direction. The survey was made on 11 August.

E.3.2 Surveying Data

The left hand bank is assumed to be vertical. The staff levels at the left hand ends of each section therefore refer to the bed levels at the base of the cliff.

Upstream Section		Centre Section		Downstream Section	
Tape distance m	Staff level m	Tape distance m	Staff level m	Tape distance m	Staff level m
0	0.0	0	1.25	0	0.69
5	0.63	5	0.60	5	0.31
10	1.04	10	0.58	10	0.30
15	1.23	15	0.32	15	0.40
20	1.25	20	0.37	20	0.41
25	1.37	25	0.52	25	0.39
30	1.46	30	0.62	30	0.27
35	1.89	35	1.14	35	0.25
40	2.05	40	1.23	40	0.31
45	2.07	45	1.26	45	0.50
50	2.85	50	1.46	50	0.82
55	3.2	55	1.51	55	1.12
56	3.2	60	1.94	60	1.37
		65	2.18	73	1.61
		68	2.67		

A datum point was set on a rock on the left hand bank, marked by blue and white spray paint. Its surveyed level was 1.632 m with the automatic level positioned as for the above data.

Distance from upstream to centre section	100 m
Distance from centre to downstream section	100 m
Total reach length	200 m

The data are plotted in Fig E8.

E.3.3 Bed Material Data

The bed material sample is shown in Table E5 and the size distribution is plotted in Fig E9. The bed was moderately sandy but also contained gravel and boulders.

$$D_{84} = 0.174 \text{ m}$$

E.3.4 Characteristic Flow Data

Mean Bed Level

Upstream section over	0 to 50 m	1.44 m
Centre section over	0 to 60 m	0.93 m
Downstream section over	0 to 60 m	0.51 m

Fall in Bed Level

From upstream to centre section	1.44 - 0.93	= 0.51 m
From centre to downstream section	0.93 - 0.51	= 0.42 m
Total	1.44 - 0.51	= 0.93 m

Bed Slope

From upstream to centre section	0.51/100	= 0.0051
From centre to downstream section	0.42/100	= 0.0042
Overall	0.93/200	= 0.00465

The characteristic flow is chosen to be contained within the vegetation line on the right bank. Examination of the data suggests the following levels.

Upstream flood level	= 2.43 m
Centre flood level	= 1.93 m
Downstream flood level	= 1.50 m

For these levels the corresponding cross-sectional areas and widths for each section are as follows.

Section	Cross-sectional Area m^2	Surface Width m
Upstream	50.1	48
Centre	59.9	60
Downstream	59.2	60

E.3.5 Characteristic Flow Discharge

Using the above data the flow within the vegetation line is calculated to be 102 m^3/s. Details of the calculation are shown on the computer printout in Table E6.

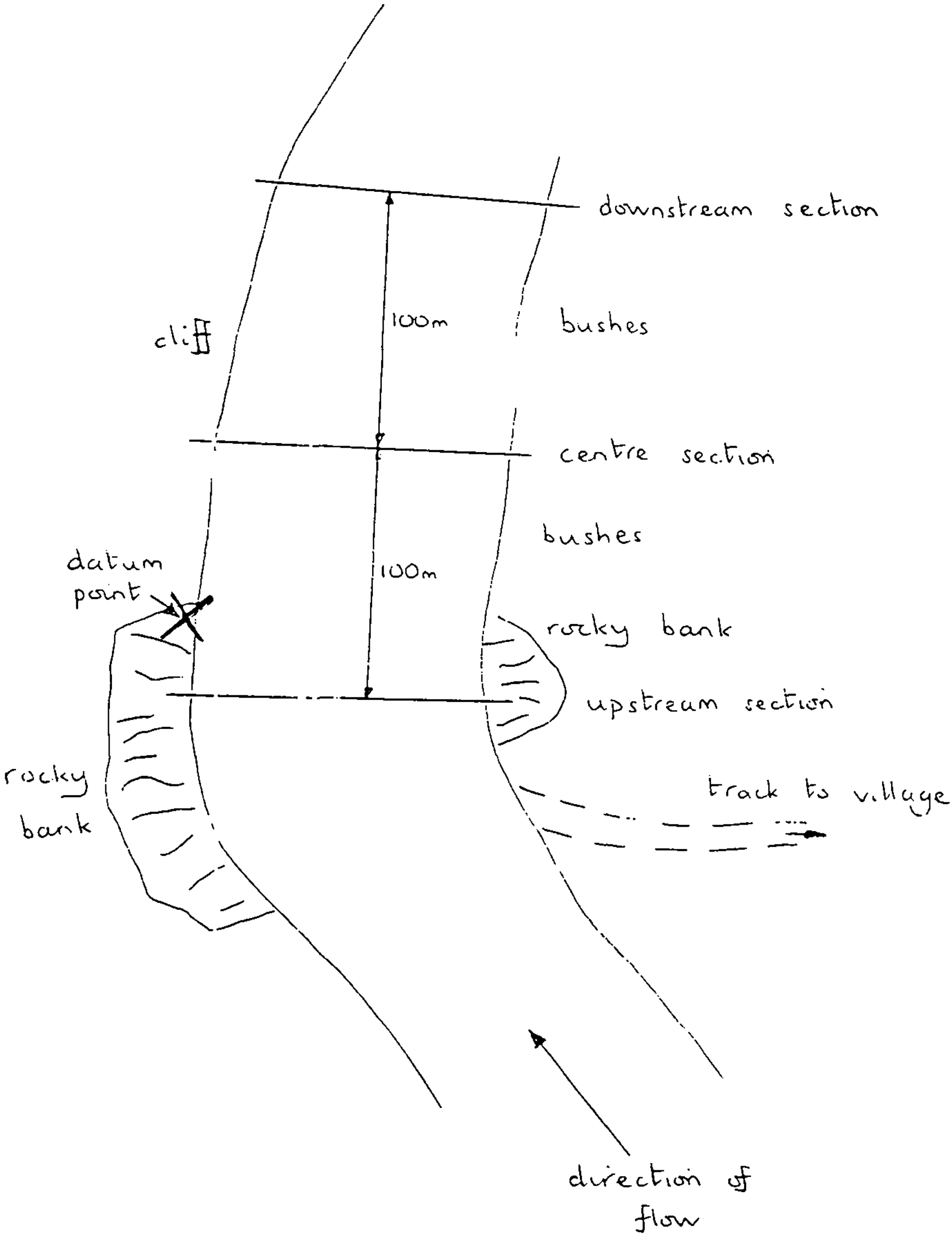


Fig E7. Sketch map showing the position of the slope-area reach in Wadi Siham.

