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THE ESTIMATION OF RIVERFLOWS IN UNGAUGED CATCHMENTS

by

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PREFACE

In the course of my duties as a hydrologist with a British regional water authority, I am frequently required to derive riverflow statistics for catchments for which there is little or no measured flow data. Whilst there are many existing methods by which flows may be estimated, my experience has been that the majority of these approaches are unreliable. This thesis describes the development of a suite of alternative, user orientated, high and low flow estimation techniques for application in ungauged catchments. As the derived methods require the cross reference between a large number of figures, these have grouped together as a separate volume, together with appendicies which include all analysed data. However, second copies of selected figures and all summary tables have been included within the main text as an aid to explanation.

INDEX

(i) FRONTISPIECE

(ii) PREFACE

(iii) INDEX

(vi) LIST OF TABLES

(vii) LIST OF FIGURES

(xi) LIST OF APPENDICES

(xii) ABSTRACT

1 INTRODUCTION

1.1 THE SIGNIFICANCE OF RIVER FLOWS 1

1.2 THE GEOGRAPHICAL PERSPECTIVE 2

1.3 APPLICATIONS OF RIVERFLOW ESTIMATES 2

1.4 THE HISTORICAL PERSPECTIVE 3

1.5 COMMENT 6

2 THE ESTIMATION OF RIVER FLOWS

2.1 INTRODUCTION 7

2.2 METHODS OF ASSESSING LOW FLOWS FOR UNGAUGED CATCHMENTS 7

2.3 METHODS OF ASSESSING HIGH FLOWS FOR UNGAUGED CATCHMENTS 12

2.4 CONCLUSIONS 23

3 THE RIVER TRENT BASIN

3.1 INTRODUCTION 26

3.2 SOLID GEOLOGY AND SURFACE DEPOSITS 28

3.3 LAND USE 34

3.4 PRECIPITATION, EVAPORATION AND EFFECTIVE PRECIPITATION 36

3.5 RUNOFF 41

4	THE QUANTIFICATION OF PHYSIOGRAPHY, GEOLOGY AND SURFACE DEPOSITS	
4.1	INTRODUCTION	46
4.2	MORPHOMETRIC (MORPHOLOGIC) FACTORS	47
4.3	GEOLOGICAL INDIC ES	61
4.4	INDICIES OF SUPERFICIAL DEPOSITS AND SOILS	67
4.5	LAND USE AND LAND USE CHANGES	72
4.6	CONCLUSIONS	75
5	THE ESTIMATION OF LOW FLOWS IN UNGAUGED AREAS OF THE TRENT BASIN	
5.1	INTRODUCTION	78
5.2	ALTERNATIVE INDIC ES OF LOW FLOW	78
5.3	DRY WEATHER FLOW IN THE TRENT CATCHMENT	80
5.4	FLOW DISTRIBUTIONS	98
5.5	THE ESTIMATION OF FLOW FREQUENCY CURVES FOR UNGAUGED CATCHMENTS.	108
5.6	THE ESTIMATION OF FLOW DURATION CURVES FOR UNGAUGED CATCHMENTS.	116
5.7	CONCLUSIONS	124
6	THE SIMULATION OF CATCHMENT RESPONSE TO RAINFALL	
6.1	INTRODUCTION	125
6.2	CONCEPTUAL MODELS	125
6.3	A GENERAL CATCHMENT CONCEPTUAL RAINFALL - RUNOFF MODEL	128
6.4	FITTING RAINFALL - RUNOFF MODELS TO MEASURED FLOW DATA	135
6.5	ASSESSMENT OF THE CHOSEN CONCEPTUAL RAINFALL - RUNOFF MODEL	141
6.6	FITTING THE UCM RAINFALL-RUNOFF MODEL TO GAUGED CATCHMENTS	154
6.7	PROBLEMS OF URBAN CONURBATIONS	163
6.8	THE ESTIMATION OF OPTIMUM CATCHMENT PARAMETER VALUES	170
6.9	THE ESTIMATION OF MODEL PARAMETERS FOR UNGAUGED CATCHMENTS	175
6.10	THE APPRAISAL OF THE UCM MODEL AS APPLIED TO UNGAUGED CATCHMENTS AND A COMPARISON WITH THE SYNTHETIC UNIT HYDROGRAPH TECHNIQUE	178
6.11	CONCLUSIONS	184

7	CONCLUSIONS	
7.1	INTRODUCTION	186
7.2	SUMMARY OF METHODS OF FLOW ESTIMATION	189
7.3	COMMMENT	192
	ACKNOWLEDGMENTS	195
	BIBLIOGRAPHY	196

LIST OF TABLES

1		COEFFICIENT OF VARIATION FOR SOME LINEAR MODELS FOR THE ROTENBACH CATCHMENT	18
2		DOMINANT SOIL TYPES OF THE TRENT CATCHMENT AND ASSOCIATED LANDUSE	32
3		RUNOFF CHARACTERISTICS OF THE TRENT BASIN	40
4		CHANNEL INDICIES CORRELATION MATRIX	59
5	a	WRIGHT's ARBITRARY GEOLOGICAL INDEX	63
	b	DERIVED GEOLOGICAL INDICES	
6		COMPARISONS OF DRY WEATHER FLOW YIELDS	97
7		COMPARISON OF LOW FLOW STATISTICS	102
8		FLOW FREQUENCY CORRELATION MATRIX	109
9		RESULTS FLOW FREQUENCY	114
10		RESULTS FLOW DURATION	121
11		RAINFALL - RUNOFF MODEL PARAMETERS	127
12		SENSITIVITY ANALYSIS - SINGLE PARAMETERS	143
13		- PAIRED PARAMETERS	144
14		- OUT OF BANK PARAMETERS	145
15		COMPARISON OF GENERAL CATCHMENTS MODEL AND THE UNGAUGED CATCHMENT MODEL	152
16		PERFORMANCE OF THE MODEL IN URBAN CONURBATIONS	162
17		OPTIMUM PARAMETERS VALUES	171
18		CATCHMENTS INDICIES CORRELATION MATRIX	174
19		RESULTS - REAL TIME FLOW SIMULATION	180

LIST OF FIGURES

(All figures are presented sequentially in Volume 2)

1		COMPARISON OF UNIT HYDROGRAPH AND MEASURED HYDROGRAPH
2		ISOLATED EVENTS MODEL
3		TRENT CATCHMENT, MAJOR RIVERS AND NATIONAL GRID (In transparent overlay form in volume 2)
4		TRENT AREA GEOLOGY
5		TRENT AREA MEAN ANNUAL PRECIPITATION
6		COMPARISON OF EFFECTIVE PRECIPITATION AND RUNOFF
7		TRENT AREA MEAN ANNUAL EFFECTIVE PRECIPITATION (ADJUSTED)
8		ARBITRARY GEOLOGICAL INDEX
	a	STATION REFERENCE NUMBERS RE FIGURE 8
9		SOIL INDEX
10		SIMPLIFIED RESIDUAL FLOW QUANTITY DIAGRAM
11		SIMPLIFIED RESIDUAL FLOW QUALITY DIAGRAM
12		RESIDUAL FLOW DIAGRAM - DRY WEATHER FLOW CONDITIONS - RIVER TRENT
	a	- RIVER IDLE
13		- RIVER TRENT
14		- RIVER TAME
15		- RIVER DOVE
16		- RIVER DERWENT
17		- RIVER SOAR
18		- RIVER IDLE
19		TRENT AREA RUNOFF COEFFICIENTS - DRY WEATHER FLOW CONDITION
20		FLOW DURATION ANALYSIS - RIVER DERWENT
21		FLOW FREQUENCY CURVES (YORKSHIRE BRIDGE, SYSTON)
22		(ROCESTER (DOVE), ROCESTER (CHURNET))
23		(ILAM, POLESWORTH, RATCLIFFE CULEY, WATERHOUSES)
24		(IZAAK WALTON, HOLLINSCLOUGH, CALTHORPE PARK)
25	FLOW DURATION CURVES	(YORKSHIRE BRIDGE, CALTHORPE PARK, SYSTON)

26 (ROCESTER (DOVE), ROCESTER (CHURNET))
27 (ILAM, POLESWORTH, RATCLIFFE CULEY, WATERHOUSES)
28 (IZAAK WALTON, HOLLINSCLOUGH)
29 FLOW FREQUENCY CURVES - 14 DAY PERIOD
30 NORMALISED FLOW DURATION CURVES
31 COMPARISON OF FLOW FREQUENCY CURVES - BLABY
32 - ASHBOURNE
33 - ROTHLEY
34 - DUFFIELD
35 NORMALISED FLOW DURATION CURVES FOR LIAS AND MARL CATCHMENTS
36 NORMALISED BASE CURVE : CARBONIFEROUS ROCKS
37 : LIAS AND MARL
38 : SANDSTONES
39 : OLD ROCKS
40 : LARGE CATCHMENTS
41 COMPARISON OF METHODS : BUTTERCRAMBE
42 : KILGRAM
43 : SNAIZEHOLME BECK
44 : KILDWICK
45 : GARSTANG
46 SCHEMATIC REPRESENTATION OF THE GENERAL CATCHMENT MODEL
47 FUNCTIONAL RELATIONSHIPS WITHIN THE SOIL MOISTURE COMPONENT OF THE RAINFALL - RUNOFF MODEL
a LOSS TO STREAMFLOW
b LOSS TO STREAMFLOW SUPERSATURATED CONDITIONS
c LOSS TO TRANSPIRATION
d LOSS TO GROUNDWATER
48 THE OPTIMUM VALUE OF ONE PARAMETER
49 THE ERROR SURFACE FUNCTION FOR TWO PARAMETERS
50 GENERAL PATTERN OF SEARCH FOR OPTIMUM
51 UCM RAINFALL - RUNOFF MODEL
52 COMPARISON OF MODELS - R TRENT, STOKE
53 - R SOW, GREAT BRIDGFORD
54 - R AMBER, WINGFIELD PARK
55 - R DOVE, IZAAK WALTON
56 RATING CURVE R SOAR - NARBOROUGH

