Hydraulics Research
Wallingford

# FLOOD DISCHARGE ASSESSMENT

Interim Report

D M Ramsbottom

Report SR 195
March 1989

Registered Office: Hydraulics Research Limited,
Wallingford, Oxfordshire OX10 8BA.
Telephone: 0491 35381. Telex: 848552

This report describes work carried out by members of Dr Paul Samuel's Section of the River Engineering Department of Hydraulics Research, under Commission A (River flood protection), programme 13F (Flood discharge assessment), funded by the Ministry of Agriculture, Fisheries and Food, nominated officer Mr R Buckingham.

At the time of reporting this project, Hydraulics Research's nominated project officer was Dr W R White.

This report is published on behalf of the Ministry of Agriculture, Fisheries and Food, but any opinions expressed are not necessarily those of that Ministry.

© Crown Copyright 1989

Published by permission of the Controller of Her Majesty's Stationery Office

SUMMARY

Hydraulics Research Ltd are studying methods of improving the assessment of flood discharge on behalf of the Ministry of Agriculture, Fisheries and Food. The research is being carried out with the co-operation of Water Authorities in England and Wales, and includes the analysis of existing measured flood flow data, and the development of new methods for assessing flood discharge.

This interim report includes a review of existing measured overbank flow data. Analytical methods have been used to predict discharge and the results have been compared with observed data. Of the simple hand calculation methods used the division line method using diagonal or vertical division lines (methods 2(c) and 2(b) on Figure 4) gave the best predictions. It is expected that better predictions will be given using the lateral velocity distribution method, currently under development. This method was applied to two sites and the results are presented.

Proposals for future work are given, including the development of new field measurement equipment.

CONTENTS

CONTENTS (Cont'd)

# 1 INTRODUCTION

## 1.1 Background

The Water Resources Act 1963 placed on the Water Resources Board the duty of collecting data relating to the demand for water and the actual and prospective water resources for England and Wales. Consequently, many gauging stations were primarily designed to establish the quantity of water available for the community. The provision of flood data was originally considered to be of secondary importance.

When a flow measurement structure or rated channel section is out-flanked by a flood flow the uncertainties associated with flow measurement rise from 3-10% for in-bank flow conditions to 30% or more for out-of-bank flood conditions. Uncertainties of this magnitude can have a profound impact on the return period associated through standard statistical techniques with a particular discharge. They may also lead to the design of a flood protection scheme being too conservative with associated economic losses, or alternatively inadequate with the benefits of the proposed scheme not being achieved.

Reporting upon the errors in Flood discharge measurement the Wolf Report (1985) stated:

"A research programme should be set up to develop new methods for measuring or estimating flow particularly over a flood plain. The objective of the project should be to produce a method which is inexpensive and effective and can possibly be applied after the event".

These recommendations formed the basis for the present research, which is being carried out by Hydraulics Research Ltd (HRL) for the Ministry of Agriculture, Fisheries and Food (MAFF). Work commenced in October 1986, and this report covers progress to the end of 1988.

## 1.2 Objectives

The objectives of the research are to develop methods of estimating or assessing the discharge, particularly peak discharge, of a flood that can be used at typical lowland gauging sites in the UK. Methods should preferably be applicable after the event.

The approach to the research includes the following components:

(a) review of current practice

(b) collection and analysis of data from several existing gauging stations

(c) laboratory and field experiments to investigate site specific measures to improve flood flow estimation in co-operation with Water Authorities

(d) examine the use of multi-dimensional computer models of gauging sites to extend the rating curve

(e) examine the use of catchment flood models to rate lowland gauging stations from data collected upstream

The research involves a high degree of co-operation with Water Authorities, particularly in items (a), (b) and (c) above.

Flows which are contained within river banks or structures may be estimated reasonably accurately using existing techniques. However, the margin of error is much greater when overbank flow occurs or the site is bypassed by flood flows. The main emphasis in the research programme is therefore the assessment of flood discharges where overbank flow occurs. During visits to the Water Authorities it became apparent that many estimates of flood discharges are made using extrapolated structure ratings. Current metering from bridges and, occasionally, bridge ratings are also used. Some attention is therefore also given to these topics.

## 1.3 Progress

All ten Water Authorities in England and Wales have been contacted, and most have been visited. Progress on the objectives referred to above is as follows:-

(a) The review of current practice was carried out during 1986/1987, and the results are contained in HRL Report No. SR 111 (Tagg and Hollinrake, 1987).

(b) Data from existing gauging stations has been collected. Various methods have been used to predict the stage discharge curves, and the results have been compared with observed data. The field data is reviewed in Section 3 of this report, and the application of prediction methods is contained in Section 4.

See reports SR 244 & 263

(c) Sites where experimental work could be carried out have been identified, and methods for estimating flood discharges are discussed in Section 5. No experimental work has been carried out to date.

See report SR 277

(d) The use of multi-dimensional computational models of gauging sites is discussed in Section 4, and proposals for the development of a model during 1989/90 are given.

(e) Sites where catchment flood models could be applied have been identified and the method is discussed in Section 6.

A suggested programme for future work is given in Section 7. The main components of the programme and laboratory and field experiments under item 1.2(c), and the use of computer models under items 1.2(d) and 1.2(e).

## 1.4 Contact with Water Authorities

An initial request for information was sent to all ten Water Authorities in England and Wales in October 1986. The response from the Water Authorities was generally good, and visits were made to the following Water Authorities, where data of possible interest was available.

Thames
Severn Trent
Wessex - Bristol Avon division
- Avon and Dorset division
Southern - Hampshire division
Yorkshire
Northumbrian
Anglian - Lincoln division
- Oundle division
- Norwich division
- Colchester division
- Cambridge division
South West
Welsh - Northern division

Sites of interest have now been identified, and the Water Authorities have been very helpful in supplying further information for these sites.

# 2 BACKGROUND INFORMATION

## 2.1 River floods

When a large flood passes down a river, the discharge generally exceeds the capacity of the natural river channel and flow occurs over land adjacent to the main channel, which may or may not be contained by flood embankments. In some cases separate channels may occur in depressions in the flood plain. At river crossings, the flow may pass through bridge openings and openings in embankments crossing the flood plain, or overtop the approaches to the bridge and possibly the bridge itself.

Field measurement of flood discharge is difficult. Floods occur infrequently, and very few gauging stations are capable of measuring discharge across the flood plain. It may be possible to supplement gauged flows in the main channel by taking flow measurements on the flood plain. However, when a river is in flood Water Authority staff may have more pressing tasks connected with preservation of life and property than gauging river and flood plain flow.

There are at present no accurate analytical methods available for estimating discharge where overbank flow occurs. The pattern of flow in two stage channels when the water level is above the bankfull level of the main channel is complex. The velocity of flow in the main channel is greater than in the flood plains and a momentum transfer mechanism is generated in the region of high shear flow between the main channel and flood plain. This has the effect of reducing local and mean velocities, discharge and boundary shear stress in the main channel and increasing local boundary shear stress in the flood plain zone near the junction.

The situation is further complicated if the main channel is meandering. At low depths of flow on the flood plain the dominant flow occurs in the main channel. At high flood plain depths the dominant flow occurs above main channel bankfull level and is parallel to the river valley and not the main channel itself. These two patterns of flow are shown in Figure 18.

Factors affecting flow on the flood plain include the following:

- Extent of active flood plain (ie. areas where significant flood plain flow occurs).

  Areas which are not active may include relatively high ground where the water is shallow, or areas of dense vegetation.

- Nature of flood plain

  Flow on flood plains may be controlled by the geometry of the flood plain. In the case of the meanders, interaction of flood plain flow with main channel flow may have a very significant effect causing backing up at the downstream end of the flood plain section. This would result in lower flow velocities on the flood plain than a calculation for the flood plain in isolation would indicate.

- Floodplain roughness

  Floodplains are often a combination of grassland, other vegetation, hedges, fences, etc. and the overall roughness of the flood plain is difficult to determine.

- Vegetation

  The amount of vegetation changes throughout the year depending on the seasons. If growth is uncontrolled the vegetation will be greatest towards the end of the summer with the most rapid change occurring in spring. A purpose built flood relief channel should have regular cutting of vegetation to maintain the capacity of the channel, but the practicality of this must be taken into account during the design. The capacity of the main channel will also vary seasonally depending on vegetation.

An important feature of river flow as the river begins to go out-of-bank is that the flow is unsteady around bankfull level. The bankfull level varies along the river, with water going over the bank at some locations and not at others. This affects the definition of bankfull discharge, which is an important parameter in the methods of analysis described in Section 4.

## 2.2 Gauging sites

There are over 1200 gauging sites in England and Wales. However very few of these are capable of measuring discharges during large floods, either because they are bypassed by flood water or the gauging structures are drowned. The main types of flow gauging stations are as follows.

<u>Low flow measurement structure</u>

Low flow measurement structures are very common on UK rivers. They are, however, generally not suitable for measuring flood discharges. Discharges which are above the range of the low flow structure are estimated by constructing rating curves for the site. This is done either by extrapolation of the low flow rating curve or by supplementing the low flow data by current metering. Such extrapolations are tentative as flood data is sparse and the amount of flow on the flood plain is generally unknown.

Full flow range measurement structure

A structure which measures the full range of flow is the most convenient method of measuring flood discharge. An example of such a structure would be a Crump weir in which all the flow passes through the structure, and which is undrowned for the full range of flow. Many structures are, however, drowned or bypassed by overbank flows during large floods.

Velocity area gauging station

Velocity area flow gauging stations include cableways and current metering from bridges. The latter is sometimes used to supplement data from low flow measurement structures. Velocity area stations are often bypassed or have overbank flows during large floods and therefore the full discharge is not recorded. Flow measurement on the flood plain is only carried out at a very small number of sites.

## 2.3 Existing methods of assessing flood discharge

Existing methods of assessing flood discharge were reported in Report SR 111 (Tagg and Hollinrake, 1987), and only a brief summary is given here.

Flood discharges may be measured at measurement structures or velocity area sites where the flow is contained at the measurement site and drowning of structures does not occur. However, at sites where the flow is not measured an alternative method of assessment is required, and the following methods are currently in use:

- Extrapolation of structure rating
- Velocity estimates combined with wrack or gauge levels
- Photographs
- Rating of bridge structures
- Hydrological assessment

Extrapolation of structure ratings is the most common of these methods but they are all subject to large errors, particularly when the flow is out-of-bank.

## 2.4 Hydraulic problems

Three particular hydraulic problems have been identified which require attention. The most important of these is overbank flow, and the main emphasis of the research project is to develop methods which may be used at sites where overbank flow occurs. Some attention is also given however to the accuracy of extrapolation of structure ratings which are currently used by Water Authorities, the accuracy of current metering from bridges, and bridge and culvert rating curves.

### Overbank flow

The flow patterns which occur in two stage channels are complex, particularly where the main channel is meandering. A number of methods of analysis have been proposed by researchers and further research is in progress, including an extensive research programme on the SERC flood channel facility at Hydraulics Research Ltd.

The approaches to the assessment of flood discharge at sites where overbank flow occurs are as follows:-

i) Sites where overbank flow has been measured.

   Investigate different methods of estimating flood discharge and compare with observed results, including the construction of computational models of gauging sites.

ii) Sites where overbank flow occurs which are close to rated sections.

   Experiment with different methods of estimating discharge and compare with observed discharge at the rated section.

iii) Easily rated sites which are downstream of another well rated site in the same catchment.

   Construct a catchment flood model using the upstream flood hydrograph. Estimate the discharge at the downstream site and compare with the observed discharge.

The number of sites where overbank flow has been measured is very limited. Only ten suitable sites have been identified and of these only three have more than 5% of the maximum recorded flood flow on the flood plain. A total of twelve sites have been identified where experimental work may be possible, and seven sites where it may be possible to construct a catchment flood model.

Extrapolation of ratings

A number of different methods are currently in use to extrapolate ratings for flow measurement structures in order to estimate high discharges. It is desirable to review the different methods of extrapolation currently in use, and check the accuracy of such extrapolations by current metering at high river flows. Some extrapolations are already based on discharges obtained by current metering, and in these cases further checks may not be necessary.

## Flow at bridges and culverts

A number of different types of flow pattern are possible at bridges and culverts. For example, flow through culverts may be drowned or undrowned, and the culvert may or may not be submerged. The discharge at such structures may be estimated from the headloss using suitable flow formulae depending on the type of flow observed. Recent research work includes research at HRL on flow through arch bridges. It is desirable to review literature on flow through bridges and culverts in order to recommend methods for estimating the flow where a significant headloss exists. It is recognised that the number of sites where these methods could be applied is limited.

Current metering from bridges is used to measure discharge, particularly at high flows. Particular problems with flow measurement at bridges include scour, and therefore variations in flow depth, and turbulent flow around bridge piers and arches. It is therefore desirable to check the accuracy of flow measurement at bridges by independent current metering upstream or downstream of the bridge.

# 3 REVIEW OF EXISTING DATA

## 3.1 General

The Water Authorities were asked if they have gauging stations where the following types of data are available

1. Overbank flow rated sites

   Sites where overbank flow has been successfully gauged and used to produce an overbank flow rating. This could be used to compare actual overbank ratings with predicted ratings using different methods of analysis.

   A variation of the method would be to choose a site where flood outlines are available locally (or where such data could easily be collected in the future). A rating curve could then be predicted using the slope area method, and compared with the observed rating.

2. Experimental sites

   Sites where all flow is measured at a gauging station and overbank flow occurs nearby. This would be valuable as a site for experimenting with new measurement techniques at the river section where overbank flow occurs, and comparing the results with the gauged flow.

3. Flow routing reaches

   Sites where flood flows are gauged at two locations on a river catchment. A flood routing method could then be applied using gauged flow at the upstream site in order to estimate the flow at the downstream site. The results would then be compared with the gauged flow at the downstream site.

A considerable amount of information was provided by the Water Authorities. The information for each site was inspected, and a list of sites which may be suitable for study in the research programme was compiled, as shown on Table 1. The experimental sites are discussed further in Section 5, and the flood routing reaches in Section 6. The sites where overbank flow data have been obtained are discussed further in this section.

It is stressed that selection of sites for the research programme was based largely on information provided by the Water Authorities, supplemented by a limited number of site visits. Some information was very detailed, and it was possible to make a good assessment of the suitability of a particular site. Other information was less detailed, and it will be necessary in some cases to obtain further information before confirming the suitability of some sites.

## 3.2 Review of flow data for sites where overbank flow has been measured

A total of twelve sites were identified where overbank flows have been measured, which may be suitable for study. A few other possible sites were rejected for a number of reasons including shortage of data, problems with the site geometry, not all flood plain flow measured, and uncertainties concerning the accuracy of flow measurements. Of the twelve sites identified,

TABLE 1 : Gauging stations considered for study

| Out of bank rated site | Experimental site | Flow routing reach | Water Authority |
|---|---|---|---|
| R Mole/Kinnersley Manor | R Wey/Tilford | R Mole/Horley to Castle Mill | Thames |
| R Blackwater/Ower | R Blackwater/Ower | | Southern (Hampshire) |
| | R Avon/Bathford | R Avon/Melksham to Bathford | Wessex (Bristol Avon) |
| | R Stour/Hammoon | R Stour/Hammoon to Throop | Wessex (Avon & Dorset) |
| R Culm/Wood Mill<br>R Torridge/ Torrington<br>R Teign/Preston | R Torridge/Torrington | | South West |
| R Severn/Montford<br>R Penk/Penkridge<br>R Trent/North Muskham | R Severn/Montford | | Severn Trent |
| | R Welland/Tixover | | Anglian (Oundle) |
| | R Kym/Meagre Farm | | Anglian (Cambridge) |
| | R Chelmer/Springfield | | Anglian (Colchester) |
| | R Elwy/Pont-y-Gwyddel | | Welsh |
| R Ouse/Skelton | | R Aire/Skipton to Aldwick<br>R Wharfe/Addington to Otley | Yorkshire |
| | | R Eden/Kirkby Stephen to Carlisle | North West (Carlisle) |
| | R Ribble/Samlesbury | | North West (Warrington) |
| R Wansbeck/Mitford<br>R South Tyne/ Haydon Bridge<br>R Tees/Low Moor | R Coquet/Rothbury | R Tees/Broken Scar to Low Moor | Northumbrian |
| 12 | 12 | 7 | TOTAL NUMBER |

ten are conventional two stage channels, and two are sites which are bypassed during floods, but the bypass flows have been measured.

Of the ten two stage channel sites, seven have only 5% or less of the total flow on the floodplain during the largest recorded flood. There are only three sites where the flood plain flow exceeds 5% during the largest recorded flood and therefore the amount of available field data for use in the assessment of methods for estimating overbank flow is very limited. The data for the ten sites is summarised in Table 2.

A limited amount of further data is known to exist from other research studies, including the River Roding (University of Bristol, 1988) and the River Main in Northern Ireland. Data is not available from these sites for this study, but one observation from the results is the considerable variations in section and roughness which occur along the channel and floodplain in the direction of flow. Methods of analysis described in Section 4 are all based on a single channel cross section.

## 3.3 Sites where overbank flow has been measured

Details of sites where overbank flow has been successfully measured are contained in Appendix 1, together with stage discharge graphs which illustrate the data available. In addition to the twelve sites listed in Table 3.1, an additional three sites (River Stour at Hammoon, River Trent at Yoxall and River Severn at Haw Bridge) are also included. These fifteen sites are briefly described in this section. The expression 'data available' in this report refers to data which has been given to HRL by the Water Authorities.

TABLE 2 : Overbank flow data

| Site | Total width / Bank top width | Discharge ($m^3/s$) Bankfull | Maximum (1) | Flow on floodplain (%) | Remarks |
|---|---|---|---|---|---|
| Culm/Wood Mill | 3.8 | 44 | 99 | 40 | |
| Severn/Montford | 3.4 | 184 | 331 | 20 | |
| Blackwater/Ower | 4.5 | 9.9 | 12 | 8 | |
| Torridge/ Torrington | 1.9 | 187 | 314 | 2 | |
| Ouse/Skelton | 1.2 | 250 | 437(700) | < 1 | Narrow berms. Banks overtopped in large floods |
| Trent/N Muskham | 1.4 | 392 | 488(858) | 4 | Single berm. Flow beyond cableway in large floods |
| Penk/Penkridge | 2.6 | 17 | 33 | 4 | |
| Tees/Low Moor | 1.9 | 268 | 401 | < 1 } | Low flow measurement weirs with cableways upstream |
| Wansbeck/Mitford | 1.9 | 31 | 145 | 5 } | |
| South Tyne/ Haydon Bridge | 1.3 | 88 | 496 | 2 } | |

NOTES:

1. Figures given are maximum recorded contained floods
   Figures in brackets are maximum recorded floods
2. Sites where bypass flows have been measured : Teign/Preston
   Mole/Kinnersley Manor

River Mole at Kinnersley Manor (Surrey)

This is a road bridge site where flow under and over the road is measured. Flood flows bypass the main channel, and it is therefore not a two stage channel site.

River Blackwater at Ower (Hampshire)

The Crump weir at this site is drowned at high flows. The floodplain appears to narrow towards a road bridge downstream. Only four overbank flows have been measured, but the data is good and includes current metering results.

River Culm at Wood Mill (Devon)

There is a low flow weir at this site and an approximately 100m wide floodplain on the left bank. The whole section is current metered. The data set is generally good, the only doubt being the possible backwater effect of a bridge downstream. A plot of the variation of Manning's 'n' with stage showed that 'n' did not fall with stage, as would normally be expected.

River Torridge at Torrington (Devon)

This is a natural section with a flood plain on the left bank. All measured floods are contained by a flood bank 30m from the river bank, but larger floods overtop this embankment. The cableway spans the river and flood plain to the embankment.

River Teign at Preston (Devon)

This is a natural current metered section. During floods, part of the discharge bypasses the gauging station, forming a separate channel on the right bank flood plain. It is therefore not a two stage channel section, but the bypass flows have been measured.

River Severn at Montford (Shropshire)

This is a natural section with a cableway extending over the main channel and both flood plains. A large amount of data is available, and this site has already been used by others to assess compound channel flow estimation methods. Actual current metering data is available.

River Penk at Penkridge (Staffordshire)

This is a two stage channel where the whole section is current metered. There is a bridge 35m downstream of the gauging site. Actual current metering data is available.

River Trent at North Muskham (Nottinghamshire)

This is a natural section with a cableway which spans the main channel and a 28m wide berm. During large floods some flow bypasses the cableway on the extensive right bank flood plain, and is not measured. The rating curve shows that the berm has little effect on the slope of the rating curve, but there is a distinct change in slope above flood bank top level, where the average flow velocity shows a marked increase. Actual current metering data is available. A physical model constructed by HRL has been used to rate one extreme flow at this site, and it was found that the measured flow was about 75% of the total flow which includes flow on the floodplain.

River Ouse at Skelton (Yorkshire)

This is a natural section with narrow berms between the channel and flood banks. The cableway spans between the flood banks, which are overtopped during large floods. Very little flow occurs on the berms, most of the flow being contained in the large main channel. The average flow velocity, however, shows a marked increase above bankfull level. Actual current metering data is available.

Rivers Wanbeck at Mitford, South Tyne at Haydon Bridge and Tees at Low Moor (Northumberland/Durham)

These three Northumbrian Water gauging stations all consist of a cableway upstream of a low flow measuring structure. All three sites have narrow berms where flood flow occurs. Only part of the floodplain flow is measured at Mitford and Low Moor, although supplementary current metering has been carried out at Low Moor, and current metering data is available.

River Stour at Hammoon (Dorset)

This compound Crump weir site appears to have a good overbank rating curve, but inspection of the structure drawings indicates that a road bridge across the weir would be overtopped during floods. It was considered that the blockage caused by the road bridge would affect the rating, and the site was not used for overbank flow estimation. It may still be useful as an experimental or flood routing site.

River Trent at Yoxall (Staffordshire)

This is a natural section with a cableway across the main channel. The site is bypassed but bypass flows are measured where they pass under Yoxall bridge. There are four overbank gauged points, of which two were recorded before and two after the construction of a training bank. This site was not used because it is not a two stage channel, and the number of gauged overbank flows is small.

River Severn at Haw bridge (Gloucestershire)

This is a road bridge site which has been considered because a reasonable number of overbank flows have been gauged. It may also prove to be a suitable experimental site, with a wide flood plain compared to the channel width. However, little data has been obtained for this site, and further data will be requested from STWA.

# 4 ANALYTICAL METHODS OF ESTIMATING FLOOD DISCHARGE

## 4.1 Introduction

The main hydraulic problem associated with the assessment of flood discharge is the estimation of discharge for sites where overbank flow occurs. A number of different methods of estimating discharge have been applied to sites where overbank flow has been measured, and compared with observed results.

The stage discharge curves have also been briefly studied in order to try to identify any obvious correlations between curve parameters and site geometry. Actual current metering data has been used to identify the actual distribution of flow for several two stage channel sections where data is available. Reference is also made in this section to methods of estimating bridge and culvert rating curves. No attempt has yet been made to construct a computational model of a gauging site, and it is recommended that this should be carried out.

## 4.2 Stage discharge curves

The stage discharge curves for the fifteen sites referred to in Section 3.3 are contained in Appendix 1. An example is given on Figure 1, which illustrates the typical form of these curves.

The stage discharge data was plotted on log-log paper in order to identify constants in the equation

$$Q = a(h + c)^b$$

where Q = discharge

h = stage

a, b, c are coefficients

The results are shown in Appendix 2, and an example is shown on Figure 2. It was possible to produce straight line fits in most cases, and the constants a, b, and c for in-bank and overbank flow are tabulated in Table 3. There is no obvious correlation between constants either for in-bank or overbank flows, although a full regression analysis has not been carried out.

All plotting and curve fitting of stage discharge data was carried out using the Institute of Hydrology data analysis package HYDATA.

Correlation of flow characteristics with channel geometry is currently being carried out for in-bank flow by G Wharton under a CASE award research project by the Institute of Hydrology. An equation of the above form has been proposed where the coefficients were presented as functions of channel geometry and roughness (Knight et al, 1984), and it may be possible to refine this equation using the available field data.

It is not, however, proposed to pursue this approach further under this research project, as other methods appear more likely to lead to a useful result. The stage discharge curves do, however, illustrate the form of curve which occurs in two stage channels, as observed in laboratory experiments, and includes the following features:

(a) Significant change of slope at bankfull level on the log-log plot

**Table 3 : Rating equation coefficients for gauging sites**

| GAUGING STATION SITE | BANKFULL DISCHARGE | $Q = a(h + c)^b$ | | | | | |
|---|---|---|---|---|---|---|---|
| | | ABOVE BANKFULL | | | BELOW BANKFULL | | |
| | | a | b | c | a | b | c |
| Mole - Kinnersley | 17.8 | 4.52 | 2.145 | -0.060 | 8.74 | 1.088 | -0.028 |
| Blackwater - Ower | 9.9 | 9.47 | 1.300 | -0.78 | 4.79 | 1.300 | -0.065 |
| Culm - Wood Mill | 44 | 6.14 | 2.796 | -0.089 | 17.03 | 1.466 | -0.060 |
| Torridge - Torrington | 187 | 128.82 | 1.040 | -1.981 | 30.45 | 1.735 | -0.401 |
| Teign - Preston | 80 | 134.26 | 1.300 | -1.918 | 22.51 | 1.300 | -0.075 |
| Severn - Montford | 184 | 89.51 | 1.032 | -2.722 | 13.75 | 1.643 | 0.538 |
| Penk - Penkridge | 16.8 | 21.48 | 1.300 | -0.74 | 6.44 | 1.755 | 0.127 |
| Trent - N. Muskham | 392 | 80.21 | 2.584 | -1.350 | 236.84 | 0.718 | -0.600 |
| Ouse - Skelton | 250 | 126.14 | 0.996 | -0.244 | 63.04 | 0.997 | -0.315 |
| Wansbeck - Mitford | 30.9 | 7.85 | 3.500 | -0.041 | 139.06 | 0.500 | -1.646 |
| South Tyne - Haydon Bridge | 88 | 56.50 | 1.897 | 0 | 85.521 | 1.261 | -0.245 |
| Tees - Low Moor | 268 | 103.87 | 1.300 | -2.568 | 40.14 | 1.300 | 0.035 |
| Stour - Hammoon | 71 | 160.45 | 1.300 | -2.070 | 21.15 | 1.300 | 0.100 |
| Severn - Haw Bridge | 413 | 204.69 | 1.060 | -2.628 | 78.24 | 1.150 | -0.150 |

(b) Discontinuity at bankfull level between in-bank and overbank sections of curve on the log-log plot, an example of which is shown on Figure 3.

### 4.3 Methods of predicting stage discharge curves

A considerable amount of research has been undertaken into compound channel flow, and several methods have been proposed by researchers for estimating the discharge. These methods include the following:

1. Single channel method

   Apply open channel flow formulae to the whole channel using a single roughness coefficient.

2. Division line methods

   Divide the compound cross section into sections and apply open channel flow formulae to each section. In some cases the division line is included in the main channel wetted perimeter, and division lines which have been proposed include the following. All division lines pass through the point where the top of the main channel side slope and the flood plain intersect:

   (a) Vertical

   (b) Vertical, but including division line in main channel wetted perimeter.

   (c) Diagonal to centre of channel

   (d) As (c), but including division line in main channel wetted perimeter.

(e) Diagonal, with a variable angle of the interface.

(f) As (e), but including division line in main channel wetted perimeter.

(g) Horizontal.

(h) Horizontal, but including division line in main channel wetted perimeter.

The division lines are illustrated in Figure 4. (For example, Wormleaton et al, 1982).

3. Apparent shear

Divide the compound cross section into main channel and flood plain sections using vertical division lines at the boundaries. The interaction between the fast moving main channel flow and the slow moving floodplain flow is represented by an apparent shear force which reduces the main channel flow velocity and increases the flood plain for velocity. (For example, Prinos and Townsend, 1984).

4. Correction factors

Divide the compound cross section into main channel and flood plain sections using vertical division lines at the boundaries. Apply open channel flow formulae to each section but apply empirical correction factors to the formulae to take into account the interaction between the flows. (For example, Karasev, 1969).

5. Lateral velocity distribution

   Estimate the lateral depth averaged velocity distribution across the section from considerations of lateral shear. Integrate the velocity across the section to give discharge (For example, Samuels 1988 and Wormleaton 1988).

Method 1 is very simple but inaccurate and underestimates the discharge. Methods 2, 3 and 4 are empirical methods which are relatively easy to apply by hand. Methods 3 and 4 both depend on the selection of suitable site specific values for variables. Method 2 depends on selecting the most suitable division lines. All methods rely on accurate estimation of roughness coefficients, as discussed in Section 4.8.

Method 5 is based on an appreciation of the actual hydraulics of the flow, and is therefore more likely to produce reasonable results when applied to a new site. Considerable research is in progress on this type of method, including work by researchers using the SERC flood channel facility at Hydraulics Research Ltd. The method involves solving non-linear equations, which can only be carried out in practice by a computer, and is therefore more difficult to apply than the other methods.

One objective of the research programme is to recommend methods for estimating flood discharge, based on available methods. Method 5 is considered to be the best method but can only be carried out using computer programs, and method 2 is considered to be the best of the simple methods. Method 5 has been applied to two sites, and division line methods 2(a), (b), (c), and (g) have been applied to the ten compound channel sites where overbank flow data is available, as listed in Table 2. The single channel method has also been applied at these sites.

## 4.4 Data preparation

An example of the division line calculation method as used to estimate stage discharge relationships for each site is given in Appendix 3. It was decided to use the Manning open channel flow formula for the division line method as this is most familiar to river engineers, although some work was done using the Colebrook-White roughness length $k_s$ for comparison purposes.

Use of the Manning equation involves calculation of a number of parameters. The methods used to calculate these parameters were chosen so that they may be applied easily at other sites using readily available information. Geometric properties of the channel and flood plain, including cross sectional area, wetted perimeter and hydraulic radius, were calculated from single river cross sections at the gauging site. The water surface slope was assumed to be equal to the ground slope, and was abstracted for Ordnance Survey 1:25,000 maps. The slope was calculated as the vertical difference between two contours divided by the river length between the contours. The flood plain slope was similarly calculated, but using valley length instead of river length.

The assessment of Manning's 'n' is difficult and subjective. Its value was calculated for several (usually three or four) in-bank flow stages using values of stage and discharge from the rating curve. It was therefore possible to observe the variation of 'n' with stage. Generally 'n' decreases with stage and this was evident at six of the ten sites. 'n' remained approximately constant with stage at three of the sites, all of which were within the backwater length of a weir or bridge, and rose with stage on the Tees at Low Moor, where the gauging station is just upstream of a low flow weir. Plots of the variation of 'n' with stage are shown on Figure 5.

It was decided to use the bankfull value of Manning's 'n' ('$n_b$') as the roughness parameter for the main channel when assessing overbank flow, as it is relatively easy to obtain and represents a fixed point on 'n' against stage curve. Where gauging data above bankfull level exists, it may be obtained by applying the Manning equation to the bankfull discharge and cross section. When gauging data for in-bank flows only exists, it may be obtained by calculating 'n' at different stages and extrapolating the 'n' against stage curve to bankfull level. Assessing of '$n_b$' at sites where no gauging data exists is discussed in Section 4.8.

The calculated values of '$n_b$' are shown on Table 4 for the ten sites plus the Teign at Preston, together with some information on the variation of 'n' with stage. Estimates of '$n_b$' are also included in the table to indicate the magnitude of error which may occur when using estimated values rather than values based on gauged flows. The estimates of '$n_b$' are typical estimates frequently made by engineers, based on all available descriptive data for the site and the method presented by Chow (Chow 1959, p 106).

Values of '$n_b$' were considered to be high at the three Northumbrian Water sites, all of which are immediately upstream of low flow weirs. This possibly reflects the backwater effect of the structure where the slope is locally less than the valley slope used in the analysis. Also, the flow depth, and therefore the cross sectional area and hydraulic radius, is raised above the normal flow depth which would occur if no structure were present.

Values of 'n' for the floodplain ('$n_f$') were estimated, based on the very limited available data on

Table 4 : Roughness coefficients for in-bank flow

| Gauging Station | River | Bankfull discharge ($m^3/s$) | Manning's 'n' Bankfull ('$n_b$') | Manning's 'n' Calculated value for lowest stage (1) | Manning's 'n' Trend with stage | Manning's 'n' Estimated bankfull (2) ('$n_{be}$') | $\frac{n_{be}}{n_b}$ |
|---|---|---|---|---|---|---|---|
| Ower | Blackwater | 10 | 0.039 | 0.04 (13) | Constant | 0.048 | 1.23 |
| Wood Mill | Culm | 44 | 0.042 | 0.038 (14) | Rises slightly | 0.040 | 0.95 |
| Torrington | Torridge | 187 | 0.028 | 0.044 (7) | Falls | 0.033 | 1.18 |
| Preston | Teign | 80 | 0.060 | 0.133 (10) | Falls | 0.040 | 0.67 |
| Montford | Severn | 184 | 0.028 | 0.069 (12) | Falls | 0.030 | 1.07 |
| Penkridge | Penk | 17 | 0.046 | 0.046 (13) | Constant | 0.045 | 0.98 |
| N. Muskham | Trent | 392 | 0.036 | 0.110 (15) | Falls | 0.028 | 0.78 |
| Skelton | Ouse | 250 | 0.046 | 0.100 (17) | Falls | 0.030 | 0.65 |
| Mitford | Wansbeck | 31 | 0.107 | 1.02 (3) | Falls | 0.045 | 0.42 |
| | | | 0.047(3) | 0.081 (22) | Falls | | |
| Haydon Bridge | South Tyne | 88 | 0.057 | 0.099 (17) | Falls | 0.042 | 0.74 |
| | | | 0.034(3) | 0.024 (17) | Rises | | |
| Low Moor | Tees | 268 | 0.048 | 0.031 (22) | Rises | 0.032 | 0.67 |

Notes: 1. Figures in brackets are percentage of bankfull discharge for calculated value of 'n'
2. Chow, 1959, p 106
3. With weir crest as artificial bed level

this subject. The problems of estimating '$n_f$' are discussed further in section 4.8. For most of the sites studied, '$n_f$' was not a critical parameter because of the small proportion of total discharge on the floodplain. The only two sites where '$n_f$' had a major affect on discharge estimation were the Severn at Montford and the Culm at Wood Mill. At these sites, attempts were made to estimate '$n_f$' by subtracting the main channel flow from the total discharge by dividing the flow using division line methods, and applying Manning's formula to the floodplain. Results of the order of 0.10 and 0.04 were obtained for the Culm and Severn respectively, although there was some variation depending on the method used to estimate the main channel discharge. '$n_f$' was also estimated from current metering results at five sites, as discussed in Section 4.7

One practical problem was assessing the bankfull value of discharge and stage. This was generally selected from cross section data, but is is apparent that there are local dips in the bank level which may produce an erroneous result. For example, the left bank of the Severn at Montford is 0.6m lower than the right bank at the gauging site. Inspection of the stage discharge curve shows that the change in slope occurs at the higher level, and it may therefore be assumed that the higher level is the correct bankfull level. This is illustrated on the stage discharge curve for the Severn at Montford given in Appendix 1. In general, the selected value of bankfull level should be the general bankfull level of the gauging reach, and this is the level normally used by the Water Authorities.

## 4.5 Data analysis

Discharge was estimated for overbank flows at several stages using division line methods 2(a), (b), (c) and (g), on Figure 4, and the single channel method. The lateral velocity distribution method was also applied to the Severn at Montford and the Culm at Wood Mill.

## Division line and single channel methods

The results are presented in the form of graphs of the ratio of predicted over observed discharge against $y_r$ (the ratio of depth above bankfull level to bankfull depth of main channel). Observed data was taken from the rating curves shown in Appendix 2, and not individual observations. This procedure averages out measurement errors and changes in vegetation, etc. Parameters used in the calculations are given in Table 5. The results are shown in Figures 6 to 10 for methods 2(a), (b), (c), (g) and the single channel method respectively.

Most of the predictions lie in the range ± 10% for methods 2(a), 2(b) and 2(c), but methods 2(g) and the single channel method both underpredict discharge. There was little to choose between the best three methods, and the accuracy of predictions depended on the accuracy of estimating parameters, particularly '$n_b$' and '$n_f$'. The results for the Culm at Wood Mill, where a large proportion of the flow is on the flood plain, was relatively insensitive to the interaction zone between main channel and floodplain flow, but was very sensitive to '$n_f$'. Figure 11 shows the predicted stage discharge curves using the five methods for the Culm, with a value of '$n_f$' of 0.100. The Severn at Montford, whilst still a good two stage channel site, was more sensitive to the method used, and the predicted stage discharge curves are shown on Figure 12.

The calculations produced some interesting conclusions about the selection of gauging sites for overbank flow measurement. The question of flood plain roughness

Table 5 : Roughness parameters and stages used to estimate discharge using division line and single channel methods

| Site | '$n_b$' | '$n_f$' | Backfull stage | Stage used for caculation | |
|---|---|---|---|---|---|
| | | | | Stage | $y_r$ |
| Blackwater at Ower | 0.039 | 0.060 | 1.8 | 1.875 | 0.036 |
| | | | | 1.925 | 0.064 |
| | | | | 1.987 | 0.098 |
| Culm at Wood Mill | 0.042 | 0.100 | 2.09 | 2.43 | 0.163 |
| | | | | 2.58 | 0.235 |
| | | | | 2.73 | 0.304 |
| Torridge at Torrington | 0.028 | 0.060 | 3.2 | 3.5 | 0.107 |
| | | | | 3.8 | 0.214 |
| | | | | 4.1 | 0.321 |
| Severn at Montford | 0.028 | 0.040 | 4.6 | 5.2 | 0.079 |
| | | | | 5.7 | 0.159 |
| | | | | 6.1 | 0.222 |
| Penk at Penkridge | 0.046 | 0.060 | 1.6 | 1.74 | 0.082 |
| | | | | 1.84 | 0.141 |
| | | | | 1.94 | 0.200 |
| Trent at N. Muskham | 0.036 | 0.060 | 2.62 | 3.00 | 0.069 |
| | | | | 3.34 | 0.131 |
| Ouse at Skelton | 0.046 | 0.060 | 4.3 | 5.0 | 0.067 |
| | | | | 5.5 | 0.115 |
| South Tyne at Haydon Bridge | 0.057 | 0.060 | 1.27 | 1.9 | 0.42 |
| | | | | 2.5 | 0.82 |
| | | | | 3.13 | 1.24 |
| Tees at Low Moor | 0.048 | 0.060 | 4.27 | 4.88 | 0.145 |
| | | | | 5.49 | 0.290 |
| | | | | 6.39 | 0.505 |

estimation is discussed further in Section 4.8, but some other points are also of interest, as follows.

Some of the sites have very small flood plains and are probably best treated as single channels. However, the use of the single channel method with '$n_b$' as the roughness parameter produced underpredictions in most cases because 'n' continued to fall with stage above bankfull level. This is particularly apparent in the case of the Trent at North Muskham, where the slope of the stage discharge curve did not change at bank top level.

The Trent at North Muskham and the Ouse at Skelton have relatively narrow berms and then an embankment. The flow is gauged across the main channel and berms but at high flood flows when the water level is above embankment level, flow occurs on the flood plain outside the cableway. It was therefore only considered reasonable to use data between bankfull level and embankment top level. It was interesting to note, however, that discharge increased rapidly with stage above bankfull level at Skelton, and embankment top level at North Muskham. The mean velocity increased at shown on the table below.

| Site: | Ouse at Skelton | Trent at N. Muskham |
|---|---|---|
| Bankfull/embankment top stage (m) | 4.30 | 3.34 |
| Max. recorded stage (m) | 5.39 | 3.86 |
| Mean velocity (m/s): | | |
| bankfull/embankment top | 0.80 | 1.23 |
| max. recorded stage | 1.15 | 1.91 |

This rapid rise in velocity may reflect a change in resistance or a change in water surface slope. Both sites are upstream of controls at the tidal limit of major rivers, and the assumption that the water surface slope is the same at all stages may not be valid at these sites.