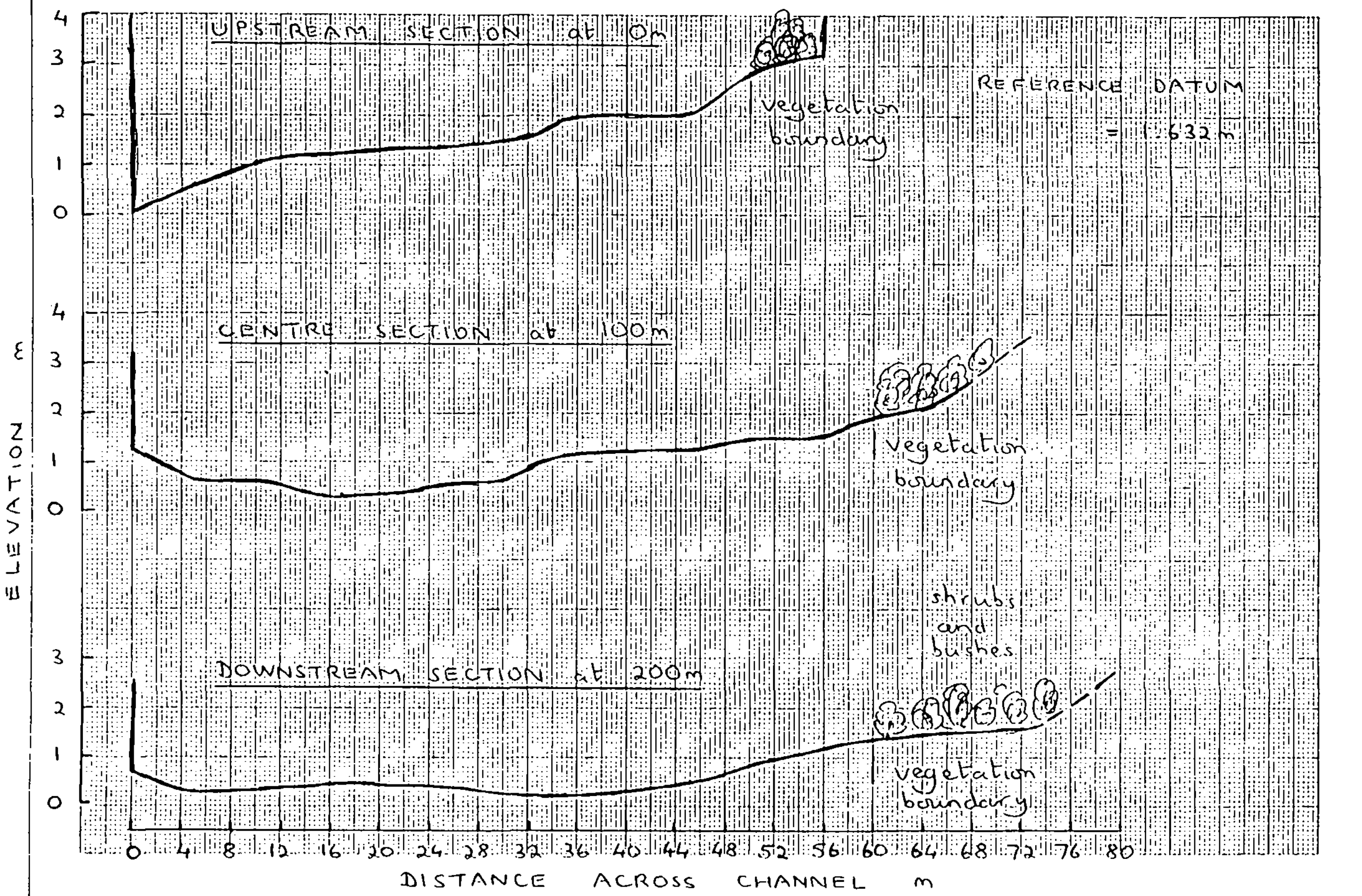


Fig E8. Channel cross sections at the slope-area site in Wadi Siham.

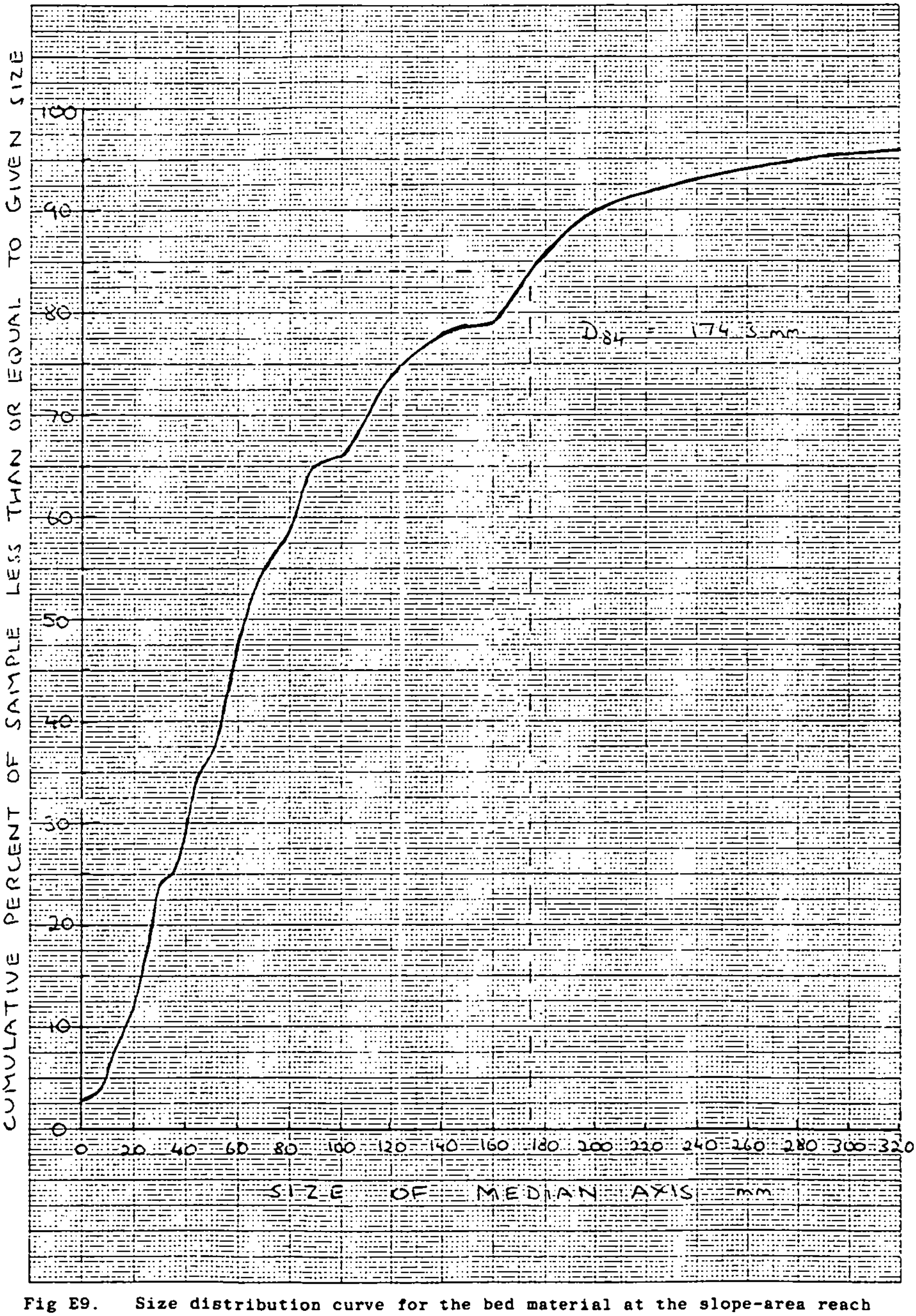


Fig E9. Size distribution curve for the bed material at the slope-area reach in Wadi Siham.

Table E5. Bed material sample

SITE WADI SIHAM SLOPE-AREA SITE AT MAHAL AL SHAMIKI : Sample along right hand side

DATE THURSDAY 11 AUGUST 1983

Moderate amounts of sand

26	69	105	170	29	500	38	400	38	210
250	220	122	18	55	250	55	170	190	110
105	22	26	26	18	73	125	190	25	145
200	58	290	55	6	90	330	110	14	2.5
51	140	90	67	27	10	19	25	45	2.5
50	165	62	55	11	180	130	43	60	25
26	45	165	36	9	92	170	64	70	85
87	115	78	36	65	55	48	90	70	230
41	185	41	55	11	89	70	72	24	60
35	115	45	32	380	175	25	102	25	105

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
0 - 2.5	|||	3	3
2.5 - 5			
5 - 7.5	|	1	4
7.5 - 10	||	2	6
10 - 15	|||	3	9
15 - 20	|||	3	12
20 - 25	||||||	6	18
25 - 30	||||||	6	24
30 - 35	|	1	25
35 - 40	||||	4	29
40 - 45	||||||	6	35
45 - 50	||	2	37
50 - 60	||||||||||	10	47
60 - 70	||||||||	8	55
70 - 80	||||	4	59
80 - 90	||||||	6	65
90 - 100	|	1	66
100 - 120	||||||||	8	74
120 - 140	||||	4	78
140 - 160	|	1	79
160 - 180	|||||||	7	86
180 - 200	||||	4	90
200 - 240	|||	3	93
240 - 280	||	2	95
280 - 320	|	1	96

D_{16} = 23.3 mm

D_{50} = 63.75 mm

D_{84} = 174.3 mm

$\log(D_{84}/D_{50}) = 0.437$

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
320 - 360	|	1	97
360 - 400	||	2	99
400 - 440			
440 - 480			
480 - 520	|	1	100

Table E6. Computer printout of the discharge calculations for the slope-area exercise in Wadi Siham.

```
      SIHAM
GAUGING STATION

    FLOOD OF
    AUG 1983

PEAK DISCHARGE BY
SLOPE-AREA METHOD

DATA ENTERED BY
JCB


     RESULTS

  FLOOD LEVELS
SECT  1    2.43 M
SECT  2    1.93 M
SECT  3    1.50 M

  DISTANCES
DIST  1   100.0 M
DIST  2   100.0 M

  SLOPE  0.00465
(UPPER = 0.00500)
(LOWER = 0.00430)


GRAVEL D84 0.174 M

  SECTION AREAS
SECT  1    50.1 M2
SECT  2    59.9 M2
SECT  3    59.2 M2

  SECTION DEPTHS
SECT  1    1.04 M
SECT  2    0.99 M
SECT  3    0.98 M

  SECTION WIDTHS
SECT  1    48.0 M
SECT  2    60.0 M
SECT  3    60.0 M

  SECTION D/D84
SECT  1    5.99
SECT  2    5.73
SECT  3    5.67

  SECTION √8/F
SECT  1    8.37
SECT  2    8.26
SECT  3    8.23


+++++++++++++++

     DISCHARGE
      102 M3/S

+++++++++++++++
```

E.4 WADI YALUL AT GOU REYZ

E.4.1 Slope-Area Site

Although the wadi is called Yalul locally, it may be shown as Balul on the map. It lies between Wadis Zabid and Rasyan.

Measurements were made along a 180 m reach within well-defined but low banks. The site was immediately upstream of the confluence with Wadi Byreck, which is about 1/2 to 2/3 of the size of the main wadi. Surveying could not be carried out downstream because the wadi bed was disturbed by small diversion dams and canal works (Fig E10). The bed at the site was also uneven as a result of naturally formed bars and troughs. The survey was made on 9 August.