57 ACCUMULATED DIFFERENCES BETWEEN ACTUAL AND MORECS RAINFALL (MAY-NOV, 1977)
58 SIMULATED AND OBSERVED FLOWS - CALTHORPE PARK
59 COMPARISON OF RAINFALL PATTERNS, CALIBRATION EVENTS 1 AND 6
60 EVENT RUNOFF PROPORTION CURVES - STOKE
61 - GREAT BRIDGFORD
62 - PENKRIDGE
63 - CALTHORPE PARK
64 - COLESHILL
65 - POLESWORTH
66 - IZAAK WALTON
67 - ILAM
68 - BASFORD BRIDGE
69 - ASHFORD
70 - WINGFIELD PARK
71 - NARBOROUGH
72 - BLABY
73 - SYSTON
74 OPTIMUM RUNOFF PROPORTION CURVE - STOKE
75 - GREAT BRIDGFORD
76 - PENKRIDGE
77 - POLESWORTH
78 - IZAAK WALTON
79 - ILAM
80 - BASFORD BRIDGE
81 - ASHFORD
82 - WINGFIELD PARK
83 - NARBOROUGH
84 - BLABY
85 - SYSTON
86 RUNOFF PROPORTION TYPE CURVE
87 RUNOFF PROPORTION CURVES - CARBONIFEROUS CATCHMENTS
88 - LIAS AND CLAY CATCHMENTS
89 PERFORMANCE OF UCM IN REAL TIME MODE - DUFFIELD
90 - DUFFIELD
91 - DUFFIELD
92 - KINGSTON
93 - KINGSTON
94 - KINGSTON

95 COMPARISON OF UCM AND UNIT HYDROGRAPH - DUFFIELD

96 - KINGSTON

97 R ECCLESBOURNE - MAXIMUM FLOW PROBABILITY DISTRIBUTION

98 KINGSTON BROOK - MAXIMUM FLOW PROBABILITY DISTRIBUTION

99 SYNTHETIC UNIT HYDROGRAPH, R ECCLESBOURNE (IN APPENDIX 13)

100 SUMMARY OF METHODS OF ESTIMATION

LIST OF APPENDICES

(All appendices are presented sequentially in Volume 2)

1 DETAILS OF PERMANENT RIVERFLOW MEASURING STATIONS USED FOR ANALYSIS

2 VALUES FOR THE COMPUTATION OF THE ROUGHNESS INDEX

3 DRY WEATHER FLOW RESIDUAL FLOW DIAGRAMS - TABULATED DATA

4 LIST OF SYMBOLS AND ABBREVIATIONS APPEARING IN APPENDIX 3

5 RIVERFLOW MEASURING STATIONS USED IN THE FLOW FREQUENCY AND DURATION ANALYSES

6 ESTIMATION OF FLOW FREQUENCY CURVE USING THE LOW FLOW STUDY (IOH, 1980) TECHNIQUE

7 GENERAL CATCHMENT MODEL COMPUTER LISTING

8 UCM MODEL COMPUTER LISTING

9 GAUGED CATCHMENT DATA

10 BEST FIT PARAMETER VALUES - ALL EVENTS

11 APPLICATION OF UCM WITH ESTIMATED PARAMETERS - INPUT DATA

12 DESIGN HYDROGRAPHS - INPUT DATA

13 ESTIMATION OF DESIGN HYDROGRAPHS USING THE UNIT HYDROGRAPH TECHNIQUE (including figure 99)

ABSTRACT

An appraisal of existing riverflow estimation techniques shows many of the methods to have deficiencies. Low flow calculation procedures take insufficient account of the influences of mans activities and catchment geology on runoff, and high flow estimation techniques, which take the form of simple parametric equations or linear synthesis models, do not reflect the non-linear processes of natural catchments. As alternatives to the existing methods, a number of user orientated, conceptual estimation techniques are developed by analysis of measured runoff and precipitation data from the Trent basin. This is a catchment of 8200 km^2 draining much of the Midlands of England. Catchment properties which cannot be measured directly : morphology, geology, surface deposits and land use, are represented by numerical indices in the computational procedures. For example, a quantification of catchment geology in terms of dry weather flow runoff yield is advocated. In all, six types of data can be calculated for the ungauged case: Dry Weather Flows, Average Flows, Flow Duration Curves, Flow Frequency Curves and Forecasts and Predictions of the Hydrographs resulting from storm rainfalls. Several different analytical techniques are used in the derivation processes, including: maps, residual flow diagrams, dimensionless base curves, regression equations and a nine parameter conceptual computer model. The derived techniques are shown to be accurate and reliable for application both within the Trent basin and a number of other catchments in the North of England. The procedures are also superior to those advocated in the Institute of Hydrology's 'Low Flow Study' and 'Flood Studies Report' for flow duration curve, flow frequency curve and hydrograph simulation.

1 INTRODUCTION

1.1 THE SIGNIFICANCE OF RIVER FLOWS

"Water comes in three quantities; too much, too little or too dirty." (Weyman, 1975, page 1)

River flows are one of earth's greatest natural resources providing water for irrigation and drinking; a source of power and cooling for industry; a carrier for wastes; a medium for transport; and a basis for many leisure activities. However, in both the developed and developing world, the problems associated with river flows in terms of flooding, drought, erosion and pollution also constitute a major hazard to human activities. To enable the maximisation of the benefits which can be gained from river flows and to minimise the potential hazards, many governments, regional and local authorities and research institutions have spent large sums of monies on river-flow measurement networks. Information on the magnitude and frequency of river flows can help considerably in improving the lives of those without adequate water supply or flood protection. Alternatively, in those countries where water resources are almost totally developed and where there are conflicting demands for water supply, effluent disposal, recreation and amenity, river flow measures provide a framework for planning and development. In Britain, Regional Water Authorities maintain 1100 permanent flow measuring stations for these purposes. There are however, many countries, regions, river basins, streams or reaches for which flow data has not, or can not, be measured. In these cases flows have to be estimated. Further, even in developed countries, as more and more resource development pressures are brought to bear, the need to assess the magnitude and variability of ungauged river flows, without having to resort to extensive and expensive stream gauging, is becoming increasingly important. If flows can be adequately estimated, planning and design can proceed without the delay of several years while measurements are

made. It is to the problem of river flow estimation that this thesis applies.

1.2 THE GEOGRAPHICAL PERSPECTIVE

The estimation of river flows provides an interesting geographical perspective. The basis of the study is physical; river flows are generated with the interface of catchment climate and catchment physiography. However, human, technical and economic factors also require consideration. Technical structures which moderate or enhance flows are omnipresent, for example, dams, reservoirs, canals, ditches, urban developments and sewerage systems. Changing agricultural and forestry practices also affect the quantity and quality of runoff. Within any region, the degree of technical and human influence on river flows are dependent on political and economic factors. For example, White (1969) has estimated that for the United States, the major decision makers involved in the allocation and use of water include at least 3,700,000 farmers, and the managers of 8,700 irrigation districts, 8,400 drainage districts, 1,600 hydroelectric power plants, 18,100 municipal water-supply systems, 7,700 industrial water-supply systems, 11,400 municipal sewer systems, and 6,600 industrial-waste disposal systems.

The study area considered in this thesis, the River Trent basin, reflects this coalescence of physical and human geography.

1.3 APPLICATIONS OF RIVER FLOW ESTIMATES

Within the Trent basin estimates of river flow are required for a number of practical applications. These include abstraction licensing, formulation of consent conditions for discharges, design of water reclamation works, fishery management, river channel design, structural design and flood forecasting. Each of these water related design or management projects requires a different type of flow

estimate. For example, the setting of licences to abstract, or consents to discharge water require the derivation and maintenance of specific 'hands off' low flows. Without such safeguards, pollution may increase, fish and wildlife may be endangered and the aesthetic features of a river may degrade. Alternatively, the design of river works or reservoirs may require the derivation of flood flows of one-in-fifty or one-in-one hundred year return period. In some cases, where life may be put at risk by extreme high discharges the requirement may be to estimate the absolute maximum flow. In contrast, some projects do not require specific estimates of high or low flows, they require an integration of the total flow in a complete year, (ie flow duration data). These estimates may be required to operate power generation plants or bankside storage reservoirs to their optimum capacity. Flood forecasts require another specific type of information, that is 'real time' estimates of flow based on discrete samples of rainfall.