The three Northumbrian Water sites are all upstream of low flow weirs. The weir on the Tees at Low Moor has a relatively small blockage area compared with the total cross sectional area of the river, and the division line methods gave reasonable predictions of overbank discharges. However, the blockage was considerable for the other two sites. Backing up upstream of the weirs undoubtedly produced unreasonably high values of '$n_b$' as discussed in Section 4.4, and the predictions of overbank discharge for the Wansbeck at Mitford were of the order of 50% of the observed discharges. Predictions for the South Tyne are also low, as shown in the results. Using weir crest level instead of bed level for the cross sectional geometry produced good predictions for the South Tyne but still under predicted for the Wansbeck. Clearly sites which are affected by structures downstream may not be suitable for applying the estimation methods described in this section.

Lateral velocity distribution

The lateral velocity distribution method was applied to the Culm at Wood Mill and the Severn at Montford. The theory of the method may be found elsewhere (for example, Samuels, 1988), but it essentially involves predicting the depth averaged distribution of velocity across the main channel and flood plain section. The main variables in the method are roughness parameters and a lateral shear parameter. The roughness parameters were estimated from field data. The lateral shear parameter was estimated from observations taken on the SERC flood channel facility at Wallingford, some details of which are given in Appendix 4.

The results are summarised in Figures 13 to 17. Good predicted were obtained for the Severn at Montford using the lateral shear parameter which also gives the best fit to results obtained on the SERC flood channel facility. A somewhat higher value of lateral shear parameter was required to obtain a good fit for the Culm at Woodmill, as the value used at Montford would overpredict by about 10 - 15%. One possible reason for this overprediction is the use of a value of '$n_f$' of 0.04 for Wood Mill, which is low and much less than the value of 0.10 used for the division line method. It may also reflect the effect of meanders in the main channel upstream. Two channel geoemtries were used for the Culm, one including the full floodplain width and the other only including the floodplain as far as the bund, 64m from the river.

The lateral velocity distribution method is based on data obtained from straight channel tests. In practice, very few sites are on straight channels but many are on reasonably straight or only slightly curved reaches where the flow patterns are likely to be similar to those observed on the SERC flood channel facility.

The lateral velocity distribution model used in the study is being developed by J Wark under a CASE award studentship, under the supervision of Dr D A Ervine (University of Glasgow) and Dr P G Samuels (Hydraulics Research Limited). The work is incomplete, and further refinement of the model is in progress. The results obtained to date, however, are encouraging and promise to provide improved methods of predictions of overbank flow in the future.

## 4.6 Summary of results

The above analyses indicate that division line methods 2(b) and 2(c) give reasonable predictions of overbank flow if reasonable estimates can be made of roughness parameters. These methods have no theoretical basis, however, and in the long term it is expected that the lateral velocity distribution method will provide a more accurate method for estimating overbank discharge.

The lateral velocity distribution method gave good predictions for stage-discharge curves at the two sites investigated. Because the method attempts to reproduce the distribution of velocity across the channel, it gives a much better representation of what is physically happening.

The methods used to predict overbank flow have been applied to sites where the flood plain flow is parallel or almost parallel to the main channel flow as shown on Figure 18(a). They are not suitable for a site where the flow pattern is of the type shown on Figure 18(c) and should be used only with caution where the flow pattern is of the type shown on Figure 18(b). Generally the methods assume that there is no significant curvature in the flow. At present no method exists for estimating overbank flow where the main channel is meandering within a flood plain as shown on Figure 18(c).

## 4.7 Current metering data

Although not specifically requested, Water Authorities provided actual current metering data for the following sites:

River Blackwater at Ower
River Severn at Montford
River Penk at Penkridge
River Trent at North Muskham
River Ouse at Skelton
River Tees at Low Moor

This provided information on the actual distribution of discharge between the main channel and flood plains. By dividing the main channel and flood plains by vertical division lines at the boundaries (method 2(a) on Figure 4) it was possible to estimate '$n_f$' for the flood plains, and also 'n' for the main channel at a stage above bankfull. The results are summarised in Table 6. It may be seen that values of '$n_f$' in the range 0.024 to 0.190 were obtained.

### 4.8 Estimation of overbank discharge

A number of methods have been described for estimating overbank flows. When considering the estimation of overbank discharge at a site where gauged data is limited or unavailable, a number of problems arise, which are discussed in this section.

Estimation of '$n_b$' is difficult. The well known guidelines presented by Chow (Chow, 1959, p 108 et seq) refer to normal flow depths. Research work in N. Ireland has provided a relationship between '$n_b$' and '$Q_b$' for rivers in Northern Ireland (Higginson and Johnston, 1988). This is reproduced on Figure 19, together with values of $n_b$ obtained from this study added. Where no data exists, guidelines of this sort must be used. It is also desirable to obtain values of '$n_b$' from other UK gauging stations, including variations of '$n_b$' with season.

The estimation of roughness of flood plain ('$n_f$') including natural channels formed by depressions in a

Table 6 : Roughness coefficients for overbank flow based on measured discharges

| GAUGING STATION | Q bankfull ($m^3/s$) | $n_b$ | Gauged discharge ($m^3/s$) | | | | Stage (m) | | Manning's 'n' | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Q Total | Q Main channel | Q Flood plains | | bankfull | gauging | Main channel | '$n_f$' | |
| | | | | | left | right | | | | left | right |
| Tees - Low Moor | 268 | 0.048 | 401 | 400 | - | 1.4 | 4.27 | 5.70 | 0.064 | - | 0.190 |
| Blackwater - Ower | 9.9 | 0.039 | 12.01 | 11.05 | 0.11 | 0.85 | 1.81 | 2.00 | 0.045 | 0.094 | 0.099 |
| Severn - Montford | 184 | 0.028 | 327 | 261 | 55 | 11 | 4.6 | 6.04 | 0.032 | 0.027 | 0.042 |
| | 184 | 0.028 | 210 | 201 | 8.5 | 0.9 | 4.6 | 5.10 | 0.029 | 0.024 | 0.047 |
| Penk - Penkridge | 16.8 | 0.046 | 32.8 | 31.4 | 0.55 | 0.80 | 1.6 | 1.94 | 0.037 | 0.137 | 0.061 |
| Trent - N. Muskham | 392 | 0.0365 | 483 | 474 | - | 9.0 | 2.62 | 3.17 | 0.0366 | - | 0.031 |
| Ouse - Skelton | 250 | 0.046 | 437 | 437 | - | - | 4.30 | 5.37 | 0.031 | - | - |

flood plain is difficult because of the mixture of roughness components which may occur. These include walls, fences, gates, hedges, tracks, trees, bushes, other vegetation, buildings, etc. The flood plain also changes in section and character in the direction of flow.

One method for estimating Manning's 'n' for different components of a complex flood plain requires the total discharge, channel geometry and slope to be known (Bruk and Volf, 1967). The flow resistance of grass cover has been studied and a method is available for calculating Manning's 'n' for grasses of different length (USDA, 1954). The most suitable available approach to analysing complex flood plains is that based on the method of Petryk and Bosmajian (1975) but application of the method is difficult. Individual components of flood plain roughness have been studied by various researchers (eg. hedges and orchards, Klaassen and Van Der Zwaard, 1974; grass in flood channel, Klaassen and Van Urk, 1985).

It is concluded that at present no satisfactory method estimating the roughness of flood plains exist except for sites with uniform grass cover.

The values of '$n_f$' given in Table 6 indicate the wide range of values which may occur, from fairly low values comparable with main channel roughness for smooth pasture to much higher values for complex flood plains with uneven ground, trees and bushes.

In order to obtain estimates of flood discharge using the methods discussed in this section, the following criteria are suggested for gauging sites:

(a) The site should be on a straight reach of channel sufficiently far from bends to prevent curvature of the flow affecting the hydraulics of the site.

(b) In view of the problems estimating '$n_f$', the site should either avoid complex flood plains with complex roughness or have a limited proportion of the total flow on the floodplain (eg. less than 10%).

(c) Sites should not be near weirs or other structures which cause significant backing up at high river stages.

Where wide flood plains are unavoidable, such as in parts of East Anglia, there may be no alternative except to use flood plain flow measurement devices, as discussed in the Section 5. In some cases it may be possible to identify features of the flood plain including flow paths and areas of the flood plain which are inactive, in order to estimate the flood plain conveyance and therefore the discharge.

## 4.9 Bypassed sites

No analysis has been carried out for the two sites where bypass flow has been gauged. The hydraulic problem is slightly different to the two stage channel problem in that there is no interaction between main channel and flood plain flow. The best documented bypassed site is the River Teign at Preston. Good rating data exists for the main channel and the problem of flood discharge estimation reduces to estimating the flow across an expansive area of flood plain consisting mainly of pasture with occasional fences and trees. This problem may be approached by estimating the conveyance and roughness of the flood plain by detailed topographical survey and treating the flood plain as a single channel. The main problems with this approach are as discussed in Section 4.8, namely understanding the behaviour of the flow on the flood plain and estimating suitable values for roughness coefficients. The alternative would be to install purpose built measurement equipment of the type considered in Section 5.

## 4.10 Bridges and culverts

An important aspect of flood discharge assessment is the estimation of discharge through bridges and culverts. There may be sites where flood flows are contained by bridges and culverts in, for example, an embankment across a flood plain, and discharge may be estimated from water levels and rating curves for the structures. Whilst no specific work is included in this study for flow through culverts and bridges, attention is drawn to the following references which may be used to estimate rating curves for individual structures.

Bridges: USBPR (1970). This is a general method for all bridge types.

Arch bridges: Brown (1988). Recommended for arch bridges.

Culverts: Carter (1957). Methods of calculation for six different classifications of culvert flow, ranging from drowned to free flow.

## 4.11 Further work

It is not proposed to carry out any further work on analysis of existing data under the project apart from the application of computational models to gauging sites. The analysis to date has indicated the methods available for assessing flood discharge, and the problems involved. The bulk of future work will be concerned with development of field monitoring equipment and methods, as described in Section 5.

## Modelling of gauging sites

Computational modelling has developed sufficiently to enable unsteady one dimensional flow models to be applied to rivers with ease and at relatively low cost. Advantages of such models over the analyses described above are that they model variations of channel and flood plain shape along a river and can include structures and associated backwater effects. It is also much easier to include, for example, variable roughness across the channel and/or flood plain than with simple hand calculation methods. The main disadvantages where compound channel flow is concerned is that they do not model the effects of interaction between main channel and flood plain flow.

It is proposed to modify a one dimensional computational model by incorporating velocity profiles calculated using the lateral velocity distribution method, which has already been applied to single river and flood plain cross sections. Whilst not being a fully two-dimensional model, it would be a significant improvement on the one dimensional model where considerable simplifications are made when modelling two stage channel flow. It would also be an improvement on the lateral velocity distribution method, as it would permit changes in geometry parallel to the direction of flow and would allow the inclusion of structures and their associated effects on the flow.

If such a model is developed successfully, it would be applied initially to two sites, which would probably be the sites where the lateral velocity distribution method has already been applied (i.e the Severn at Montford and the Culm at Wood Mill).

The next stage in development of computational modelling of gauging sites would be to produce a two dimensional model which would allow flow in two dimensions in plan (i.e in the directions along the channel and across the channel). A depth averaged mean velocity would still be used and there would be no flow in the vertical direction. Some work has already been done on such a model under previous MAFF sponsored research (Samuels, 1985). It is not, however, proposed to further develop the model under this project during 1989/90.

# 5 EXPERIMENTAL WORK

## 5.1 Introduction

Experimental work is to be carried out both in the field and in the laboratory to investigate site specific measures to improve flood flow estimation, in co-operation with the Water Authorities. Sites are to be selected where overbank flow occurs which are close to well rated sections. Different methods of estimating flood discharge will be used at the experimental sites, and the discharge recorded at the rated section would be used as an overall check of the total discharge at the experimental site.

The procedure for carrying out experimental work is as follows

(a) Identify methods of estimating flood discharge

(b) If new measuring equipment is proposed, carry out laboratory trials prior to installation in the field

(c) Select suitable sites

(d) Carry out field trials

These four stages are discussed in the following Sections 5.2 - 5.5. Experimental work on bridges and rating curves is discussed in Section 5.6.

## 5.2 Experimental methods

A number of experimental methods are discussed in this section, and the next stage in the study must be to consider the practicality of these methods in further detail.

One consideration which became apparent from studying gauged field data is the importance of estimating discharge both in the main channel and on the flood plain. The use of a bankfull main channel roughness coefficient '$n_b$' may lead to considerable error when estimating main channel discharge above bankfull level. It may be shown that the average difference between '$n_b$' and the main channel roughness coefficient shown on Table 6 for overbank flow is about 20% for the six sites where current metering data is available.

<u>Slope area method</u>

The slope area method involves the measurement of the water surface slope between two points in a river. The discharge is calculated using, for example, the Manning equation, although it is necessary to estimate roughness coefficients.

Using this method to measure flood discharges would require the installation of two maximum water level gauges of the type shown in Figure 20. The slope would be calculated from the maximum levels recorded at each gauge. It would also be necessary to survey a river and flood plain cross section.

If this method is applied to a new site it is advisable to calibrate the site by current metering in order to obtain a roughness coefficient for the main channel, although the variation of roughness with stage must also be taken into account. It would still be necessary to estimate the flood plain roughness when estimating flood discharges.

The data obtained using the method would be as follows

(a) water surface slope (S)

(b) channel geometry, from which flow area (A), and hydraulic radius (R) could be calculated

(c) roughness coefficient for main channel based on calibration flow measurements

This data may be used to obtain discharge (Q) using, for example, the Manning equation

$$Q = \frac{A R^{2/3} S^{1/2}}{n}$$

where 'n' is the Manning's roughness coefficient. A method of applying the flow formula to compound cross sections would still be required, and it would be necessary to consider such methods as the division line method, or the lateral velocity distribution method.

A further difficulty of this method is that it would not identify which parts of the floodplain are "active" (i.e where water is flowing), and which parts are "passive" (i.e where water is not flowing).

The slope area method would be improved in conjunction with computational modelling, because it would be possible to incorporate more geometrical data than a single cross section. A computational model could include as many cross sections as necessary to reproduce the geometry of the site. However, the accuracy of the slope area method using a computational model would still depend on the accuracy of the representation of flow used by the model.

Physical effects of flow to estimate velocity

If it was possible to estimate the maximum velocity of flow at locations across the main channel and floodplain, it would then be possible to estimate the maximum discharge by the velocity area method in conjunction with a cross section survey and maximum water levels. Maximum water levels could be recorded using maximum water level gauges, and it may be possible to use a device which uses the physical effects of flow to estimate velocity. Such a device would have to be constructed and calibrated in a laboratory, and some possibilities are as follows

(a) The movement of a plate about an axis, as shown on Figure 21. In this case, the plate is set inside a post mounted on the flood plain or in the channel

(b) A pitot tube device in which the velocity is estimated from the difference between static pressure and pressure in the moving fluid. It may, however, be difficult to develop a device which is sufficiently sensitive and robust

(c) Scour around the base of a post set in a sand bed. It would be necessary to install a vertical chain in the bed which would collapse as the hole was scoured. This would identify the maximum depth of scour, as the hole may fill up again as the velocity drops. This type of device has been considered before at HRL, but was thought to be a rather insensitive method of measuring velocity

(d) Other ideas include tension in a wire attached to a float, and force on a deformable object.

All these ideas would require protection against damage by trash and vandalism. Any device in a river channel must not form a hazard to navigation.

## Float tracking

A laboratory technique for observing flow direction and estimating velocity is float tracking. Floating objects placed in the flow are photographed using a timed exposure, and the length of the trace of the object on the photograph would be a measure of the local velocity of flow. This could be used in conjunction with water level gauges (preferably continuously recording) and geometric data to estimate discharge by the velocity area method. The requirement for overhead photography using, for example, radio controlled aircraft may make this an unacceptably expensive option, but it may be possible to use this method at a constricted site where there is a suitable observation point on high ground.

## Floodplain measurement structures

The headloss through a hedge or a perforated wall, or across a low weir such as a farm road, would give an estimate of the flood plain flow. Any such structure across a flood plain would, however, result in higher upstream levels which may not be acceptable. Accumulation of trash at a hedge or perforated wall would affect the accuracy of the results.

Permanently installed measurement equipment

The permanent installation of measurement equipment at several locations across the river and flood plain could be used to provide a continuous record of discharge during a flood. For example, current meters set in posts could be used in conjunction with water level recorders to obtain the discharge by the velocity area method.

Use of sites where flow is constricted

A major difficulty with flood discharge estimation is the problem of measuring flows on flood plains. If sites can be identified where all the flow passes through constricted areas, such as a combination of bridges and culverts in an embankment, it may be easier to obtain estimates of the total discharge. Maximum water level gauges upstream and downstream could be used to estimate the head loss at the structure, and this in turn may be used to estimate the discharge. Alternatively, current metering may be practical at constricted sites where the area to be current metered is relatively small.

Difficulties with methods

A number of difficulties with methods have already been identified above. Any field installation is subject to damage or clogging by trash, and is also liable to damage by vandalism. Scour and siltation also occur during floods and may seriously affect channel sections, particularly in the vicinity of bridges or culverts. Any measurement device in the main channel must not form a hazard to navigation.

Any equipment mounted in the main channel will require inspection by boat, and access to equipment on the flood plain may be difficult during periods of flooding. The whole question of staff safety must be carefully considered in the selection and development of field measurement methods.

## 5.3 Laboratory tests

If it is decided to experiment with new types of measurement equipment, it would first be necessary to construct and test such a device in the laboratory. The first stage would be to construct the device, which would be mounted in a flume and calibrated for a range of velocities. Design and construction problems would be overcome as far as possible at this stage. Experiments on the effect of trash could then be carried out, and suitable trash deflectors provided. The effects of trash on the calibration of the device would also be observed.

If the device has performed satisfactorily in the laboratory, field trials could then be carried out.

## 5.4 Selection of experimental sites

A number of sites have been identified which may be suitable for experimental work following discussions with the Water Authorities, as described in Section 3.1.

It is expected that only about two sites will be required in order to concentrate efforts on obtaining good field data. The primary requirement is for a gauging station where reliable flow measurements are taken during floods, and a suitable experimental site exists close to the gauging site where overbank flow occurs with reasonable regularity.

Co-operation with Water Authorities is essential, and it would be desirable for Water Authority staff to be actively involved in regular inspection of the experimental equipment and keeping records. A convenient location reasonably close to a Water Authority centre of operation may therefore be one criterion in the selection of suitable sites.

The following sites have been identified which may be suitable for experimental work.

River Wey at Tilford (Surrey)

Thames Water gauging station 39011
Bankfull discharge $37.5m^3/s$ at stage 1.22m

There is a Crump weir at this site and a 100m wide floodplain on the left bank. There is a good reach downstream for experimental work where overbank flow occurs fairly frequently. The weir drowns at high flows and the crest tappings block. The weir rating has therefore been extended using Simpson's Method. It would be necessary to check the extension of the rating curve by current metering if this site was used.

River Blackwater at Ower (Hampshire)

Southern Water (Hampshire division) gauging station 42014.

Bankfull discharge $9.9m^3/s$ at stage 1.80m.
Maximum recorded discharge $12.0m^3/s$ at stage 1.99m.

The Crump weir at this site is drowned at high flow but the rating has been extended by current metering.

River Avon at Bathford (Avon)

Wessex Water (Bristol Avon division) gauging station 53018.

This is a natural channel site where flood flows are contained by a single bridge arch and floodplain flow is believed to occur upstream, although further details are required.

<u>River Stour at Hammoon</u> (Dorset)

Wessex Water Authority (Avon and Dorset division) gauging station 43009.

Bankfull discharge $80m^3/s$ at stage 2.44m.
Maximum recorded discharge $151m^3/s$ at stage 3.0m.

The compound Crump weir at this site is supplemented by current metering from a bridge downstream. Suitability as an experimental site requires further investigation.

<u>River Torridge at Torrington</u> (Devon)

South West Water gauging station 50002.

Bankfull discharge $187m^3/s$ at stage 3.25m.
Maximum recorded discharge $314m^3/s$ at stage 4.07m.

This site is a natural section with a flood plain on the left bank. The cableway extends over part of the flood plain to a bund.

<u>River Severn at Montford</u> (Shropshire)

Severn Trent Water gauging station 54005.

Bankfull discharge $184m^3/s$ at stage 4.6m.
Maximum recorded discharge $331m^3/s$ at stage 6.09m.

The entire section including the river and two flood plains is spanned by a cableway. This is therefore an excellent site for experimental work. Eleven overbank flow events have been recorded in the period 1981 to January 1988, approximately three events every two years.

<u>River Welland at Tixover</u> (Leicestershire)

Anglian Water (Oundle division) gauging station 31005

This is a velocity area flow gauging station with a well contained natural section. Flow goes out-of-bank both upstream and downstream, and therefore this is a promising experimental site.

<u>River Kym at Meagre Farm</u> (Cambridgeshire)

Anglian Water (Cambridge division) gauging station 33012.

Structure full discharge $16m^3/s$ at stage 1.52m.
Bankfull discharge $49m^3/s$ at stage 2.28m.

The compound weir at this site has a theoretical rating curve for high discharges. This could be a useful experimental site if the rating curve was confirmed by field measurements.

<u>River Chelmer at Springfield</u> (Essex)

Anglian Water (Colchester division) gauging station 37008

Bankfull discharge $12.0m^3/s$ at stage 1.10m.
Structure full discharge $85m^3/s$ at stage 2.05m.

All flow is contained at the Essex weir at this site. Overbank flow occurs upstream, and this appears to be a very promising experimental site.

River Elwy at Pont-y-Gwyddel or River Clwyd at Pont-y-Cambwll (Clwyd)

Welsh Water (Northern division) gauging stations 66006 and 66001.

The flow is contained in a channel and narrow flood plain at both these sites, and therefore it may be relatively easy to measure flood discharge. Further information is required on suitable nearby experimental sites.

River Ribble at Samlesbury (Lancashire)

North West Water (Warrington division) gauging station 71001

High flows are contained at this site when overbank flow occurs upstream and downstream. This appears therefore to be a promising experimental site, although further details are required.

River Coquet at Rothbury (Northumberland)

Northumbrian water gauging station 22009

High flows are contained at this site when overbank flow occurs upstream and downstream. This appears therefore to be a promising experimental site, although further details are required.

It is proposed that the above twelve sites are considered for experimental work. It should be possible to eliminate some sites by further discussion with Water Authorities. It would then be necessary to visit the remaining sites with Water Authority staff in order to make the final selection. Aspects which must be considered in approximate order of importance are as follows:

(a) Frequency of overbank flow at the experimental site.

(b) Quality of the experimental site.

(c) Quality and accuracy of flow measurement at the gauging site for high flows where overbank flow occurs at the experimental site.

(d) Level of co-operation which could be provided by the Water Authorities.

(e) Accessibility.

## 5.5 Field trials

Having selected methods to be used for the field trials, and sites for the experimental work, it would then be necessary to install equipment at the sites. It is recommended that checks on the calibration of rating structures at the sites are made by current metering if a structure rating is to be used. Locating field equipment must take flooded outlines and flood water levels into account. It is likely that depths of flow on the flood plain will be 0.3m or less in many cases, and therefore any measurement equipment must be able to take readings at these low depths.

It is hoped to install field equipment in readiness for taking readings during winter 1989/90. This puts an important constraint on the programme, as all preparatory work including field installation should be complete by the end of October 1989. Base data for the site including water levels and discharge measurement would be obtained from the associated gauging station. When a flood occurs the gauging station staff would alert HRL, and arrangements would be made between HRL and the Water Authority to photograph the experimental site during the flood, and obtain as much information as possible on the flood flow. Additional current meterings may also be taken to confirm the calibration of the rating structure for high flows. After the event it will be necessary to record data from the measurement equipment, re-set the equipment, and repair any damage.

## 5.6 Structure and bridge ratings

Rating curves for low flow structures have often been extended to estimate high flows either by rating extrapolation, theoretical considerations or by current metering from, for example, a nearby bridge. Extensions of rating curve produced by these methods are liable to result in errors in estimated discharges. It would therefore be desirable to check the rating curves by current metering at high discharges.

Some of the proposed experimental sites have stage discharge relationships which are based on extensions to structure ratings of the types described above. Current metering at these sites has already been suggested in order to check the rating of the structure. It may be possible to check the rating of other structures at high flows, although it is likely that resources provided by HRL for the project would already be committed to experimental sites during periods of high flows, and would therefore not be available for this activity. It is therefore not proposed to carry out any further experimental work in connection with structure ratings under this project.

During the forthcoming experimental programme, it is proposed to take the opportunity to discuss structure and bridge/culvert ratings with Water Authority staff.

Any available data will be collected and, if it appears worthwhile to do so, proposals will be made in the future for further study of structure and bridge ratings.

## 6 FLOOD ROUTING

It may be possible to estimate flood discharge by the use of a catchment flood model. The method would involve obtaining flow data from an upstream gauging station and applying it to a flood routing model such as the HRL package RIBAMAN, which is described in Appendix 5. This would provide discharge estimates for other locations in the catchment. It is proposed to carry out experimental work on a catchment with two stations which are capable of measuring high flows. Flow data from the upstream station would be fed into the model, and predictions for the downstream station would be compared with the recorded flow.

This method would require lateral inflow data for the reach between the two gauging stations. This would be determined using FSR rainfall runoff methods (NERC, 1975), although it is well established that these estimates are themselves subject to considerable error (NERC, 1985).

The usefulness of this method is limited by the amount of input data required, including an upstream gauging station and lateral inflow information. It is therefore of limited value when compared to other methods which require site specific data only, but it may be useful in certain cases. It is therefore proposed to apply this method at one site, in order to work through the method and identify difficulties with data collection, etc.

It is proposed to select one of the seven routing reaches listed in Table 7 for applying for the flood routing method. This would be done initially by

TABLE 7 : Flood Routing Reaches

| River | From | To | Water Authority | Reach Length (km) | Nr Tributaries | Remarks |
|---|---|---|---|---|---|---|
| Mole | Horley | Castle Mill | Thames | 17 | 12 | Includes Kinnersley Manor, where overbank flows are measured |
| Avon | Melksham | Bathford | Wessex (Bristol Avon division) | 24 | 9 | |
| Stour | Hammoon | Throop | Wessex (Avon and Dorset division) | 52 | 14 | |
| Aire | Skipton | ~~Aldwick~~ Kildwick | Yorkshire | | | Study already in progress, by others |
| Wharfe | ~~Addington~~ Addingham | Otley | Yorkshire | | | |
| Eden | Kirkby Stephen | Carlisle | North West (Carlisle division) | | | |
| Tees | Broken Scar | Low Moor | Northumbrian | 35 | 3 | Some work already carried out by NWA |

consultation with the Water Authorities and inspection of data, but it may be necessary to visit some of the sites in order to make the final selection.

## 7 PROPOSED PROGRAMME FOR 1989/90

It is proposed to carry out the following items of work under this project during 1989/90:

(a) Experimental work

- assess methods (Section 5.2)
- laboratory tests on chosen methods (Section 5.3)
- select sites (probable maximum of two sites) (Section 5.4)
- field trials (Section 5.5)

(b) Computational modelling of gauging site

- apply computational river model to two sites including the Culm at Wood Mill (Section 4.11).

(c) Flood routing (Section 6)

- apply catchment flood model to one site

In addition, the following activities are considered desriable for improving the assessment of flood discharge, but are not specifically included in the project.

(a) Further data collection on overbank flow (Section 3.3) and bankfull roughness coefficients (Section 4.8).

(b) Further work on stage discharge curves (Section 4.2)

(c) Extension of structure ratings and bridge/culvert ratings (Section 5.6)

A provisional programme for 1989/90 is shown on Figure 22. The main emphasis in this programme is on the development of field measurement equipment, but provision is also made for the application of a computational river model to two gauging stations, and the computational flood routing model RIBAMAN to one river catchment. The estimated cost of these studies is as follows

| | £ |
|---|---|
| Experimental work | 21,000 |
| Computational modelling of two gauging stations | 5,500 |
| Computational flood routing model for one catchment | 3,500 |
| | 30,000 |

Clearly the experimental work is very open ended, being completely exploratory in nature. It is not proposed to start the computational modelling work until after the installation of field equipment, when the amount of money spent on equipment development will be known. No provision is made in the above costings for survey work and flow data collection for the computational models, as it is assumed that this will be provided by the Water Authorities concerned. It is likely that additional topographic survey work will be required. Clearly if the Water Authorities are unable to carry out this work it would be undertaken by HRL using the research budget.

# 8 CONCLUSIONS

1. The main hydraulic problem associated with the assessment of flood discharge is overbank flow.

Estimates of flood discharge where overbank flow occurs are liable to errors of 30% or more.

2. Flow data for sites where overbank flow occurs have been obtained from Water Authorities.

3. Several analytical methods have been used to estimate discharge where overbank flow occurs, and compared to observed results. Vertical division line method 2(b) and diagonal division line method 2(c) (see Figure 4) gave the best predictions for the simple methods tried. The lateral velocity distribution method, currently under development, is expected to give better predictions.

4. The accurate assessment of roughness parameters, particularly on the flood plain, is important in the accurate assessment of flood discharge using analytical methods and the slope area experimental method.

5. Sites have been identified where experimental work may be possible. Sites have also been identified for possible application of computational flood routing models.

6. The proposed programme for future work includes the following items:

   (a) Development of field measurement equipment, and field trials at a maximum of two sites.

   (b) Construction of computational models of two flow gauging stations.

   (c) Construction of a flood routing model for one river catchment.

## 9 ACKNOWLEDGMENTS

The helpful co-operation of all ten Water Authorities in England and Wales is gratefully acknowledged. Most of the Water Authorities have been visited by members of the research team, and a considerable amount of information has been provided by the Water Authorities for use in this research project. The development and application of the lateral velocity distribution method was carried out by James Wark under the supervision of Dr D A Ervine (University of Glasgow) and Dr P G Samuels (Hydraulics Research Limited) under a CASE award studentship.

## 10 REFERENCES


BROWN P M. "Afflux at arch bridges", Report No SR 182, Hydraulics Research Ltd, December 1988.

BRUK S and VOLF Z. "Determination of roughness coefficients for very irregular rivers with large floodplains". Proceedings 12th IAHR Congress, Fort Collins, Colorado. Paper A12 pp95-99, 1967.

CARTER R W. "Computation of peak discharge at culverts", US Geological Survey, Circular 37b, 1957.

CHOW VEN TE. "Open Channel Hydraulics", McGraw-Hill, 1959.

HIGGINSON N N J and JOHNSTON H T. "Estimation of friction factor in natural streams", International Conference on River Regime, Hydraulics Research Ltd, J Wiley and Sons Ltd, 1988.

KARASEV I F. "Influence of the banks and flood plain on channel conveyance". Soviet Hydrology, Selected Papers, 1969, 5.

KLAASSEN G J and VAN DER ZWAARD. "Roughness coefficients of vegetated floodplains". Journal of Hydraulics Research. Vol 12, pp43-63, 1974.

KLAASSEN G J and VAN URK A. "Resistance to flow on floodplains with grasses and hedges". Proceedings 21st IAHR Congress Melbourne. Vol 3, pp468-473, 1985.

KNIGHT D W, DEMETRIOU J D and HAMED M E. "Stage discharge relationship for compound channels". Proc Int Symposium on channels and channel control structures, Southampton, 1984.

NERC (1975). "Flood Studies Report", National Environment Research Council, 5 Volumes, and subsequent supplementary reports.

NERC (1985). "A review of the Flood Studies Report rainfall-runoff model parameters estimation equations", Institute of Hydrology, Report No 94, June 1985.

PETRYK S and BOSMAJIAN G. "Analysis of flow through vegetation". Journal of the hydraulics division. ASCE. Vol 101, HY7 pp871-884, 1975.

PRINOS P and TOWNSEND R D. "Comparison of methods for predicting discharge in compound open channels," Adv Water Resources, Volume 7, December 1984.

SAMUELS P G. "Modelling river and flood plain flow using the finite element method", Report No SR 61, Hydraulics Research Ltd, 1985.

SAMUELS P G. "Lateral shear layers in compound channels". International conference on fluvial hydraulics, Budapest, 1988.

TAGG A F and HOLLINRAKE P G. "Flood discharge assessment. Current UK practice", Report No SR 111, Hydraulics Research Ltd, February 1987.

USDA. "Handbook of channel design for soil and water conservation". US Department of Agriculture - Soil Conservation Services SCS-TP-61, 1954.

USBPR. "Hydraulics of bridge waterways", US Bureau of Public Roads, 1970.

UNIVERSITY OF BRISTOL. "Two stage channel flow", Department of Civil Engineering. Report for Thames Water Authority, 1988.

WORMLEATON P R, ALLEN J and HAJIPANOS P. "Discharge assessment in compound channel flow," ASCE, Journal of Hyd Division, September 1982.

WORMLEATON P R. "Determination of discharge in compound channels using the dynamic equation for lateral velocity distribution", International Conference on fluvial hydraulics, Budapest, 1988.

FIGURES

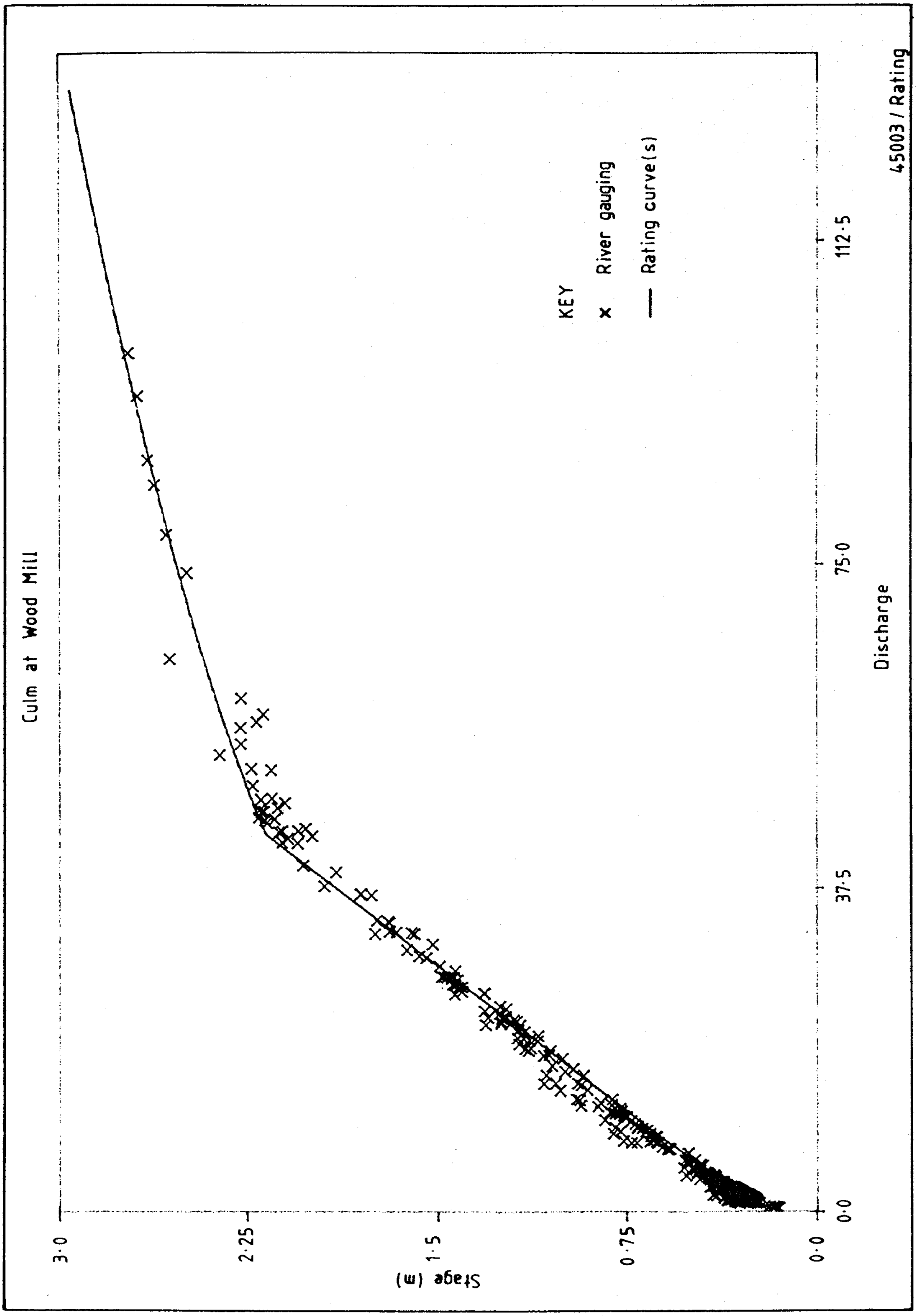



Fig 1 Example of stage discharge curve (natural scales)

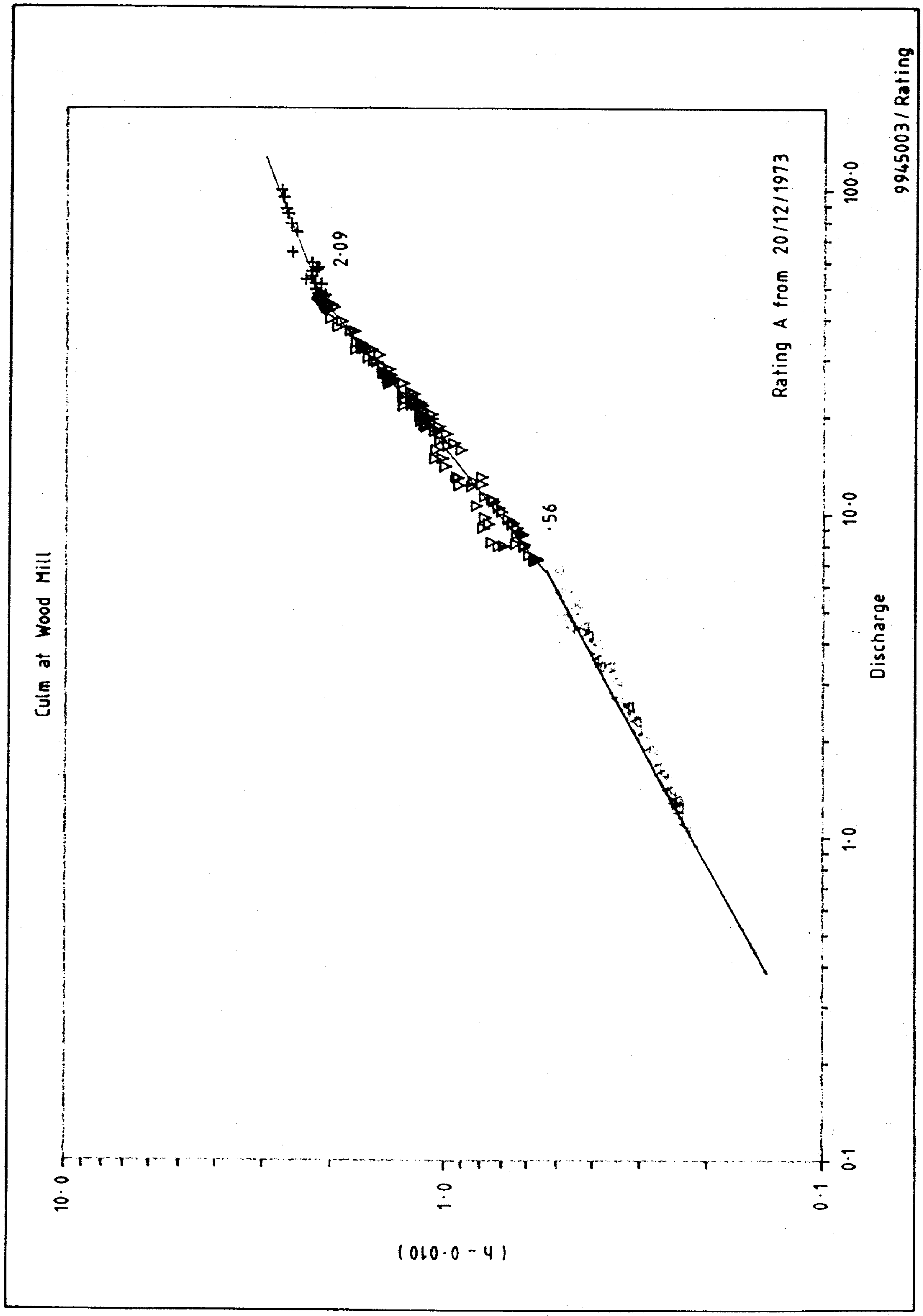



Fig 2     Example of stage discharge curve ( log scales )