E.4.2 Surveying Data

Surveys were made at only two cross sections.

Upstream Section		Downstream Section	
Tape distance m	Staff level m	Tape distance m	Staff level m
0	5	0	1.55
3.3	2.60	1.5	0.02
5	2.60	5	-0.02
10	2.61	10	0.73
15	2.30	15	0.49
20	2.70	20	0.58
25	3.30	25	0.81
30	2.40	30	0.82
35	2.53	35	0.78
40	2.57	40	0.83
45	2.46	45	0.73
50	2.25	50	0.89
55	2.26	55	0.95
60	2.61	60	1.39
65	2.73	65	1.41
70	1.97		
72.2	3.05		
73.1	3.40		

Total reach length = 180 m

The data are plotted in Fig E11.

E.4.3 Bed Material Data

The bed material sample is shown in Table E7 and the size distribution is plotted in Fig E12.

$$D_{84} = 0.085 \text{ m}$$

E.4.4 Characteristic Flow Data

Mean Bed Level

Upstream section over 3.3 to 70 m = 2.54 m

Downstream section over 1.5 to 55 m = 0.66 m

Fall in Bed Level

Total fall 2.54 0.66 1.88 m

Bed Slope

Overall slope = 1.88/180 0.0104

The characteristic flow is chosen to be the natural bankfull flow, which is best defined by the right hand bank levels. The left hand side is affected by flood diversion embankments. Examination of the data suggests the following levels.

Upstream flood level 3.4 m

Downstream flood level 1.5 m

For these levels the corresponding cross-sectional areas and widths for each section are as follows.

Section	Cross-sectional Area m^2	Surface Width m
Upstream	60.1	71
Downstream	47.6	60

E.4.5 Characteristic Flow Discharge

Although only two cross sections were surveyed, the computer program (which requires data for three cross sections) can be used if data are typed in for an imaginary centre cross section. These data values should be the exact average of those for the two surveyed sections. Details are shown on the computer printout in Table E8 and the discharge is calculated to be 141 m^3/s. This result may be checked using Eq A.13, in Appendix A, which is derived specifically for reaches with only two cross sections.

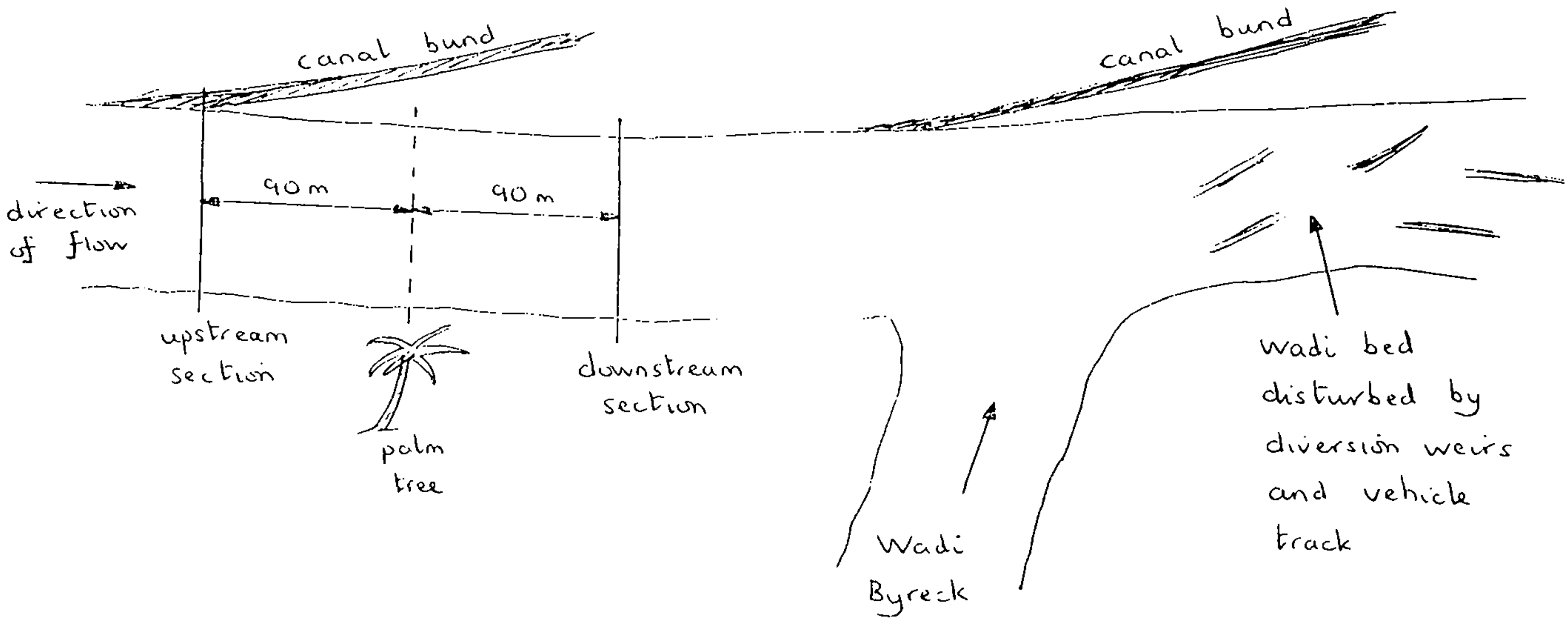


Fig E10. Sketch map showing the position of the slope-area reach in Wadi Yalul.