The procedures described in subsequent chapters of this thesis are primarily concerned with meeting these data requirements for the Trent basin. However, several of the techniques can also be applied in other areas for practical or research purposes. In the research environment, some of the derived methods could be of importance to those considering the variability of channel morphology, river channel adjustments to human activity, erosion and sedimentation, hydrological mapping and channel ecology. For example, the method of median flow determination described in section 5.6.4 is being used in ongoing research into fish muscle size: The two measures seemingly being highly correlated (Eastern, 1983).

1.4 THE HISTORICAL PERSPECTIVE

Progress in the techniques of hydrology has generally occurred in a series of spurts followed by periods of consolidation and widening of experience. One of the first noteworthy development phases came in the 1880's. For

example, in 1883, Reynolds published the results of his classic experiments on the resistance to flow in fluids, and in 1889, Kuichling published a formula of the 'Rational' type, whereby peak runoff for a catchment could be calculated from catchment area and rainfall intensity. Also, in 1890, Manning produced his much used equation whereby river velocity and hence flow could be calculated from channel characteristics. Coincidentally, Britains longest continuous flow record commenced in the 1880's. This is the measurement of the River Thames at Teddington (1883).

Empirical equations of the Kuichling and Manning type are still popular with engineers and hydrologists today for the estimation of river flows in ungauged catchments, and many similar equations are still being developed. For example, many recent research projects have involved <u>regression analysis</u> whereby the integrated output from one catchment is correlated against the integrated output from another catchment in terms of geomorphological, geological and climatological characteristics.

A second important phase of hydrological advance came in the 1930's. In 1933, the British Institution of Civil Engineers produced their classic paper 'Floods in Relation to Reservoir Practice' to provide guidance for engineers who were entrusted with the inspection or design of reservoirs in accordance with the Reservoir (Safety and Provisions) Act 1930. In the USA, a similar Act, the Floods Control Act, appeared in 1936. One of the most used of all hydrological techniques appeared in 1932. This was the Unit Hydrograph method (Sherman, 1932) of hydrograph estimation. This simple method of <u>runoff synthesis</u> is based on <u>linear analysis</u>, (ie the principles of superposition and invariance of response apply, see section 2.3.4). Since 1932, there have been many analyses to find relationships between the properties of the unit hydrograph and catchment characteristics and hence apply a form of the method to ungauged catchments. The work of Nash (1960) probably being the most influential.

The importance of the quantification of landforms in relation to hydrology came to prominence in the 1930's and 1940's with the work of Horton (e.g., 1932) and Langbein (1947). Each author suggesting a number of indices describing catchment physiography. In turn, these indices (and others subsequently derived) have been used to describe the hydrological processes occurring within catchments or the variability of response between catchments.

The most recent period of hydrological advance came in the 1960's. In Britain, the 1963 Water Resources Act committed river authorities to the preparation of hydrometric schemes and the determination of minimum acceptable flows, thus giving a major boost to those involved in river flow data collection and analysis. 1965 was the beginning of the International Hydrological Decade, and at about the same time the use of computers became popular for hydrological analysis. One of the major benefits of the computational power of electronic computers was the development of what Amorocho and Hart (1964) called ROP models (Reconstruction of past sequences, Or, Prediction of future ones). These are in fact Deterministic - Conceptual models which are discussed in section 2.3.6. In Britain, a research institution was formed in 1962, which was subsequently to have a profound influence on world hydrology: the Hydrological Research Unit, which became the Institute of Hydrology in 1969. Recently this Institute has produced two very important contributions to the estimation of flows in ungauged catchments; the 'Flood Studies Report' (NERC, 1975) and the 'Low Flow Study' (IOH, 1980). These reports are referred to in several further sections of this thesis.

In contrast to the activity of the International Hydrological Decade, the late 1970's and early 1980's have provided few major hydrological advances and a historical perspective shows it to be a period of consolidation rather than a period of invention. This is probably due to the world economic recession more than any other single factor.

1.5 COMMENT

Whilst there has been a long history of development of mathematical procedures by which flows may be estimated for ungauged catchments, many authors agree that there remains scope for further developments. For example, in considering low flow estimation techniques, the TASK Committee of the American Society of Civil Engineers (TASK, 1980, page 729) stated that "Methods of estimating low flow characteristics at sites without flow data are not adequate." With respect to high flows, it is pertinent that conceptual models have never been widely adapted for flow prediction and forecasting in ungauged areas. In 1980, at the conference 'Flood Studies Report - Five Years On', Lowing and Read (1980, page 41) concluded "It is only the unit hydrograph losses model which copes directly with ungauged catchments." Yet, ten years earlier, whilst making a case for the Flood Studies Project, Nash and Sutcliffe (1970) suggested that the extension of the unit hydrograph technique to ungauged catchments was not possible and that "Greater emphasis be placed on modelling the real physical processes" (p285).

The aim of this thesis is to continue the development of techniques by which flows are estimated in ungauged catchments. Most of the methods will be developed specifically for local application in the Trent basin, but it is hoped that some will be applicable to other areas. The research is described in five further chapters. Chapter 2 considers existing methods of flow estimation. Chapter 3 describes the River Trent basin and also outlines a simple method by which mean flow can be determined for any location within the basin. Chapter 4 evaluates the indices by which catchment morphology and geology can be quantified. Chapter 5 derives techniques for low flow estimation and Chapter 6 outlines methods of forecasting and predicting flow hydrographs. Finally, Chapter 7 contains a summary of the methods of estimation.

2 THE ESTIMATION OF RIVER FLOWS

2.1 INTRODUCTION

The long history of research into the development of mathematical procedures by which flows may be estimated for ungauged catchments briefly discussed in section 1.4 showed that three analytical methods are commonly employed; regression analysis, partial systems synthesis using linear analysis (eg unit hydrograph) and non-linear system synthesis (deterministic-conceptual models). Low flow estimation procedures are almost all of the former type, whereas all three techniques have been employed to assess high flows.

2.2 METHODS OF ASSESSING LOW FLOWS FOR UNGAUGED CATCHMENTS

2.2.1 The earliest analyses of low flows were undertaken specifically to derive the yield of direct supply impounding reservoirs. For example, Lapworth (1949) analysed the runoff records from 17 gauged catchments to ascertain minimum runoffs for various periods when rainfall was assumed not to exceed certain percentages of the long term average. Some of the records fortuitously included the 1933-34 drought and thus the Lapworth chart corresponds to a 1% to 2% probability of low flow occurrence. (Low flow probability distributions are defined and discussed in section 5.4.)

More recently, methods have been produced by which low flows can be estimated for a range of other purposes such as licence enquiries, consents to discharge and the design of water reclamation works. In 1976, McMahon in a review of computational procedures and in an annotated bibliography showed that regional analyses to derive specific indices, or complete distributions, of flow frequencies or flow durations for ungauged areas, had been undertaken in seven countries, Australia, Finland, New Zealand, Poland, South Africa, the United Kingdom and the USA. In McMahon's review and also in more recent literature, by far the greatest number of examples of methods by which low flows can be estimated have

been developed in the USA. This reflects a greater availability of riverflow data from which relationships can be determined, and possibly a greater awareness of the importance of this type of research. Typical recent examples of research undertaken in the USA to derive specific indices of low flow in ungauged catchments, are the work of Chang and Boyer (1977), Osbourne (1975) and Thomas and Benson (1970). Working in West Virginia, Chang and Boyer reported that 99.9% of the spatial variability of the 7 day 10 year flow ($Q_{7.10}$, lowest seven consecutive day flow in 10 years) can be explained from watershed perimeter (CO), main channel length (CL), watershed form (WF), precipitation (R) and temperature (T). Their estimation equation is:-

$$\text{Ln } Q_{7.10} = 37.05 + 0.039\ CO - 0.04\ CL - 3.674\ WF - 0.577\ R + 1.67T \quad (1)$$

Osborn (1975), developed correlations between the two year and twenty year seven-day flow, and drainage area, basin relief and stream length for a number of river basins in the east coast states. The most extensive of the American studies is that of Thomas and Benson (1970) who, using multiple regression analysis, related low flow characteristics (90% flow duration, 7 day 2 year and 7 day 20 year flows) to 30 meteorological and physical characteristics of catchments. The analysis applied to four very different regions in the USA. An example of a relationship developed by Thomas and Benson is given as equation 2.

$$\log Q_{7.2} = \log 2.74 + 1.08 \log A + 3.92 \log P - 0.61 \log F + 2.08 \log Si \quad (2)$$

The 7 day 2 year flow is thus related to catchment area (A), an index of forest cover (F), a soil index (Si) and mean annual precipitation (P). These three examples have been chosen because they are typical of the many methods by which catchments are classified into physiographic types and low flow data transferred in a dimensionless or specific form

between catchments in the same region. The catchment indices vary from method to method and most refer to the importance of catchment geology without actually using it as an index.

In Britain, consideration has been given to low flows in the form of a catalogue of lowest recorded current meter gaugings (Water Resources Board, 1970) and general analyses of specific droughts (Rodda et. al, 1976; Rowntree et. al, 1961; Doornkamp et. al, 1980). Only Wright (1970, 1974) has developed a regional prediction equation for estimating a specific low flow in ungauged areas. The lowest mean flow in the Lothians of Scotland is estimated using catchment slope and area as independent variables. The prediction error is then associated with catchment geology and a table of numerical geological indices for different classes of material derived. (This geological index is discussed further in section 4.3.2).