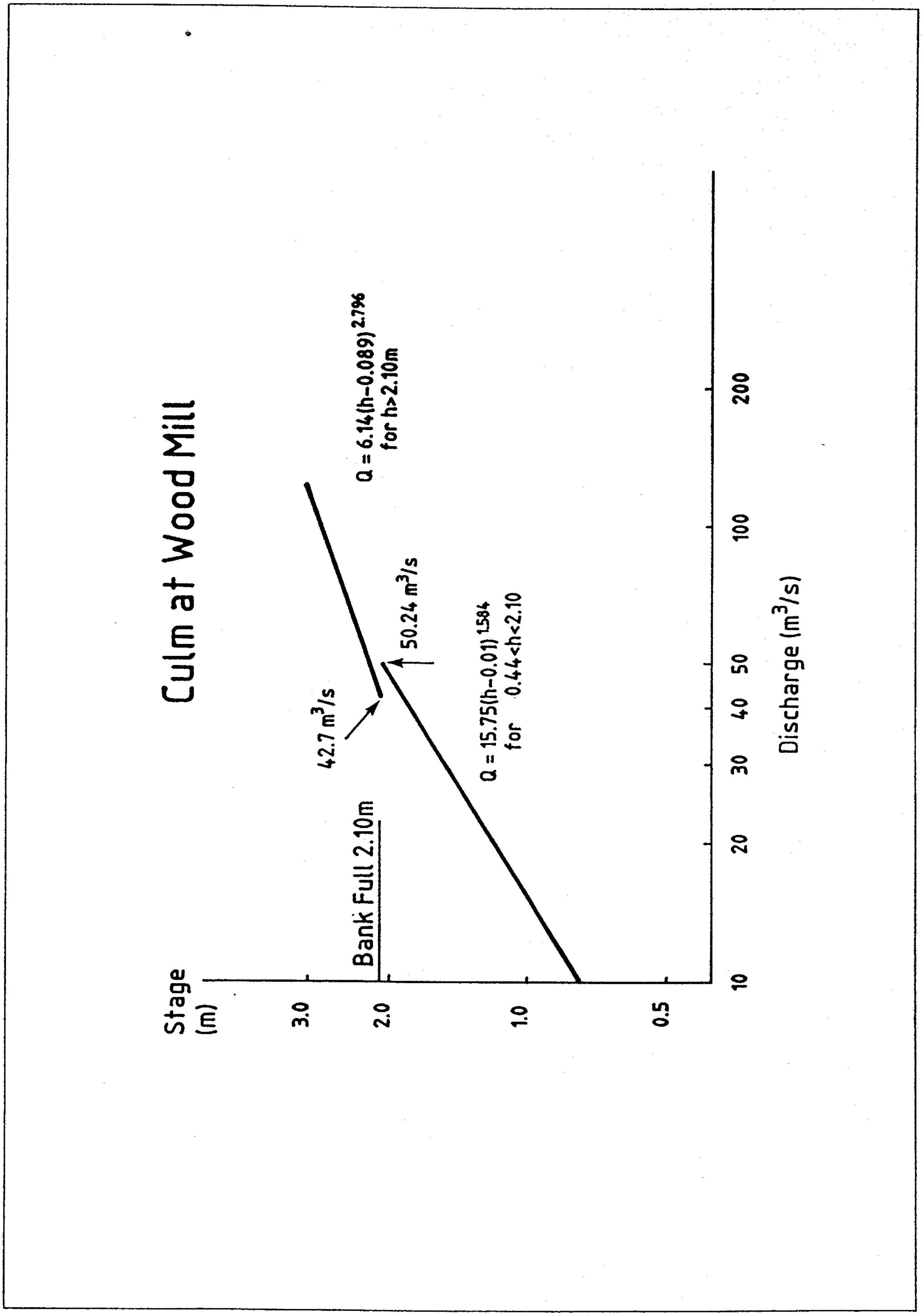
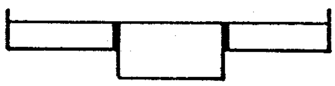


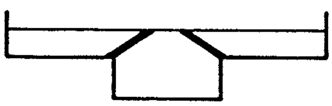

Fig 3 Stage discharge curve near bank full level

# Division Lines for Methods of Computation of Compound Channel Flow

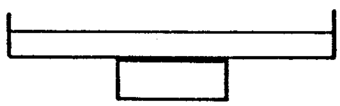


a) Vertical Division
methods 2(a), 2(b)

b) Diagonal Division
methods 2(c), 2(d)



c) Diagonal Division
methods 2(e), 2(f)



d) Horizontal Division
methods 2(g), 2(h)

Methods 2(b), 2(d), 2(f), 2(h) include division line in main channel wetted perimeter

Fig 4

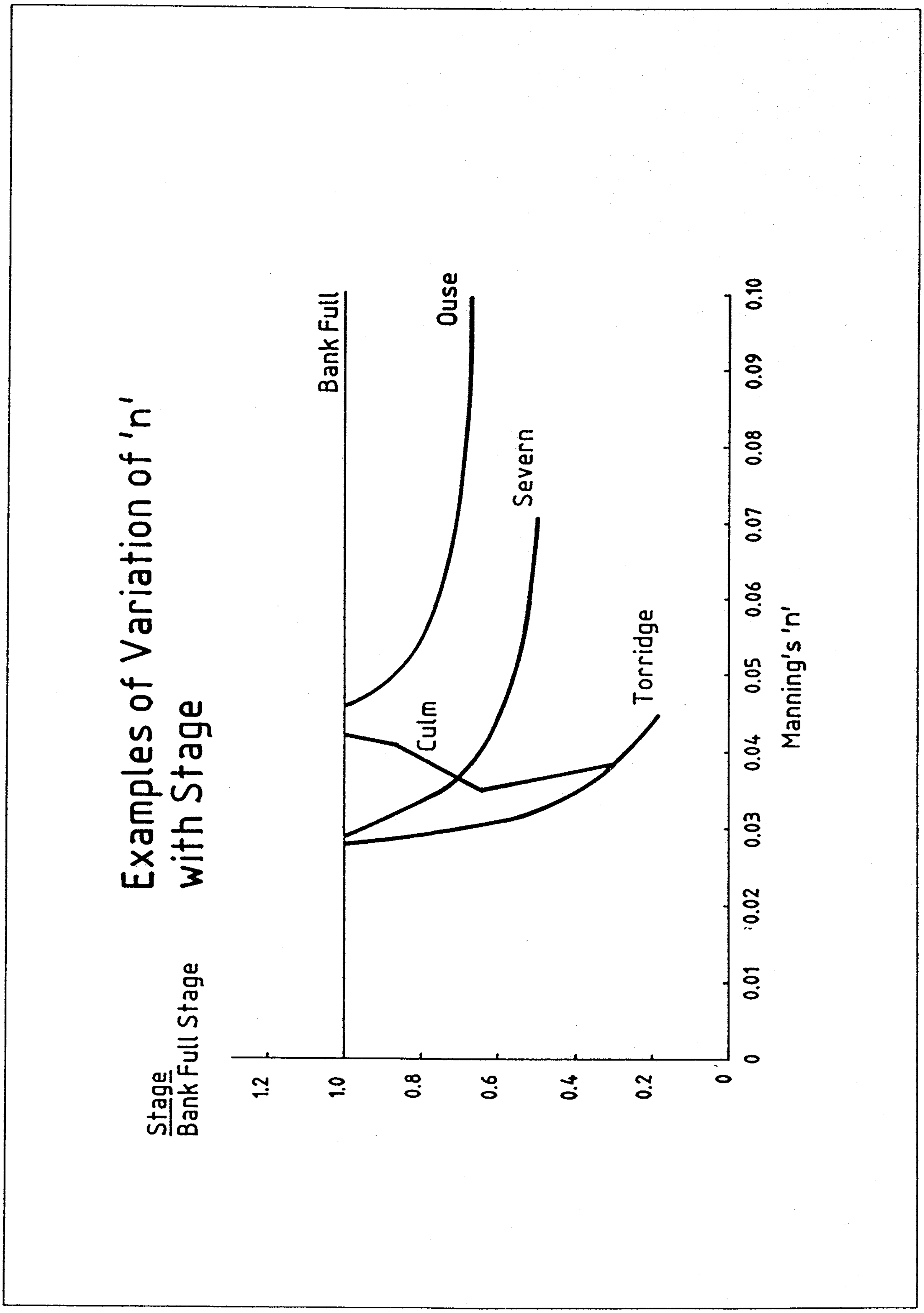

Examples of Variation of 'n' with Stage
Stage / Bank Full Stage
1.2
1.0
0.8
0.6
0.4
0.2
0
Bank Full
Ouse
Severn
Torridge
Culm
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
Manning's 'n'

Fig 5

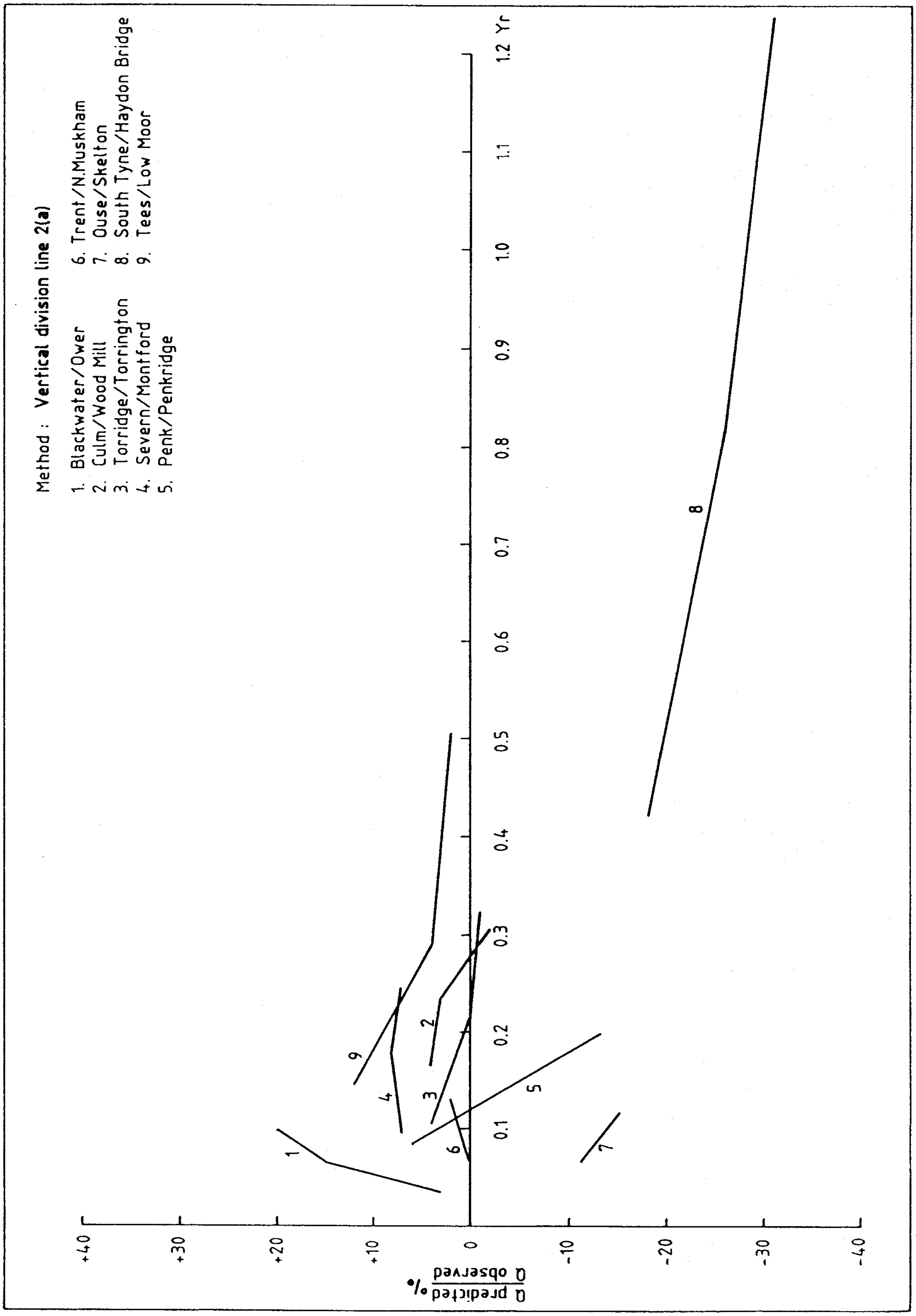



Fig 6 Discharge predictions : vertical division line method 2(a)

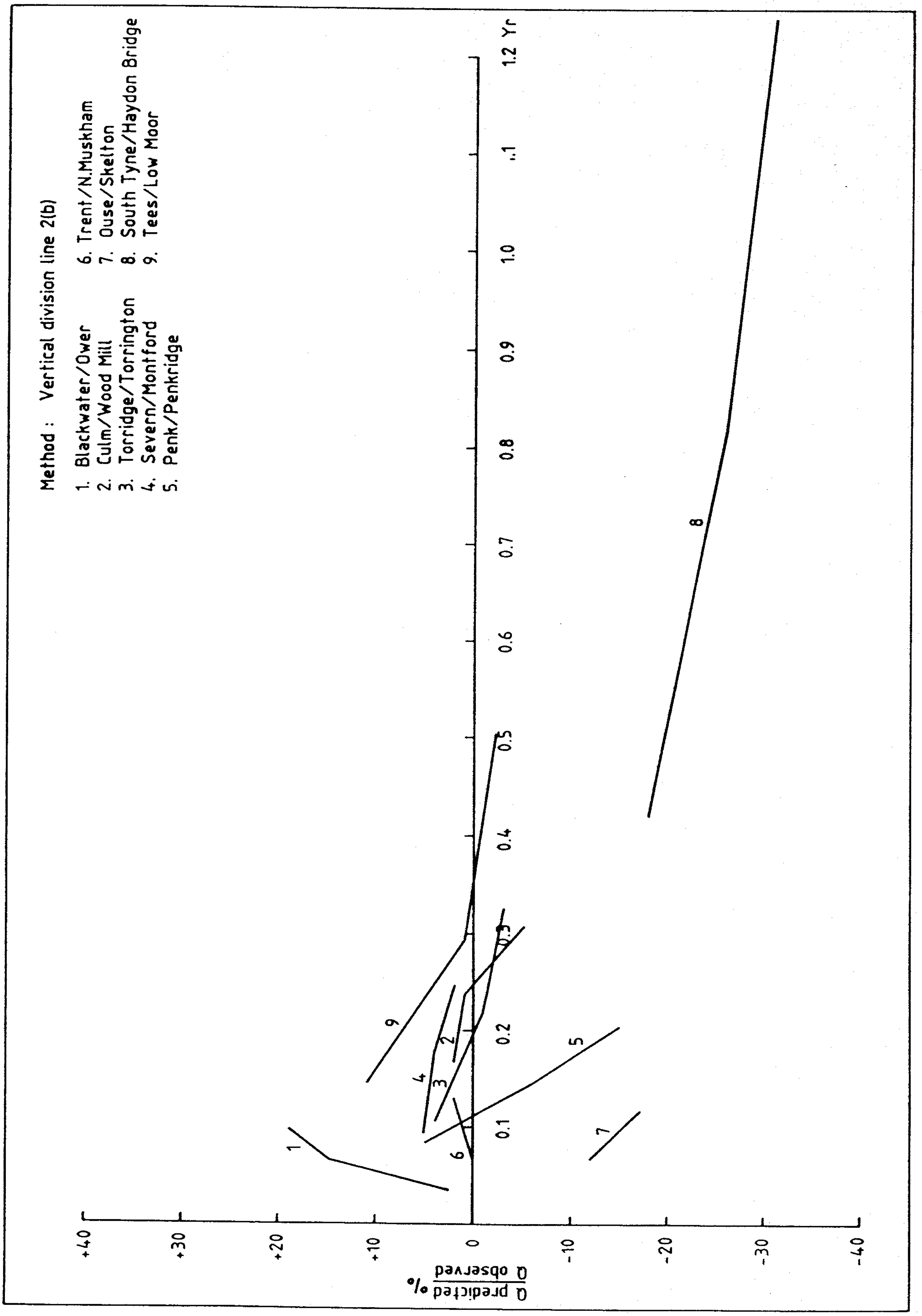



Fig 7 Discharge predictions : vertical division line method 2(b)

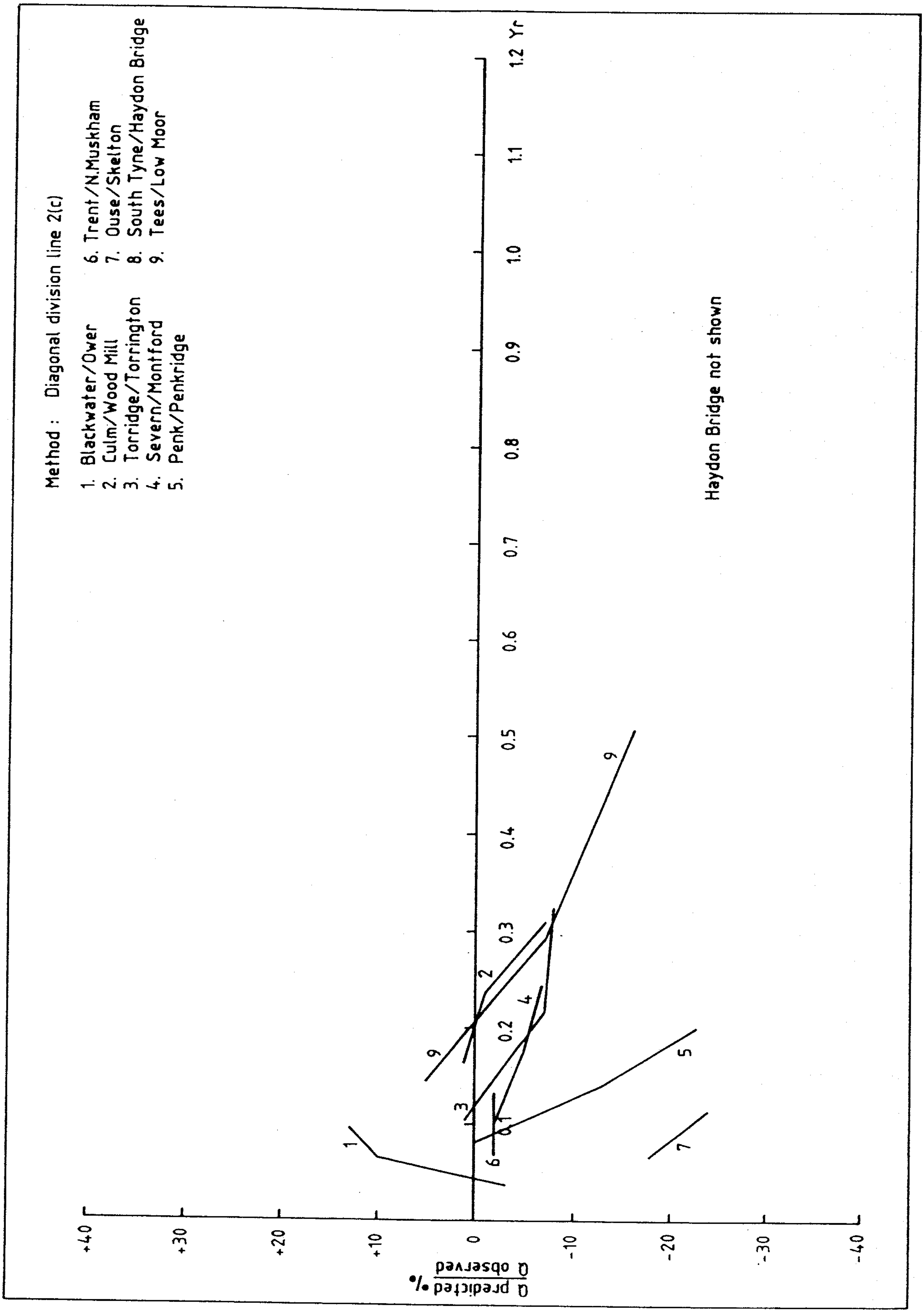



Fig 8 Discharge predictions : diagonal division line method 2(c)

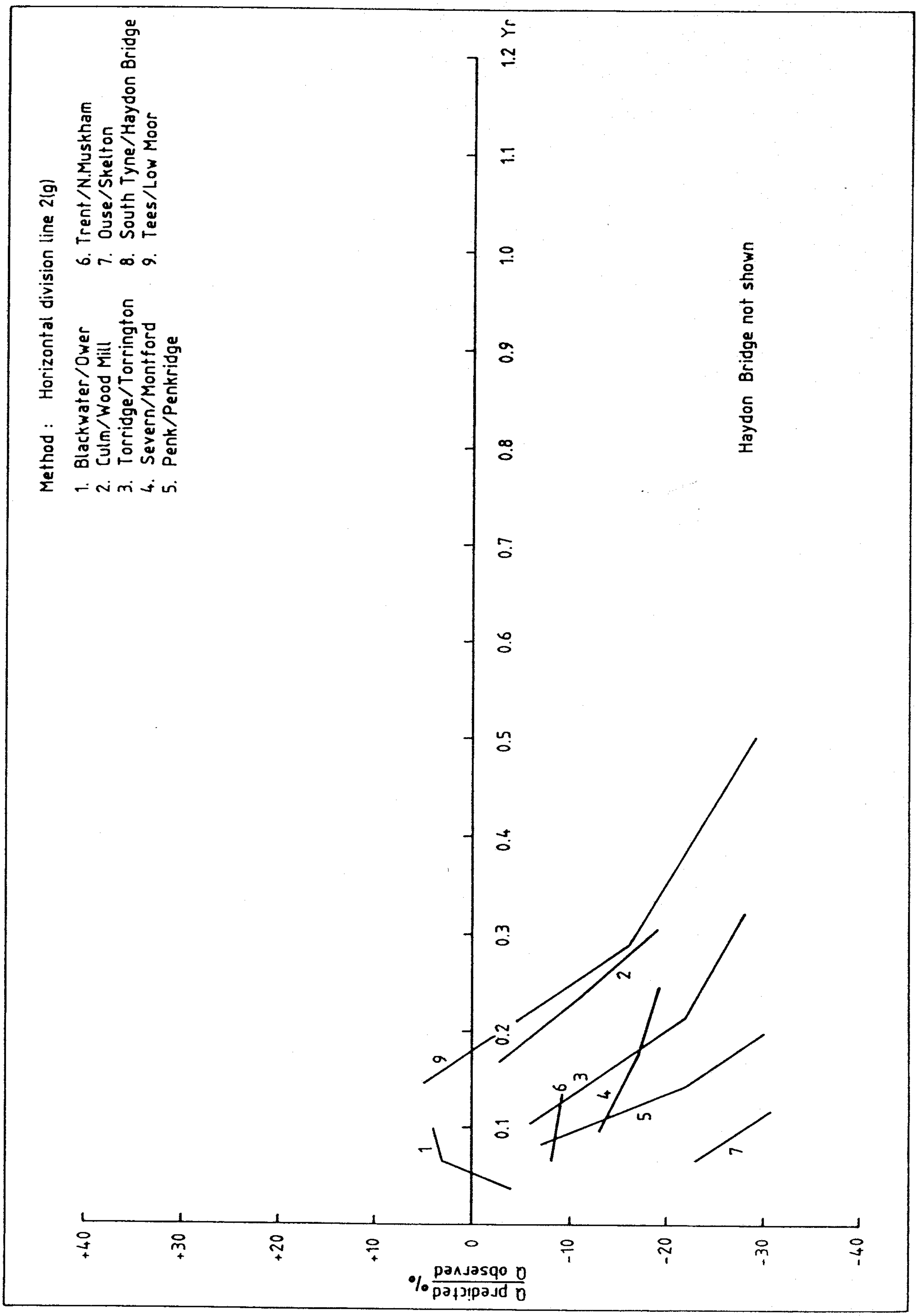



Fig 9 Discharge predictions : horizontal division line method 2(g)