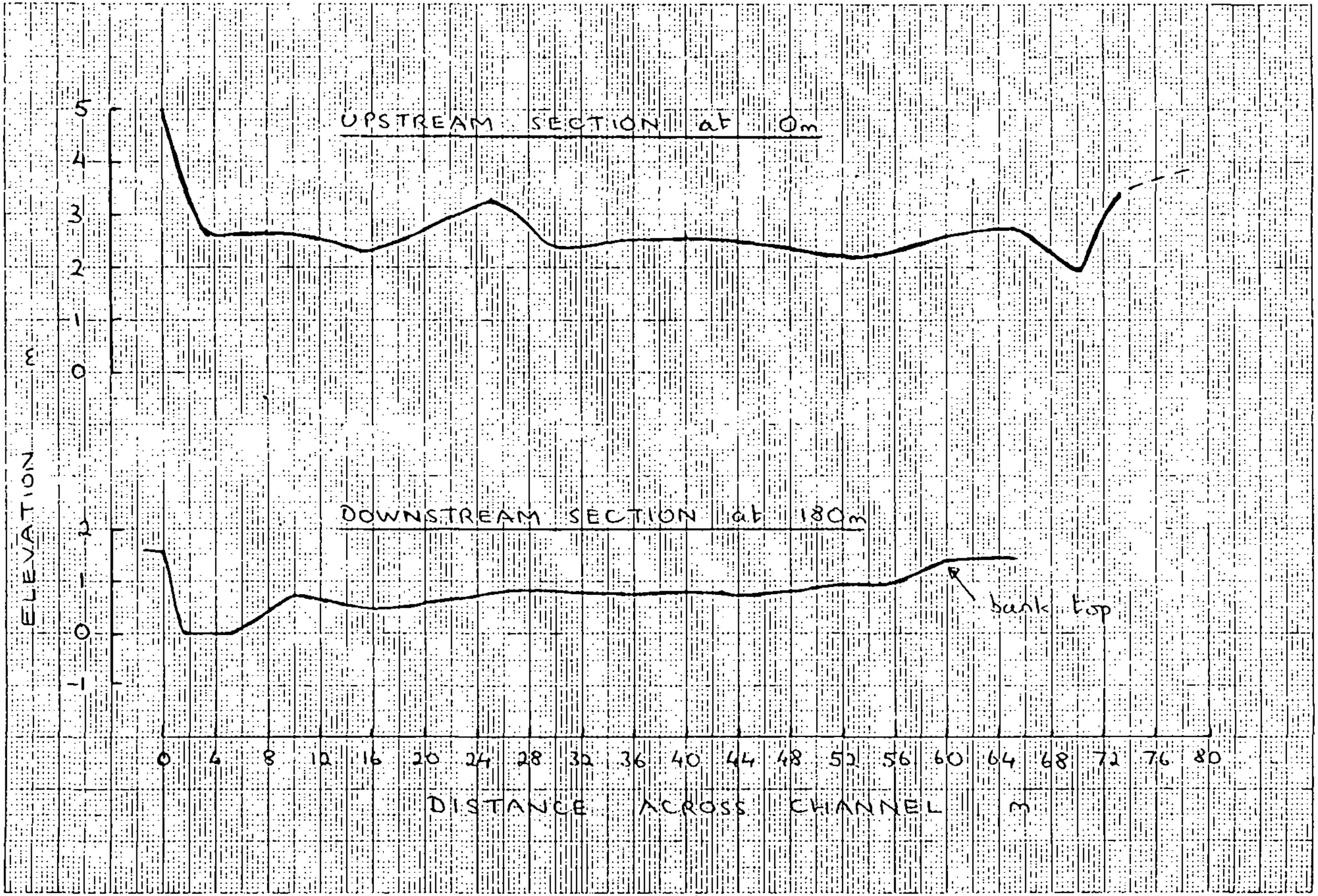


Fig E11. Channel cross sections at the slope-area site in Wadi Yalul

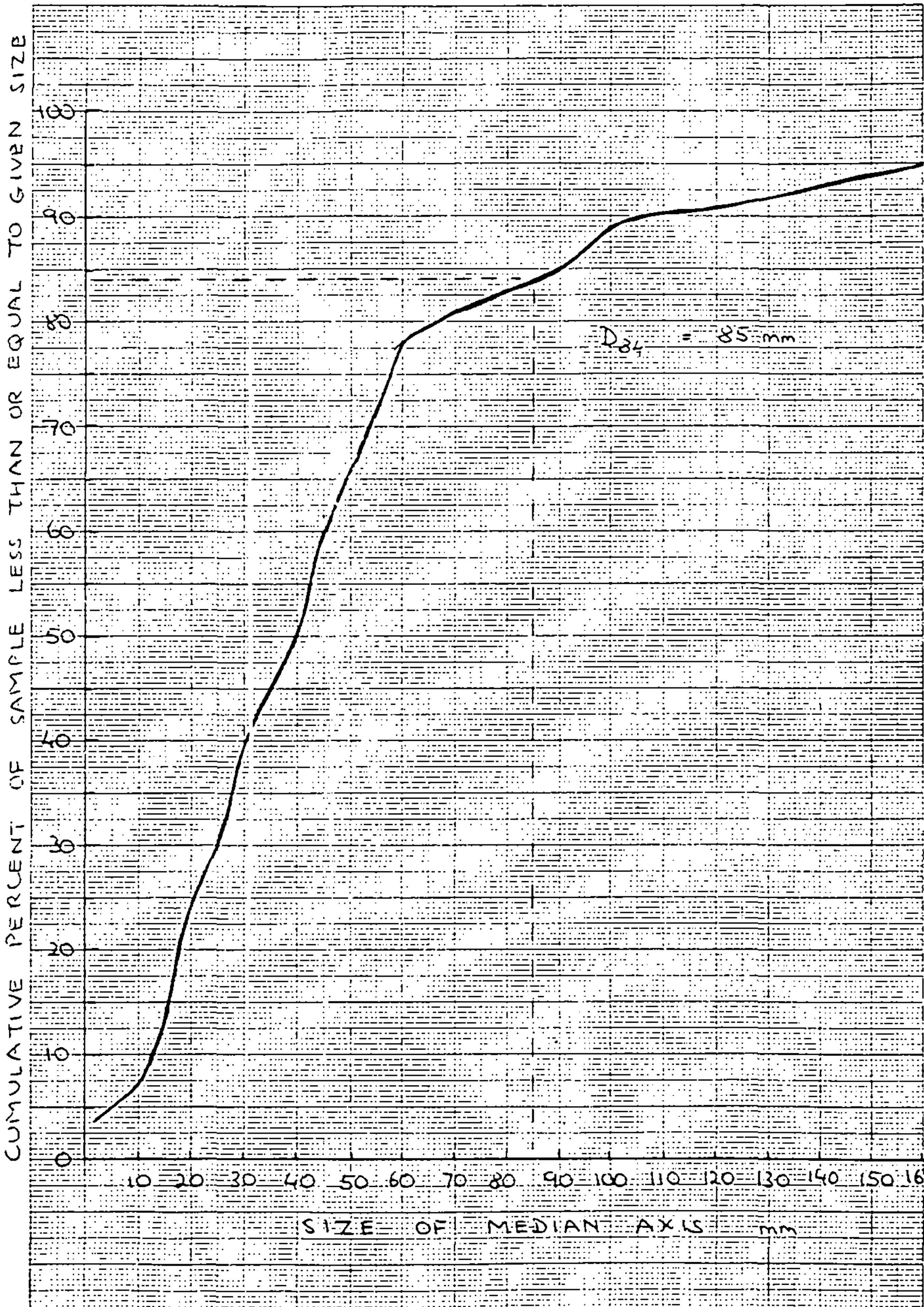


Fig E12. Size distribution curve for the bed material at the slope-area reach in Wadi Yalul.

Table E7. Bed material sample:

SITE WADI YALUL SLOPE-AREA REACH AT GOU REYZ

DATE TUESDAY 9 AUGUST 1983

12	380	23	38	55	29	98	112	20	26
19	26	9	44	19	50	46	40	21	45
24	130	83	36	34	55	46	160	41	64
170	16	58	2.5	20	125	14	95	220	55
76	340	15	27	27	180	44	88	98	68
53	2.5	16	20	50	44	105	14	28	37
98	30	18	39	32	75	24	31	55	58
33	42	44	16	2.5	2.5	7	28	70	12
43	48	56	6	18	145	52	30	55	60
45	24	23	13	46	35	29	58	42	16

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
0 - 2.5	||||	4	4
2.5 - 5			
5 - 7.5	||	2	6
7.5 - 10	|	1	7
10 - 15	||||||	6	13
15 - 20	|||||||||||	11	24
20 - 25	||||||	6	30
25 - 30	||||||||||	10	40
30 - 35	|||||	5	45
35 - 40	|||||	5	50
40 - 45	||||||||||	10	60
45 - 50	||||||	6	66
50 - 60	||||||||||||	12	78
60 - 70	|||	3	81
70 - 80	||	2	83
80 - 90	||	2	85
90 - 100	||||	4	89
100 - 120	||	2	91
120 - 140	||	2	93
140 - 160	||	2	95
160 - 180	||	2	97
180 - 200			
200 - 240	|	1	98
240 - 280			
280 - 320			

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
320 - 360	|	1	99
360 - 400	|	1	100

D_{16} = 16.4 mm

D_{50} = 40 mm

D_{84} = 85 mm

$\log\left(\frac{D_{84}}{D_{50}}\right) = 0.327$

Table E8. Computer printout of the discharge calculations for the slope-area exercise in Wadi Yalul.

```
       YALUL
  GAUGING STATION

      FLOOD OF
      AUG 1983

 PEAK DISCHARGE BY
 SLOPE-AREA METHOD

 DATA ENTERED BY
 JCB


      RESULTS

   FLOOD LEVELS
 SECT  1    3.40 M
 SECT  2    2.45 M
 SECT  3    1 50 M

   DISTANCES
 DIST  1    92.0 M
 DIST  2    90.0 M

   SLOPE  0.01055
 (UPPER =  0.01055)
 (LOWER =  0.01055)


GRAVEL D84 0.085 M

   SECTION AREAS
 SECT  1    68.1 M2
 SECT  2    53.9 M2
 SECT  3    47.6 M2

   SECTION DEPTHS
 SECT  1    0.84 M
 SECT  2    0.82 M
 SECT  3    0.73 M

   SECTION WIDTHS
 SECT  1    71.0 M
 SECT  2    65.5 M
 SECT  3    60.0 M

   SECTION D/D84
 SECT  1    9.95
 SECT  2    9.68
 SECT  3    9.33

   SECTION √8/F
 SECT  1    9.60
 SECT  2    9.54
 SECT  3    9.45


 ++++++++++++++

       DISCHARGE
        141 M3/S

 ++++++++++++++
```

E.5 WADI IBRAHIM AT DHUHRA

E.5.1 Slope-Area Site

Although the wadi is now called Ibrahim locally, it apparently used to be called Abu Salah and may be shown on the map as Asalah. It lies between Wadis Rima and Siham.

Measurements were made along a 100 m reach within well-defined banks. The left hand bank is artificially raised by a field embankment and the bed is partially covered by scattered scrub and weeds (Fig E13). The survey was made on 13 August.

E.5.2 Surveying Data

Upstream Section		Centre Section		Downstream Section	
Tape distance m	Staff level m	Tape distance m	Staff level m	Tape distance m	Staff level m
0	5.50	0	4.10	0	3.61
2	3.80	1.5	2.79	0	0.81
4	2.09	2	2.37	2	0.33
6	1.93	4	1.60	4	0.32
8	1.91	6	1.40	6	0.39
10	1.84	8	1.34	8	0.47
12	1.75	10	1.16	10	0.48
14	1.62	12	1.02	12	0.52
16	1.73	14	0.92	14	0.45
16.7	2.10	16	0.74	16	0.76
18	4.13	18	0.83	18	1.40
		20	1.00	19.3	2.92
		22	3.33		

Distance from upstream to centre section = 50 m

Distance from centre to downstream section = 50 m

Total reach length = 100 m

The data are plotted in Fig E14.

E.5.3 Bed Material Data

The bed material sample is shown in Table E9 and the size distribution is plotted in Fig E15.