2.2.2 Methods by which complete low flow <u>frequency or flow duration distributions</u> are derived for ungauged catchments are much less prevalent in the literature. One of the earliest works was Lane and Lei (1949) who produced an index of stream flow variability based on catchment geology, soil cover and the presence of lakes and swamps. They suggested the index could then be developed to define flow duration curves for areas where stream flow records were either short or non existent. Searcy (1959) produced a method of flow duration curve estimation using a limited number of spot current meter gaugings and index stations. In 1975, Osborn produced a method by which flow frequency curves could be estimated for ungauged catchments using measures of basin area, relief and stream length. The most impressive of these studies is probably the earliest, (Lane and Lei) even though the application to ungauged areas was suggested rather than proven. In particular, the lack of dependence on local index stations and the recognition of the importance of geology are significant.

In Britain, the Institution of Water Engineers and the Society of Water Treatment Examination Research Panel (1966) considered the properties of measured frequency and flow duration diagrams. Unfortunately the panel seemed confused by the fundamental difference between these two types of curves, both being considered under the same title. (Both types of distribution are defined and discussed in this report in sections 5.4.2 and 5.4.3). Nevertheless, the Panel (1966, page 233) recommended that "Further study seems especially merited to generate flow frequency curves from rainfall data" This was one approach considered by the Institute of Hydrology (1980) in a comprehensive study of low flow data. Four reports were published under the title of 'Low Flow Study'. All available British flow records were analysed and six catchment indices identified, which can be used to calculate flow duration and flow frequency data for ungauged catchments. The indices are catchment area, catchment average rainfall, stream frequency, stream length and base flow index. The base flow index is an indirect measure of geology. Examples of the Low Flow Study equations are given as equations 3 and 4.

$$Q95(10) = 11.9 / \overline{BFI} + 0.115 / \overline{SAAR} - 8.03 \quad (3)$$

$$MAM(10) = 11.2 / \overline{BFI} + 0.0982 / \overline{SAAR} - 6.81 \quad (4)$$

where Q95(10) = 95 percentile 10 day flow
MAM(10) = Mean annual minimum 10 day flow
BFI = Base flow index
SAAR = Annual average rainfall (1941-70)

2.2.3 Although there are many examples of techniques from which low flow statistics can be estimated for ungauged catchments, few are reliable. Frye and Runner (1970) reported that low flow characteristics at ungauged sites on natural streams, minor or principal cannot be estimated by regression. Thomas and Benson (1970, page 1) concurred, "Low flow characteristics can only be weakly defined".

In 1980, the American Society of Civil Engineers Task Committee on Low Flow Evaluation, Methods and Needs (TASK, 1980, page 729) stated "Methods for estimating low flow characteristics at sites without any flow data are not adequate" and "An in-depth study of various types of problems is needed to indicate the most suitable ways of using low flow information".

Whilst the Task Committee Report is critical of many of the methods available to estimate low flows in ungauged catchments, the report was prepared prior to the publication of the Institute of Hydrology 'Low Flow Study': This being the only method applicable to the Trent basin. However, Pirt and Douglas (1982) and Pirt and Simpson (1982), have shown, by the analysis of river flow data for a number of catchments in the North and Midlands of England, that little confidence can be placed in the 'Low Flow Study' methods of assessing flow duration or flow frequency data for ungauged catchments. In comparing the 'Low Flow Study' method of flow duration curve synthesis with measured data for five catchments, Pirt and Douglas found the mean error of estimation of the one day 91 percentile flow was 57%. In comparing the flow frequency curve synthesis method with measured data for six catchments, Pirt and Simpson found the mean error in estimation of the seven day 2.33 year return period low flow (annual average) to be 84%. Further analyses of the "Low Flow Study" methods are included in Chapter 5.

2.2.4 There are several possible reasons for the general lack of success with low flow estimation techniques.

(i) Very few of the methods include an adequate measure of the influence of geology on low flows. The TASK Committee (1980, page 723) state: "The effect of geology on low flows has often been reported but very rarely defined".

(ii) Some of the analyses have been based on very extreme flows, for instance the 7 day 20 year flow. Few

gauging stations are designed to measure extremely low flows, and recorded data may be subject to large measurement errors. If less extreme flows are considered, analysed data are more prevalent and of higher accuracy. For this reason Thomas and Benson (1970) were able to estimate the 7 day 2 year flow for ungauged catchments to a much higher standard of accuracy than the 7 day 20 year flow.

(iii) Few attempts have been made to adequately naturalise measured flow data. On this subject the 'Low Flow Study' (IOH, 1980, page 4) states "Only catchments whose gaugings represent reasonably natural conditions were accepted" and because of mine drainage "Many gauged catchments in the Trent area were downgraded to unsuitable". The principle of ignoring data with an artificial element (ie flows affected by man's activity) severely reduces the number of records available for analysis. However this approach is preferable to analyses based on a data set containing both natural, and artificially influenced flows.

2.2.5 Although there has been extensive research into low flow hydrology, a requirement remains for simple techniques that will reliably predict low flows in ungauged areas of the Trent basin. Evidence from the literature suggests that small local studies, although introversive, are more likely to be successful than wide ranging national studies. Particular attention has to be paid to catchment geology, data quality, and the respective proportions of natural and artificial flows.

2.3 METHODS OF ASSESSING HIGH FLOWS FOR UNGAUGED CATCHMENTS

2.3.1 There are many equations, by which high flows can be estimated for ungauged catchments, which are based on only a single parameter, drainage area. These formulae are of the form of equation 5.

$$Q_m = C\ A^n \tag{5}$$

where Q_m is the flood discharge, A is the catchment area and n an exponent.

For the United Kindom, Bransby Williams proposed

$$Q_m = 2700\ A^{0.75} \tag{6}$$

for catchments smaller than 26 Km^2 and

$$Q_m = 4600\ A^{0.52} \tag{7}$$

for catchments greater than 26 Km^2 in area.

In some cases relationships of this type are not specifically stated as formulae, but instead, envelope curves based on previous flood experience have been derived to estimate flood magnitudes for different sizes of catchment. This was the case in 'Floods in Relation to Reservoir Practice' published by the Institution of Civil Engineers in 1933. This much used report was reprinted in 1960 with little modification apart from the inclusion of a small number of additional records.

Another simple method of flow estimation which has remained popular with engineers for many years is the 'Rational Method' (Kuichling, 1889; Lloyd-Davis, 1906). This approach assumes that the maximum flood discharge from a catchment (Qm) can be represented by an equation of the form:

$$Q_m = CIA \tag{8}$$

where C is a runoff coefficient indicating the percentage of rainfall which appears as quickflow, I, the mean rainfall intensity during the period of concentration (the time required for the most distant part of the catchment to contribute to outflow from the catchment) and A, the area of the catchment.

Many other formulae have been developed which extend the concepts described above by the inclusion of various measures of the morphological characteristics of the catchment and/or indices of rainfall characteristics. British examples are: Nash & Shaw (1966) who related the mean annual flood and the coefficient of variation of the annual flood to catchment characteristics, which included area, slope and mean annual rainfall; Cole (1966) divided England and Wales into regions where the mean annual flood was adjusted to a common period and related to area, the coefficient of variation was assumed homogeneous in each region; and Rodda (1969) who found that the mean annual flood could be predicted from equation 9.

$$Q = 1.08\ A^{0.77} R^{2.92}\ D^{0.81} \qquad (9)$$

where A is catchment area, R is the mean annual daily maximum rainfall and D the drainage density.

The most recently derived parametric equation to achieve widespread acceptance by British hydrologists and engineers was produced by the Flood Studies Group (NERC, 1975). This was a study of all Nationally available flood records. All recorded flood peaks and volumes were analysed and related to regional effects and catchment characteristics. The mean annual flood for any site within the British Isles can be estimated from equation 10.

$$Q = C.AREA^{0.94} STMFRQ^{0.27} S1085^{0.16} SOIL^{1.23} RSMD^{1.03} (1 + LAKE)^{0.85} \qquad (10)$$

C is a coefficient which varies from region to region, AREA is catchment area in km^2, STMFRQ is the number of stream junctions per km^2, S1085 is the slope from 10 to 85 per cent of the main stream length in m/km, SOIL is an index based on the winter rain acceptance potential of the catchment, RSMD is the net daily rainfall having a return period of five years in mm, and LAKE is the proportion of the catchment draining through lakes. All the catchment characteristics incorporated in equation 10 can either be

read directly from topographic maps or obtained from standard tables. Regional frequency curves for each of eleven regions of the British Isles are then used to produce design floods for any return period. There are many examples of estimation techniques similar to equations 5 to 10 for application in other countries of the world. A review of some of these equations is to be found in the 'World Meteorological Office Manual of Flood Computation (Methods Derived from Worldwide Experience)' (Sokolov et. al 1976).

2.3.2 Whilst the parametric equations outlined in the previous section have the common virtue of simplicity, they have two fundamental drawbacks.

(i) They are not very accurate.