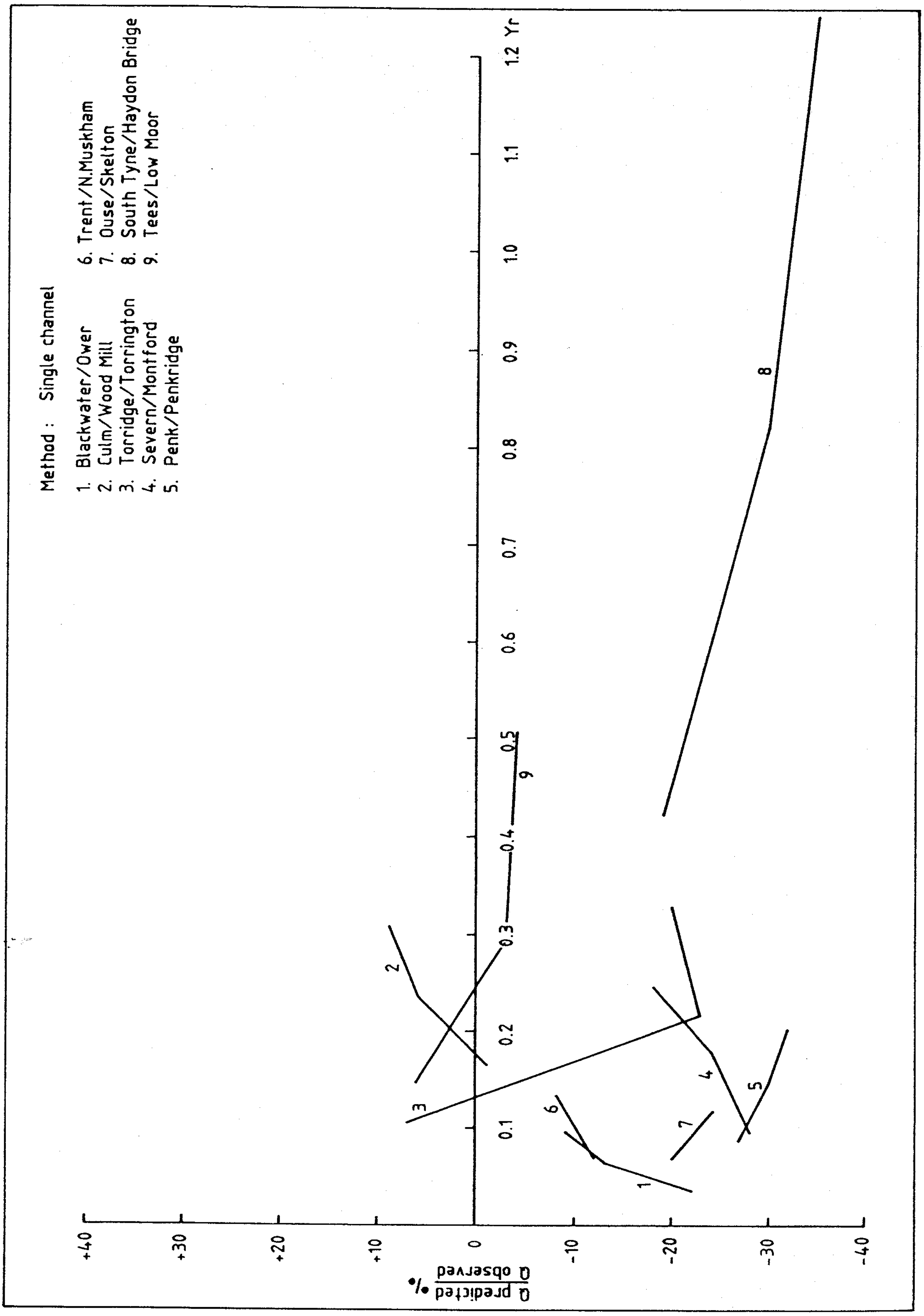



Fig 10 Discharge predictions : single channel method

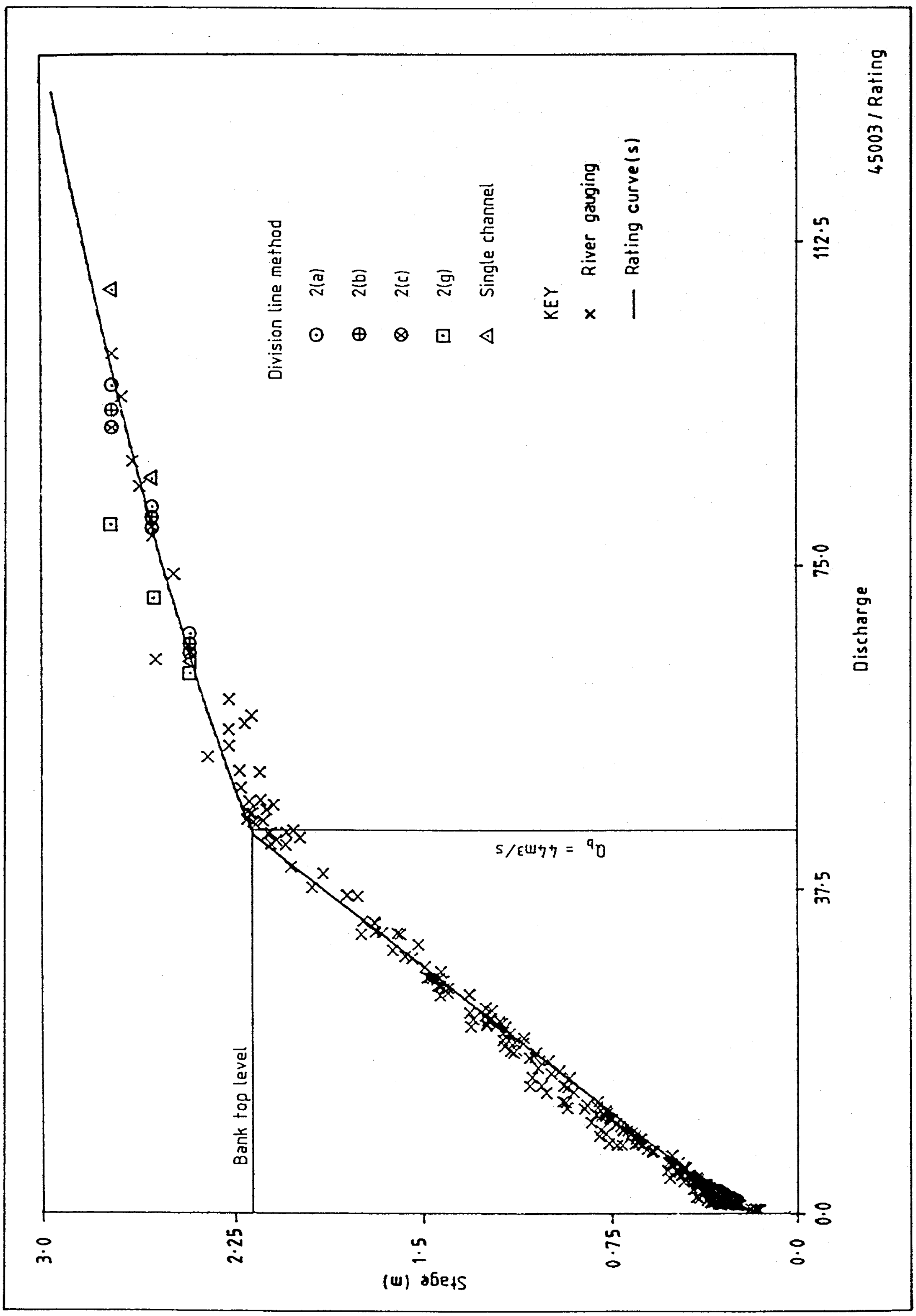



Fig 11 Discharge predictions : Culm at Wood Mill

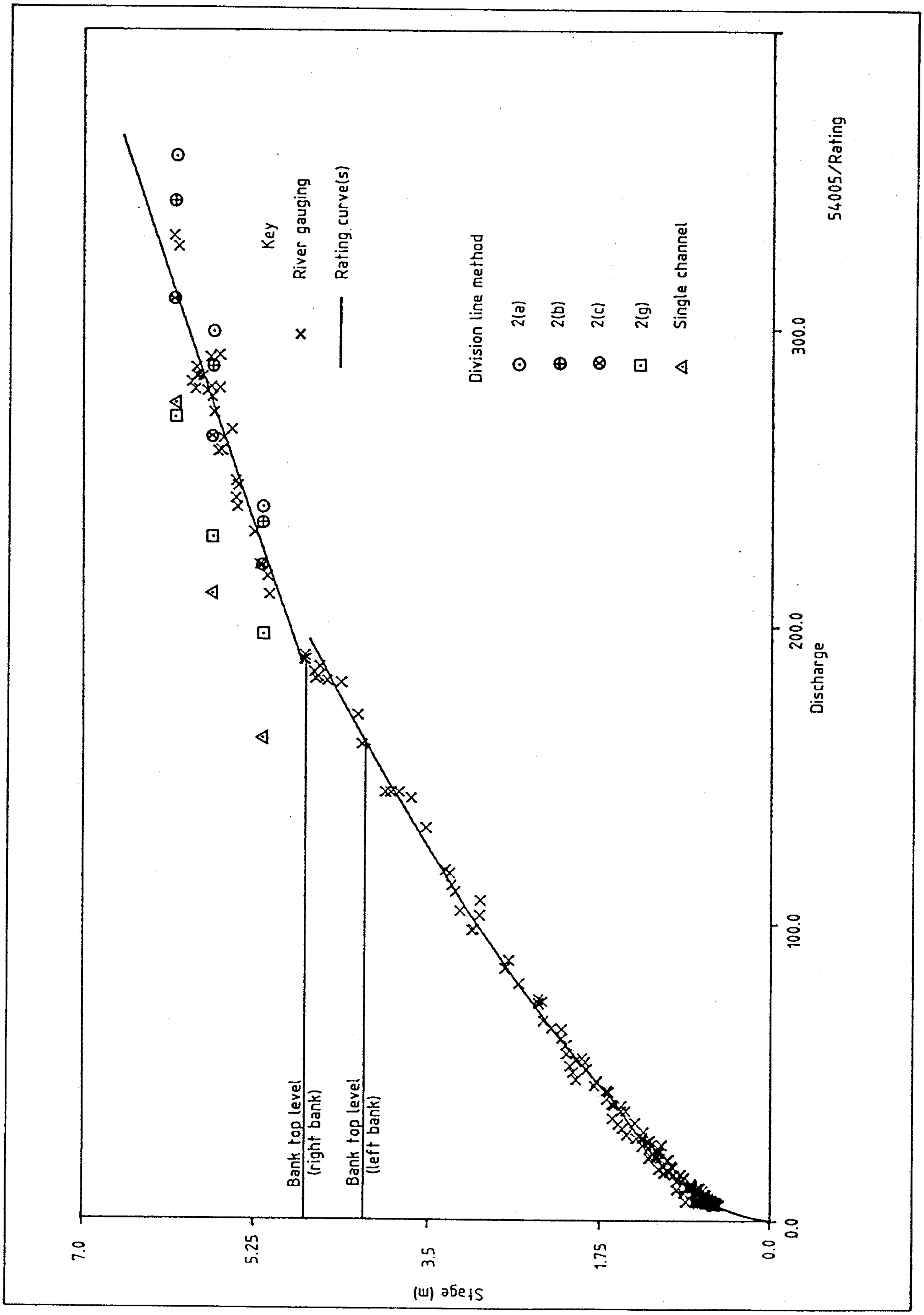



Fig 12 Discharge predictions : Severn at Montford

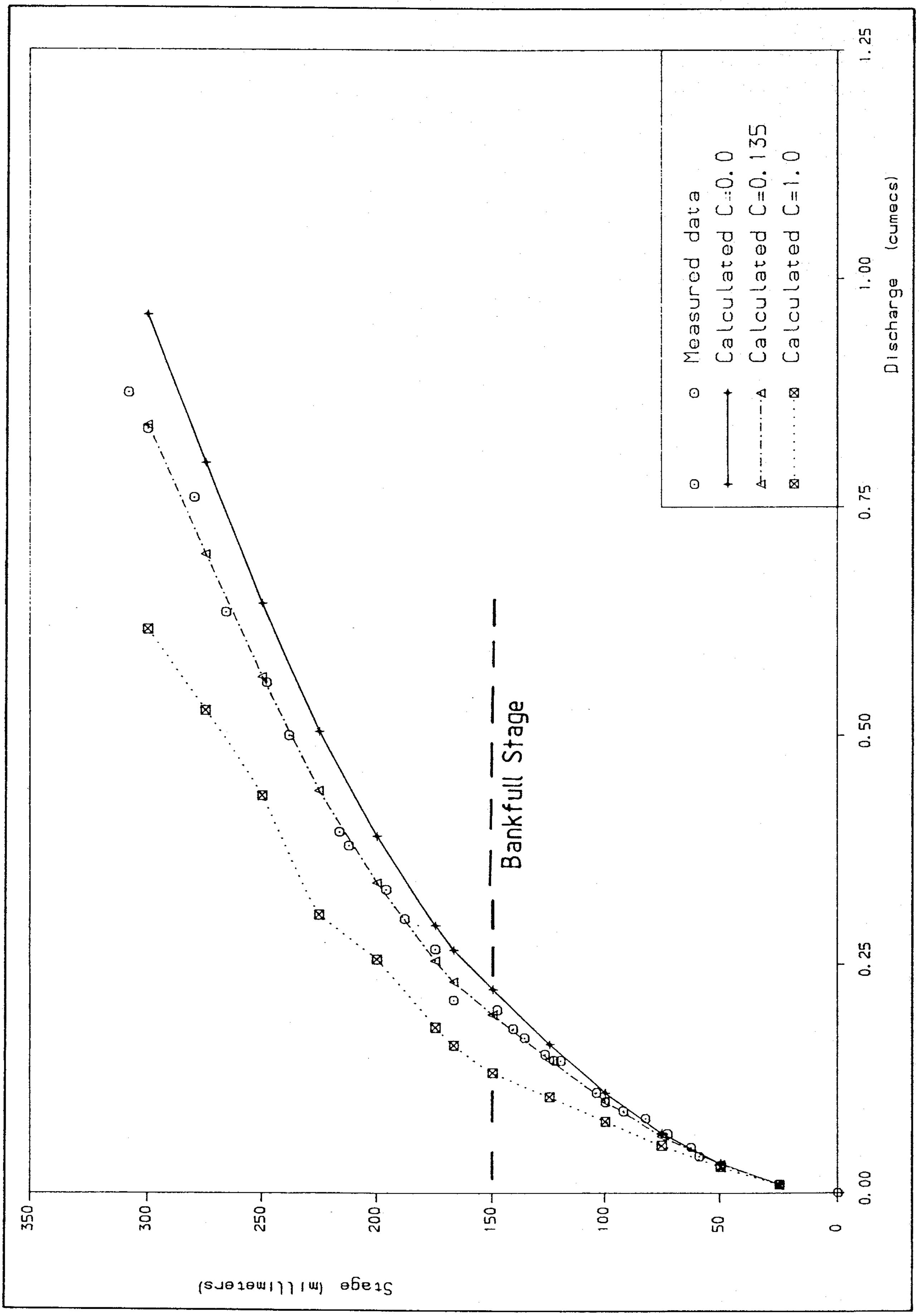



Fig 13 Stage Discharge relationship SERC flume
H-h/H = 0.1 B/b = 2.2

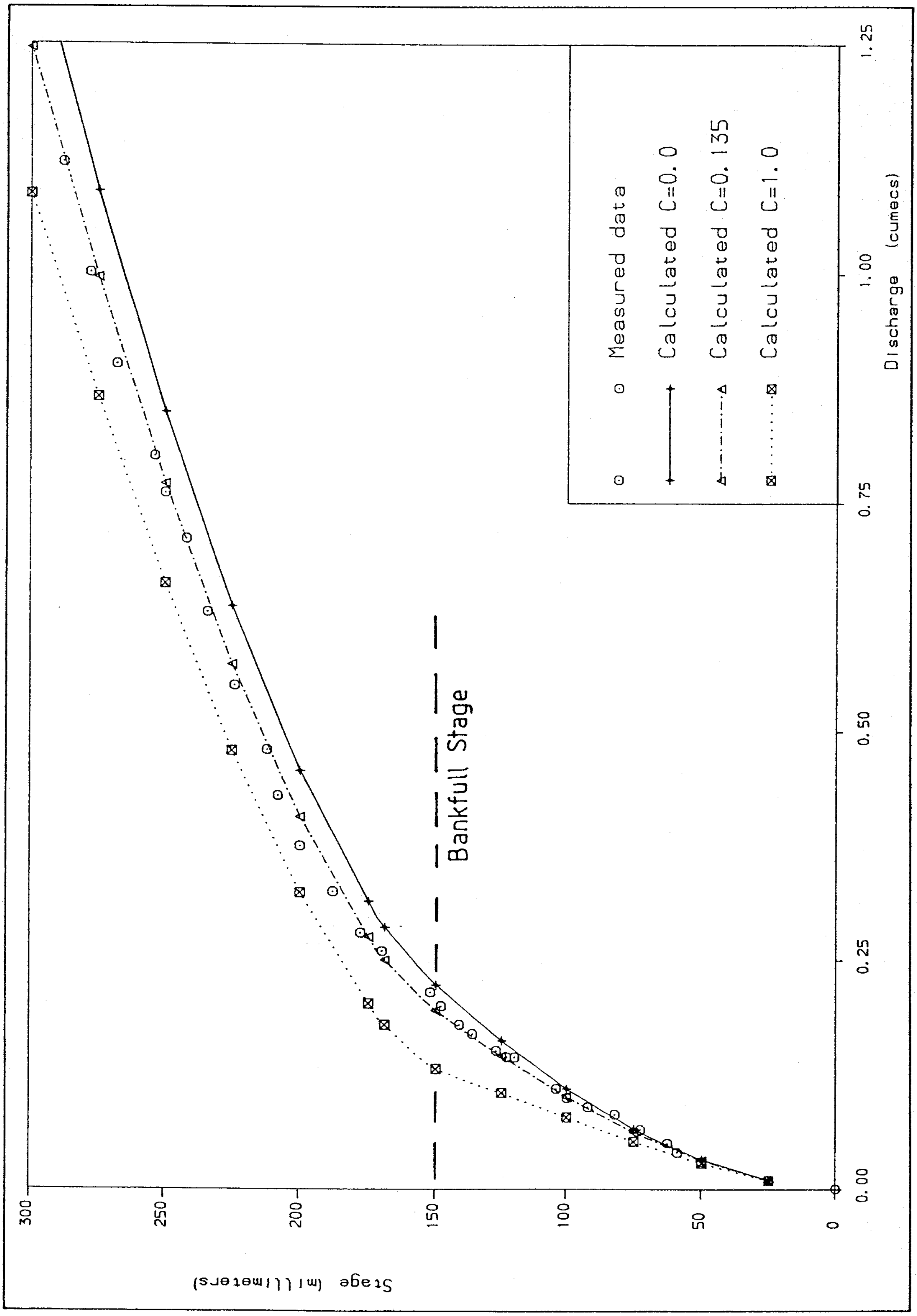



Fig 14 Stage Discharge relationship SERC flume
H-h/H = 0.1 B/b = 4.2

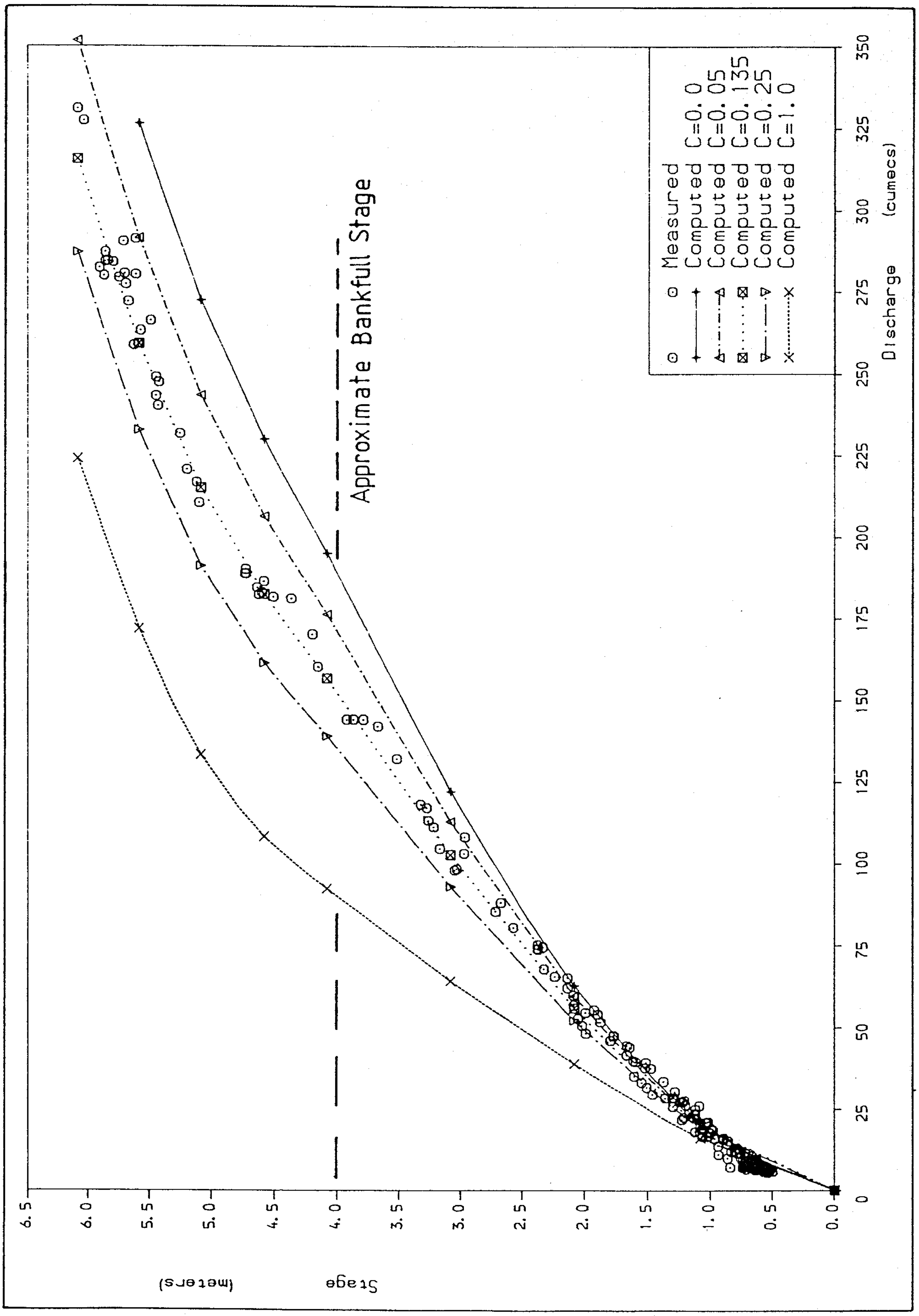



Fig 15 River Severn at Montford Stage Discharge

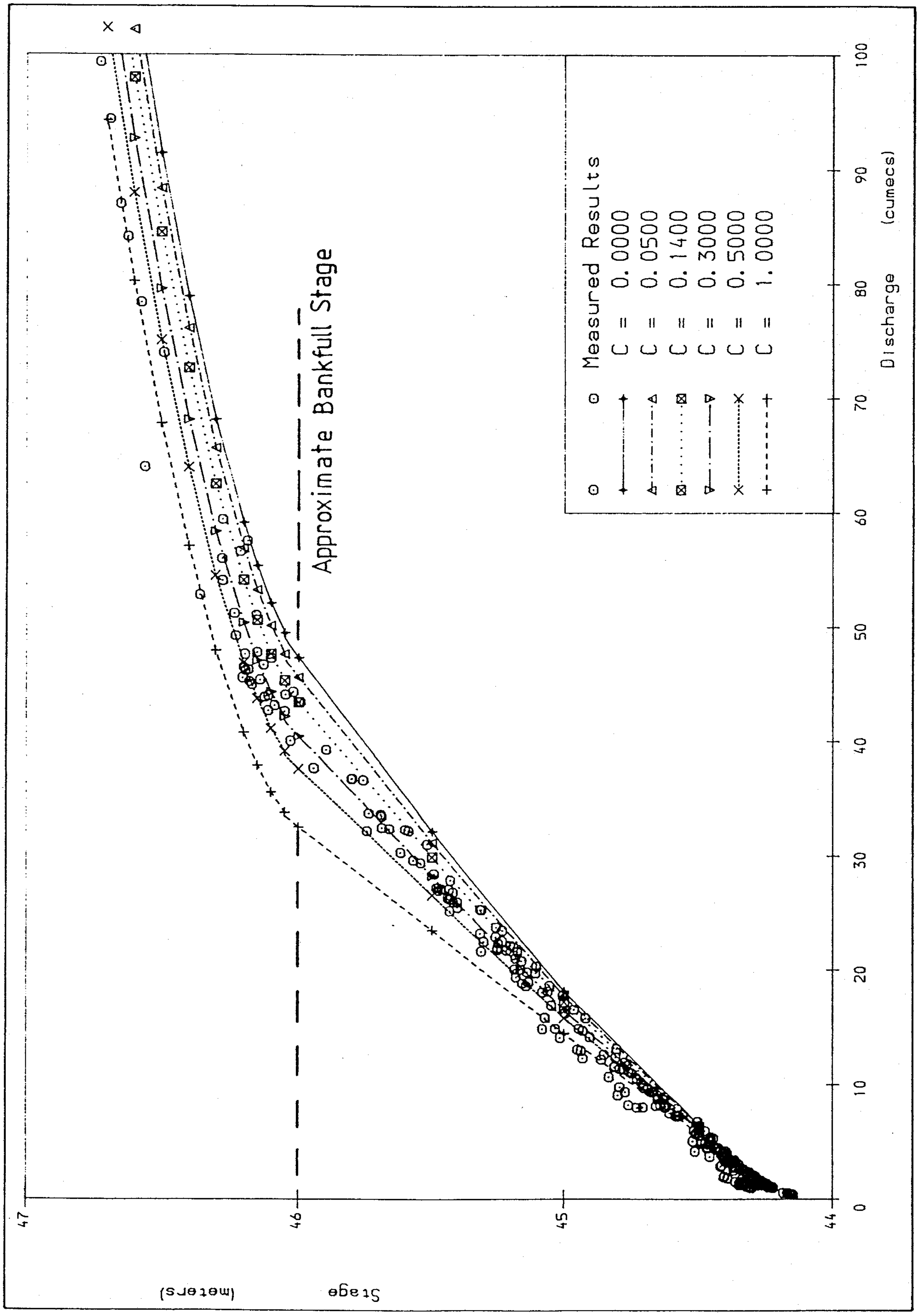



Fig 16 River Culm at Woodmill Stage Discharge
(for channel shape no.1)

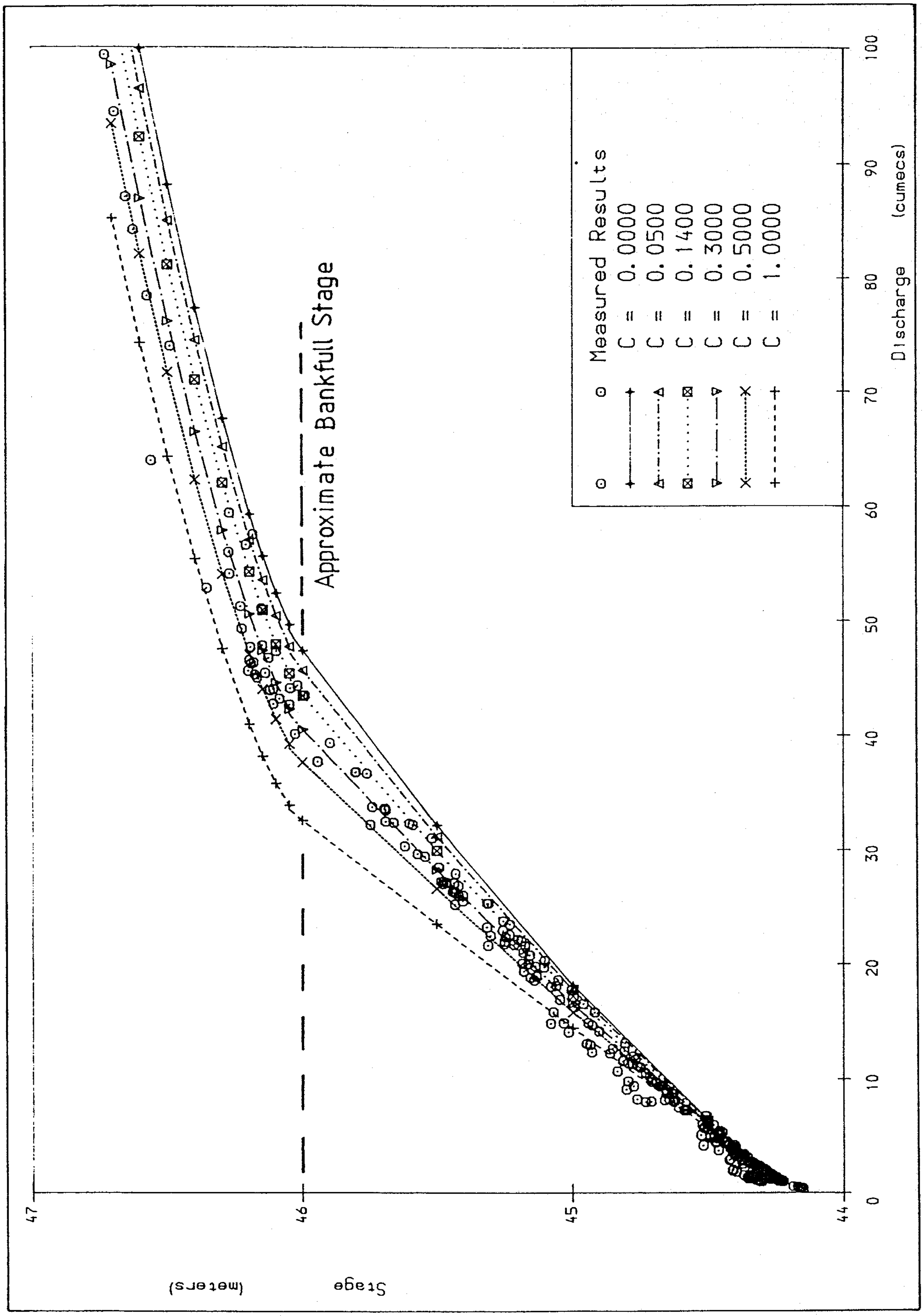



Fig 17 River Culm at Woodmill Stage Discharge
(for channel shape no.2)

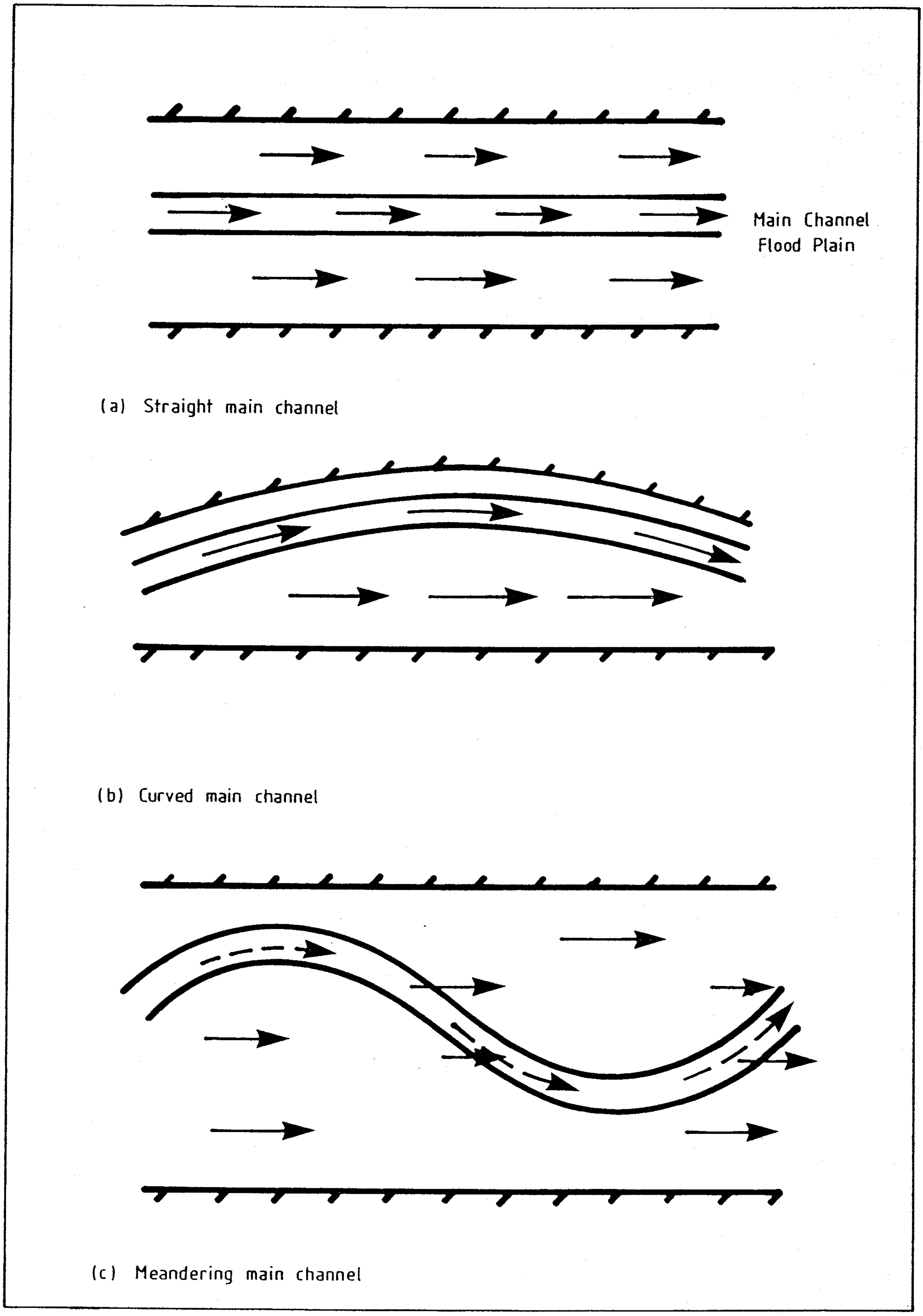



Fig 18 Compound channel flow patterns

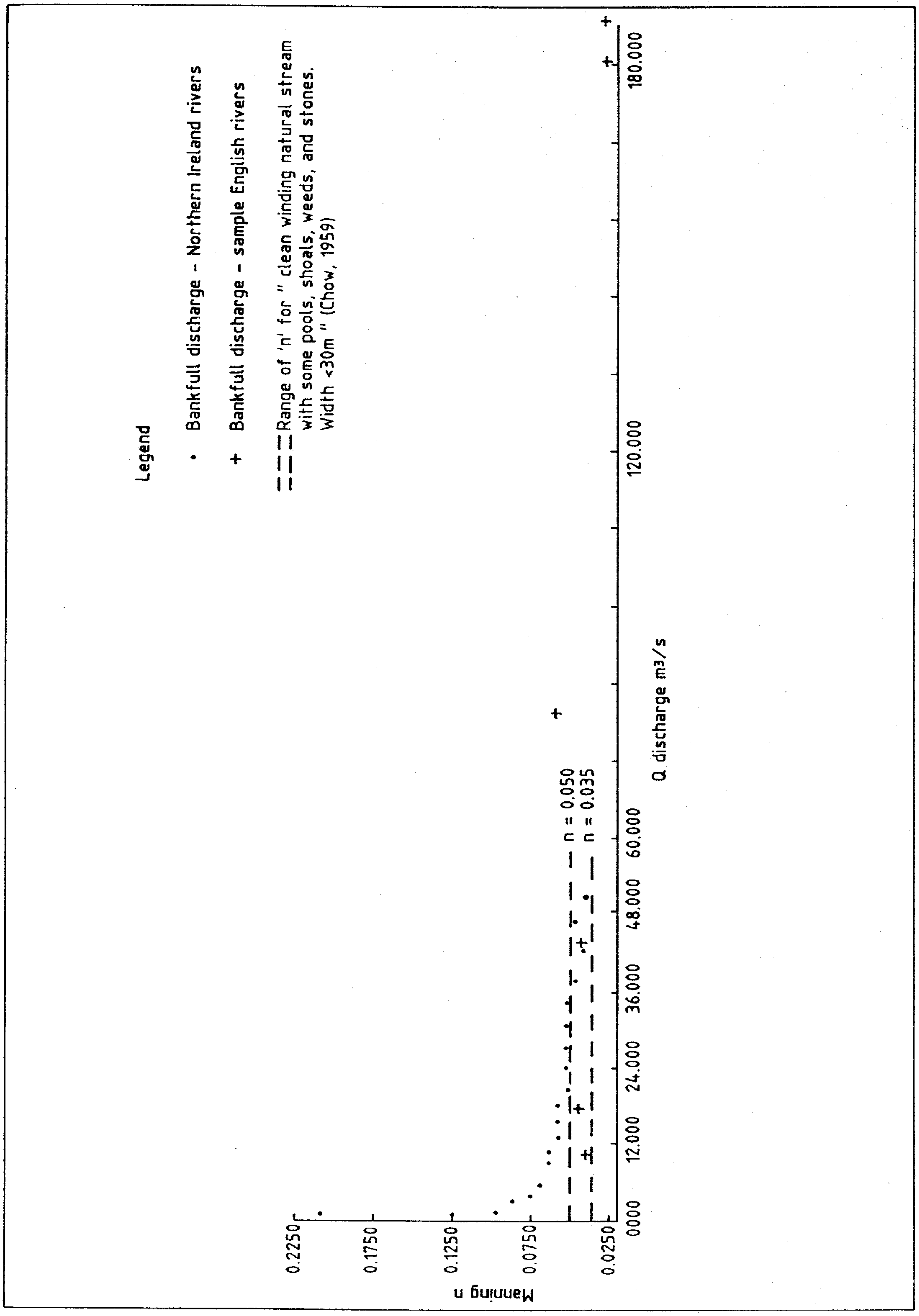
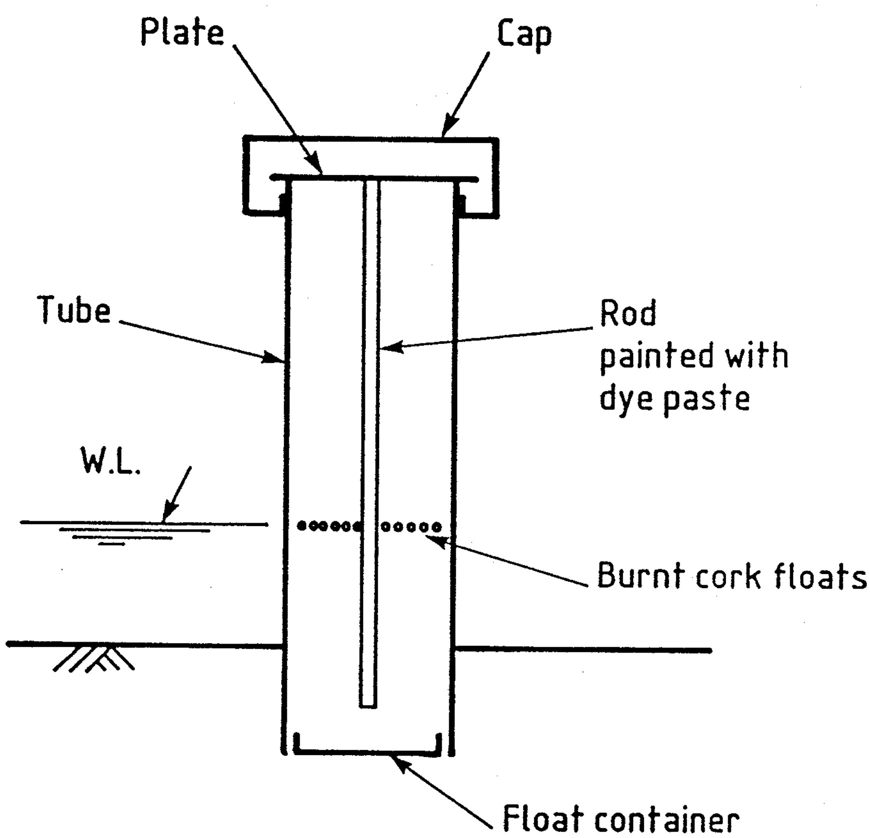



Fig 19 Manning's 'n' values for bankfull discharge




## Maximum Water Level Gauge

Dye changes colour
Floats cling to rod/sides of tube

Fig 20

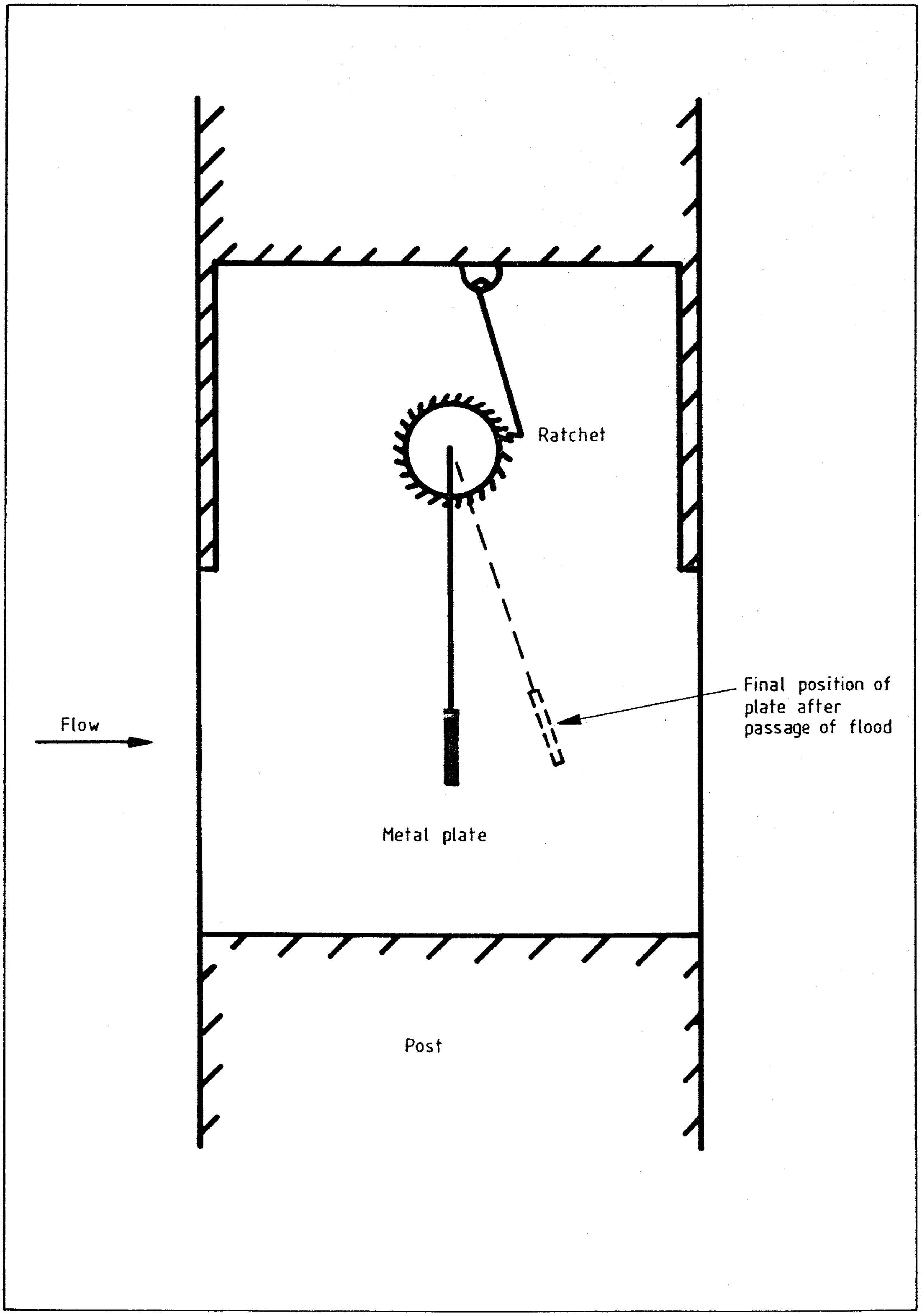



Fig 21 Example of maximum velocity measurement device

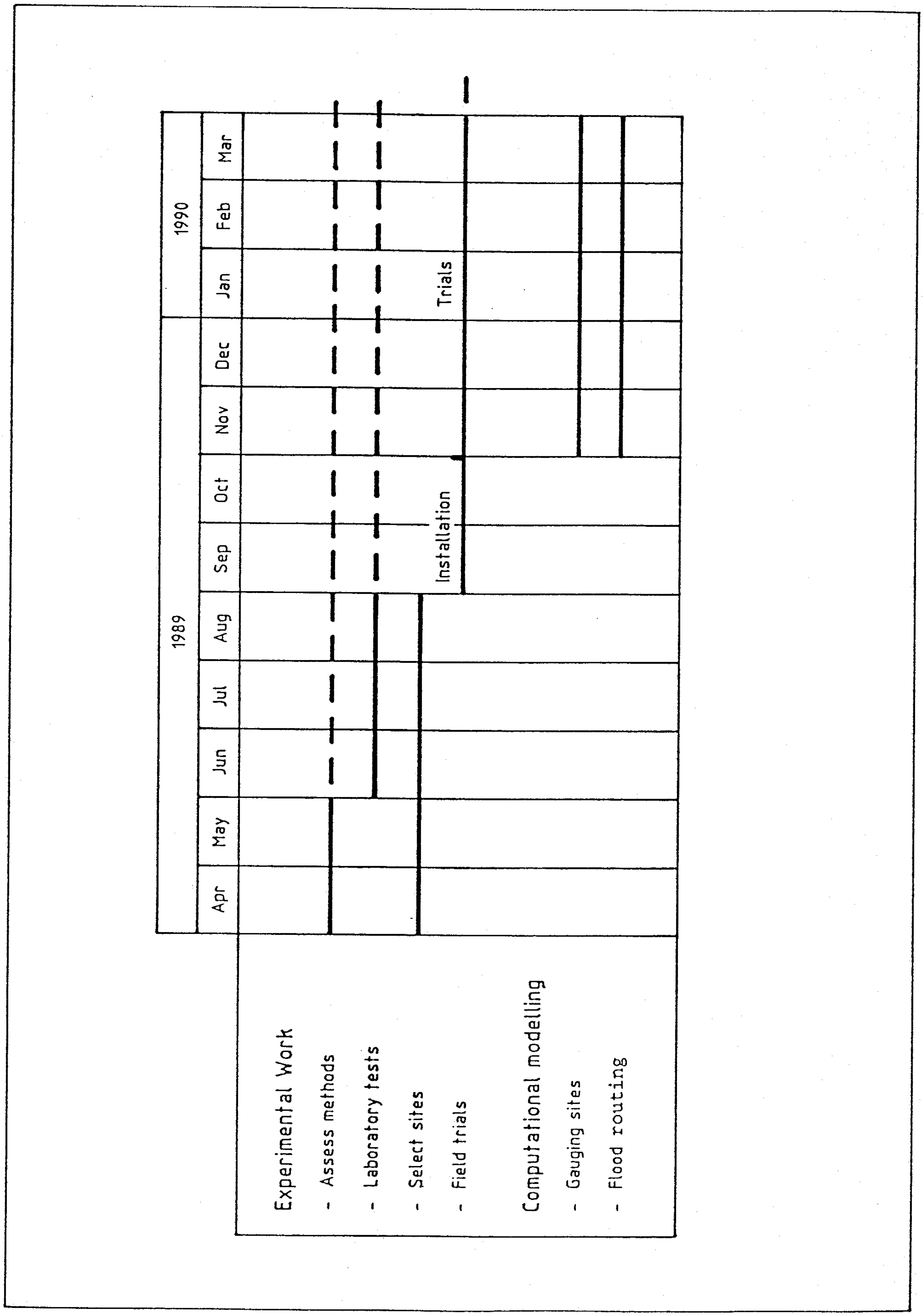



Fig 22 Flood discharge assessment. Provisional programme for 1989/90

# APPENDIX 1

## Site data and stage discharge curves

SITE DATA

SITE : KINNERSLEY MANOR
RIVER : MOLE
GAUGING STATION NUMBER : 36369

WATER AUTHORITY : THAMES

---

BRIEF DESCRIPTION Concrete rectangular section at road bridge

Channel bed material :
Floodplain vegetation/topography :

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 6 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | √ | | Horley to Castle Mill |

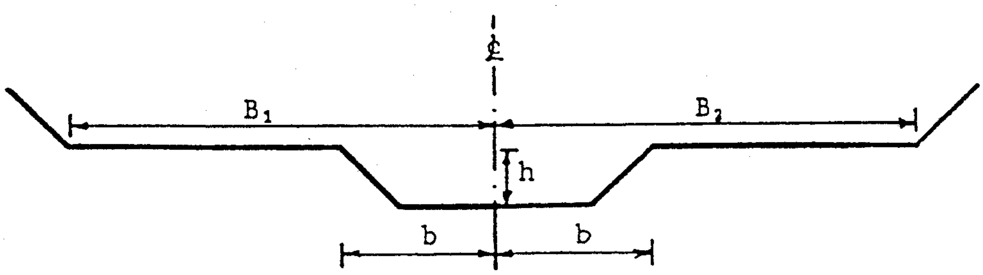
---

REMARKS

Flow measured at road bridge = flow in main channel + flow in side channel + flow over road
No geometric data for site
Weir at Castle Mill takes very high flows before overtopping, but no adjacent experimental site.

---

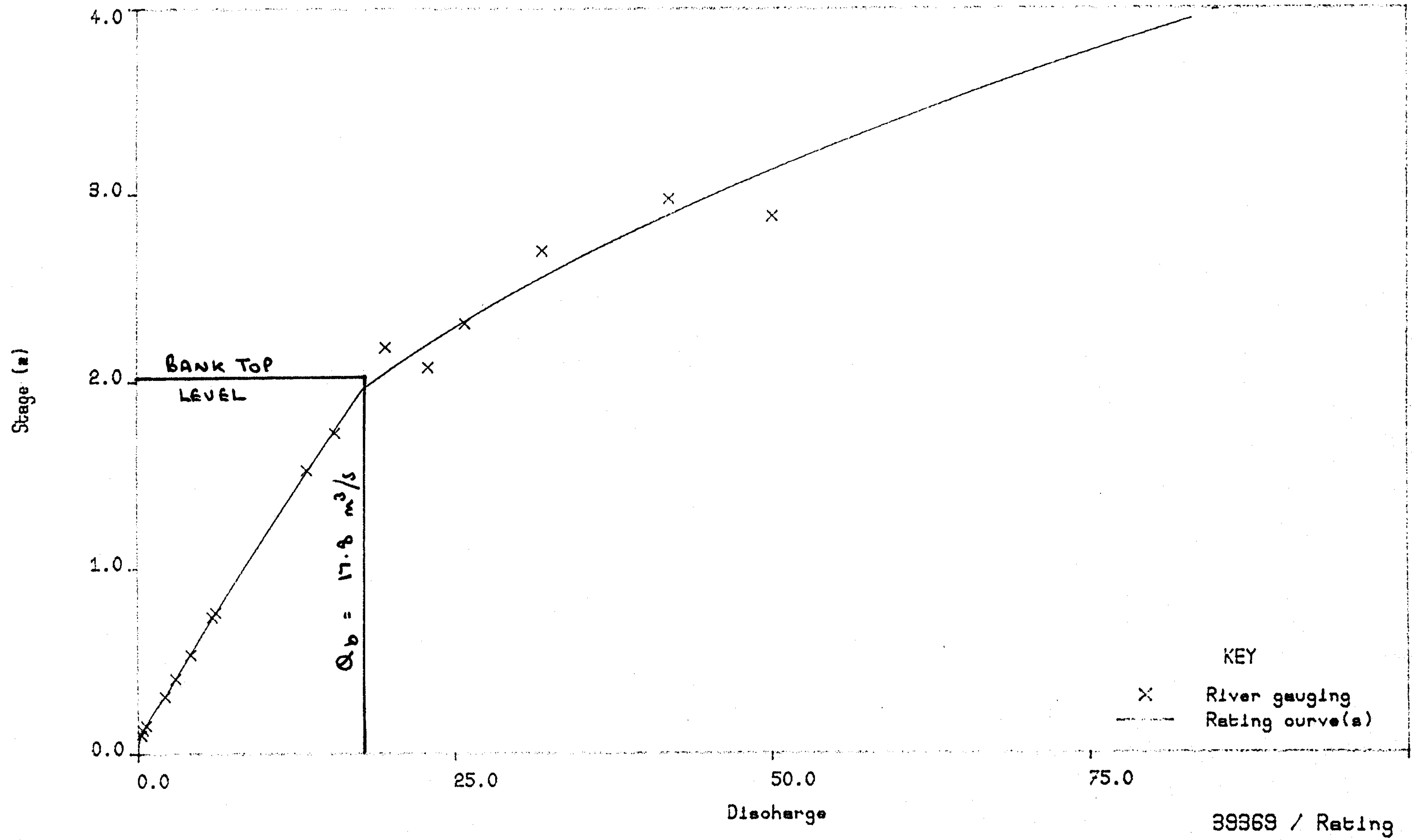
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | |
|---|---|---|---|
| Half width of main channel (b) | | m | $B_1$ |
| Bankfull depth of main channel (h) | | m | $B_2$ |
| Area of main channel at bankfull stage | | $m^2$ | |
| Hydraulic radius of main channel at bankfull stage | | m | |
| Bankfull discharge (stage 2.02m) | 17.8 | $m^3/s$ | |
| Maximum recorded discharge (stage 2.88m) | 50.2 | $m^3/s$ | |
| Channel slope | | m/km | |
| Valley slope | | m/km | |
| Sinuosity (length of channel/length of valley) | | | |

Mole at Kinnersley Manor




39369 / Rating

SITE DATA

SITE : OWER
RIVER : BLACKWATER
GAUGING STATION NUMBER : 42014

WATER AUTHORITY : SOUTHERN (HAMPSHIRE)

---

BRIEF DESCRIPTION Crump weir, drowned at high flow. Rating extended using current metering.