D_{84} 0.11 m

E.5.4 Characteristic Flow Data

Mean Bed Level

Upstream section over 4 to 16 m	1.83 m
Centre section over 4 to 20 m	1.09 m
Downstream section over 2 to 16 m	0.45 m

Fall in Bed Level

From upstream to centre section	1.83 - 1.09	0.74 m
From centre to downstream section	1.09 - 0.45	0.64 m
Total	1.83 - 0.45	1.38 m

Bed Slope

From upstream to centre section	0.74/50		0.0148
From centre to downstream section	0.64/50		0.0128
Overall	1.38/100	=	0.0138

The characteristic flow is chosen to be the natural bankfull flow, which is best defined by the right hand side bank levels. Examination of the data suggests the following levels.

Upstream flood level	4.27 m
Centre flood level	3.53 m
Downstream flood level	2.90 m

For these levels the corresponding cross-sectional areas and widths for each section are as follows.

Section	Cross-sectional Area m^2	Surface Width m
Upstream	35.2	16.5
Centre	45.5	21.3
Downstream	43.5	19.3

E.5.5 Characteristic Flow Discharge

Using the above data the bankfull flow is calculated to be 301 m^3/s. Details of the calculations are shown on the computer printout in Table E10.

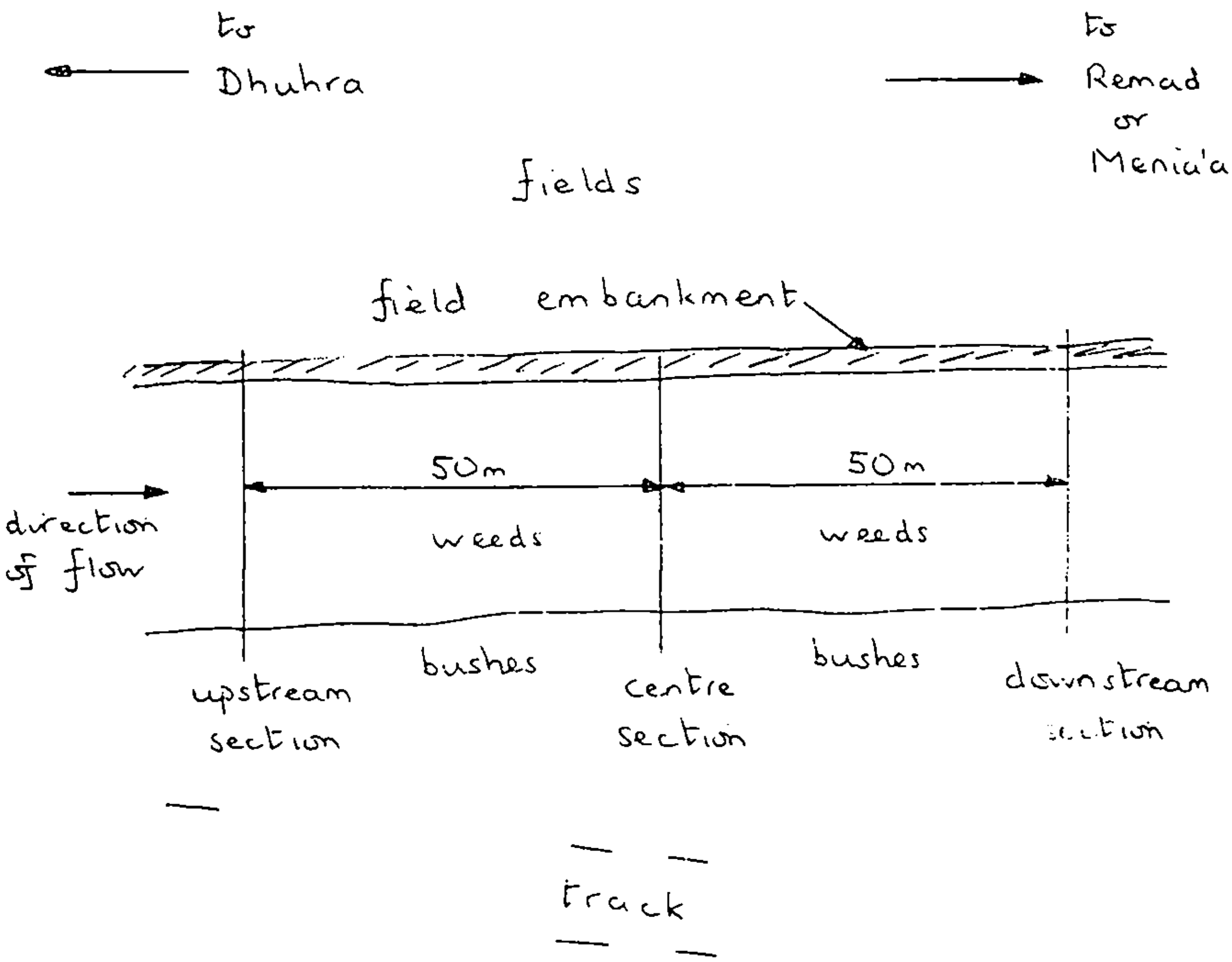


Fig E13. Sketch map showing the position of the slope-area reach in Wadi Ibrahim.

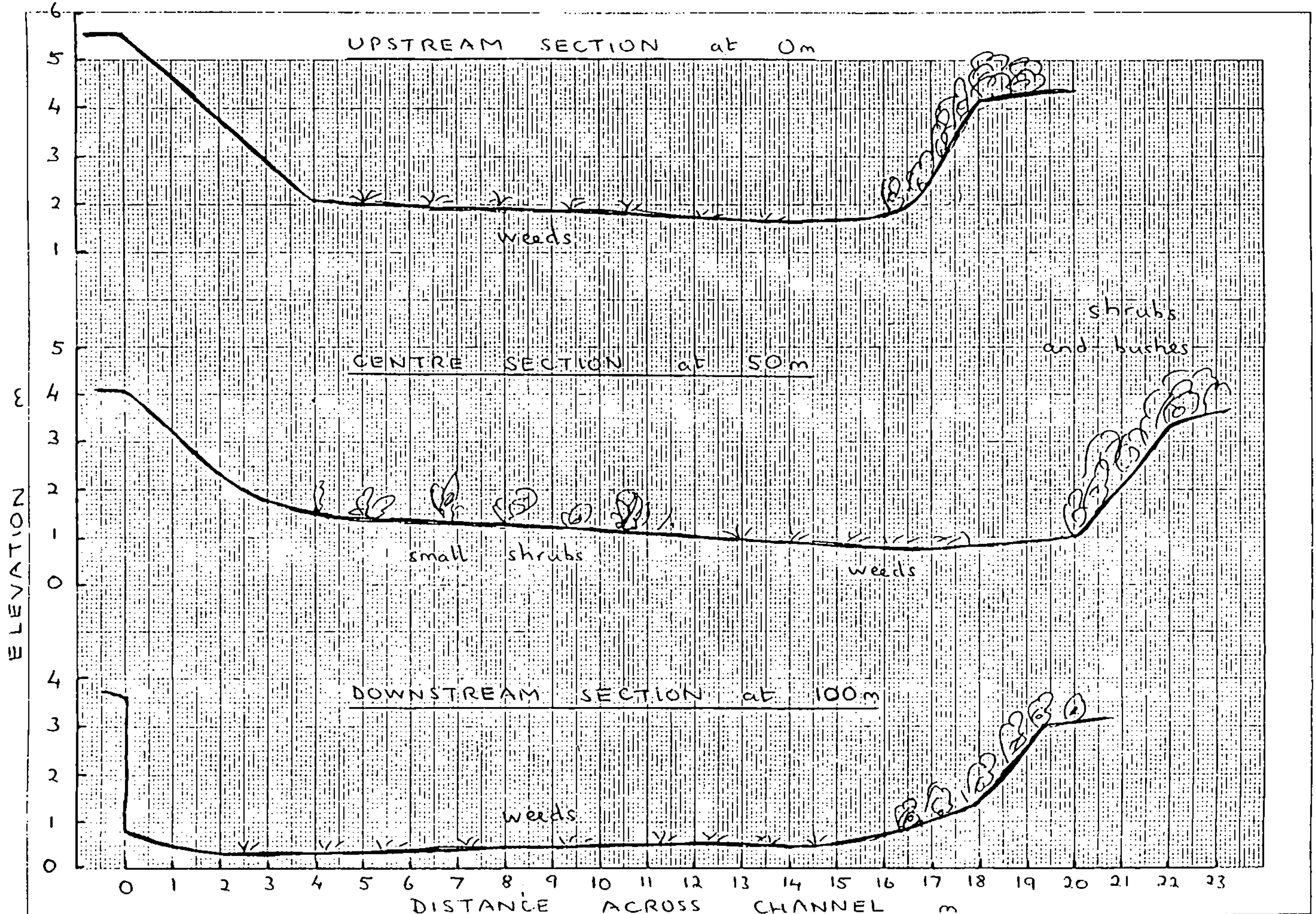


Fig E14. Channel cross sections at the slope-area site in Wadi Ibrahim.