Francis (1973) considered 37 flood prediction equations. 20 were of the simplest type with only a single variable (catchment area) and 17 involved other variables (rate of rainfall, catchment slope etc). In each case, a flood was predicted for an imaginary, circular catchment in Britain of 129 km^2. The mean estimate for Q_{max} from the simple methods was 410 cumecs $\pm$ 240 cumecs and the mean estimate from the slightly more complex methods was 387 cumecs $\pm$ 258 cumecs. The ICE envelope curve (1933) indicated a flow of 272 cumecs for the same catchment area. Simpson (1977) tested the Flood Studies catchmemt model (equation 10) against measured data from 32 catchments in the Severn Trent Water Authority area. This was not an ideal test, as most of the data available to Simpson, had been used by the Institute of Hydrology in deriving the equations. Nevertheless, the estimated mean annual flood (MAF) varied from +109% to -38% of the measured MAF. The mean error was 31%. The model overestimated MAF twice as often as it underestimated MAF.

(ii) The simple methods only provide estimates of hydrograph peak.

Estimates of peak flows of specific return periods are very useful information, but there are many more instances when simulations of complete hydrographs are of greater importance. For example, reservoir safety calculations require not only the maximum possible rate of inflow, but also the total volume of inflow. Further, if hydrograph simulation techniques for ungauged areas could be adapted to provide real time information (forecasts), then they could provide a completely new hydrological service. At present, riverflow forecasts are provided by some Regional Water Authorities for a limited number of major, gauged rivers. Yet, there are many communities lying on large streams or rivers which are prone to flooding which cannot, because of time of response, be served by these regional forecasting systems. A simple simulation model, operated locally, using real time input data could be of substantial benefit in these cases.

2.3.3 Nearly all currently used methods of hydrograph prediction for ungauged catchments have their origin in unit hydrograph theory (Sherman, 1932). As a stream hydrograph reflects many of the physical characteristics of a catchment area, Sherman considered that similar hydrographs would be produced by similar rainfalls occurring with comparable antecedent conditions. Thus, once a typical or unit hydrograph has been determined for certain clearly defined conditions, it is possible to estimate runoff from a rainfall of any duration or intensity. In gauged catchments the unit hydrograph is constructed by selecting recorded hydrographs from several uniform isolated storms, preferably with fairly large volumes of runoff, isolating the base runoffs, and dividing the discharge ordinates of the remaining direct runoff hydrographs according to the volumes under the hydrographs, thus obtaining several unit hydrographs, that is hydrographs of 25mm (1 inch) of runoff. From the hydrographs a mean unit hydrograph is produced. For application in catchments without streamflow records it is necessary to establish the

relationships between the physical characteristics of the catchment area and the resulting hydrographs. Snyder (1938) was one of the earliest workers to derive synthetic unit hydrographs and found that the shape of the catchment and its lag, the time from the centre of the mass of rainfall to the hydrograph peak, were the main influencing characteristics. Many subsequent investigations have been undertaken to find the properties of the unit hydrograph and to correlate them with catchment characteristics. These include the work of Taylor and Schwarz (1952), Henderson (1963) and Nash (1960). In the 'Flood Studies Report' (NERC, 1975) the shape of the unit hydrograph is related to main stream length, main stream slope, urban proportion and RSMD (the net daily rainfall having a return period of five years).

2.3.4 There are several arguments which suggest that the almost universal acceptance of unit hydrograph theory as a means of predicting design hydrographs for ungauged catchments is illfounded. Two of the basic assumptions of the unit hydrograph method of relating a rainfall excess on a catchment to the resulting hydrograph of direct runoff are:

(1) Invariance of response; the same rainfall excess, whenever it is applied, will always produce the same direct runoff hydrograph.

(2) Superposition of responses; the runoff due to two or more different rainfalls applied together is the arithmetic sum of the separate runoffs caused by each of the rainfalls applied separately.

Unit hydrograph theory is therefore based on the assumption that the catchment is a time-invariant linear system, at least so far as rainfall excess and direct runoff are concerned. This has been proved not to be the case by Amorocho (1963), Amorocho and Hart (1961) and by Francis (1973). In 1970 (page 285), Nash and Sutcliffe stated that "The principal cause of this sterility (in unit hydrograph theory) lies in the dependence of these techniques on the

TABLE 1

COEFFICIENT OF VARIATION FOR SOME LINEAR MODELS FOR

THE ROTENBACH CATCHMENT (NAEF, 1980)

Forecast = effective rainfall	1.60
Unit hydrograph as a rectangle	0.80
Unit hydrograph as a triangle	0.75
Unit hydrograph computed with least squares	0.77
Unit hydrograph computed with CLS	0.74
Nash cascade method (Nash, 1960)	0.76

Coefficient of variation is a measure of the quality of computed discharges as defined by the World Meteorological Organisation, 1975.

CLS = Constrained linear system model (Todini, 1977)

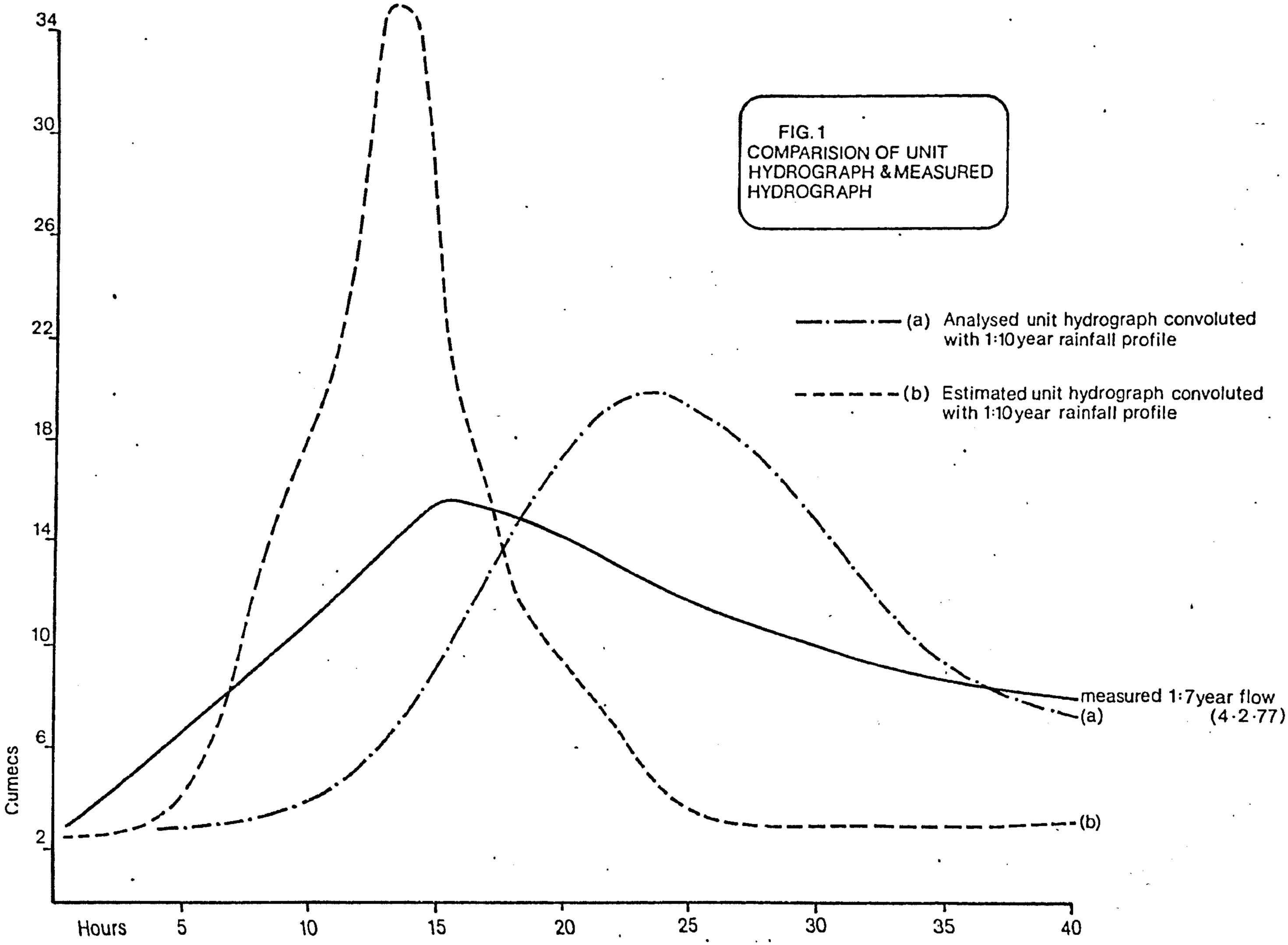


FIG. 1
COMPARISION OF UNIT HYDROGRAPH & MEASURED HYDROGRAPH

—·——·— (a) Analysed unit hydrograph convoluted with 1:10year rainfall profile

– – – – – (b) Estimated unit hydrograph convoluted with 1:10year rainfall profile

attempted identification in the hydrograph of at least two components which are usually called storm runoff and baseflow, but which are not adequately defined in terms of their physical origin". They also conclude "While traditional methods (unit hydrograph) applied to the records of an individual catchment may provide reasonably valid relations, extension to ungauged catchments has not been possible. The extension would require finding links between the physical characteristics of the catchment and the parameters of both the rainfall - runoff conversion and the unit hydrograph". "Further progress would seem dependent on the rejection of the a priori division of hydrographs into ill defined components and a greater emphasis being placed on modelling the real physical processes". Further, Naef (1980, page 4) in his paper 'Can We Model the Rainfall-Runoff Process Today' concludes "The search for the optimal unit hydrograph is useless". Also that the "Unit hydrograph computation is not very sensitive and the use of more sophisticated methods has only a small effect". Some of Naef's results are summarised in Table 1.