Channel bed material : Silty and muddy. Copious weed growth
Floodplain vegetation/topography : Pasture; some trees; bushes on river bank

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 4 |
| Structure rating with nearby floodplain | √ | | |
| Flood routing reach | | √ | |

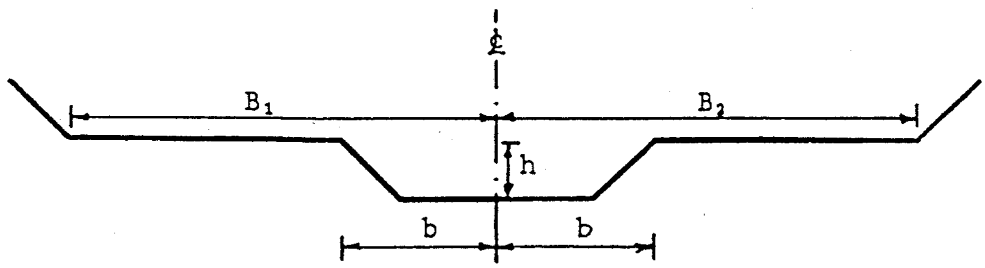
---

REMARKS

Floodplain narrows towards road bridge (c 100m downstream)
Current metering data available
Photographs

---

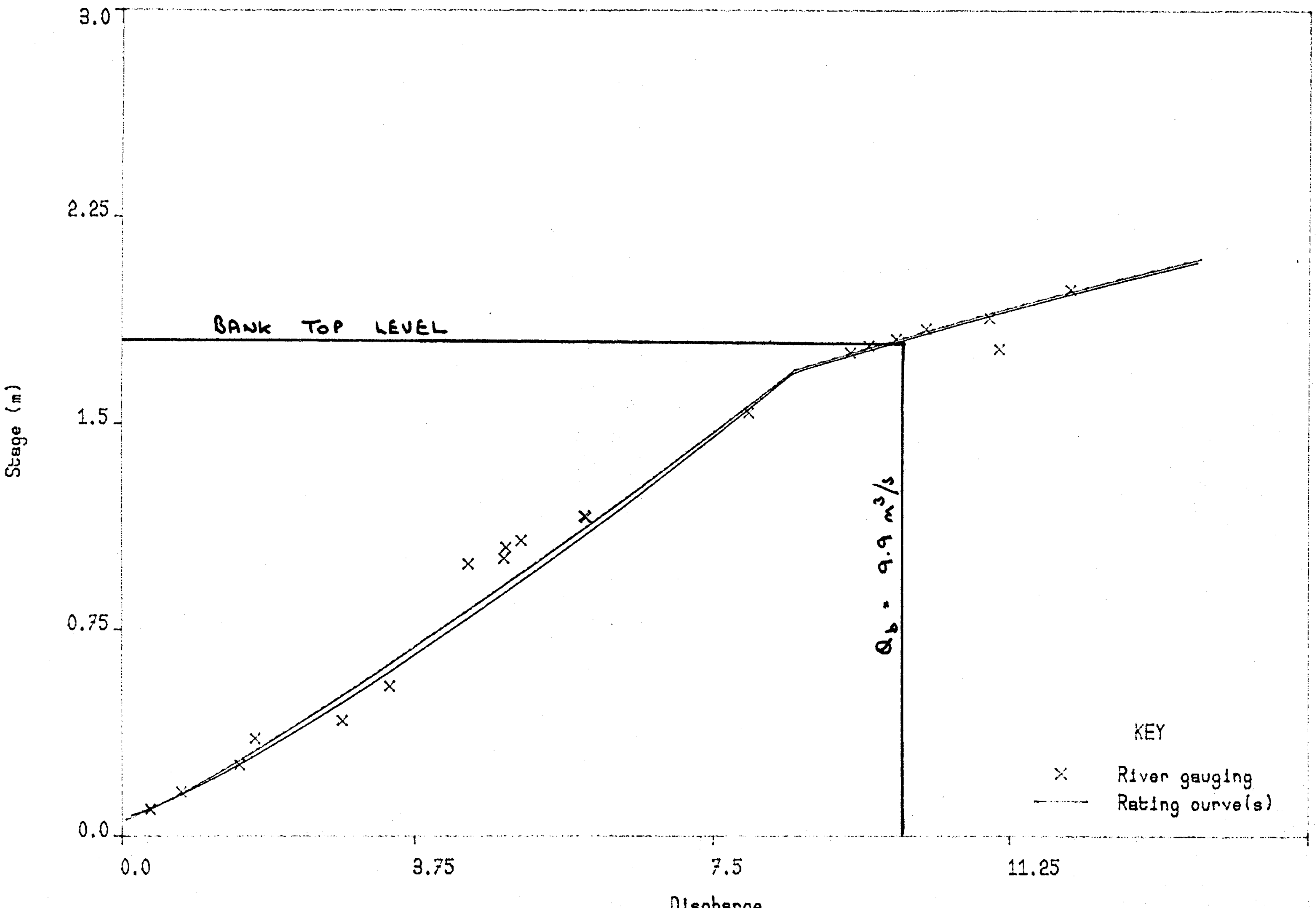
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | | |
|---|---|---|---|---|---|
| Half width of main channel (b) | 6 | m | $B_1$ | 14 | m |
| Bankfull depth of main channel (h) | 1.8 | m | $B_2$ | 40 | m |
| Area of main channel at bankfull stage | 11.7 | $m^2$ | | | |
| Hydraulic radius of main channel at bankfull stage | 0.79 | m | | | |
| Bankfull discharge (stage 1.8m) | 9.9 | $m^3/s$ | | | |
| Maximum recorded discharge (stage 1.99m) | 12.0 | $m^3/s$ | | | |
| Channel slope | 1.52 | m/km | | | |
| Valley slope | 1.69 | m/km | | | |
| Sinuosity (length of channel/length of valley) | 1.11 | | | | |

Blackwater at Ower




42014 / Rating

SITE DATA

SITE : WOOD MILL
RIVER : CULM
GAUGING STATION NUMBER : 45003

WATER AUTHORITY : SOUTH WEST

---

BRIEF DESCRIPTION Low flow weir with approx 100m flood plain on left bank. Whole section current metered

Channel bed material : Sandy gravel. Extensive weed growth
Floodplain vegetation/topography : Short grass (pasture). Tree lined stretches u/s and d/s. Topography gently undulating

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 27 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

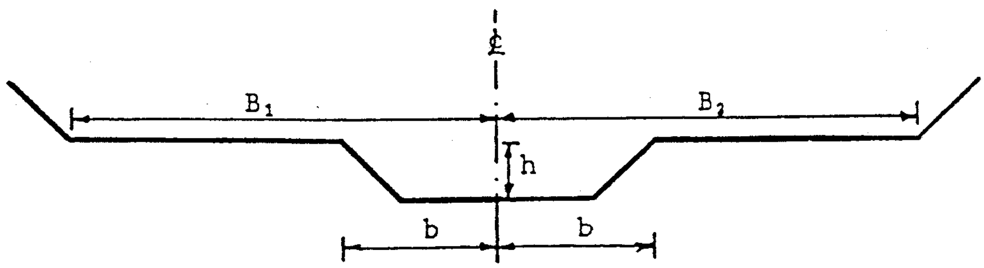
---

REMARKS

371 gaugings
Manning's 'n' rises slightly with stage for in-bank flow (possible afflux from road bridge 500m d/s)
Photographs
Max recorded stage 3.33m

---

DATA FOR OVERBANK FLOW CALCULATION

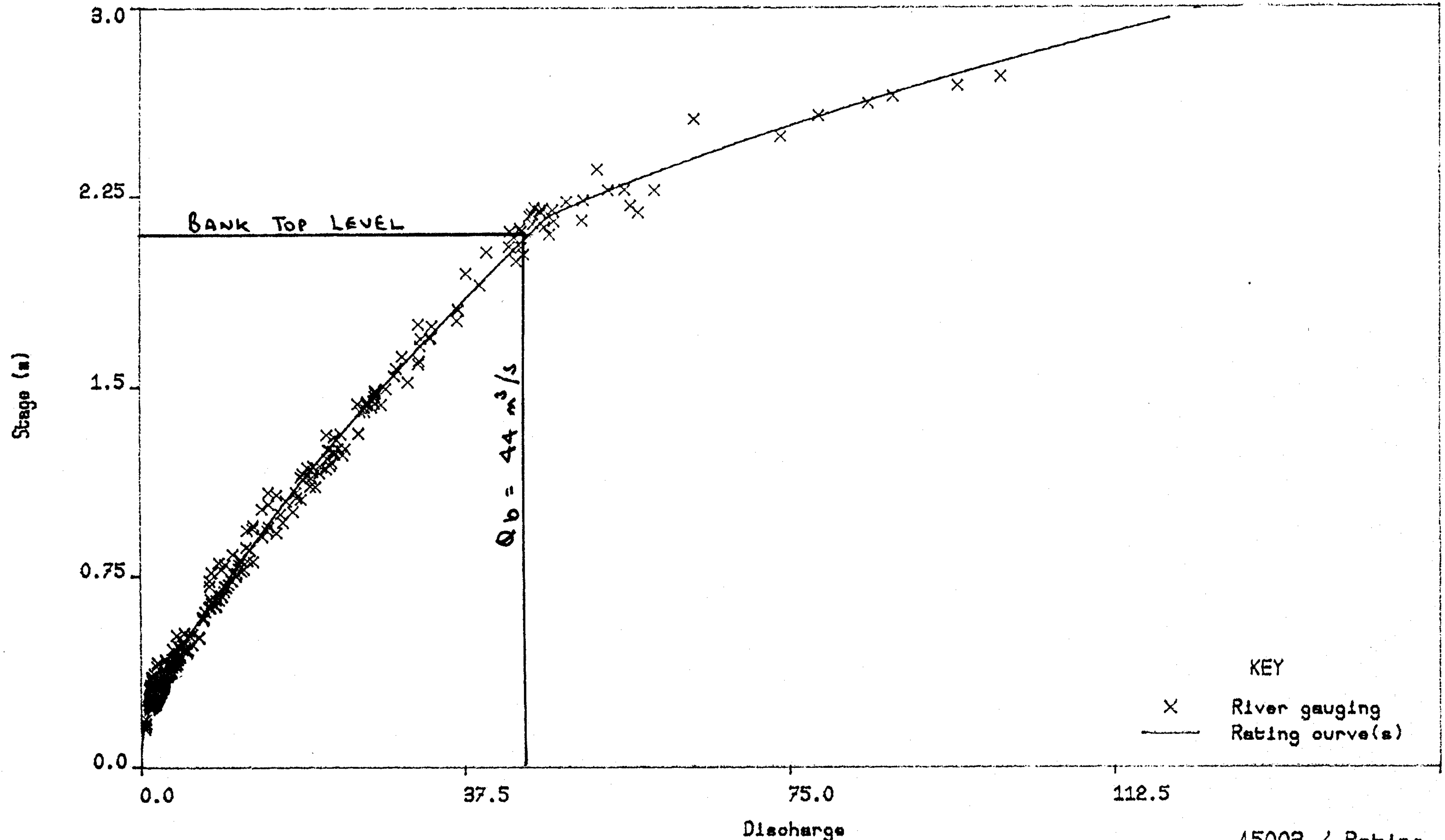



SECTION
(looking downstream)

| | | | | | |
|---|---|---|---|---|---|
| Half width of main channel (b) | 10 | m | $B_1$ | 100 | m* |
| Bankfull depth of main channel (h) | 2.3 | m | $B_2$ | 11 | m |
| Area of main channel at bankfull stage | 31 | $m^2$ | | | |
| Hydraulic radius of main channel at bankfull stage | 1.52 | m | | | |
| Bankfull discharge (stage 2.09m) | 44 | $m^3/s$ | | | |
| Maximum recorded discharge (stage 2.73m) | 99 | $m^3/s$ | | | |
| Channel slope | 2.06 | m/km | | | |
| Valley slope | 2.18 | m/km | | | |
| Sinuosity (length of channel/length of valley) | 1.06 | | | | |

* (64m to bund at level 2.62m)

Culm at Wood Mill




45003 / Rating

SITE DATA

SITE : TORRINGTON
RIVER : TORRIDGE
GAUGING STATION NUMBER : 50002

WATER AUTHORITY : SOUTH WEST

---

BRIEF DESCRIPTION Natural section with approx 100m flood plain on left bank. Whole section current metered

Channel bed material : Small stones to 0.3m diameter rocks
Floodplain vegetation/topography : Pasture. Trees along river bank and floodbank

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 13 |
| Structure rating with nearby floodplain | √ | | |
| Flood routing reach | | √ | |

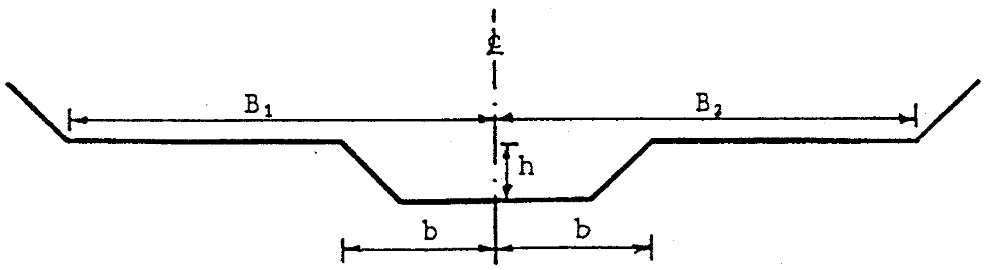
---

REMARKS

Maximum recorded stage 5.76m (28.12.79)
Cableway across river to flood bund at level 4.4m

---

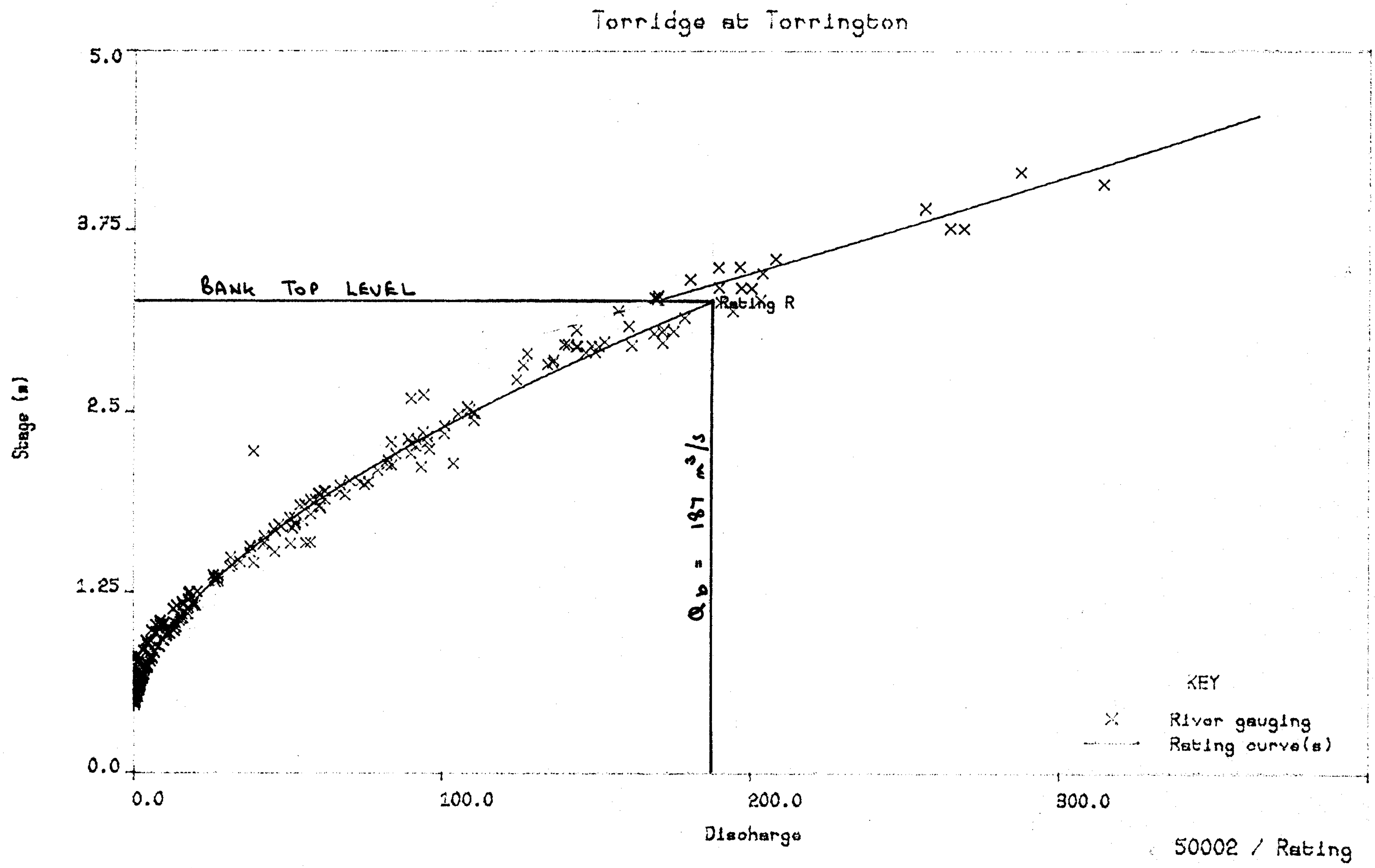
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | | |
|---|---|---|---|---|---|
| Half width of main channel (b) | 14.5 | m | $B_1$ | 106 | m* |
| Bankfull depth of main channel (h) | 2.8 | m | $B_2$ | 14.5 | m |
| Area of main channel at bankfull stage | 71.6 | $m^2$ | | | |
| Hydraulic radius of main channel at bankfull stage | 2.4 | m | | | |
| Bankfull discharge (stage 3.2m) | 187 | $m^3/s$ | | | |
| Maximum recorded discharge (stage 4.07m) | 314 | $m^3/s$ | | | |
| Channel slope | 1.39 | m/km | | | |
| Valley slope | 1.52 | m/km | | | |
| Sinuosity (length of channel/length of valley) | 1.09 | | | | |

* (42m to bund at level 4.4m)


Torridge at Torrington
Stage (m)
5.0
3.75
2.5
1.25
0.0
BANK TOP LEVEL
Rating R
Qb = 187 m³/s
0.0
100.0
200.0
300.0
Discharge
KEY
River gauging
Rating curve(s)
50002 / Rating

SITE DATA

SITE : PRESTON
RIVER : TEIGN
GAUGING STATION NUMBER : 46002

WATER AUTHORITY : SOUTH WEST

---

BRIEF DESCRIPTION Natural section. Site bypassed during floods on right flood plain (200m wide). Velocity area flow gauging station

Channel bed material : Small gravel and sand
Floodplain vegetation/topography : Pasture, a few fences, occasional bushes

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 5 (bypass flow measured) |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

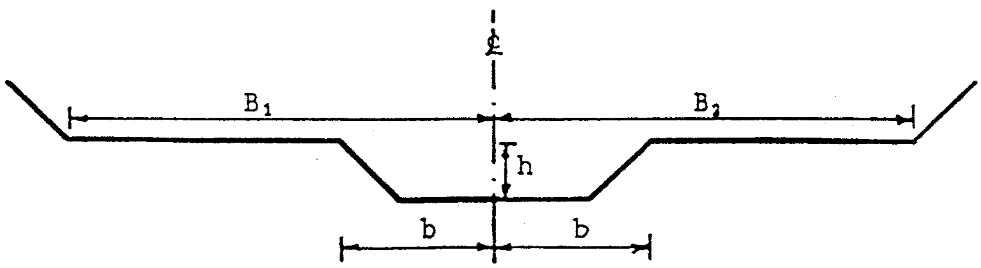
---

REMARKS

Highest recorded stage 3.15m. Photographs. Left bank flood plain reduced to negligible proportions by tipping, 1979. Right bank flood plain separated from river by local highspots. Therefore not a true overbank flow site.

---

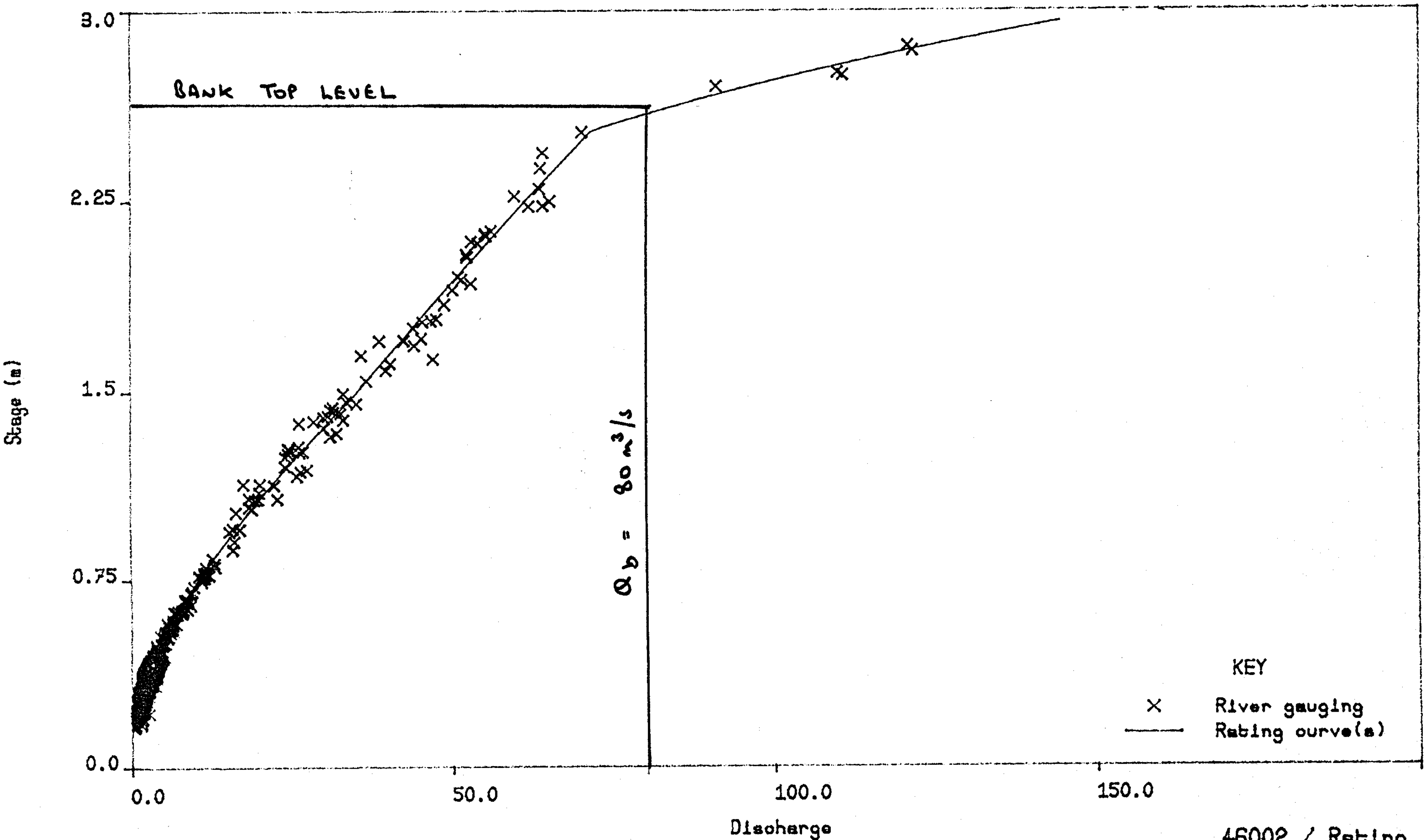
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | |
|---|---|---|---|
| Half width of main channel (b) | | m | $B_1$ |
| Bankfull depth of main channel (h) | | m | $B_2$ |
| Area of main channel at bankfull stage | | $m^2$ | |
| Hydraulic radius of main channel at bankfull stage | | m | |
| Bankfull discharge (stage 2.63m) | 80 | $m^3/s$ | |
| Maximum recorded discharge (stage 2.84m) | 121 | $m^3/s$ | |
| Channel slope | | m/km | |
| Valley slope | | m/km | |
| Sinuosity (length of channel/length of valley) | | | |

Teign at Preston




46002 / Rating

SITE DATA

SITE : MONTFORD
RIVER : SEVERN
GAUGING STATION NUMBER : 54005

WATER AUTHORITY : SEVERN TRENT

---

BRIEF DESCRIPTION Velocity area station. Cableway extends over channel and both floodplains (since 1985)

Channel bed material :
Floodplain vegetation/topography : Grass covered

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 37 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

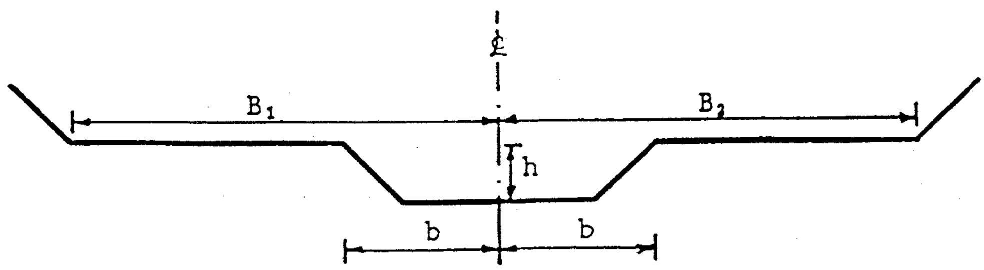
---

REMARKS

Excellent overbank flow site on straight reach of river.
Cableway extended 65m including right bank flood plain only up to 1985.
Prone to weed growth in summer
Photograph

---

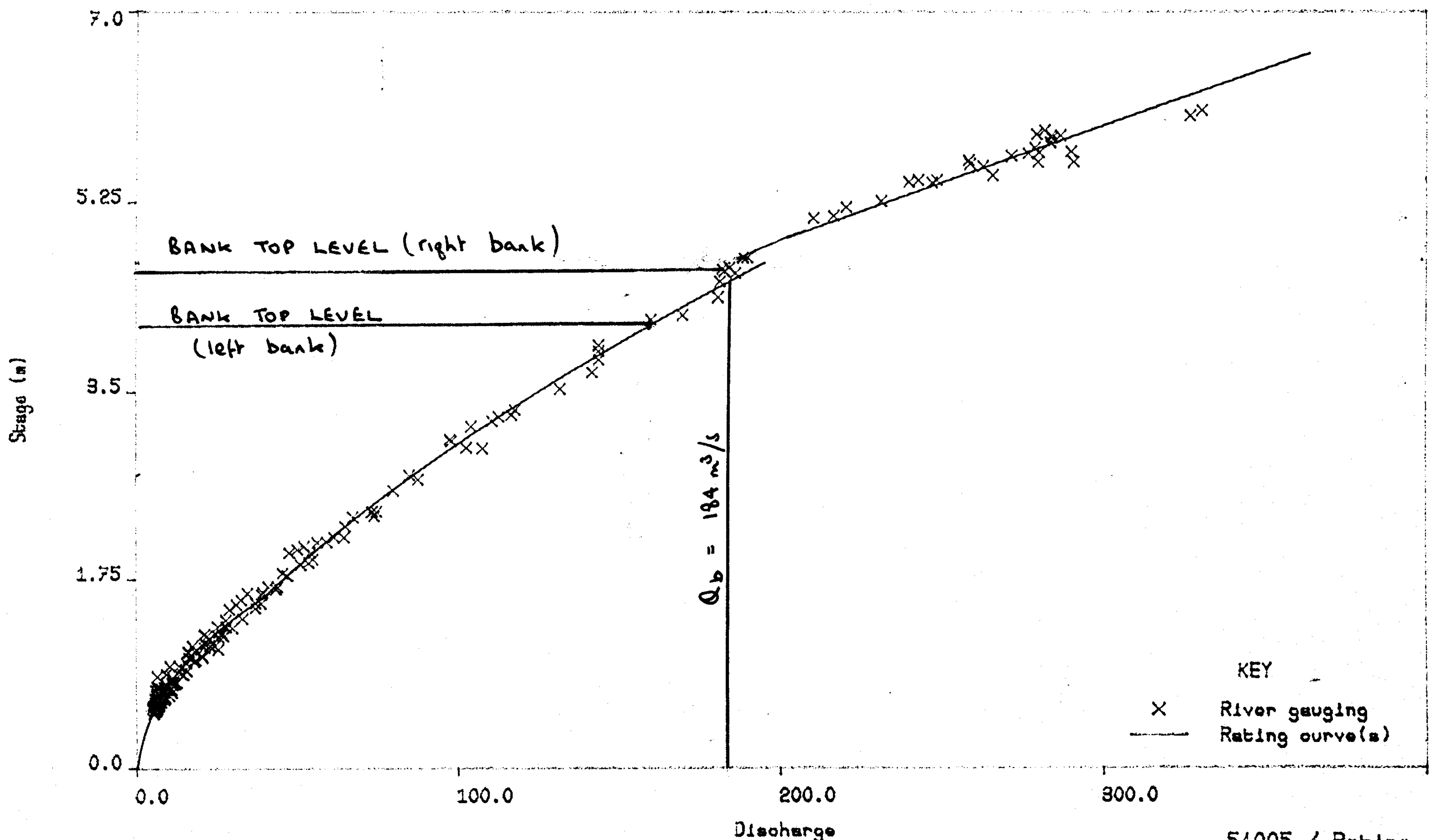
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | | |
|---|---|---|---|---|---|
| Half width of main channel (b) | 19.5 | m | $B_1$ | 80 | m |
| Bankfull depth of main channel (h) | 6.3 | m | $B_2$ | 45 | m |
| Area of main channel at bankfull stage | 162 | $m^2$ | | | |
| Hydraulic radius of main channel at bankfull stage | 3.41 | m | | | |
| Bankfull discharge (stage 4.6m) | 184 | $m^3/s$ | | | |
| Maximum recorded discharge (stage 6.09m) | 331 | $m^3/s$ | | | |
| Channel slope | 0.195 | m/km | | | |
| Valley slope | 0.249 | m/km | | | |
| Sinuosity (length of channel/length of valley) | 1.28 | | | | |

Severn at Montford




54005 / Rating

SITE DATA

SITE : PENKRIDGE
RIVER : PENK
GAUGING STATION NUMBER : 28053

WATER AUTHORITY : SEVERN TRENT

---

BRIEF DESCRIPTION Velocity area gauging station. Cableway spans main channel

Channel bed material : Alluvial with sand and gravels
Floodplain vegetation/topography : Grass, with trees lining right bank

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 10 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

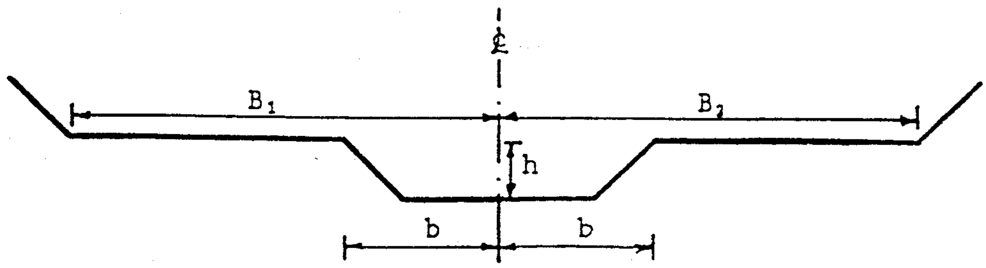
---

REMARKS

Bridge 35m downstream
Current meter data indicates cableway spans floodplains (total width 40m)
Noticable difference between summer and winter overbank ratings

---

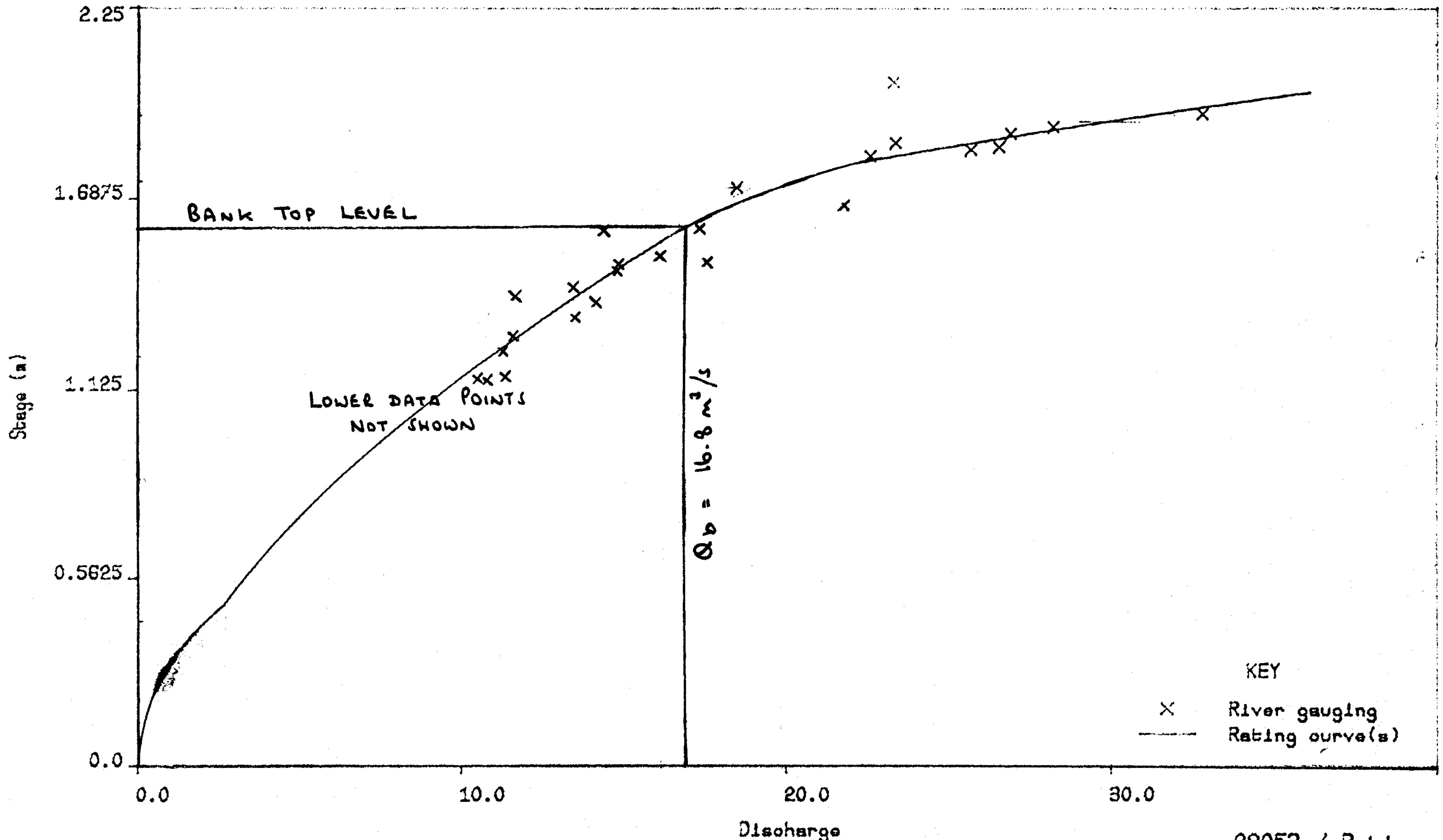
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | |
|---|---|---|---|---|
| Half width of main channel (b) | 7.5 | m | $B_1$ | 22.5m |
| Bankfull depth of main channel (h) | 1.8 | m | $B_2$ | 17 m |
| Area of main channel at bankfull stage | 18.3 | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | 1.13 | m | | |
| Bankfull discharge (stage 1.60m) | 16.8 | $m^3/s$ | | |
| Maximum recorded discharge (stage 1.94m) | 32.8 | $m^3/s$ | | |
| Channel slope | 1.5 | m/km | | |
| Valley slope | 1.7 | m/km | | |
| Sinuosity (length of channel/length of valley) | 1.13 | | | |

Penk at Penkridge




28053 / Rating

SITE DATA

SITE : NORTH MUSKHAM
RIVER : TRENT
GAUGING STATION NUMBER : 28022

WATER AUTHORITY : SEVERN TRENT

---

BRIEF DESCRIPTION Velocity area gauging station. Cableway covers main channel and berm. Bypassing at high flows

Channel bed material : Fine gravel/alluvial silts
Floodplain vegetation/topography : Mainly grass. Some small trees and bushes

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 35 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

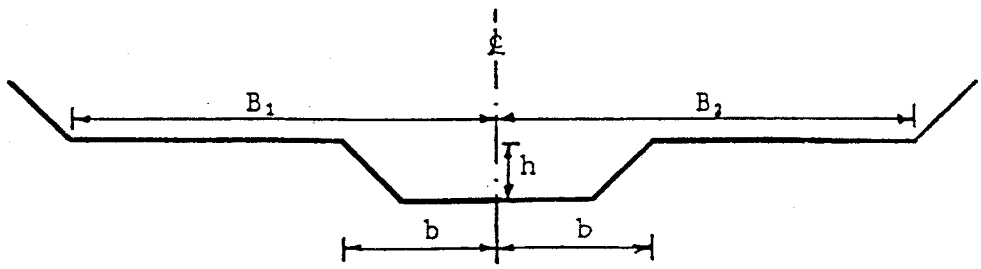
---

REMARKS

Site within backwater of Cromwell weir, 1.3km downstream
300m wide floodplain on right bank. Flow occurs in floodplain outside cableway above stage 3.34m approx
Photograph

---

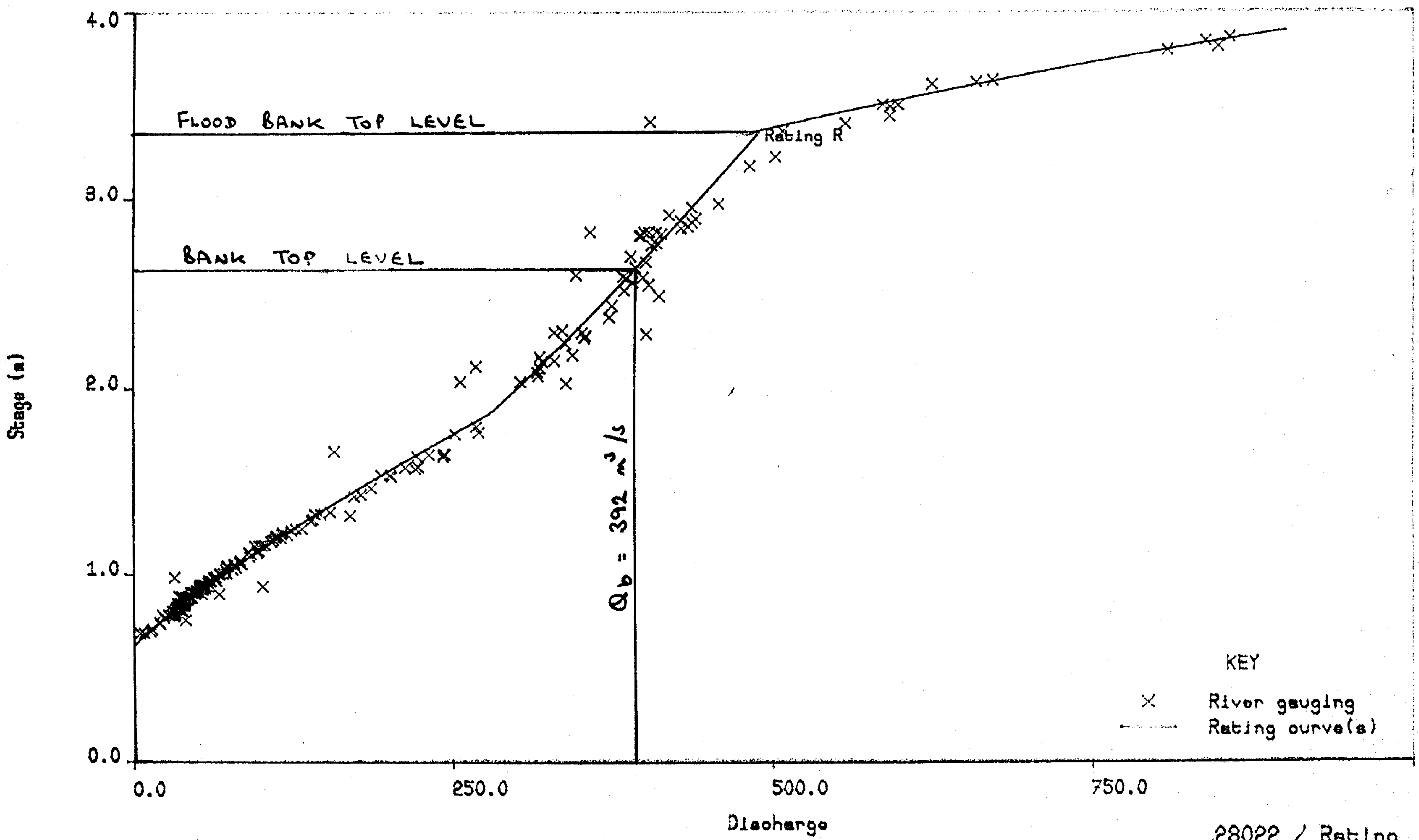
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | |
|---|---|---|---|---|
| Half width of main channel (b) | 36 | m | $B_1$ | 36m |
| Bankfull depth of main channel (h) | 5.6 | m | $B_2$ | 64m |
| Area of main channel at bankfull stage | 321 | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | 4.36 | m | | |
| Bankfull discharge (stage 2.62m) | 392 | $m^3/s$ | | |
| Maximum recorded discharge (stage 3.86m) | 858 | $m^3/s$ | | |
| Channel slope | 0.28 | m/km | | |
| Valley slope | 0.35 | m/km | | |
| Sinuosity (length of channel/length of valley) | 1.25 | | | |

Trent at North Muskham




28022 / Rating

SITE DATA

SITE : SKELTON
RIVER : OUSE
GAUGING STATION NUMBER : 27009

WATER AUTHORITY : YORKSHIRE

---

BRIEF DESCRIPTION Natural section with narrow berms spanned by cableway. Floodbanks overtopped at high discharges