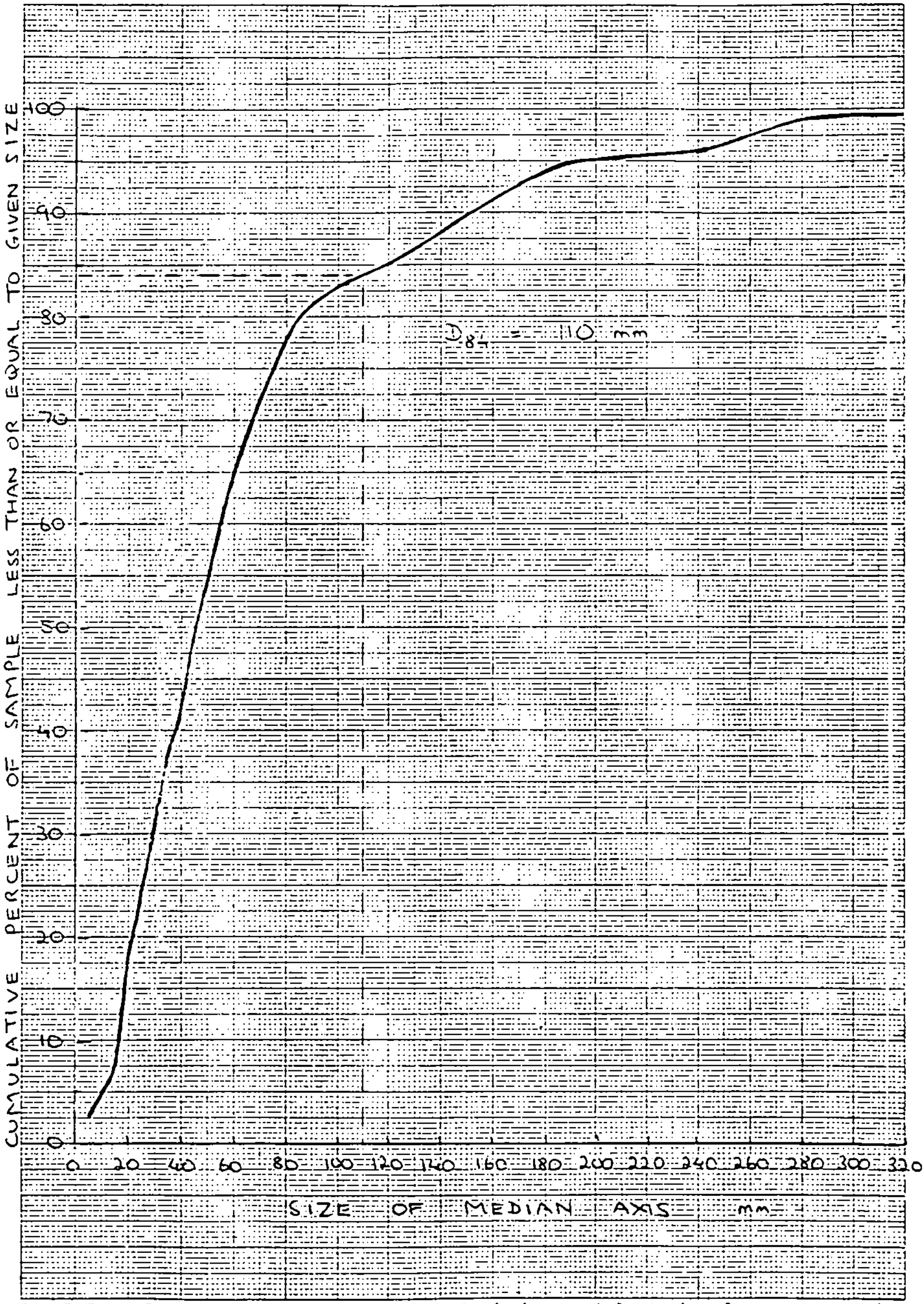


Fig E15. Size distribution curve for the bed material at the slope-area reach in Wadi Ibrahim.

Table E9. Bed material sample

SITE WADI IBRAHIM SLOPE-AREA SITE

DATE SATURDAY 13 AUGUST 1983

48	62	44	44	42	140	48	82	37	19
34	16	17	20	24	11	23	22	72	20
43	170	21	54	52	155	148	42	165	22
6	103	33	19	27	70	50	73	56	52
35	76	17	86	62	195	260	30	12	70
105	220	77	16	52	28	19	34	64	89
175	48	7	260	140	23	59	26	31	18
156	78	6	64	9	280	58	74	36	51
32	33	98	95	8	500*	56	41	26	49
18	28	39	55	130	51	45	21	45	63

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
0 - 2.5			
2.5 - 5			
5 - 7.5	III	3	3
7.5 - 10	II	2	5
10 - 15	II	2	7
15 - 20	IIIIIIIIIII	11	18
20 - 25	IIIIIII	7	25
25 - 30	IIIIII	6	31
30 - 35	IIIIIII	7	38
35 - 40	III	3	41
40 - 45	IIIIIIII	8	49
45 - 50	IIIII	5	54
50 - 60	IIIIIIIIIII	11	65
60 - 70	IIIIIII	7	72
70 - 80	IIIIII	6	78
80 - 90	III	3	81
90 - 100	II	2	83
100 - 120	II	2	85
120 - 140	III	3	88
140 - 160	III	3	91
160 - 180	III	3	94
180 - 200	I	1	95
200 - 240	I	1	96
240 - 280	III	3	99
280 - 320			

D_{16} = 19.1 mm

D_{50} = 46 mm

D_{84} = 110 mm

$\log(D_{84}/D_{50})$ = 0.379

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
320 - 360			
360 - 400			
400 - 440			
440 - 480			
480 - 520	I	1	100

Table E10. Computer printout of the discharge calculations for the *slope-area exercise* in Wadi Ibrahim.

```
      IBRAHIM
  GAUGING STATION

      FLOOD OF
      AUG 1983

PEAK DISCHARGE BY
SLOPE-AREA METHOD

DATA ENTERED BY
JCB


      RESULTS

   FLOOD LEVELS
SECT  1    4.27 M
SECT  2    3.53 M
SECT  3    2.90 M

   DISTANCES
DIST  1    50.0 M
DIST  2    50.0 M

   SLOPE   0.01370
(UPPER =   0.01460)
(LOWER =   0.01260)


GRAVEL D84 0.110 M

   SECTION AREAS
SECT  1    35.2 M2
SECT  2    45.5 M2
SECT  3    43.5 M2

   SECTION DEPTHS
SECT  1    2.13 M
SECT  2    2.13 M
SECT  3    2.25 M

   SECTION WIDTHS
SECT  1    16.5 M
SECT  2    21.3 M
SECT  3    19.3 M

   SECTION D/D84
SECT  1  19.39
SECT  2  19.41
SECT  3  20.48

   SECTION √8/F
SECT  1  11.23
SECT  2  11.23
SECT  3  11.37


++++++++++++++

      DISCHARGE
       301 M3/S

++++++++++++++
```

E.6 WADI HARAD

E.6.1 Slope-Area Site

A kilometre or so before it passes through its final mountain gorge, the wadi undergoes a transition in which it changes from a narrow channel with rocky banks to a wide sandy channel with poorly defined banks. Just upstream of this transition is the reach selected for slope-area surveying (Fig E16).

The 200 m long reach used for the measurements is one of the better sites investigated in the slope-area exercises, having straight, well defined banks which are moderately steep with rock outcrops and a grass covering. It has a mainly sandy bed although deposits of cobbles and boulders occur at the sides and on bars. Sand bedload transport occurs at low flows with bedforms including ripples, low dunes, flat bed and antidunes. The main large-scale bed features are wide, low bars. The survey was made on 7 August.

E.6.2 Surveying Data

The survey did not extend far up the bank slopes, especially at the downstream section where surveying was obstructed by tall grass.

Upstream Section		Centre Section		Downstream Section	
Tape distance m	Staff level m	Tape distance m	Staff level m	Tape distance m	Staff level m
4	2.65	4	2.68	0	1.07
6	2.35	6	2.18	5	0.87
8	1.99	8	1.75	10	0.88
10	1.99	10	1.58	15	0.85
15	2.08	15	1.30	20	0.87
20	2.17	20	1.38	25	1.15
25	2.14	25	1.43	30	0.94
30	2.08	30	1.42	35	0.55
35	1.92	40	1.44	40	0.75
40	1.90	45	1.32	45	0.82
45	1.91	50	1.05	50	0.64
50	1.92	52.2	1.20	53.5	1.47
55	2.28	55	1.80		
58.5	2.83	60	2.91		

Distance from upstream to centre section	100 m
Distance from centre to downstream section	100 m
Total reach length	200 m

The data are plotted in Fig E17.

E.6.3 Bed Material Data

The bed material sample which is shown in Table E11 was made on several bars which contained gravel and boulders. The corresponding size distribution is plotted in Fig E18 and D_{84} = 0.0775 m. Much of the bed, though, was sandy, at least at low flow.