2.3.5 An example of the difficulties which may be encountered in applying the unit hydrograph method of flow prediction are shown in figure 1. A 1 in 10 year storm rainfall profile has been convoluted with unit hydrographs derived by two methods:

(i) A unit hydrograph derived by the analysis of six flow hydrographs measured at the Izaak Walton gauging station (SK 146 509, 83km^2). The analytical method was that outlined in the 'Flood Studies Report' (NERC, 1975), volume 1, section 6.4. This method follows the general principles outlined in section 2.3.3, but the actual derivation is by means of matrix inversion.

(ii) A synthetic unit hydrograph derived for the River Dove catchment to Izaak Walton using catchment indices as outlined in the 'Flood Studies Report', volume 1, section 6.8.2. An example of this calculation procedure is given in Appendix 13.

Also shown is an actual measured runoff hydrograph of approximately 1 in 7 year return period. A 1 in 7 year flow is the order of magnitude flow expected from a 1 in 10 year rainfall in a non urban area ('Flood Studies Report', Section 6.8.2, fig 6.6.1).

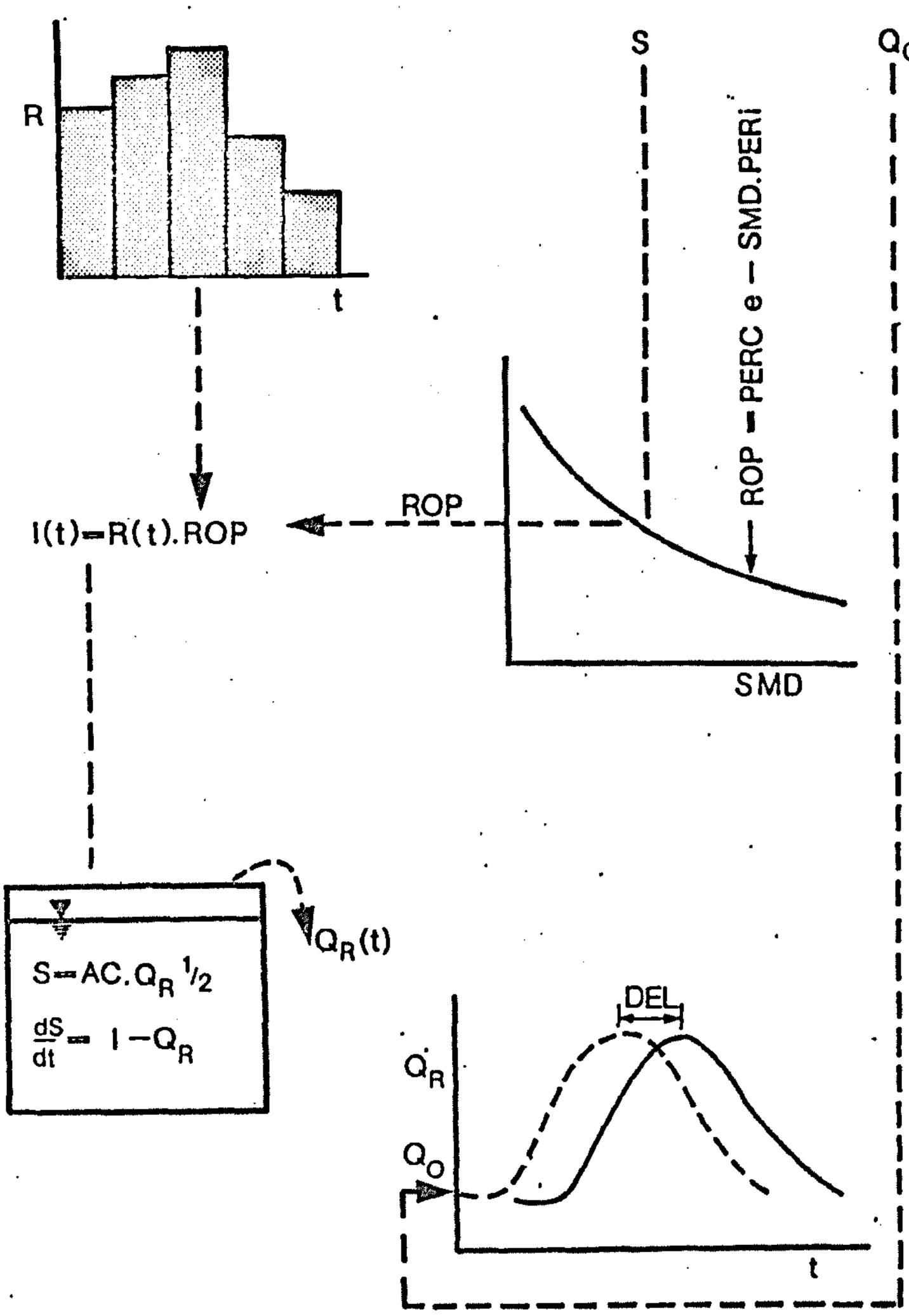
The hydrograph derived by analysis gives approximately the same volume of runoff as the measured hydrograph but with very poor timing, whereas the synthetic hydrograph gives good timing but very poor volume estimates. The very large differences between the hydrographs produced by the two methods gives cause for concern.

2.3.6 Because of the stated theoretical and practical drawbacks of the unit hydrograph approach, some hydrologists have rejected the method and have turned to <u>deterministic-conceptual modelling</u>. Any model is a simplified representation of a complex system, but ideally deterministic-conceptual models specify completely the properties of, and the processes that occur in all the relevant components of a catchment. Such descriptions may be possible because river basins are not a random assembly of different parts, but are geomorphological systems whose parts are related to each other by a long common history. Further, if the relationships between these operations and the physical features of a catchment can be recognised, the operation of ungauged catchments might also be forecast from a study of these features. One of the earliest conceptual models was the Stanford Watershed Model (Crawford and Linsley, 1966) which simulated the whole land phase of the hydrological cycle in a catchment. In Britain, models of a similar type also appeared in the 1960's and 1970's at the Institute of Hydrology, a number of Universities and some Regional Water Authorities (Ibbitt, 1970; Manderville et. al., 1970; Nash and Sutcliffe, 1970; O'Connell et. al., 1970; Douglas, 1974; and Manley, 1978.)

It is the explicit soil moisture accounting function of conceptual models that many believe to be their strongest asset. Sittner (1976) summarising a World Meteorological

FIG. 2

Isolated Events Model



t = time (hours)
R = Rainfall (mm)
SMD = Soil Moisture Defecit (mm)
Q_0 = Initial Discharge
Q_R = Runoff Hydrograph Ordinates

PERC
PERi
AC
DEL
} Parameters

Office intercomparison of forecasting models states "Explicit soil moisture accounting models are worthwhile if the user is obliged to work in any area other than one which is continuously humid" (their) "Superiority may be noted during and immediately after a long dry spell" (p 208). There is also a belief (Manley et al, 1980) that non-linear conceptual models, because of their supposed hydrological reality, offer the best hope of forecasting extreme floods, and in particular floods greater than those to which the model has been fitted. However, most deterministic models, because of their size and complexity, can only be applied to gauged catchments with extensive data. This drawb ack was recognised by the Flood Studies Group, "Most previous conceptual modelling has been concerned with fitting long term records" (NERC, 1975, page 513). In a move away from both empirical and multiparameter conceptual models, the Flood Studies Group proposed a simple four parameter conceptual model of catchment response known as IEM4, the Isolated Events Model. Figure 2 is a schematic representation of this model. The format of the model is such that it could be developed for simulation and forecasting in ungauged catchments. However, insufficient progress was made with the model during the Flood Studies Project and it was not offered as a workable system. By 1980, at the conference 'Flood Studies Report - Five Years On' Lowing and Reed reported no further progress with the Isolated Events Model. Prediction equations had not been developed to allow model parameters to be estimated for ungauged catchments. Lowing and Reed concluded that it is only the Unit Hydrograph/Losses Model which will forecast a hydrograph from rainfall in real time on an ungauged catchment.

2.4 CONCLUSIONS

Section 2.2 and 2.3 have considered 'the state of the art' of flow estimation in ungauged catchments. In theory, estimates of low flows should be more reliable than the estimates of high flows. Low flows are predominantly maintained by

groundwater and their magnitude should be closely related to catchment size and geology. In contrast, high flows are related to many more catchment properties: Catchment size, shape, slope and geology; channel size and slope; catchment moisture status and antecedent conditions all influence the rate and volume of runoff response. However, in practice, nearly all techniques by which high and low flows are estimated for ungauged catchments have severe limitations and there is an outstanding requirement for techniques that will accurately define flow information for ungauged sites.