Channel bed material : Clay
Floodplain vegetation/topography : Grass with numerous trees and bushes

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 12 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

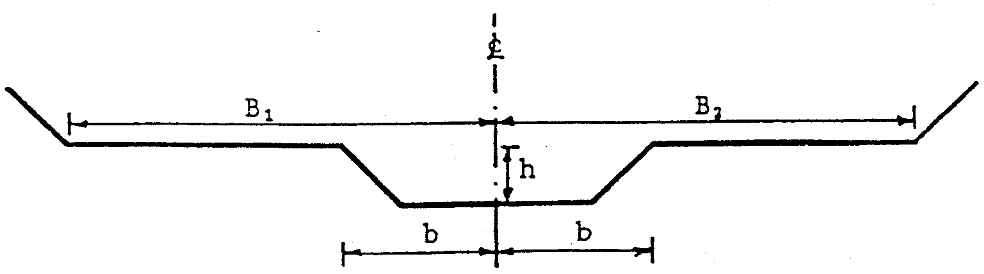
---

REMARKS

Berms very small compared to main channel
Limited value as overbank flow site
Numerous photographs
Rapid increase in velocity above bankfull level which confounds all flow estimation methods (also observed at North Muskham)
Flood bank levels approx 5.6m
Maximum estimated discharge 700m³/s (stage 6.41m)

---

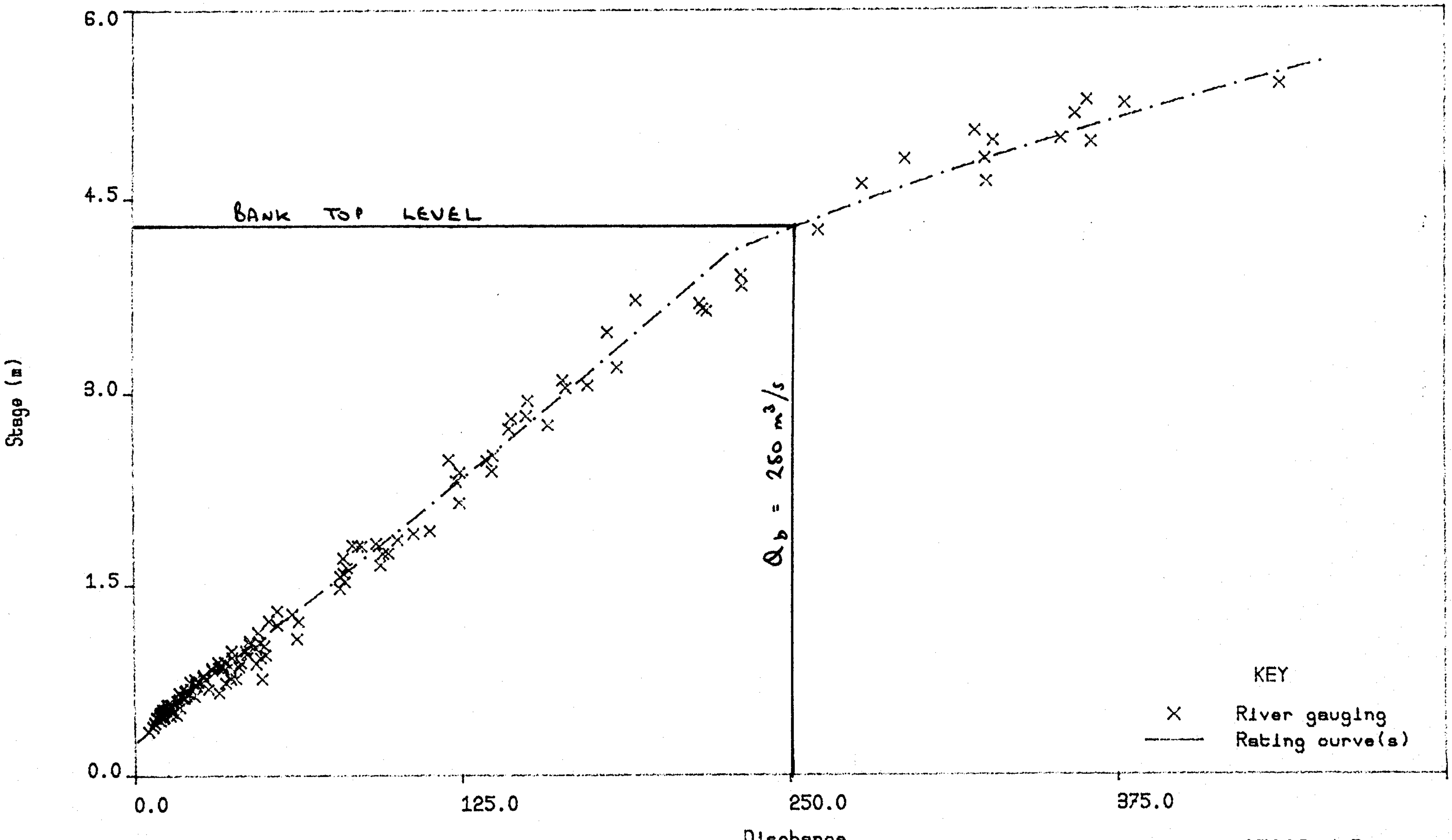
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | |
|---|---|---|---|---|
| Half width of main channel (b) | 27 | m | $B_1$ | 34m |
| Bankfull depth of main channel (h) | 9.4 | m | $B_2$ | 34m |
| Area of main channel at bankfull stage | 314 | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | 5.3 | m | | |
| Bankfull discharge (stage 4.3m) | 250 | $m^3/s$ | | |
| Maximum recorded discharge (stage 5.39m) | 437 | $m^3/s$ | | |
| Channel slope : | 0.15 | m/km | | |
| Valley slope | 0.15 | m/km | | |
| Sinuosity (length of channel/length of valley) | 1 | | | |

Ouse at Skelton




27009 / Rating

SITE DATA

SITE : MITFORD
RIVER : WANSBECK
GAUGING STATION NUMBER : 22007

WATER AUTHORITY : NORTHUMBRIAN

---

BRIEF DESCRIPTION Low flow weir and cableway

Channel bed material : Cobbles/silt
Floodplain vegetation/topography : Right bank : grass with trees along bank. Left bank : grass upstream. Scrub at recorder house

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 12 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

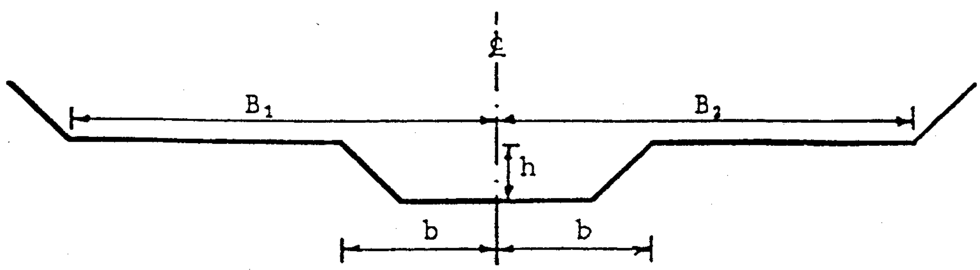
---

REMARKS

Details of structure and site geometry available
Cableway 60m u/s of weir spans channel and part of floodplain (length 32m)
Therefore only part of floodplain flow measured.
Two sets of rating data (1968-69 and 1976 to date), before and after weir construction. Latter set used
Photographs

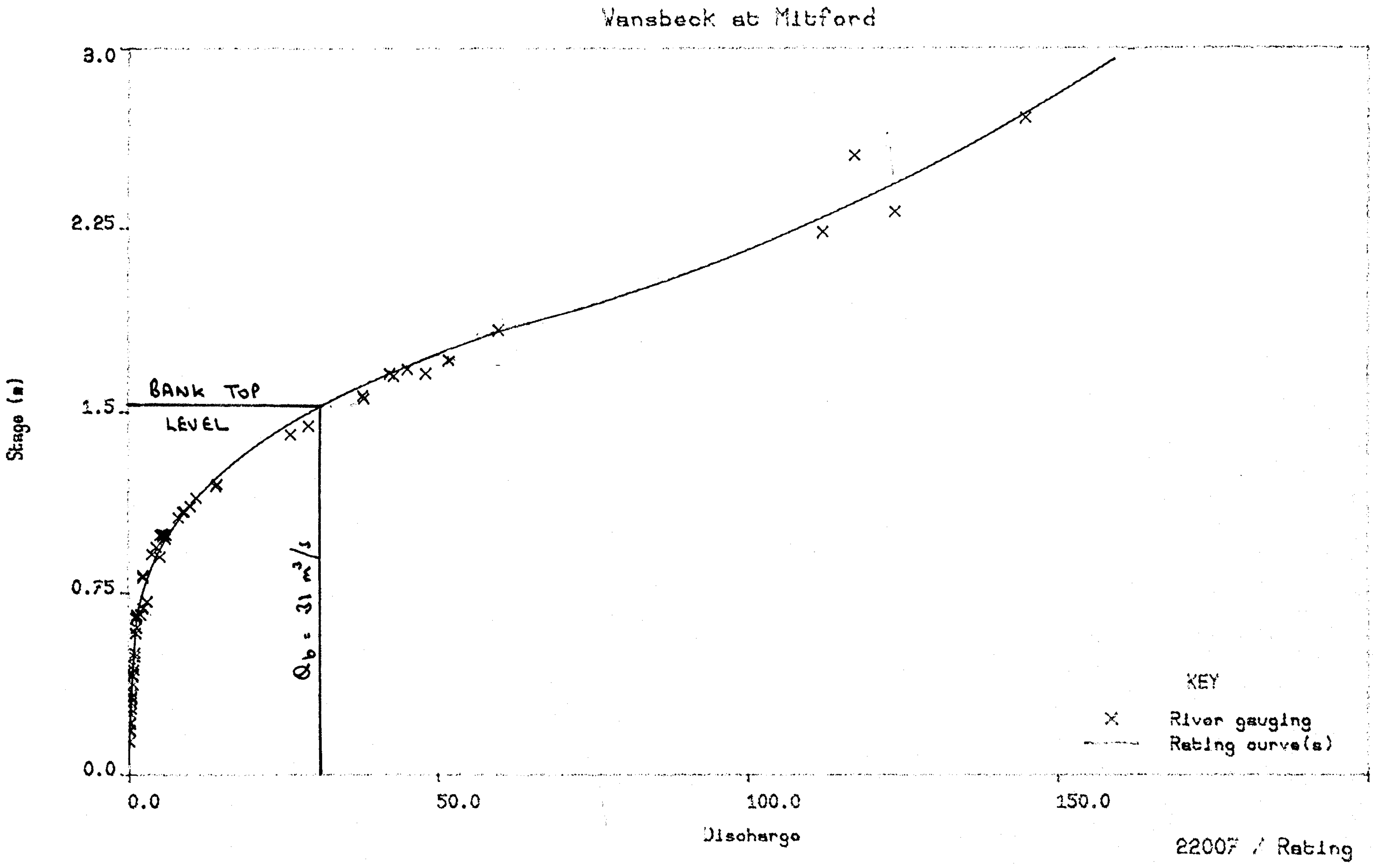
---

DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | |
|---|---|---|---|---|
| Half width of main channel (b) | 10.5 | m | $B_1$ | 25m |
| Bankfull depth of main channel (h) | 1.8 | m | $B_2$ | 14m |
| Area of main channel at bankfull stage | 36.8 | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | 1.58 | m | | |
| Bankfull discharge (stage 1.52m) | 30.9 | $m^3/s$ | | |
| Maximum recorded discharge (stage 2.71m) | 145 | $m^3/s$ | | |
| Channel slope | 4.35 | m/km | | |
| Valley slope | 4.76 | m/km | | |
| Sinuosity (length of channel/length of valley) | 1.09 | | | |


Wansbeck at Mitford
3.0
2.25
1.5
0.75
0.0
Stage (m)
BANK TOP
LEVEL
Qb = 31 m3/s
0.0
50.0
100.0
150.0
Discharge
KEY
River gauging
Rating curve(s)
22007 / Rating

SITE DATA

SITE : HAYDON BRIDGE                    WATER AUTHORITY : NORTHUMBRIAN
RIVER : SOUTH TYNE
GAUGING STATION NUMBER : 23004

---

BRIEF DESCRIPTION Cableway with low flow weir downstream. Narrow berms

Channel bed material : Cobbles/boulders in sand matrix. Bedrock downstream
Floodplain vegetation/topography : Pasture. Some trees and bushes

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 7 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

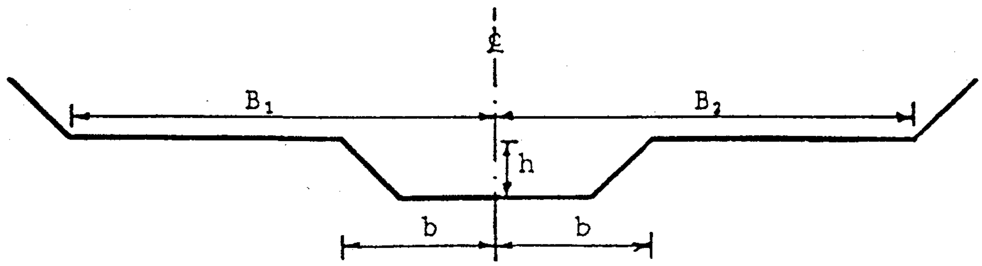
---

REMARKS

Low flow weir crest level approx 0.22m (flat-V)
Details of structure and site geometry available
Photographs

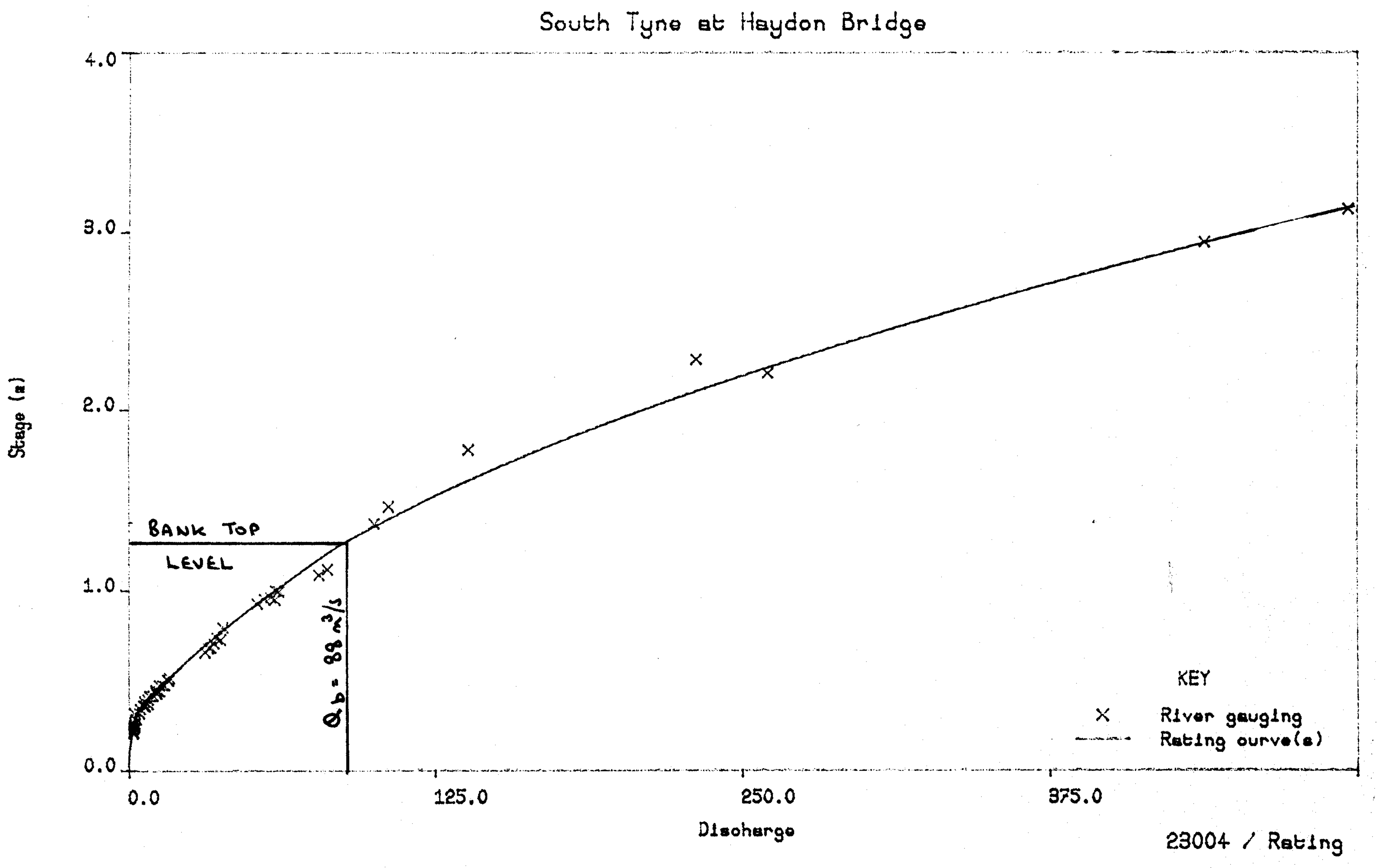
---

DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | |
|---|---|---|---|---|
| Half width of main channel (b) | 25.5 | m | $B_1$ | 41m |
| Bankfull depth of main channel (h) | 1.6 | m | $B_2$ | 27m |
| Area of main channel at bankfull stage | 74 | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | 1.40 | m | | |
| Bankfull discharge (stage 1.27m) | 88 | $m^3/s$ | | |
| Maximum recorded discharge (stage 3.13m) | 496 | $m^3/s$ | | |
| Channel slope | 2.9 | m/km | | |
| Valley slope | | m/km | | |
| Sinuosity (length of channel/length of valley) | | | | |


South Tyne at Haydon Bridge
4.0
3.0
2.0
1.0
0.0
Stage (m)
BANK TOP
LEVEL
$Q_b$ = 88 $m^3/s$
KEY
River gauging
Rating curve(s)
0.0
125.0
250.0
375.0
Discharge
23004 / Rating

SITE DATA

SITE : LOW MOOR
RIVER : TEES
GAUGING STATION NUMBER : 25009

WATER AUTHORITY : NORTHUMBRIAN

---

BRIEF DESCRIPTION Velocity area gauging site with ford downstream and low flow control (flat-V, crest 0.45 - 0.8m)

Channel bed material : Gravel and sand
Floodplain vegetation/topography : Grassed, with some trees (no scrub) on right bank only

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 5 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | √ | | Broken Scar to Low Moor |

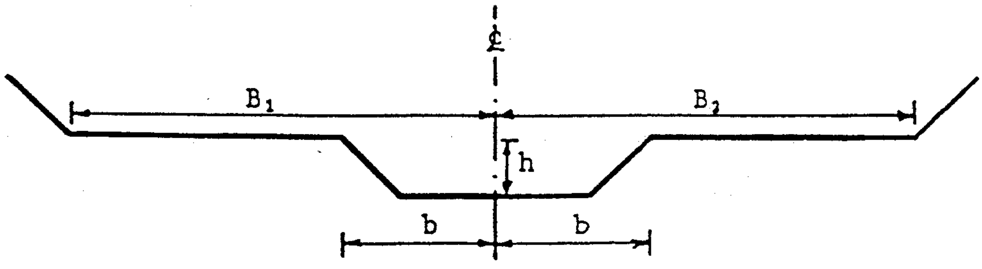
---

REMARKS

Cableway spans main channel. Some current metering in floodplain. North bank flood bund overtops at about 5.86m

---

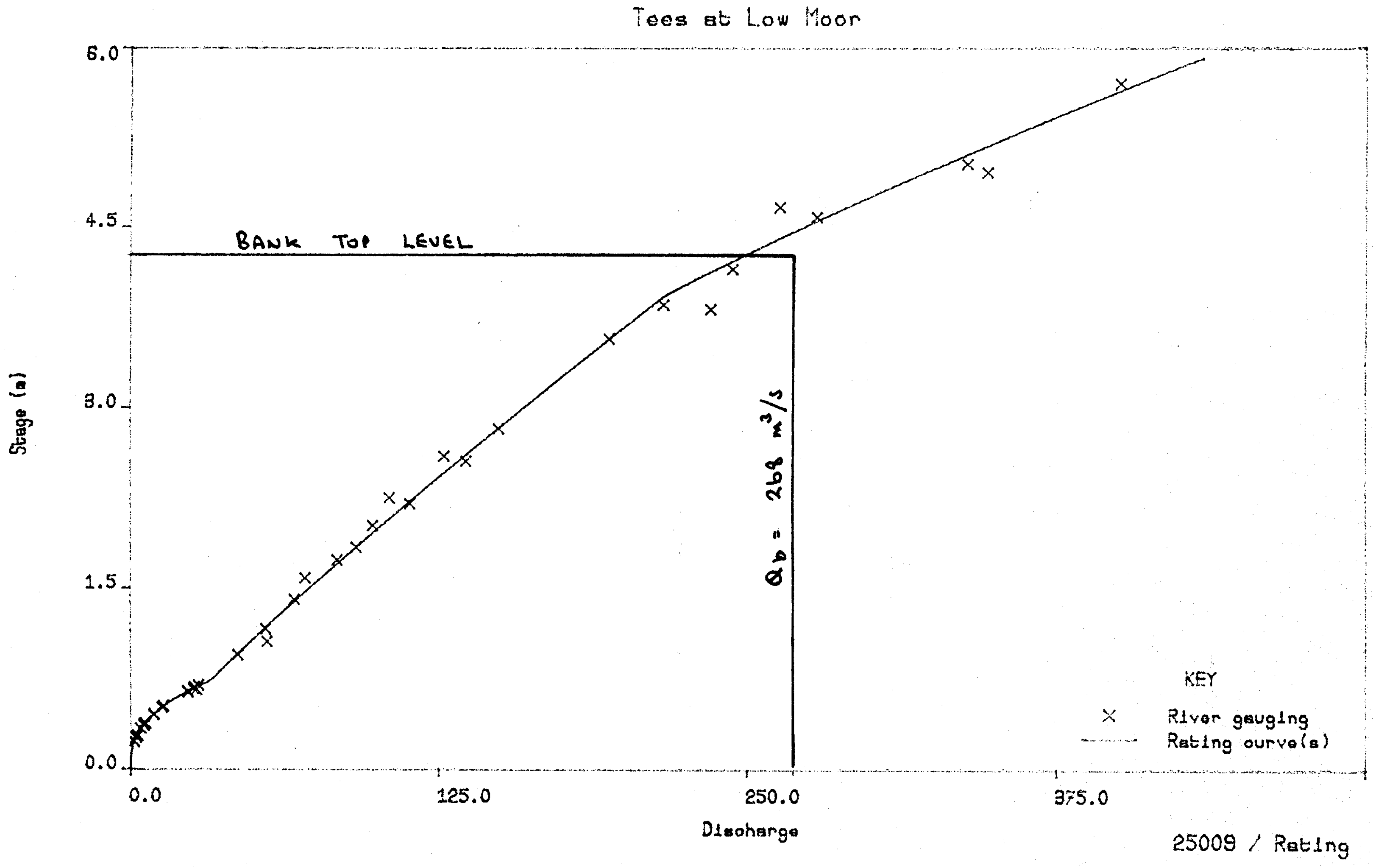
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | |
|---|---|---|---|---|
| Half width of main channel (b) | 27 | m | $B_1$ | 85m* |
| Bankfull depth of main channel (h) | 4.3 | m | $B_2$ | 70m |
| Area of main channel at bankfull stage | 206 | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | 3.55 | m | | |
| Bankfull discharge (stage 4.27m) | 268 | $m^3/s$ | | |
| Maximum recorded discharge (stage 5.7m) | 401 | $m^3/s$ | | |
| Channel slope | 0.73 | m/km | | |
| Valley slope | 0.82 | m/km | | |
| Sinuosity (length of channel/length of valley) | 1.12 | | | |

* (35m to bund at 5.86m)



Tees at Low Moor
6.0
4.5
3.0
1.5
0.0
Stage (m)
BANK TOP LEVEL
Qb = 268 m³/s
0.0
125.0
250.0
375.0
Discharge
KEY
River gauging
Rating curve(s)
25009 / Rating

SITE DATA

SITE : HAMMOON WATER AUTHORITY : WESSEX
RIVER : STOUR
GAUGING STATION NUMBER : 43009

---

BRIEF DESCRIPTION Compound Crump weir supplemented by current metering at bridge downstream

Channel bed material :
Floodplain vegetation/topography :

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | (√) | | 5 |
| Structure rating with nearby floodplain | (√) | | |
| Flood routing reach | √ | | Throop to Hammoon |

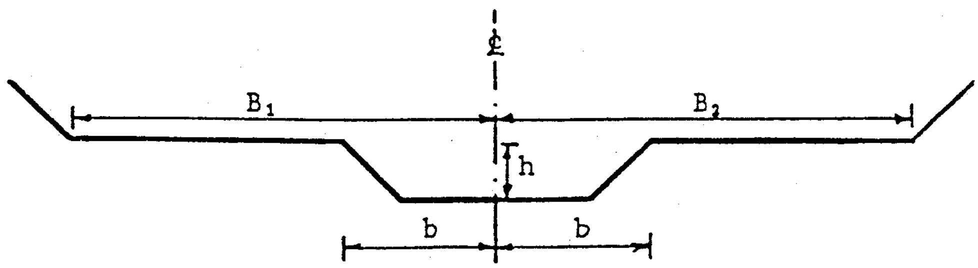
---

REMARKS

Considerable blockage to main channel flow caused by bridge between levels 2.15 and 2.65, which would appear to affect rating
Site data available including maps and details of structure
Suitability as experimental site requires further investigation

---

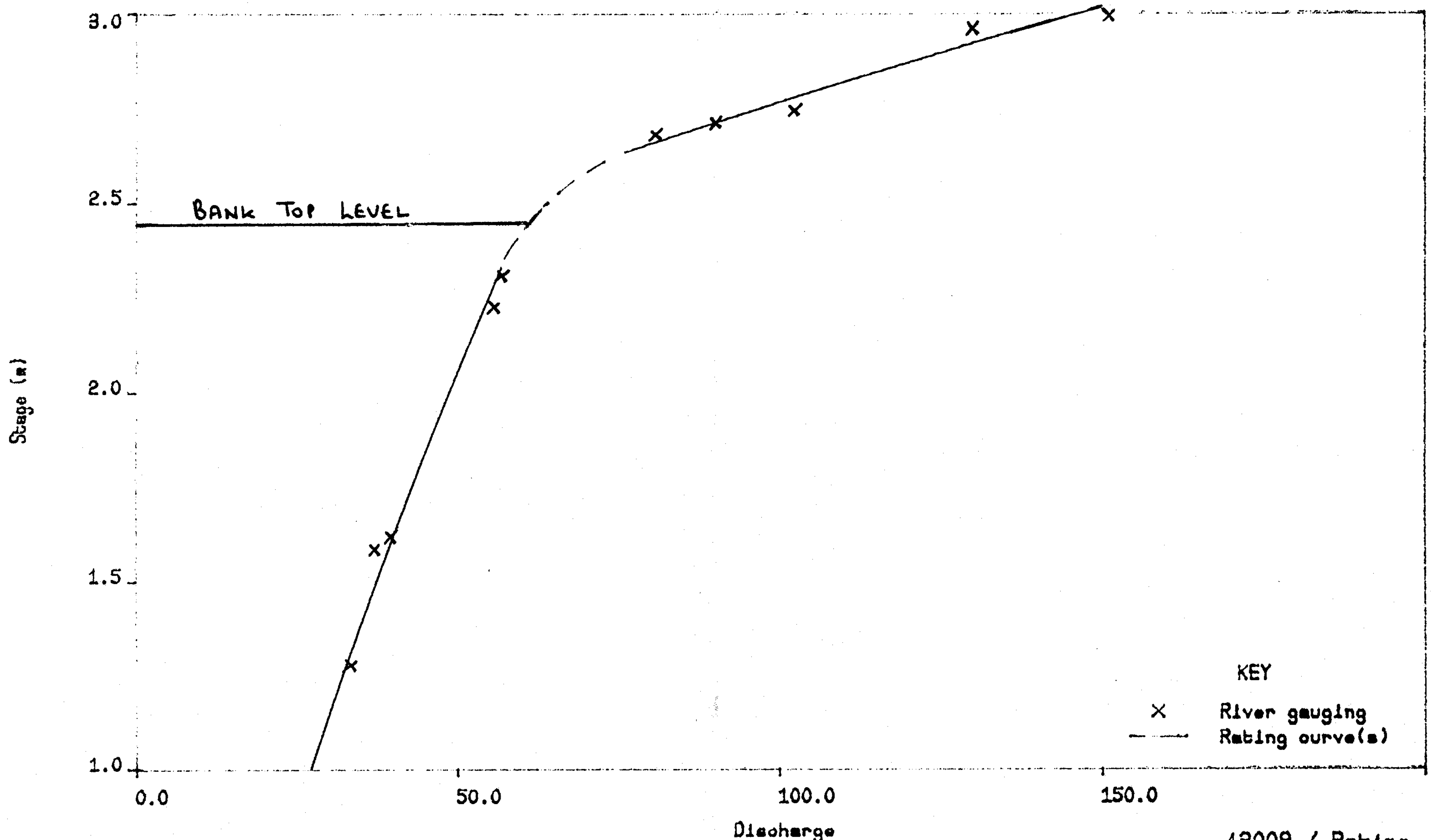
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | | |
|---|---|---|---|---|---|
| Half width of main channel (b) | | m | $B_1$ | m |
| Bankfull depth of main channel (h) | | m | $B_2$ | m |
| Area of main channel at bankfull stage | | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | | m | | |
| Bankfull discharge (stage 2.44m) | 71 | $m^3/s$ | | |
| Maximum recorded discharge (stage 3.0m) | 151 | $m^3/s$ | | |
| Channel slope | | m/km | | |
| Valley slope | | m/km | | |
| Sinuosity (length of channel/length of valley) | | | | |

Stour at Hammoon




43009 / Rating

SITE DATA

SITE : YOXALL
RIVER : TRENT
GAUGING STATION NUMBER : 28012

WATER AUTHORITY : SEVERN TRENT

---

BRIEF DESCRIPTION Velocity area gauging station with large right bank flood plain

Channel bed material : Gravels
Floodplain vegetation/topography : Grass with some bushes

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | (√) | | 4 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

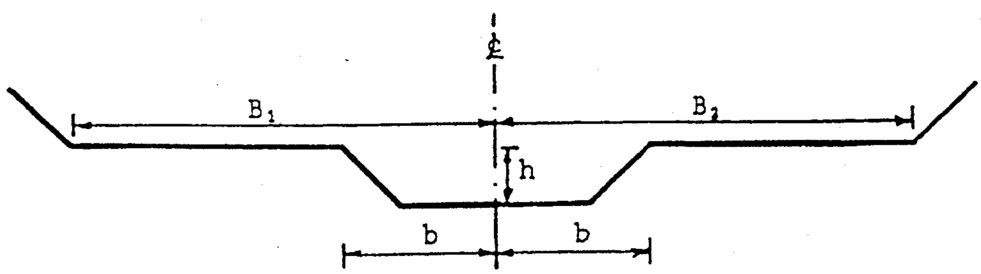
---

REMARKS

Photograph. Cableway gauges main channel. Site bypassed by flow through culverts at Yoxall Bridge, 100m upstream. Total flow = main channel + gauged culvert flows. Main channel and culvert flow separated by training bank (level 2.9m, constructed 1986-7). Possible errors in rating prior to 1986-7. Station prone to weed growth in summer. Not true overbank flow site

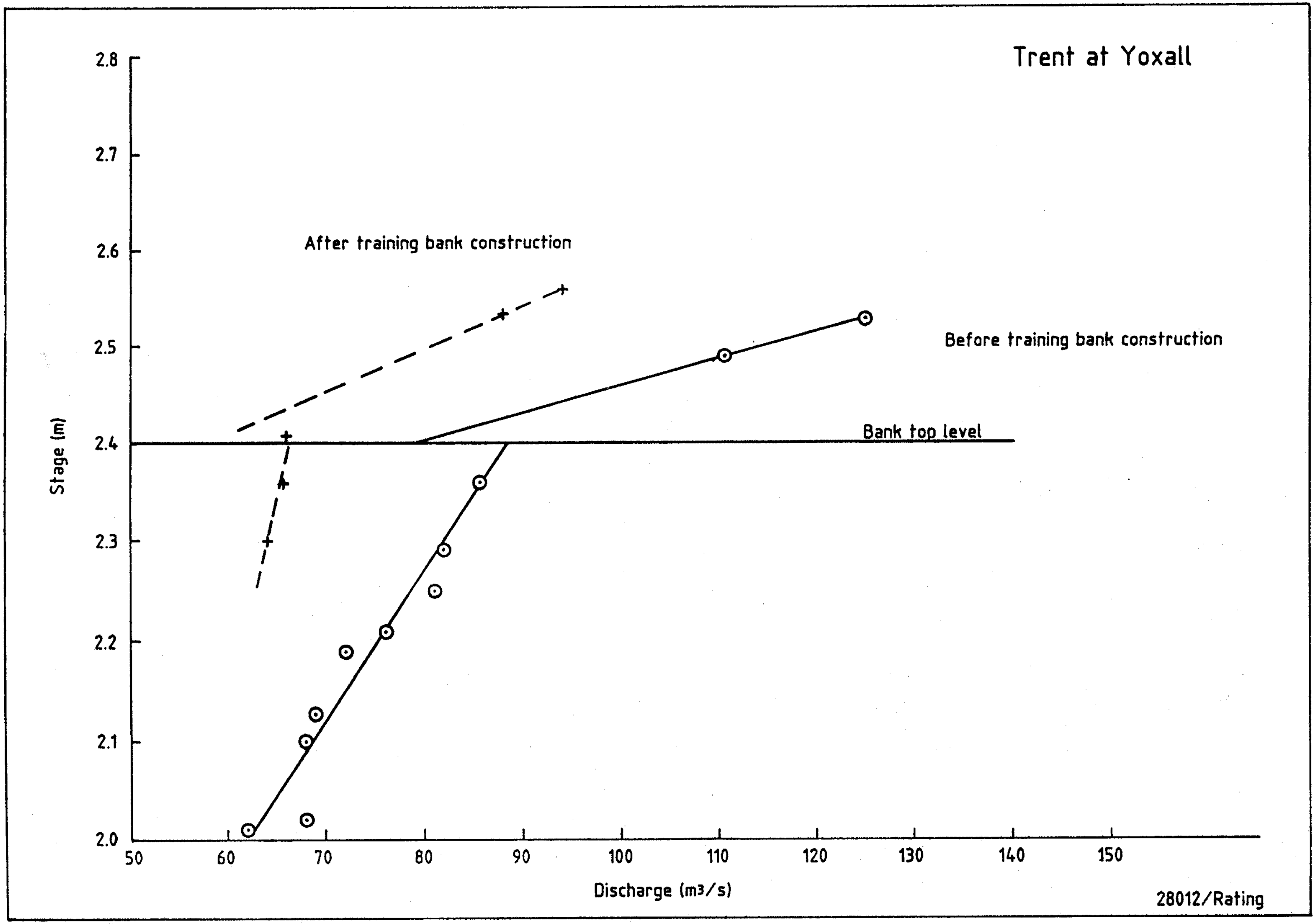
---

DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | |
|---|---|---|---|---|
| Half width of main channel (b) | | m | $B_1$ | m |
| Bankfull depth of main channel (h) | | m | $B_2$ | m |
| Area of main channel at bankfull stage | | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | | m | | |
| Bankfull discharge (stage 2.4m) | 88 | $m^3/s$ | | |
| Maximum recorded discharge (stage m) | | $m^3/s$ | | |
| Channel slope | | m/km | | |
| Valley slope | | m/km | | |
| Sinuosity (length of channel/length of valley) | | | | |


Trent at Yoxall
After training bank construction
Before training bank construction
Bank top level
Stage (m)
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
50
60
70
80
90
100
110
120
130
140
150
Discharge (m3/s)
28012/Rating

SITE DATA

SITE : HAW BRIDGE
RIVER : SEVERN
GAUGING STATION NUMBER : 54057

WATER AUTHORITY : SEVERN TRENT

---

BRIEF DESCRIPTION Road bridge site. Water flows under and over road on left bank during floods

Channel bed material :
Floodplain vegetation/topography :

---

| SITE CATEGORY | YES | NO | Nr overbank points |
|---|---|---|---|
| Overbank flow rating | √ | | 13 |
| Structure rating with nearby floodplain | | √ | |
| Flood routing reach | | √ | |

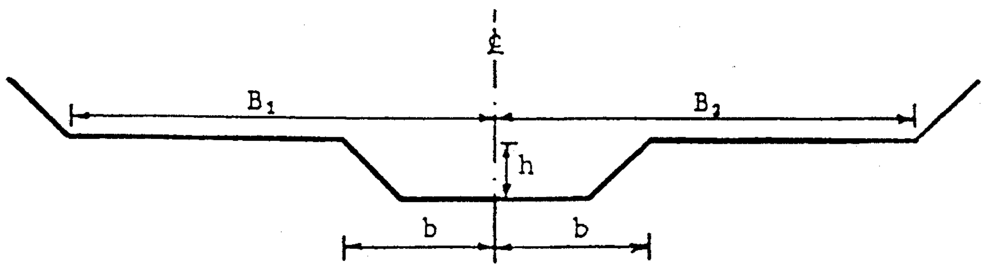
---

REMARKS

No detailed site data available at present

---

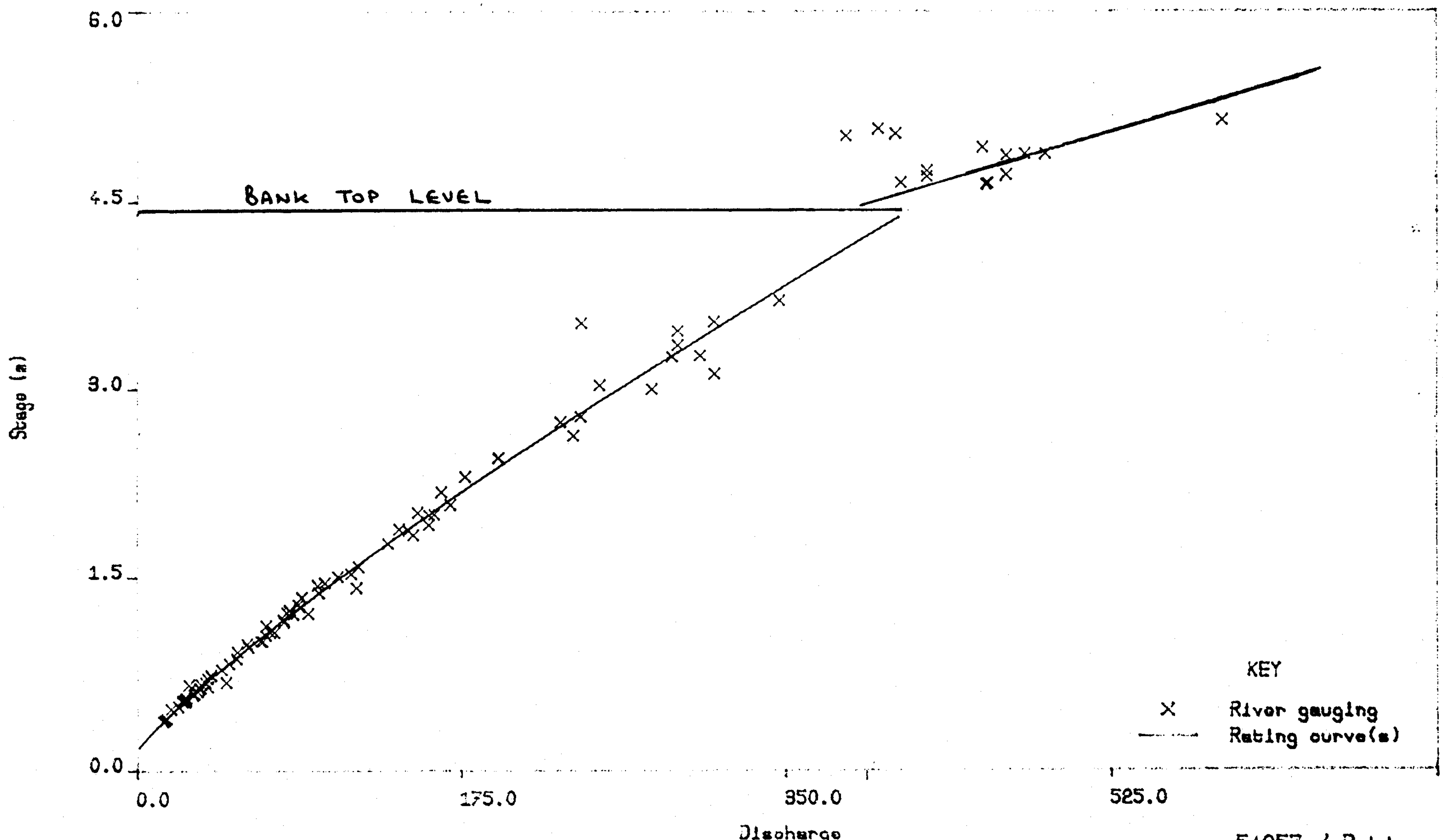
DATA FOR OVERBANK FLOW CALCULATION




SECTION
(looking downstream)

| | | | | |
|---|---|---|---|---|
| Half width of main channel (b) | approx 15 | m | $B_1$ | 200 m approx |
| Bankfull depth of main channel (h) | 4 | m | $B_2$ | 30 m approx |
| Area of main channel at bankfull stage | | $m^2$ | | |
| Hydraulic radius of main channel at bankfull stage | | m | | |
| Bankfull discharge (stage 4.4m) | 400 | $m^3/s$ | | |
| Maximum recorded discharge (stage 5.15m) | 585 | $m^3/s$ | | |
| Channel slope | | m/km | | |
| Valley slope | | m/km | | |
| Sinuosity (length of channel/length of valley) | | | | |