E.6.4 Characteristic Flow Data

Mean Bed Level

Upstream section over 8 to 50 m	=	2.02 m
Centre section over 15 to 52.2 m	=	1.39 m
Downstream section over 5 to 50 m	=	0.84 m

Fall in Bed Level

From upstream to centre section	=	2.02 - 1.39	=	0.63 m
From centre to downstream section	=	1.39 - 0.84		0.55 m
Total	=	2.02 - 0.84	=	1.18 m

Bed Slope

From upstream to centre section	=	0.63/100	=	0.0063
From centre to downstream section	=	0.55/100	=	0.0055
Overall	=	1.18/200	=	0.0059

The characteristic flow is chosen to be contained by the channel within the vegetation line. The relevant level at the centre section is about 2 m, from which the corresponding levels at the other two sections are found using the change in bed level from the centre section. Thus

Centre flood level = 2 m

Upstream flood level = 2 + 0.63 = 2.63 m

Downstream flood level = 2 - 0.55 = 1.45 m

For these levels the corresponding cross-sectional areas and widths for each section are as follows.

Section	Cross-sectional Area m^2	Surface Width m
Upstream	29.7	53.5
Centre	29.1	49.2
Downstream	31.2	53.5

E.6.5 Characteristic Flow Discharge

Because it is not clear whether the wadi bed acts as a sand bed or a gravel bed at high flow, the characteristic discharge was calculated for both circumstances. For the gravel-bed, the flow resistance was calculated as usual by Eq 2.3 while for the sand bed it was calculated by Eq 2.4 (assuming a plane bed). These two approaches should indicate the limits within which the real discharge is likely to lie. The results are, for the gravel bed case, 48 m^3/s and, for the sand bed case, 83 m^3/s. Details of the calculations are shown on the computer printouts in Table E12.

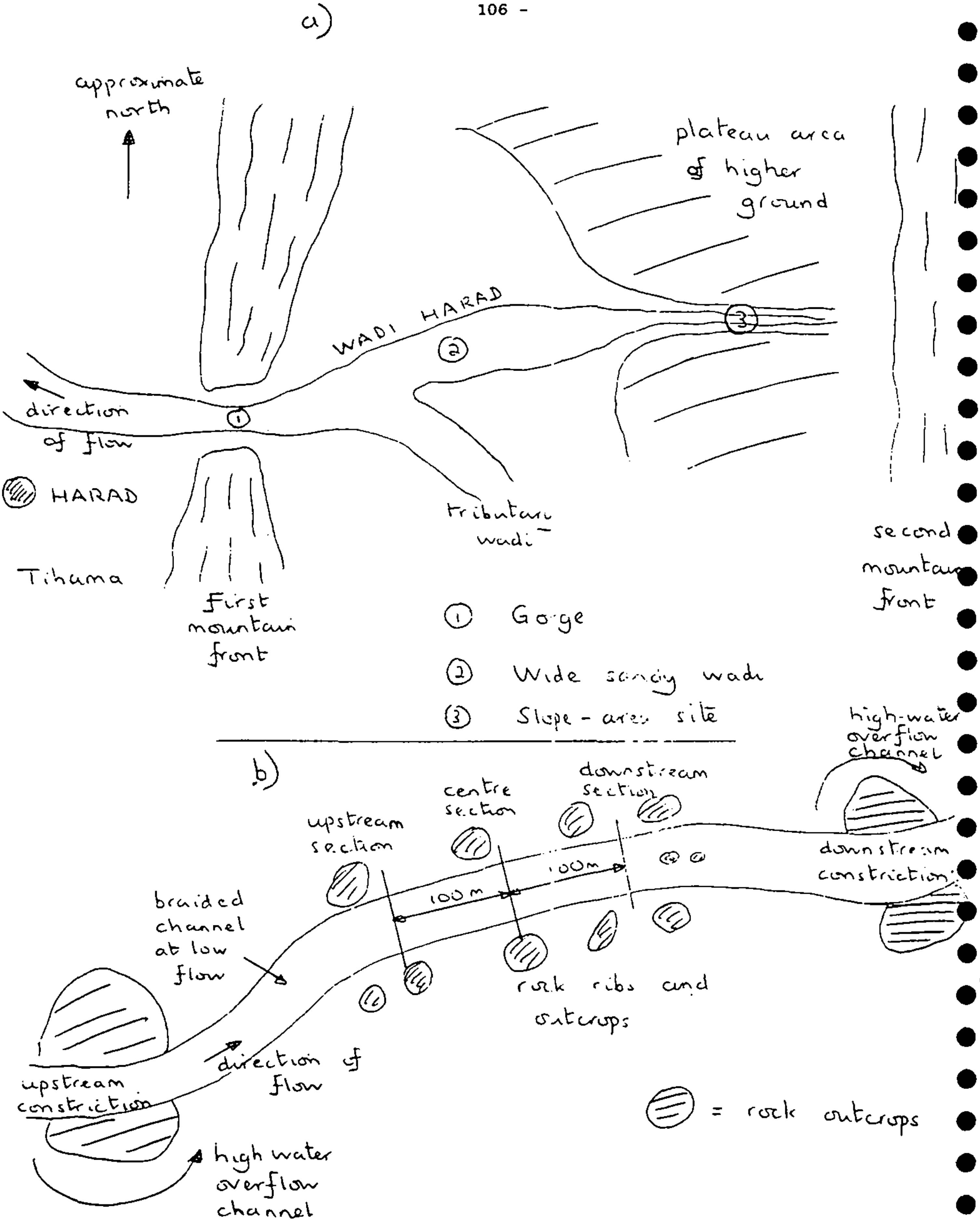


Fig E16. Sketch map showing the position of the slope-area reach in Wadi Harad.

a) General location.

b) Reach details.

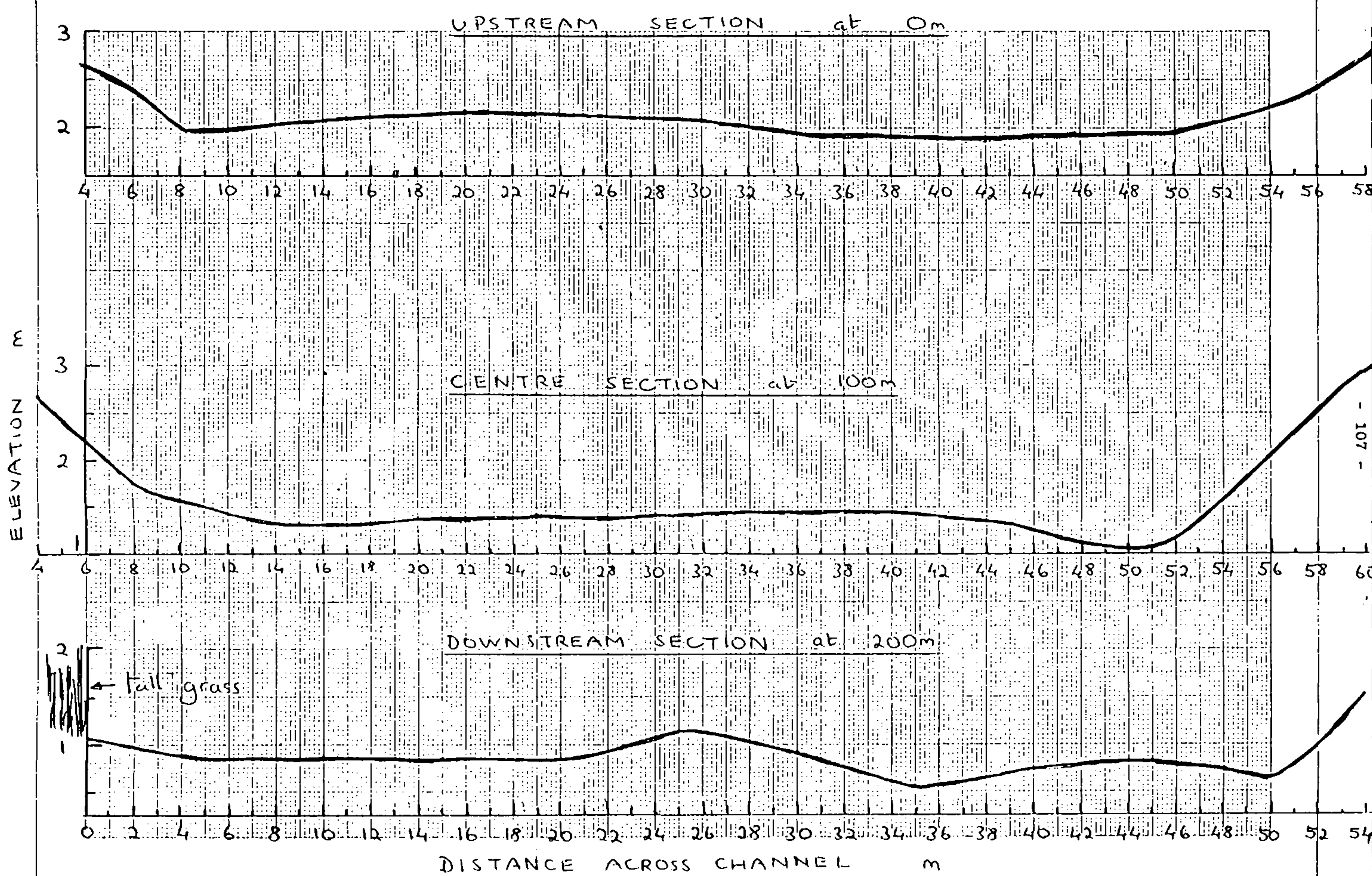


Fig E17. Channel cross sections at the slope area site in Wadi Harad.