Section 1.3 has shown that information of this type is required by Regional Water Authorities for: Abstraction licensing and formulating consents to discharge; designing river channels, structures and water reclamation works; fishery management and flood forecasting. There are also many research projects which could benefit from reliable estimates of river flow. Section 1.3 has also shown that many of these projects require different types of flow statistic. For example, some require an index of low flows, others flow duration distributions and some forecasts or predictions of runoff hydrographs. However, if the following statistics could be estimated for any catchment then most requirements would be met:

(i) Predictions and forecasts of <u>total runoff response to storm rainfall</u>

(ii) A single <u>index of average low flow</u> for both industrial and 'clean' rivers

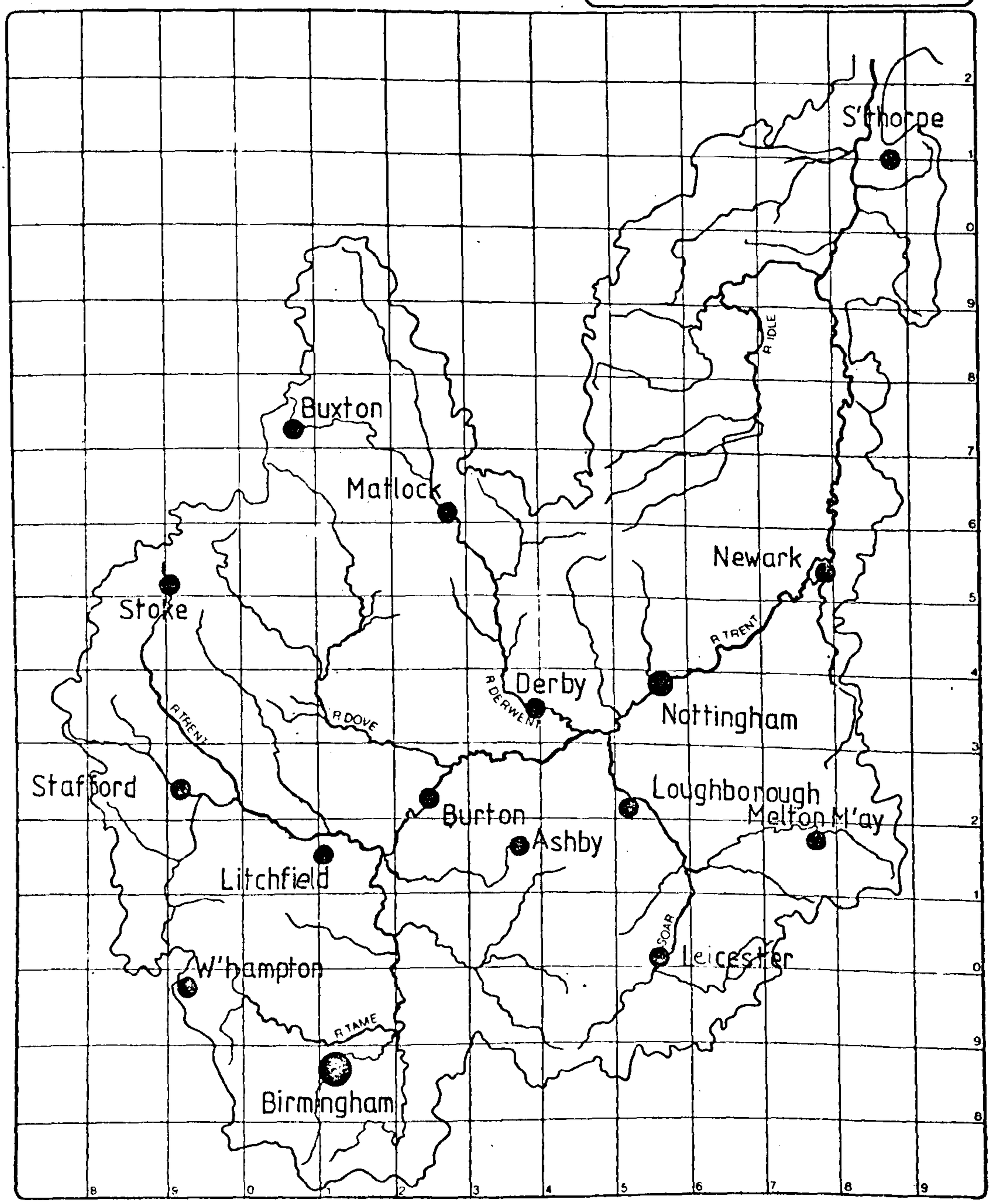
(iii) <u>Flow duration curves</u>

(iv) <u>Flow frequency curves</u>

Subsequent paragraphs describe the development of these techniques for application in ungauged catchments, with particular reference to the Trent basin.

FIGURE 3
MAJOR RIVERS & NATIONAL GRID

RIVER TRENT BASIN



Note : In Volume 2 this figure is reproduced as a transparent overlay.

3 THE RIVER TRENT BASIN

3.1 INTRODUCTION

3.1.1 The analyses described in subsequent sections of this thesis relate to the catchment of the River Trent. This is an area of 8200 km draining much of the Midlands of England.

In 1951, D L Linton discussed a proto river Trent as an ancient river rising in the higher ground of North Wales and pursuing an easterly course across the Midlands south of the Pennines, and out to the sea somewhere near the Wash (Linton, 1951). Straw (1963) has since identified two evolutionary phases of the middle-lower Trent occurring during the latter stages of the Quaternary era. During the Penultimate Interglacial, the Trent probably flowed in a west to east direction south of the present location of Nottingham and to the sea via the Vale of Belvoir. Latter, in the Penultimate Glaciation, the Trent assumed a more northerly course, flowing to the sea via the Lincoln gap (SK 970 710). Today, the Trent rises in Staffordshire to the north of the Potteries and flows to the Humber Estuary and the North Sea. At first the Trent follows a southerly course, but near Stone, the river's course begins to turn to the east, before assuming a north-easterley direction near Burton on Trent. The Trent keeps to its north-easterly course through Nottingham before turning due north near Newark. All four of the Trent's major tributaries; the Dove and the Derwent flowing from the north and the Tame and the Soar flowing from the south; join the Trent at the centre of the basin, in the reach between Lichfield and Nottingham. These features are shown in Figure 3.

3.1.2 The physiography of Trent catchment is diverse, yet few topographic boundaries exist that can be precisely defined. Four approximate regions can be identified:

LIAS

MERCIA MUDSTONE

SHERWOOD SANDSTONE

PERMIAN LIMESTONE

WESTPHALIAN (COAL MEASURES)

NAMURIAN (MILLSTONE GRIT)

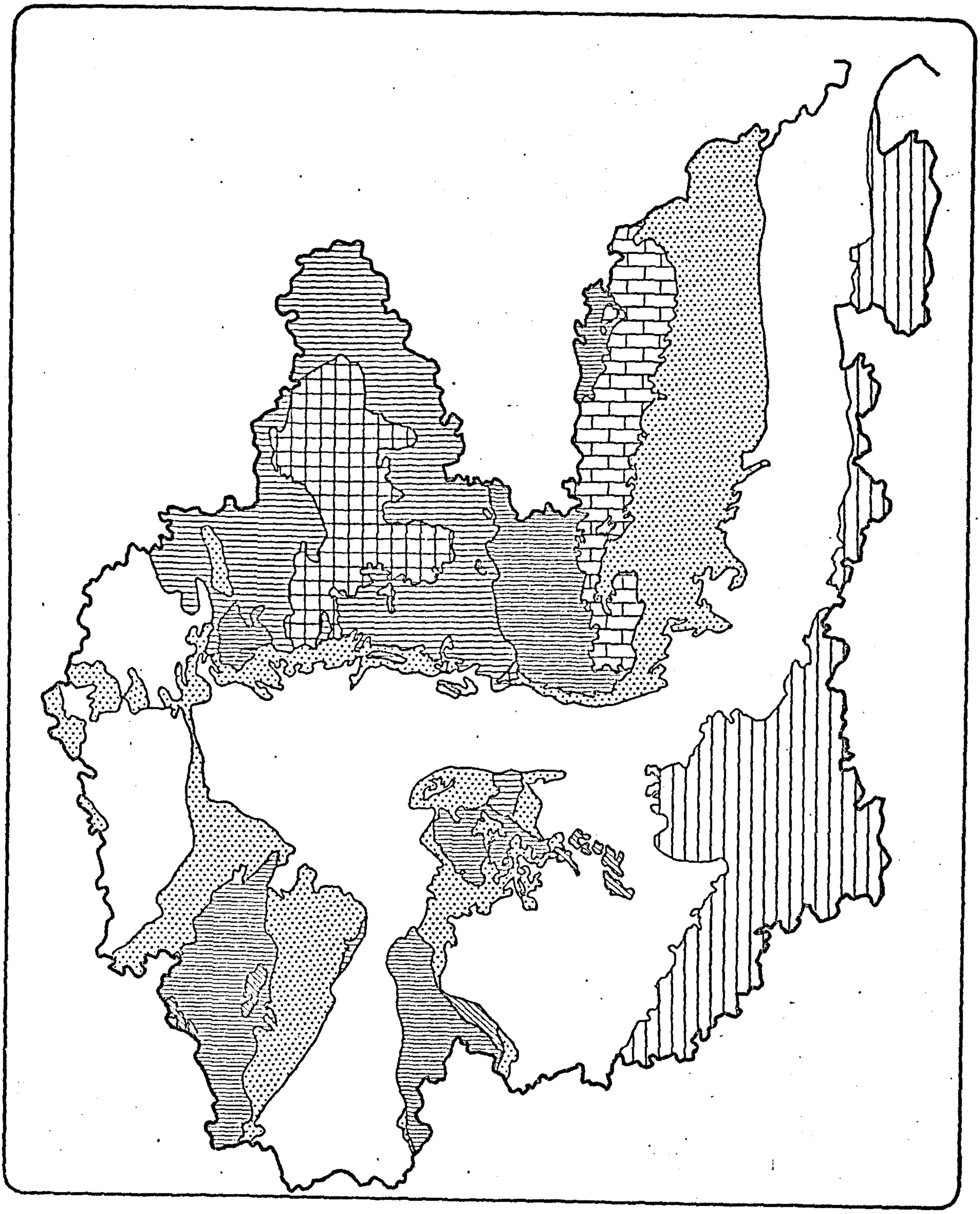
DINANTIAN (CARB. L'STONE)

PRE CAMBRIAN

TRENT AREA GEOLOGY

FIG. 4

0 10 20 30 Kilometres



(i) The Uplands Of The South Pennines. This area, centred on the Peak District, is drained by the Rivers Dove, Manifold, Wye and Derwent. Altitudes are generally greater than 300m AOD and in places exceed 600m AOD.