Severn at Haw Bridge

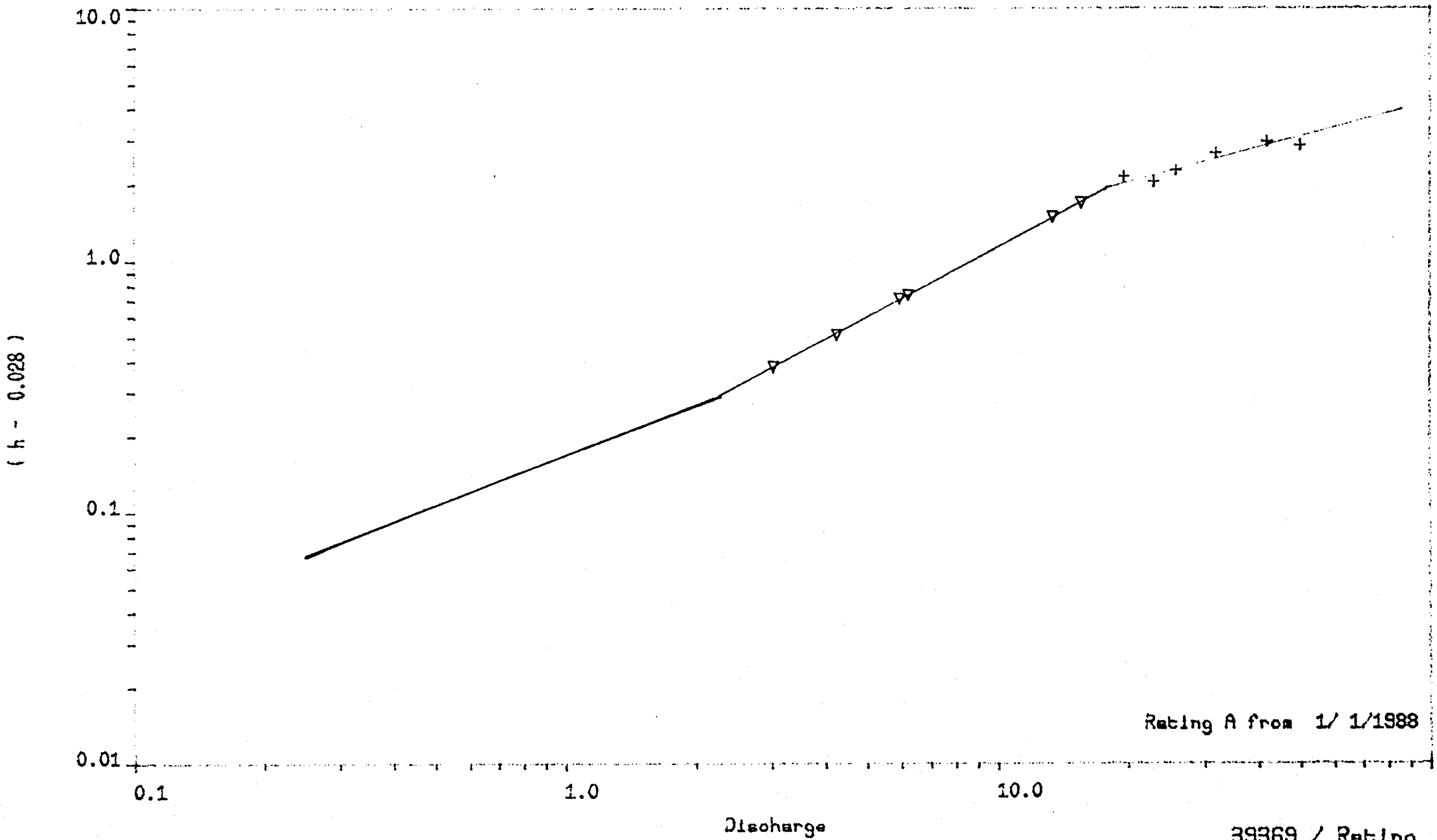



.54057 / Rating

# APPENDIX 2

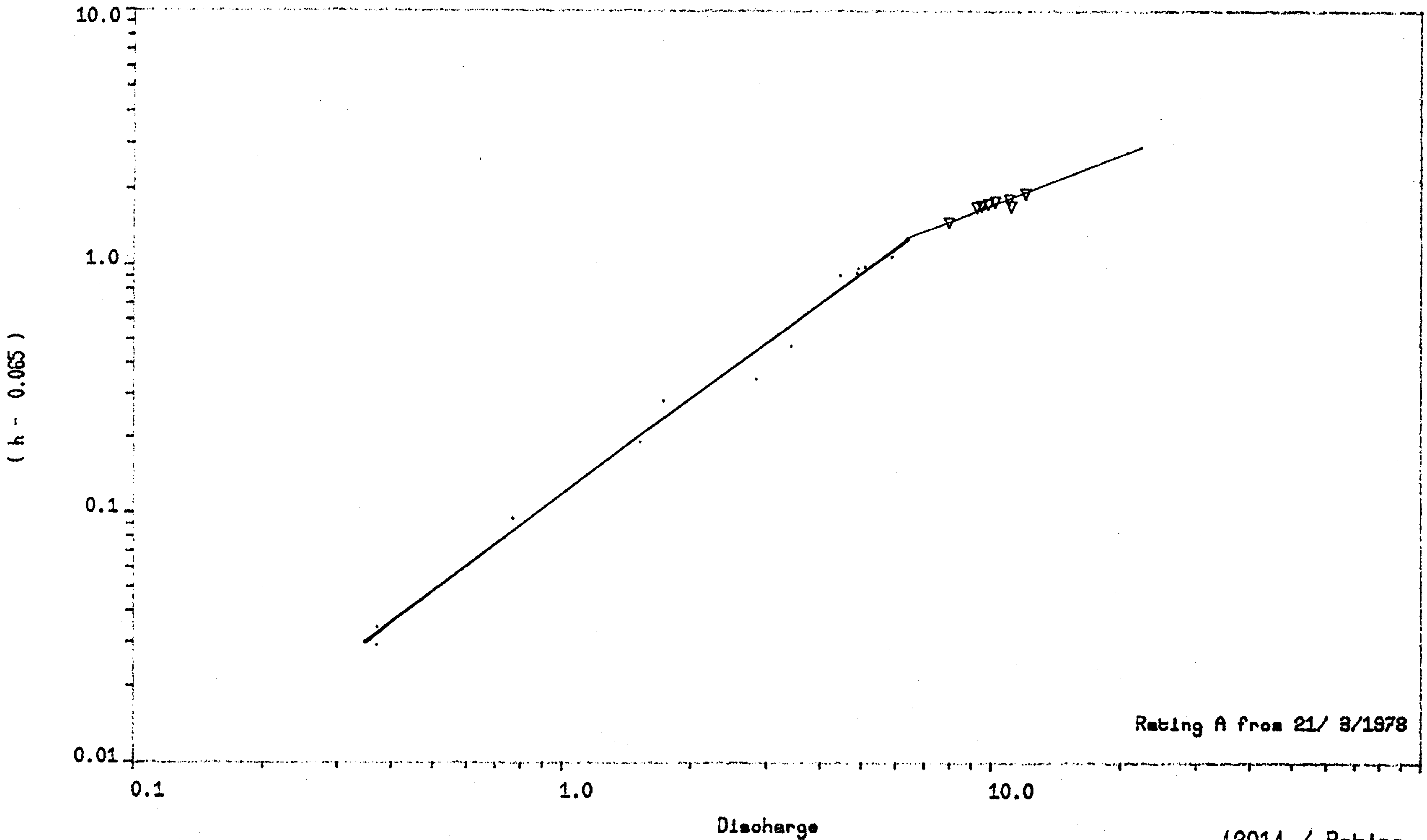
Stage discharge curves plotted on log-log paper

Mole at Kinnersley Manor

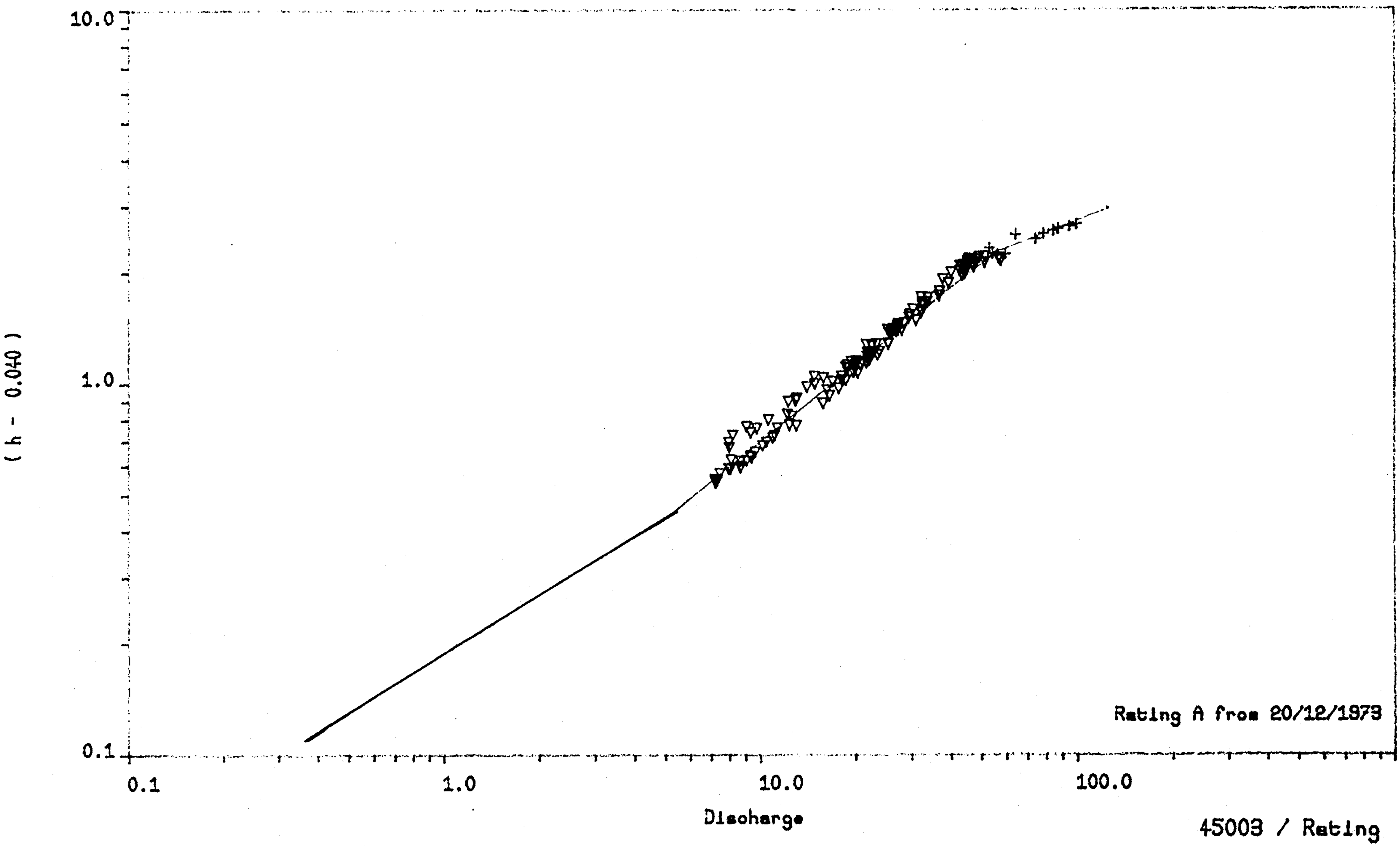


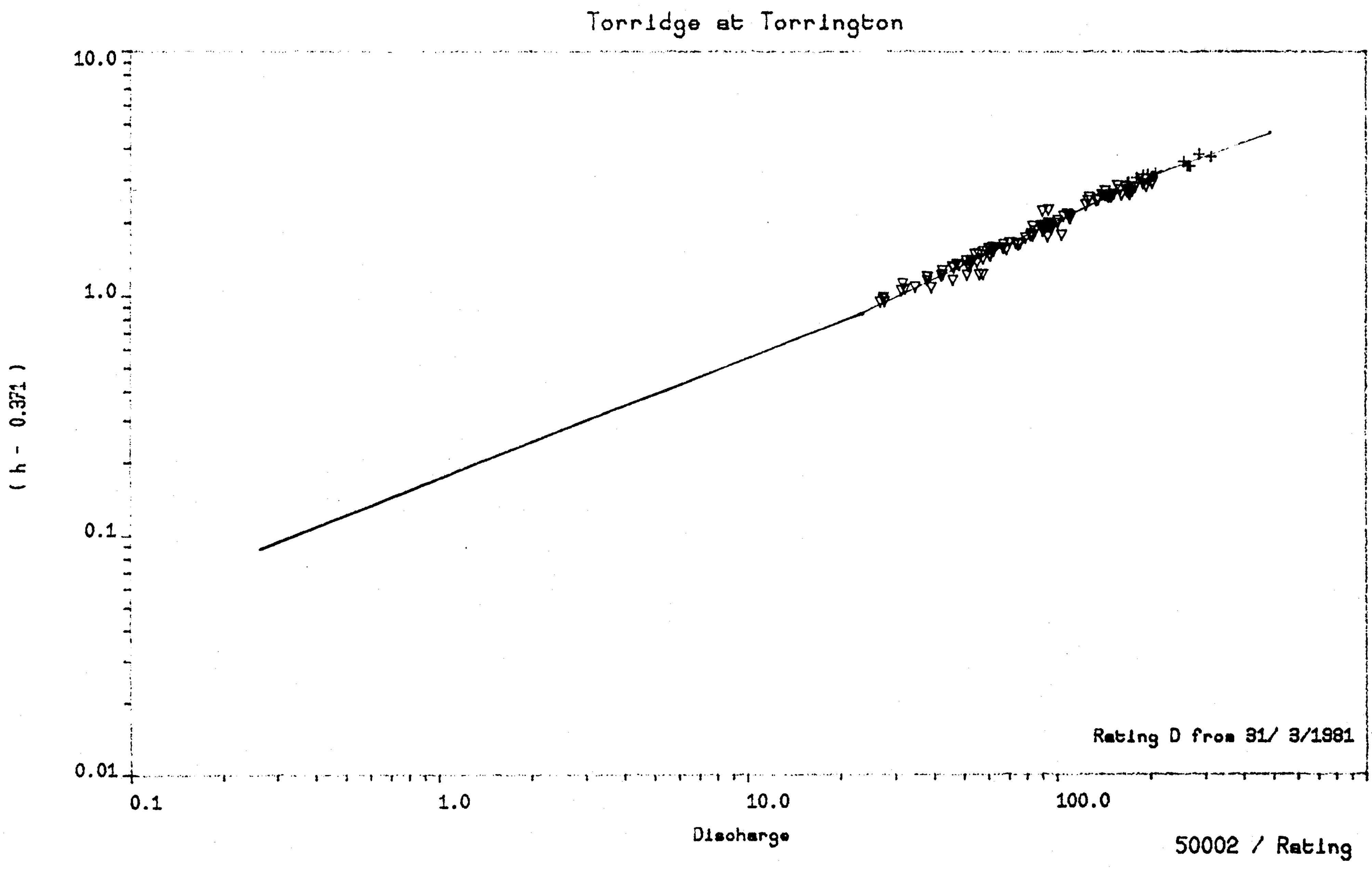

39369 / Rating

## Blackwater at Ower

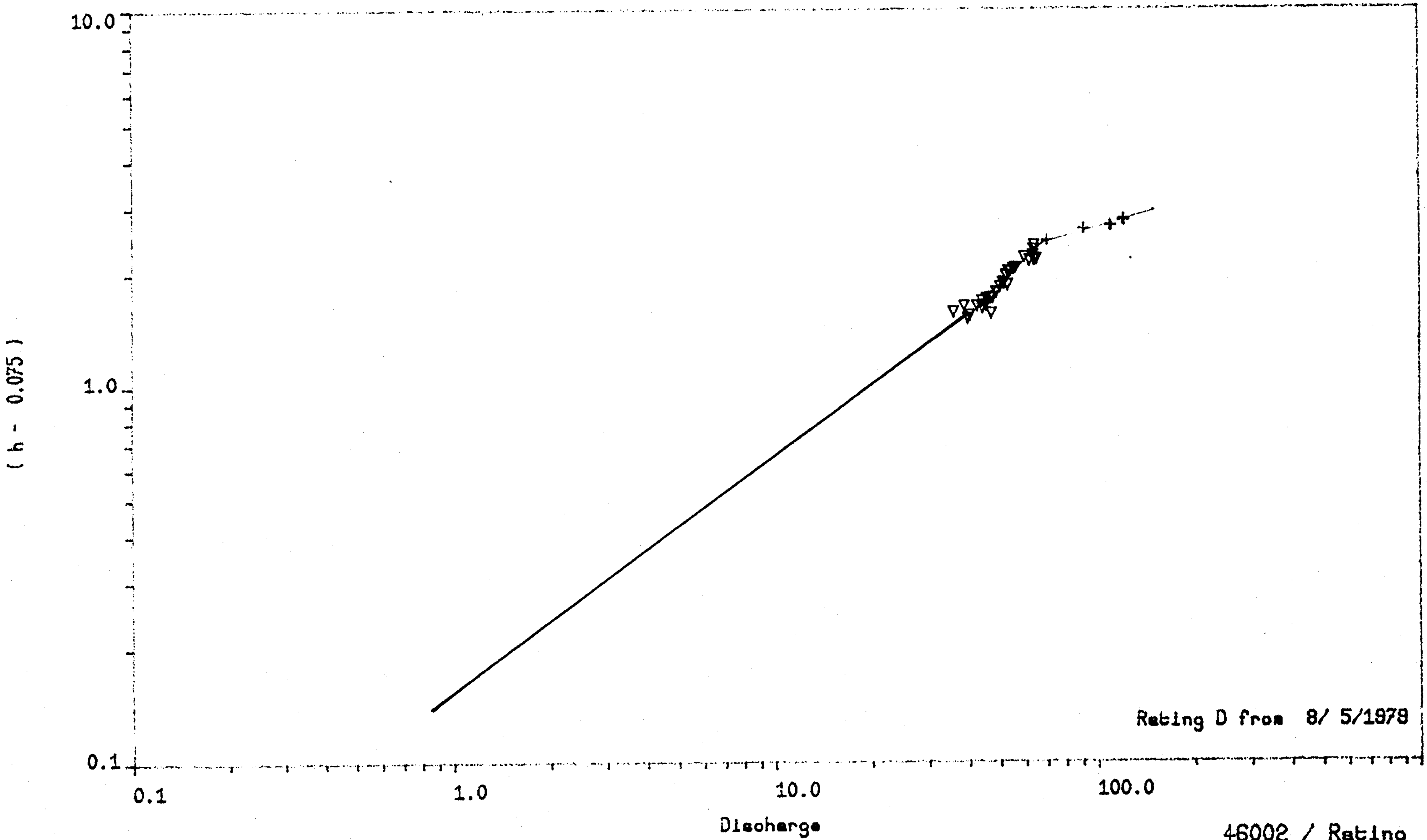



42014 / Rating


10.0
1.0
0.1
( h - 0.040 )
0.1
1.0
10.0
100.0
Discharge
Rating A from 20/12/1973
45003 / Rating

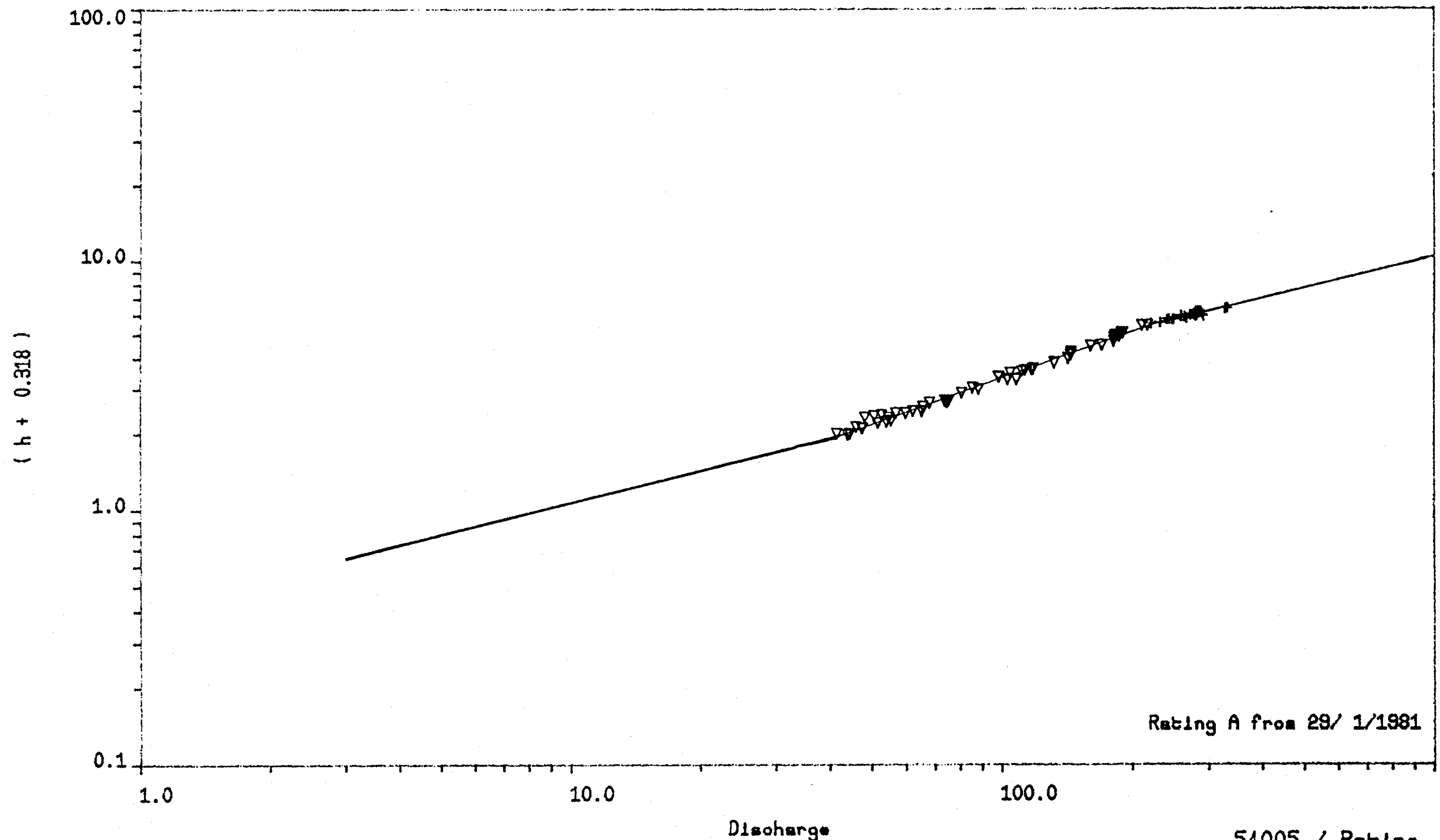

Torridge at Torrington
10.0
1.0
0.1
0.01
( h - 0.371 )
0.1
1.0
10.0
100.0
Discharge
Rating D from 31/ 3/1981
50002 / Rating

Telgn at Preston

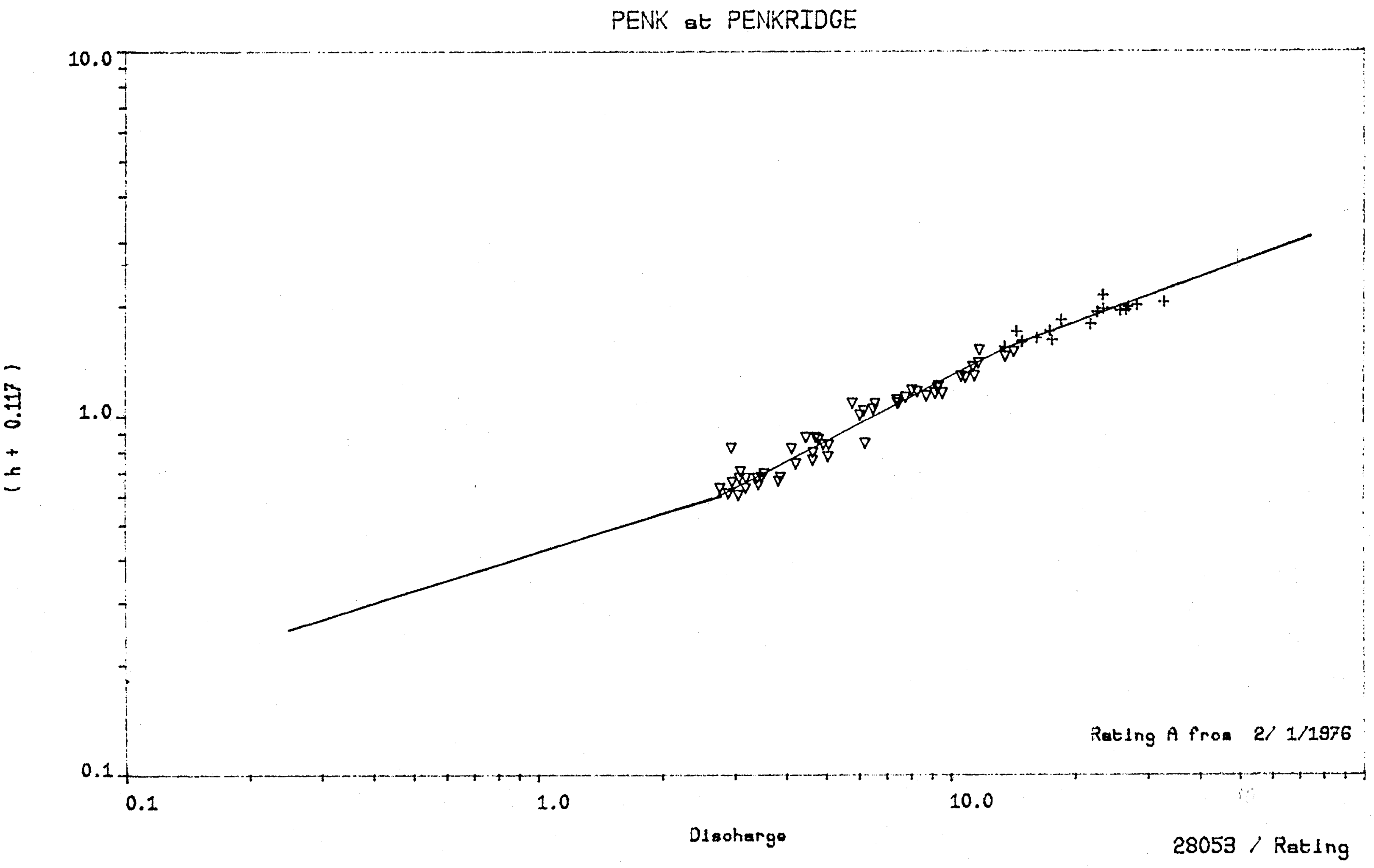


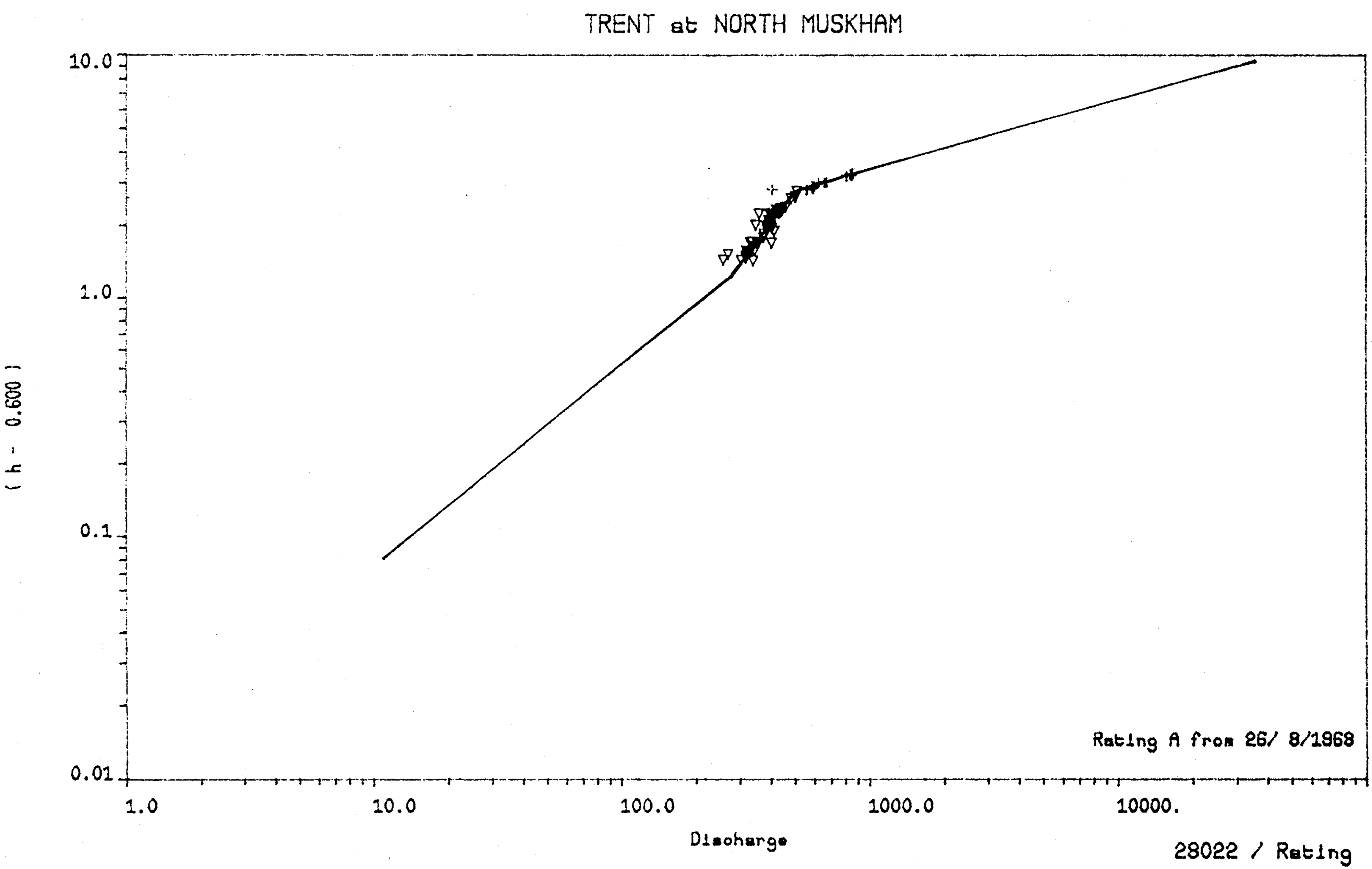

46002 / Rating

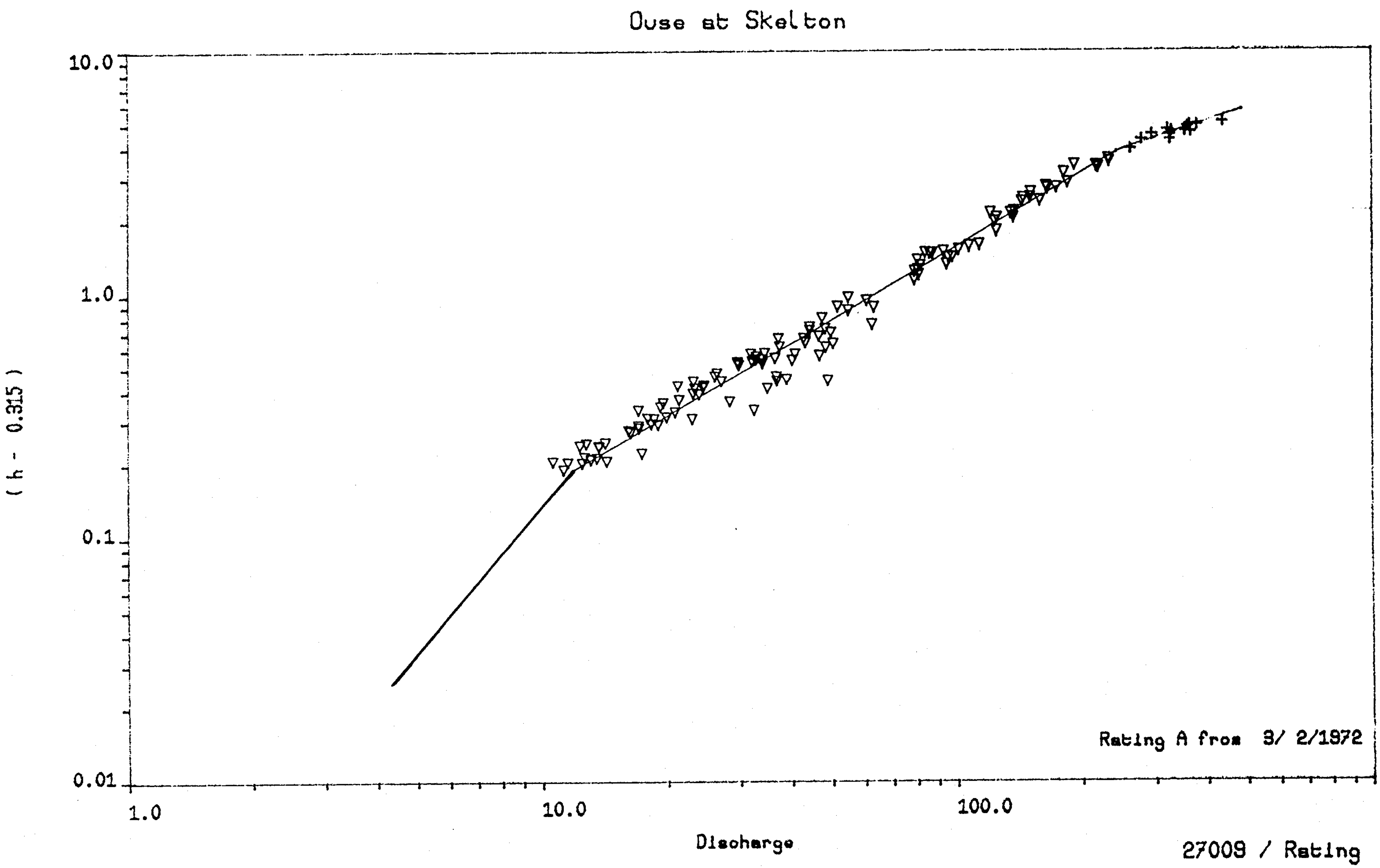
SEVERN at MONTFORD




54005 / Rating

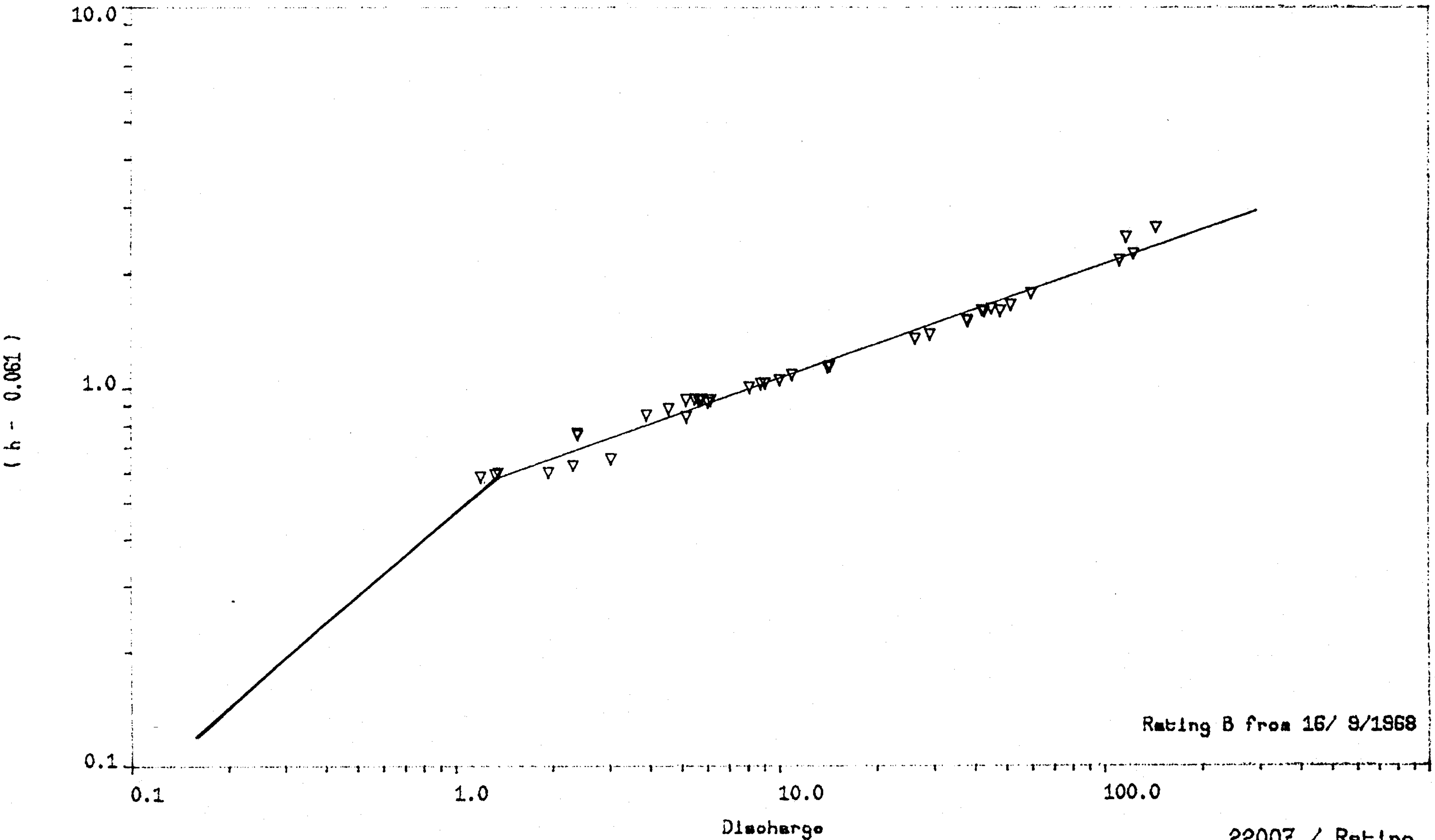

PENK at PENKRIDGE
10.0
1.0
0.1
( h + 0.117 )
0.1
1.0
10.0
Discharge
Rating A from 2/ 1/1976
28053 / Rating