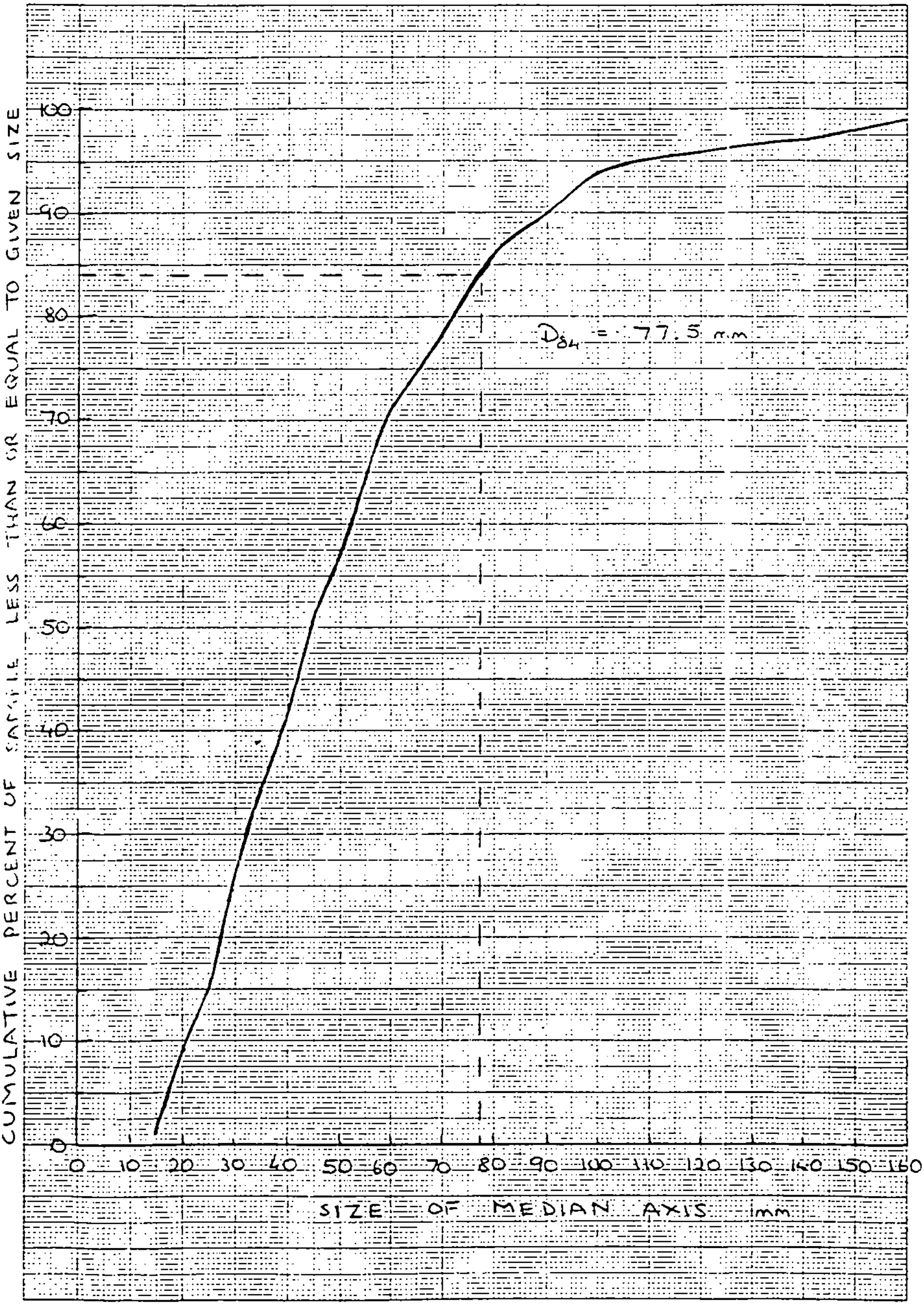


Fig E18. Size distribution curve for the bed material sampled on bars at the ~~slope-area reach in Wadi Harad.~~

Table E11 Bed material sample :

SITE WADI HARAD SLOPE-AREA SITE : Sample on bars only ; channel bed is largely coarse sand

DATE SUNDAY 7 AUGUST 1983

55	45	33	83	93	83	92	55	30	37
70	82	42	44	24	32	43	21	35	19
42	65	16	29	41	75	37	25	75	33
38	51	32	63	17	24	64	50	96	190
29	59	18	59	26	46	50	41	76	58
44	60	20	21	43	48	62	27	78	16
125	145	35	72	27	57	59	53	65	28
22	46	36	63	13	59	45	38	34	27
80	90	114	53	26	16	36	48	150	105
26	38	79	26	52	51	33	54	95	16

SIZE RANGE mm	NUMBER IN RANGE		CUMULATIVE TOTAL
0 - 2.5			
2.5 - 5			
5 - 7.5			
7.5 - 10			
10 - 15	I	1	1
15 - 20	IIIIIIII	8	9
20 - 25	IIIIII	6	15
25 - 30	IIIIIIIIIII	11	26
30 - 35	IIIIIIII	8	34
35 - 40	IIIIIII	7	41
40 - 45	IIIIIIIIII	10	51
45 - 50	IIIIII	6	57
50 - 60	IIIIIIIIIIIIII	14	71
60 - 70	IIIIIII	7	78
70 - 80	IIIIIIII	8	86
80 - 90	IIII	4	90
90 - 100	IIII	4	94
100 - 120	II	2	96
120 - 140	I	1	97
140 - 160	II	2	99
160 - 180			
180 - 200	I	1	100
200 - 240			
240 - 280			
280 - 320			

D_{16} = 25.5 mm

D_{50} = 44.5 mm

D_{84} = 77.5 mm

$\log\left(\frac{D_{84}}{D_{50}}\right) = 0.241$

Table E12. Computer printout of the discharge calculations for the slope-area exercise at Wadi Harad:

a) assuming a gravel bed

```
      HARAD
 GAUGING STATION

     FLOOD OF
     AUG 1983

 PEAK DISCHARGE BY
 SLOPE-AREA METHOD

 DATA ENTERED BY
 JCB


      RESULTS

   FLOOD LEVELS
 SECT  1    2.63 M
 SECT  2    2.00 M
 SECT  3    1.45 M

   DISTANCES
 DIST  1   100.0 M
 DIST  2   100.0 M

   SLOPE   0.00590
 (UPPER =  0.00630)
 (LOWER =  0.00550)


GRAVEL D84 0.077 M

   SECTION AREAS
 SECT  1    29.7 M2
 SECT  2    29.1 M2
 SECT  3    31.2 M2

   SECTION DEPTHS
 SECT  1    0.55 M
 SECT  2    0.59 M
 SECT  3    0.58 M

   SECTION WIDTHS
 SECT  1    53.5 M
 SECT  2    49.2 M
 SECT  3    53.5 M

   SECTION D/D84
 SECT  1    7.16
 SECT  2    7.63
 SECT  3    7.52

   SECTION √8/F
 SECT  1    8.80
 SECT  2    8.96
 SECT  3    8.92


 ++++++++++++++

     DISCHARGE
      48 M3/S

 ++++++++++++++
```

b) assuming a sand bed

```
      HARAD
 GAUGING STATION

     FLOOD OF
     AUG 1983

 PEAK DISCHARGE BY
 SLOPE-AREA METHOD

 DATA ENTERED BY
 JCB


      RESULTS

   FLOOD LEVELS
 SECT  1    2.63 M
 SECT  2    2.00 M
 SECT  3    1.45 M

   DISTANCES
 DIST  1   100.0 M
 DIST  2   100.0 M

   SLOPE   0.00590
 (UPPER =  0.00630)
 (LOWER =  0.00550)


GRAVEL D84 0.005 M

   SECTION AREAS
 SECT  1    29.7 M2
 SECT  2    29.1 M2
 SECT  3    31.2 M2

   SECTION DEPTHS
 SECT  1    0.55 M
 SECT  2    0.59 M
 SECT  3    0.58 M

   SECTION WIDTHS
 SECT  1    53.5 M
 SECT  2    49.2 M
 SECT  3    53.5 M

   SECTION D/D84
 SECT  1  111.02
 SECT  2  118.29
 SECT  3  116.63

   SECTION √8/F
 SECT  1  15.13
 SECT  2  15.33
 SECT  3  15.29


 ++++++++++++++

     DISCHARGE
      83 M3/S

 ++++++++++++++
```