TRENT at NORTH MUSKHAM
10.0
1.0
0.1
0.01
( h - 0.600 )
1.0
10.0
100.0
1000.0
10000.
Discharge
Rating A from 26/ 8/1968
28022 / Rating

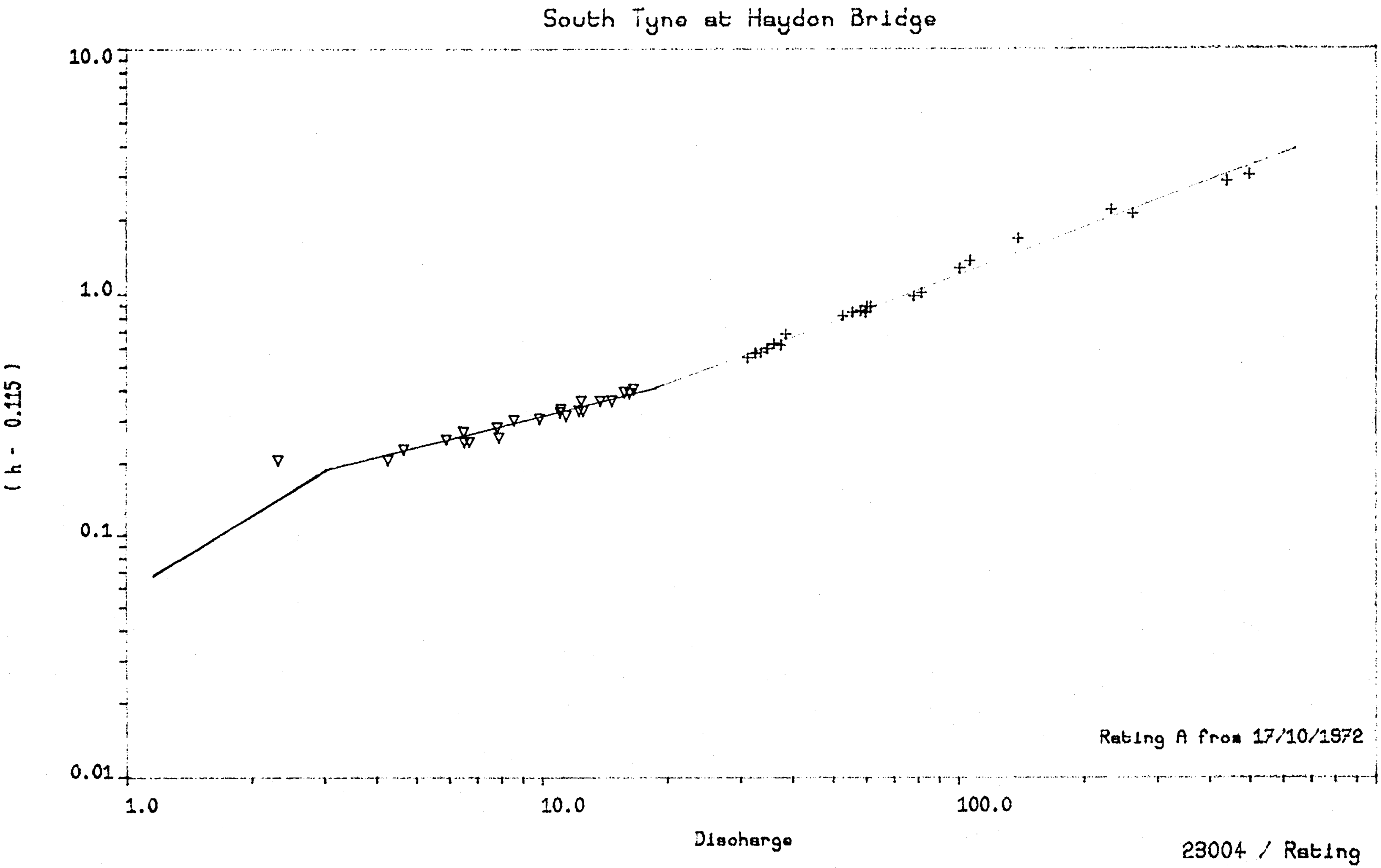


Ouse at Skelton
10.0
1.0
0.1
0.01
( h - 0.315 )
1.0
10.0
100.0
Discharge
Rating A from 3/ 2/1972
27009 / Rating

Wansbeck at Mitford

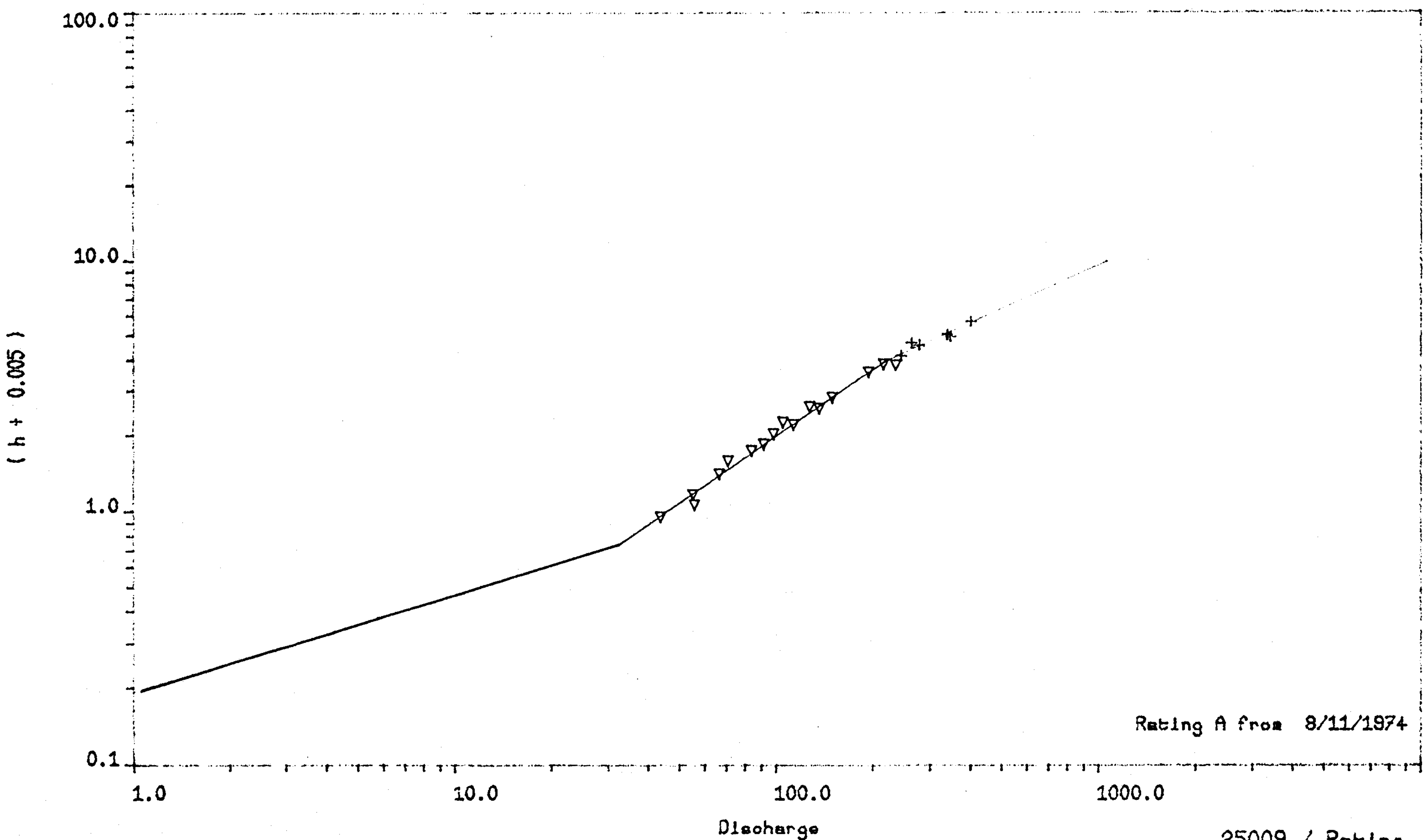



22007 / Rating



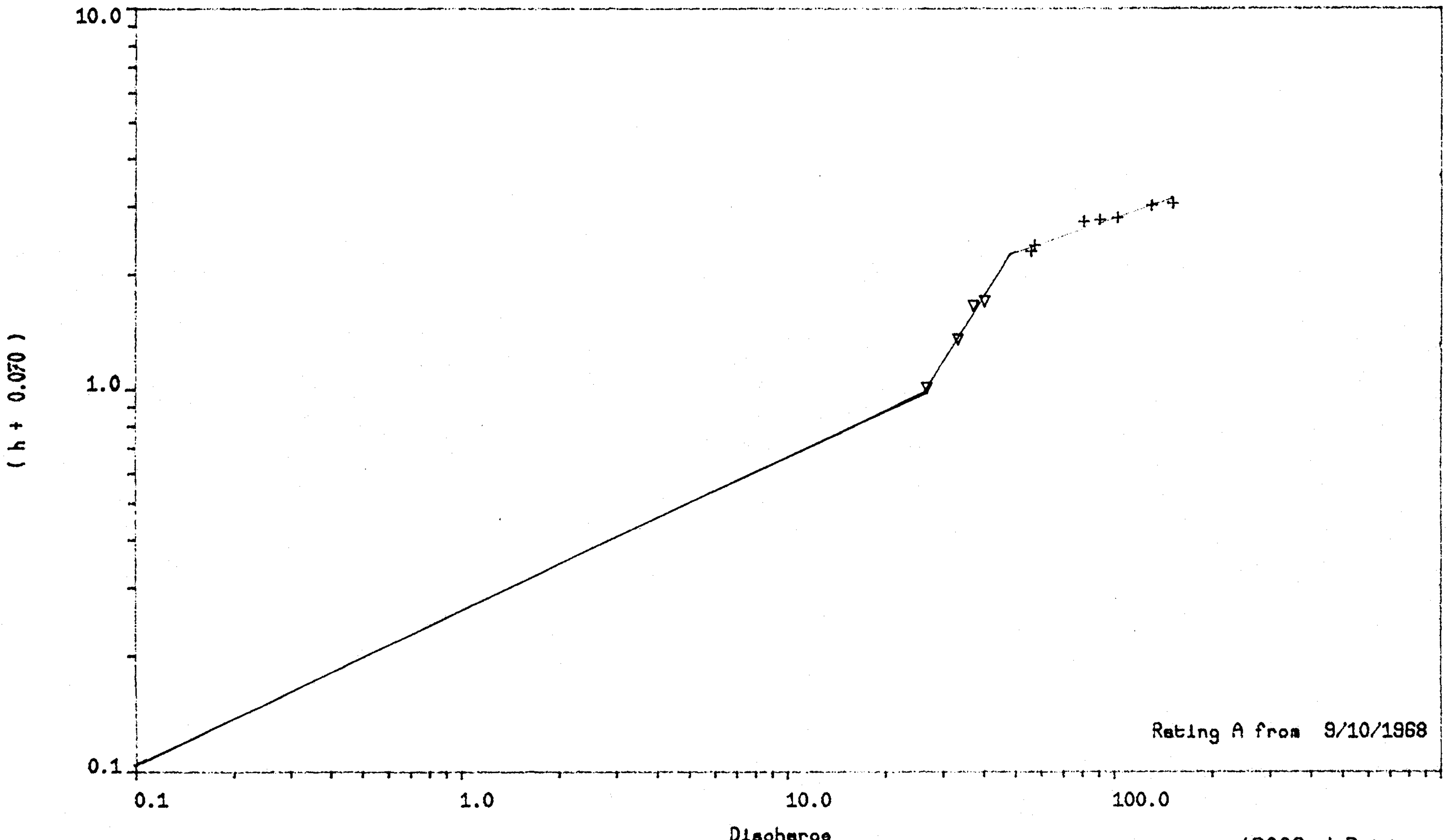
South Tyne at Haydon Bridge
10.0
1.0
0.1
0.01
( h - 0.115 )
1.0
10.0
100.0
Discharge
Rating A from 17/10/1972
23004 / Rating

Tees at Low Moor

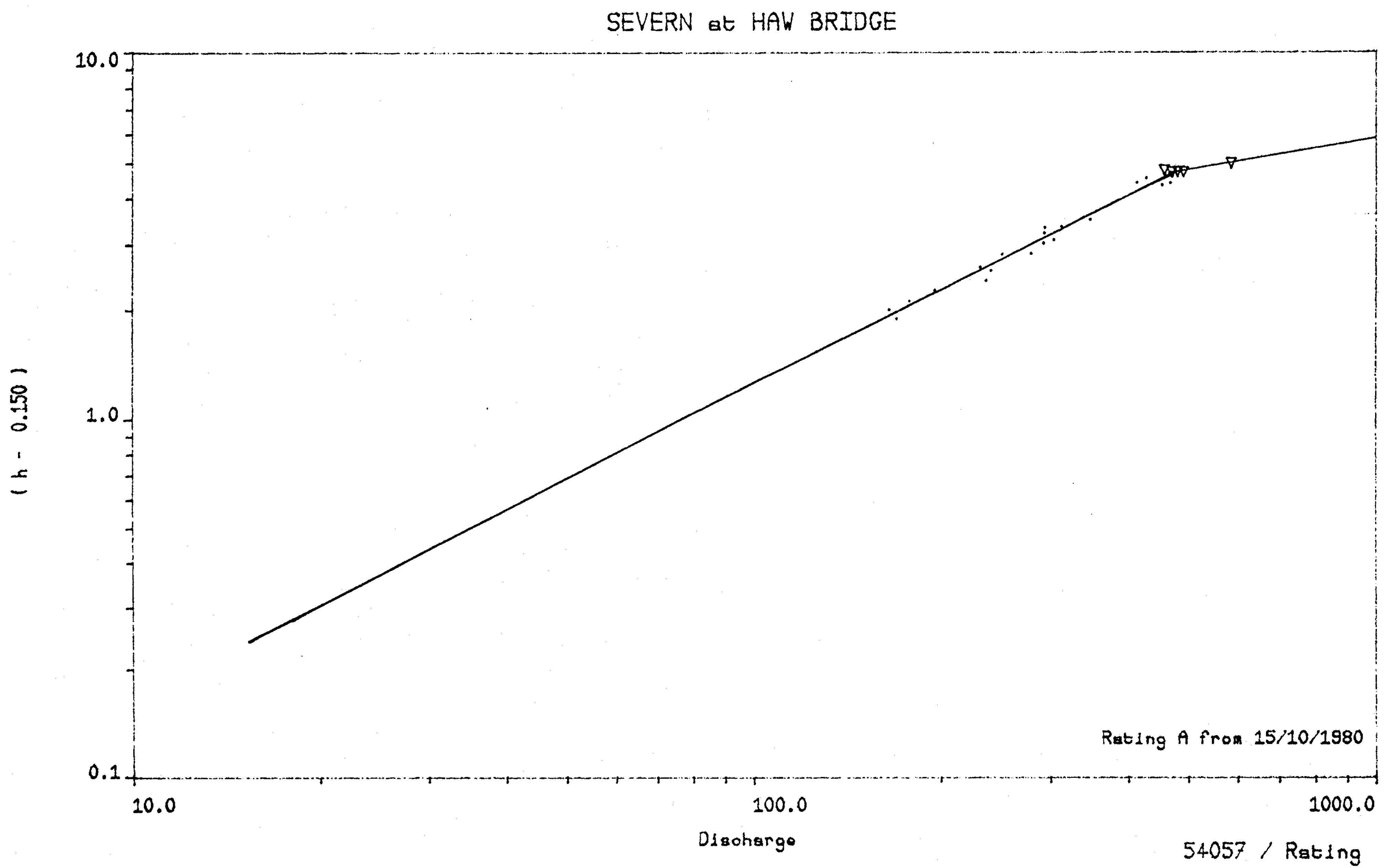



25009 / Rating

Stour at Hammoon




43009 / Rating



SEVERN at HAW BRIDGE
10.0
1.0
0.1
( h - 0.150 )
10.0
100.0
1000.0
Discharge
Rating A from 15/10/1980
54057 / Rating

# APPENDIX 3

## Example of discharge calculation using division line method

**A Calculation of Mannings 'n' roughness coefficient for in-bank flows**

A1. Manning's Formula $Q = \frac{A R^{2/3} S^{1/2}}{n}$

Q discharge
A flow area
R hydraulic radius
S water surface slope
n Mannings roughness coefficient

Rearranging : $n = \frac{A R^{2/3} S^{1/2}}{Q}$ —— 1

A2. Select 3 or more in-bank river stages and obtain corresponding discharges from the rating curve.

A3. Draw the water levels on the channel cross section and measure A and P (wetted perimeter).

$R = A/P$

A4. Obtain S from Ordnance Survey maps by measuring river length between contours.

$$S = \frac{\text{contour interval}}{\text{river length between contours}}$$

A5. Subsitute for A, R, S and Q in equation 1 to obtain 'n' for each value of stage. Plot results graphically.

A6. Manning's 'n' for bankfull conditions '$n_b$' may be obtained by repeating the above procedure for **bankfull river stage and discharge.**

**B Example of flow estimation using division line method for overbank flow**

Diagonal division line method 2(c)

B1. Draw river cross section

B2. Select 3 or more overbank river stages and obtain corresponding discharges from the rating curve. The highest river stage chosen should be equal to the highest stage where the discharge has been recorded.

B3. Calculate main channel slope $S_m$ by method given step A4 above.

Calculate flood plain slope $S_f$

$$S_f = S_m \times \left(\frac{\text{length of main channel}}{\text{length of flood channel}}\right)$$

In most cases considered in the study

$$S_m = S_f$$

because the floodplain is a relatively narrow strip running parallel with the river.

B4. Divide the river cross section as follows for each selected stage

Artwork missing!

$A_{f_1}$ $A_{f_2}$

$A_m$

wetted perimeter with 'n' = '$n_b$'
wetted perimeter with 'n' = '$n_f$'

B5. Measure A and P for the main channel and floodplain for each selected stage

B6. $Q = Q_m + Q_{f_1} + Q_{f_2}$

Subscript 'm' refers to main channel, '$f_1$' to left floodplain and '$f_2$' to right flood plain

$$Q_m = \frac{A_m R_m^{2/3} S_m^{1/2}}{n_b}$$

$n_b$ = Manning's 'n' at bankfull stage obtained from A6 above

$$R_m = {}^{A_m}/_{P_m}$$

$$Q_{f_1} = A_{f_1} \frac{R_{f_1}^{2/3}}{n_f} S_f^{1/2}$$

$$Q_{f_2} = A_{f_2} \frac{R_{f_2}^{2/3}}{n_f} S_f^{1/2}$$

$n_f$ = Estimated value of Manning's 'n' for the floodplain

$$R_{f_1} = {}^{A_{f_1}}/_{P_{f_1}}$$

$$R_{f_2} = {}^{A_{f_2}}/_{P_{f_2}}$$

Repeat procedure for all stages

B7. Compare calculated values of Q with observed value.

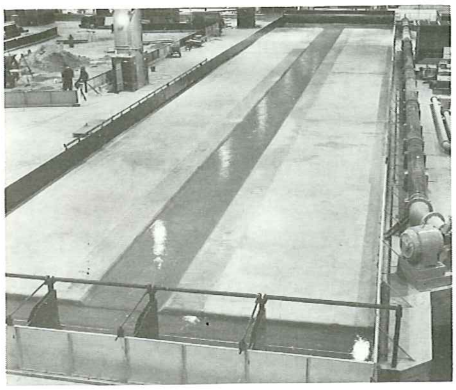
$$\text{Percentage error} = \left(\frac{Q\ \text{predicted}}{Q\ \text{observed}}\right) \times 100 - 100$$

# APPENDIX 4

## The SERC flood channel facility

# SERC FLOOD CHANNEL FACILITY

**A large flood channel 56 m long by 10 m wide with a discharge capacity of up to 1.1 m³/s has been constructed at Hydraulics Research Limited to investigate the complex interaction between flows in a river channel and over a flood plain. The size of the channel makes it possible to reproduce flows representative of those that occur in natural rivers—those that are strongly three-dimensional in character with large lateral transfer of momentum between the flood plain and the main channel.**

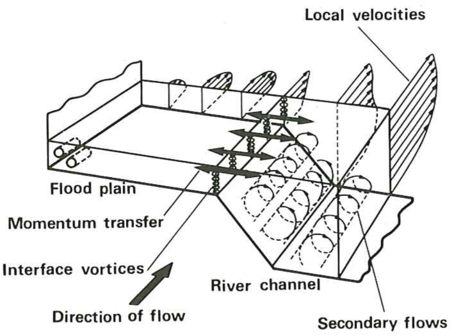

Flood channel facility

Instrumentation on the channel includes a laser anemometer for measuring the 'instantaneous' turbulent velocities of the flow. Data is stored and accessed on a microcomputer.

The Science and Engineering Research Council (SERC) commissioned the facility in November 1985 as a result of enhanced funding of civil engineering research. This arose from a report in 1981 of the Task Force on the long term research needs of the industry. Hydraulics Research has agreed to subsidize the materials and operating costs. The facility will be used by SERC grant holders to undertake a coordinated research programme involving several British universities.

## Why a large flood channel facility?

Laboratory channels in universities are typically 15 m long and less than 1 m wide.



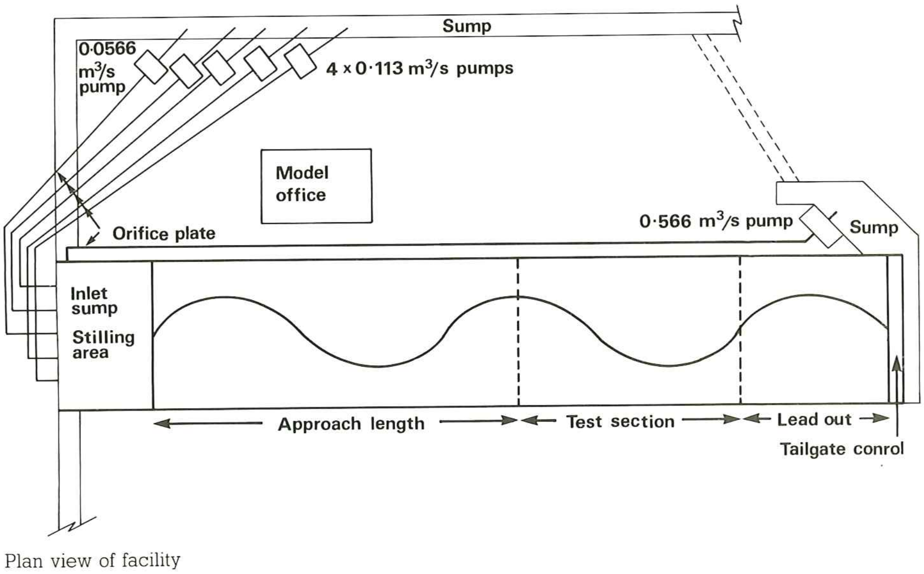
Flow characteristics in a compound channel

These are generally too small for experiments in which the full width of the flood plain and the sinuousity of the main channel are to be studied. Furthermore, each university cannot afford to build its own large facility together with full instrumentation and a data collection system. This motivated the construction of a single central facility which will also ensure close cooperation between university researchers on the one hand and practising engineers in industry on the other. This collaboration will yield better and more cost-effective solutions to flood protection problems.

## Flood protection problems

The prime reason for constructing the facility is that current knowledge of flow in compound channels is inadequate. A compound channel comprises a deep section—a main river channel or tidal channel at low water—flanked on one or both sides by an area of shallower flow which may be inundated only occasionally. Such channels feature in many flood alleviation schemes either by the excavation of a flood berm alongside the river channel or by the construction of flood protection embankments. The crucial question is what size to design these works. Uncertainties in the existing design methods may lead to the capacity of the channel being over or under estimated.

The programme of research associated with the flood channel facility should lead to a better understanding of the basic fluid mechanics of these flows. The size of the facility will allow scale effects to be assessed between it and the smaller flumes used in many universities. This will provide in turn estimates of scale effects between the facility and typical prototype situations. The ability to measure the detailed turbulence structure of the flow will also facilitate development of refined computational models applicable to this type of problem. To this end, data from the facility will also be analysed at Hydraulics Research under the terms of our strategic research contract with the Ministry of Agriculture, Fisheries and Food, who have statutory responsibility for river flood protection.



Plan view of facility

## Details of the facility

The facility comprises a tank constructed of 1 m high plates with the base moulded in cement mortar to the required geometry. The length of the flume may be considered in three parts; an upstream entry length of 25 m, a 15 m test section, followed by the lead out section to the tail gate controls. In the test section there are pressure tappings every 1 m along the bed of the channel leading to stilling pots and gauges to measure water level to ±0.1 mm. The discharge is provided by six pumps whose rated capacity varies from 0.057 to 0.57 $m^3/s$. This allows the flow to be controlled within ±2% over the range 0.01 $m^3/s$ to the full capacity of 1.08 $m^3/s$.

Although traditional instrumentation, such as miniature current meters, electromagnetic flow meters and Preston tubes, is available, the facility is also equipped with a sophisticated laser anemometry system to measure the turbulent flow velocities. The laser anemometer has a miniaturized optical head which is a cylinder 15 mm diameter by 100 mm long. This is coupled by a 20 m long armoured fibre optic cable to the laser and transmission optics. The probe head therefore may be placed anywhere in the test area, with the laser itself mounted at the side of the facility. The probe senses two velocity components simultaneously in the plane normal to the axis of the probe head and thus produces sufficient information to calculate the turbulent Reynolds stresses. It is only now, with the advent of laser anemometry and the exploitation of fibre optic technology, that experimental data can be conveniently gathered to validate turbulence models on the scale of the flood channel facility.

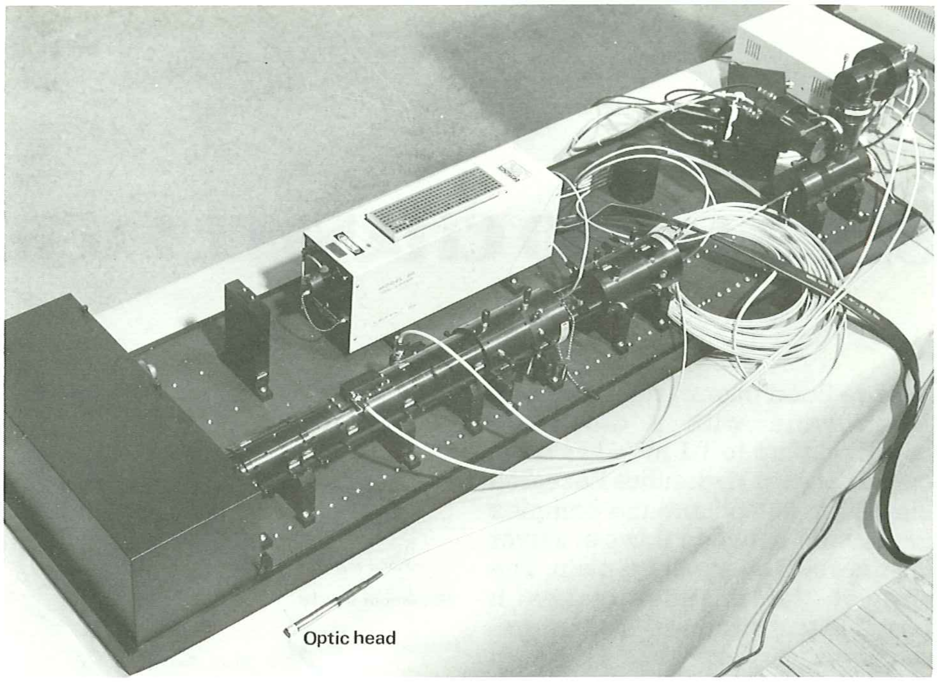
The data from all the instruments is logged and processed by a PDP micro 11/73 computer installed in an office adjacent to the facility.

## The research programme

The programme of research is governed by grants approved by the SERC. The initial projects will look at straight compound channels and a deep straight channel set at a skew to the base of the facility. Following that, a series of tests is planned on meandering channels of varying sinuousity. It is also proposed to undertake a set of loose boundary experiments to study certain aspects of sediment movement. The results of this research will be disseminated as widely as possible, both in terms of the actual observations and analysis of the data. It is hoped that the research will also lead to a new design manual for river and drainage engineers.

## Principles of laser anemometry

Although in the body of the text we refer to the laser anemometer measuring the turbulent flow velocity, it actually measures the velocity of minute particles, typically a few microns in diameter, suspended in the flow. It is assumed that, provided such particles are small, they will move with the local velocity of the surrounding fluid. To explain the principle of the technique we shall concentrate on the measurement of a single velocity component. For a two component system, as installed on the facility, several of the parts are duplicated.

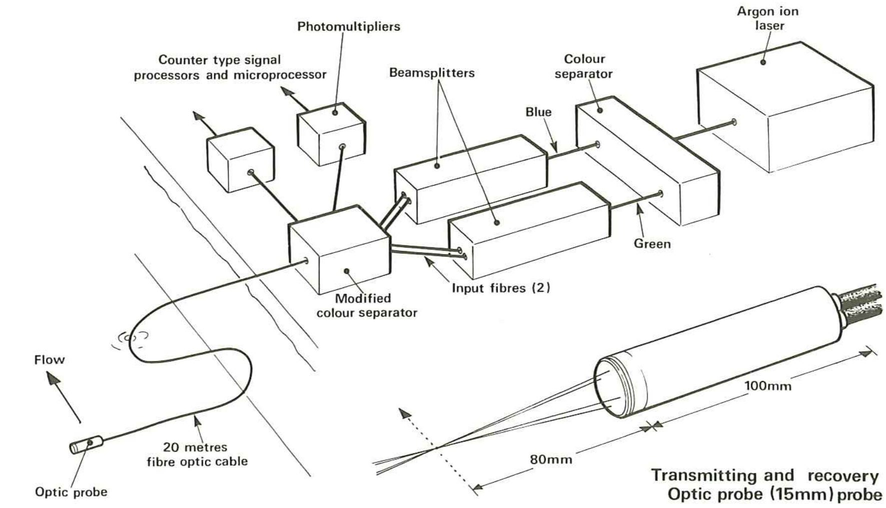



Laser anemometer

To measure a single component of the velocity (its value in a particular direction for example) two beams of laser light from the same source are focussed at the measuring volume. In this volume, where size depends upon the diameter of the beam and the geometry of the optics, the two beams interact to form a pattern of light and dark interference fringes. As a particle moves across the fringe pattern the intensity of the scattered light varies according to the intensity of the fringes. The scattered light is collected using the same optics as for the transmission of the incident laser beams and passes to a photo-multiplier which is coupled to a signal processor. The velocity of the scattering particle is then calculated from the fringe spacing and the time it takes to cross a number of fringes.

In order to measure both positive and negative values of the velocity component the fringe pattern is made to move by slightly altering the frequency of the light in one of the incident laser beams. If no frequency shift is employed then the fringe pattern is static and the system only senses the magnitude of the velocity component.

The laser anemometer used on the flood channel facility uses a single Argon-ion laser which emits light of several frequencies. The two strongest frequencies are selected by colour separators and focussed at the same point but in perpendicular planes, and two velocity components are measured as described above.




Components of a laser anemometer

DDB 2/88

**Hydraulics Research Limited**, Wallingford, Oxfordshire OX10 8BA Telephone: 0491 35381 Telex: 848552
Telegrams: Hydraulics Wallingford England Fax: 0491 32233 $G_3/G_2$

# APPENDIX 5

## The RIBAMAN flood routing model

# RIBAMAN

**RIBAMAN is a computational model for engineers responsible for RIver BAsin MANagement.**

**RIBAMAN will:**

- **analyse run-off and flows in a stream network;**
- **design and analyse storage ponds.**

**Using either observed or design rainfall events RIBAMAN calculates unsteady run-off discharges at points in a network of streams draining a series of sub-catchments. These may be wholly rural or partly urbanised.**

## How to use RIBAMAN

To use RIBAMAN the engineer must first identify the main catchment and sub-catchment boundaries and the points at which each sub-catchment contributes run-off to the stream system. Riparian sub-catchments without a single identifiable outfall can be input as distributed inflow along a reach length.

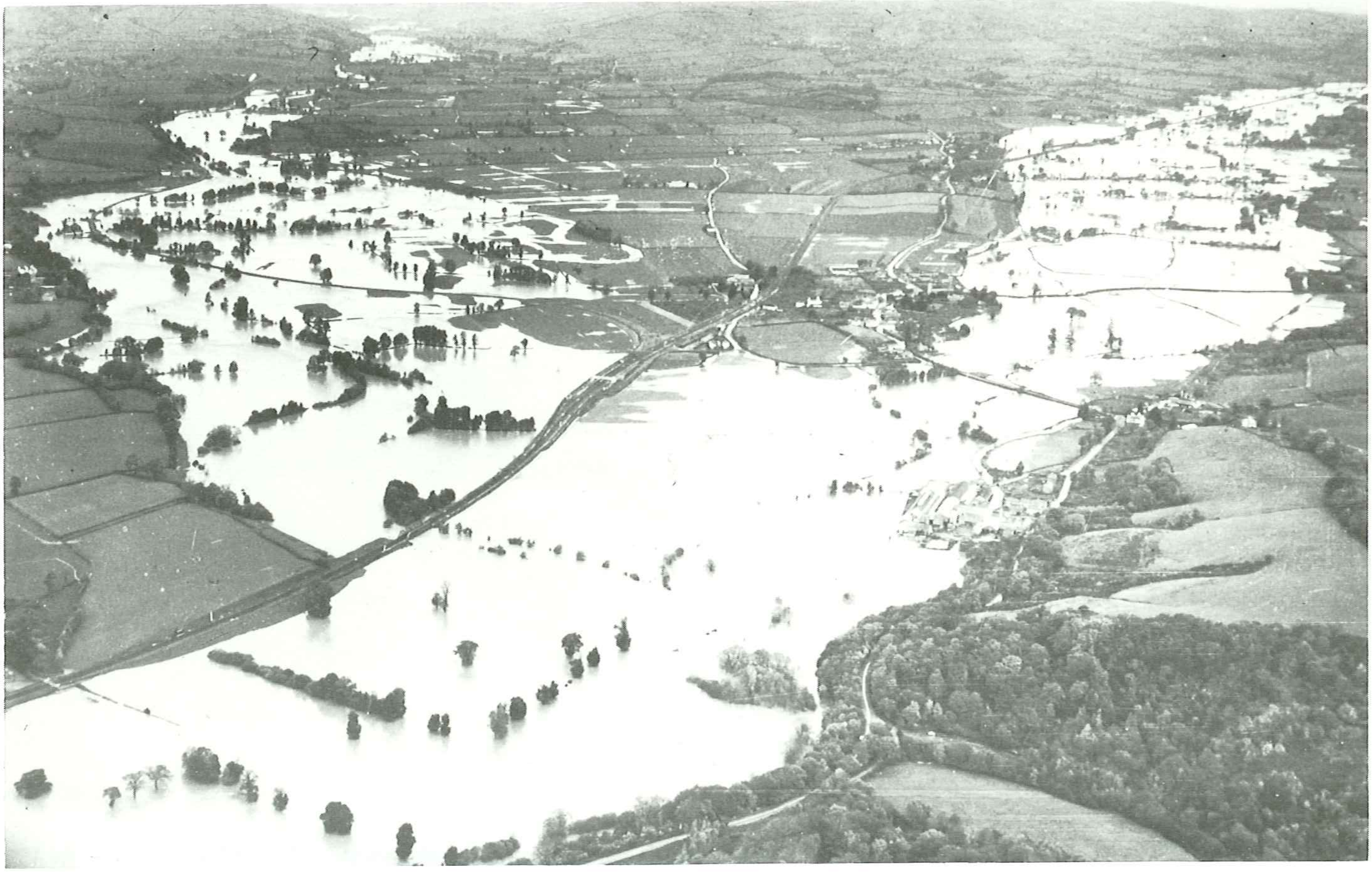
### Analysing run-off and flows

For UK catchments RIBAMAN calculates run-off from each sub-catchment using unit hydrographs and a 'losses' model, as recommended in the Flood Studies Report. To calculate run-off in overseas catchments it uses the method developed by the US Soil Conservation Service. RIBAMAN is also able to synthesize unit hydrographs from observed rainfall and run-off data.

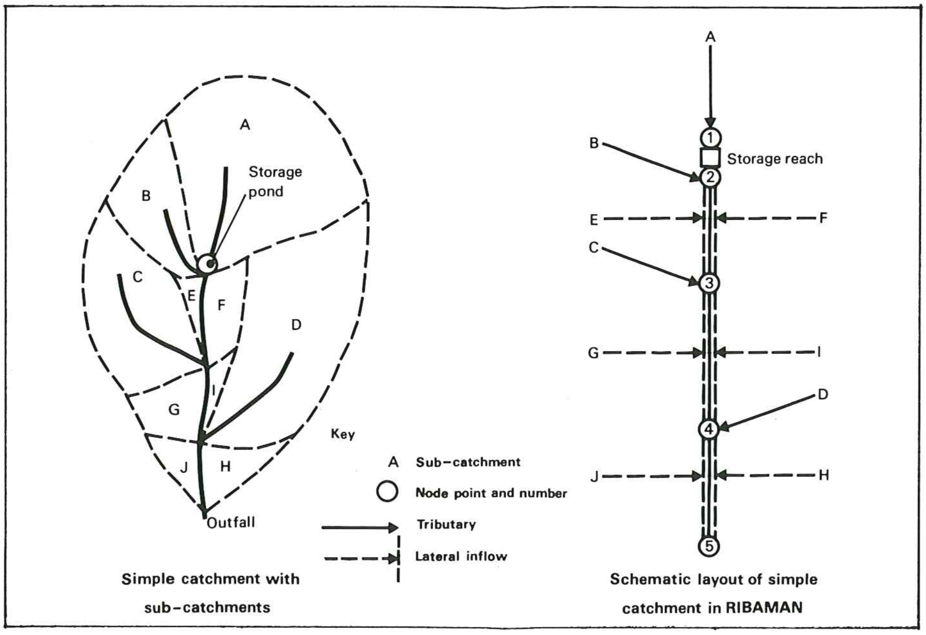
In the stream network flood routing is based on the fast and efficient numerical procedures first developed at Wallingford for the FLOUT model.

### Designing and analysing storage ponds

To route through existing on-and off-line storage ponds RIBAMAN requires a storage volume/water level relationship for the pond and a discharge/water level relationship for the outlet (inlet) structure. The latter may be in the form of dimensions, levels and discharge coefficients for use in simple weir or sluice equations, or it may be represented as a data table for more complex structures. RIBAMAN can also be



*River Exe, Devon.* *Photograph by courtesy of Western Morning News, Plymouth.*




*Simple catchment with its representation in RIBAMAN.*

used to examine whether a new storage pond will meet the maximum downstream flow criteria specified by the engineer.

Flow diversions from one stream to another, without significant storage, can also be modelled by defining discharge/water level relationships for the diverted and continuation flows.

## Presentation of results

RIBAMAN can provide both tabular and graphical output at a level giving either basic results or in-depth data for complete analysis.

RIBAMAN computes only discharges. It does not predict flood levels. To predict flood levels it is necessary to use the Hydraulics Research FLUCOMP model. A direct link is provided for this.

## Software

The RIBAMAN package includes user-friendly facilities to give ready access to any part of the program. A selection is made from a main 'menu' and an attractive data capture and edit program for each stage simplifies the task of setting-up or modifying the database for a catchment. 'Help' information is always available at the press of a button.

## Hardware

RIBAMAN is available on Apricot XEN, IBM XT, IBM AT, or on IBM compatible micros with a minimum of 512 Kb RAM, operating under PC or MS-DOS. Epson FX 80, 100 or LQ printers are preferred with a Watanabe plotter.

DDB 5/88

**Hydraulics Research Limited,** Wallingford, Oxfordshire OX10 8BA Telephone: 0491 35381 Telex: 848552
Telegrams: Hydraulics Wallingford England Fax: 0491 32233 G3/G2