(ii) The Trent Valley And Associated Terraces. The area represents a wide arc of low lying ground between Stafford and Scunthorpe. Near Nottingham, the lowland extends eastwards into the Vale of Belvoir. This latter area is drained by the River Devon and its tributaries.

(iii) The Uplands To The South Of The Trent. This arc of undulating country includes the Potteries, Cannock Chase, the Birmingham Plateau, the hills of Warwickshire and Leicestershire and Charnwood Forest. The area is drained by the Rivers Penk, Sow, Tame, Soar, Sence, and Wreake,

(iv) The Dukeries And Sherwood Forest. This upland country to the north of Nottingham and west of the River Trent has a westerly facing scarp and easterly facing dip slopes. The area is drained by the River Idle and its tributaries.

3.2 GEOLOGY

3.2.1 Solid Geology.

The solid geology of the Trent basin is dominated by sedimentary rocks of Carboniferous, Permo-Triassic and Jurassic ages. Outcrops of igneous and metamorphic rocks are confined to small areas in the Peak District and Charnwood Forest. A simplified map of the solid geology is given as figure 4 and the predominant rock types are described below.

(i) Jurassic Strata: Impermeable Lias clay and shales, which dominate the Jurassic sequence, form the eastern

extremity of the Trent basin. The rocks form a narrow band which reaches a maximum width of 30km in the Melton Mowbray area.

(ii) Permo-triassic Strata: In pure geological terminology it is impossible to define the exact boundary between the Permian and the overlying Trias. Sedimentation opened with the spreading of a piedmont breccia and gravel on a desert plain, continued by marls and limestone of the Zechstein sea, and was completed with pebbles, sands and evaporates thickly laid down on a land surface (Dury, 1963).

(a) Triassic Strata: The Trias is dominated by an upper argillaceous (clay) sequence (Mercia Mudstone) and a lower arenaceous (sand) sequence (Sherwood Sandstones). The Mercia Mudstones consist of a monotonous sequence of impermeable red and, less commonly, green and grey mudstones and subordinate sandstones. Thin beds of sandstone as well as occasional beds of gypsum and salt are also found in the succession. The Mudstones occur in the central and southern part of the catchment with the River Trent following the outcrop virtually from its source to the Humber; extensive outcrops are also found in the Soar and Tame catchments. The underlying Sherwood Sandstones consist of red, yellow and brown sandstones with pebbles scattered throughout much of the sequence. Subordinate marl bands occur in the lower part of the sequence but these become more common higher up and the boundary with the overlying Mercia Mudstones is taken where the marl beds are more common than the sandstone beds.

The largest outcrop of the Sandstones occurs in Nottinghamshire to the west of the lower reaches

of the River Trent. Other major outcrops occur in the area between Nottingham and Stoke-on-Trent, between Lichfield and Birmingham, in the Rugeley/Wolverhampton area. Small outcrops are found to the south and west of Stoke-on-Trent and in the Ashby-de-la-Zouch area. All of the tributaries of the Trent, with the exception of Soar, drain some of these outcrop areas.

(b) Permian Strata: The limestone and marl horizons of the Permian occur in a narrow south to north band extending from Nottingham to Doncaster. To the east, the Permian dips down under the Sherwood Sandstones while to the west, the Permian dies out against the exposed Nottinghamshire Derbyshire Coalfields. Many of the rivers entering the lower reaches of the River Trent drain the outcrop area.

(iii) Carboniferous Strata: The Carboniferous series is divided up into three groups:

(a) Westphalian (Coal Measures): The Coal Measures consist of imperable marls, mudstones, shales and occasional sandstones. Actual coal seams form only a very small percentage of the total sequence, but some are the most productive in the whole of England. There are five major coalfields centred on Yorkshire and Nottinghamshire, Leicestershire, South Derbyshire, North Staffordshire, and Warwickshire. Most of the coalfields are considerably folded and faulted.

(b) Namurian (Millstone Grit): The Millstone Grit sequence consists of a repetitive sequence of shales and coarse sandstones (gritstones). The

major outcrops occur on both the western and eastern flanks of the Pennines in the catchments of the Derwent, Manifold and Churnet.

(c) Dinantian (Carboniferous Limestone): Carboniferous Limestone rocks form the 'Peak District' of the southern Pennines. In general, the rocks are of the standard facies (thick bedded with minimal shale partings) but round the margins of the underlying block (Manifold Valley and West Staffordshire) limestones of both the reef and basin facies are also found, (HMSO, 1954). In the basin facies in particular, limestone is inter-bedded with thick bands of shale. In the northern areas of Derbyshire to the east of Buxton and also further south near Matlock the limestone contains both intrusive and extrusive igneous rocks.

(iv) Lower Paleozoic and Pre Cambrian: To the south west of Loughborough, rocks of this period along with Carboniferious coal measures form the uplands of Charnwood Forest. The short, western tributaries of the River Soar drain the area.

3.2.2 Surface deposits.

Surface deposits of recent and Pleistocene ages are found in all sections of the Trent basin. Large tracks of the less elevated parts of the basin were covered by a mantle of Pleistocene deposits, but subsequent erosion, has largely disected this mantle. The products of this erosional period are partly preserved in the terrace gravels and alluvial deposits lying in the main valleys. Four main types of surface deposit can be identified (Downing et al 1970): Peat, valley deposits, boulder clay, sand and gravel.

TABLE 2

DOMINANT SOIL TYPES OF THE TRENT CATCHMENT AND ASSOCIATED LAND USE

	REGION	DOMINANT GROUP	ASSOCIATED GROUP	PARENT MATERIAL	ASSOCIATED LAND USE
1	Pennines	a Brown earths	Argillic brown earths	Dinantion limestone	Dairying, rearing
		b Stagnohumic gley soils	Peats and humic gleys	Namurian sandstone	Rearing
		c Raw peat soils	-	Blanket peat	Rearing, forestry
2	Central Valley	a Argillic brown earths	Argillic pelosols, stagnogley soils and brown earths	Triassic mudstone, sandstones, and drift	Arable or horticulture
		b Alluvial gley soils	Brown alluvial	River alluvium	Dairying
3	Southern uplands	a Stagnogley soils	Argillic brown or brown earths	Boulder clay	Dairying, arable
4	Dukeries and Sherwood Forest	a Brown calcareous earths	Argillic brown earths	Permian limestone and drift	Arable, dairying
		b Brown sands	Brown earths and podzols	Permo-Triassic sandstones and drift	Arable, mixed, forestry.

(i) Peat: The principal outcrops of peat are located in the most northerly parts of the catchment overlying the Namurian rocks.

(ii) Valley deposits and river terraces: All major rivers in the Trent basin flow through flood plains of considerable latteral extent. The deposits of these plains being alluvium. In some areas, above the present valley levels, are river terraces composed of materials laid down by the major rivers when they were flowing at a higher level than present.

(iii) Boulder Clay: This glacial deposit consists of relatively imperable clays in which are embedded pebbles and boulders of various sizes and lithologies. The largest and thickest deposits of boulder clay are found in the Soar catchment.

(iv) Glacial sands and gravels: Flüvioglacial sands and gravels, with lens of silt and clay, commonly form flat lying, level outcrops flanking river valleys, adjacent to, but at a higher level than, river terraces. They are most extensive in the Upper Trent, southern Tame and lower reaches of the Dove.

3.2.3 Soils

The Soil Survey of England Wales (1974) names 15 different soil types that occur in the Trent catchment. The dominant soils in each physiographic area are listed in Table 2 along with their parent material and associated land use classification. In the catchment as a whole Brown Earths and Argillic Brown Earths are most common soil types.

A detailed discussion of soil types and their influence on runoff is given in section 4.4.

3.3 LAND USE

Land use within the Trent basin mirrors the topography, soils and geology (Table 2). The 'Central Valley' and the 'Uplands of the South' are predominately given over to arable and dairy farming. In contrast the higher ground of the southern Pennines is mainly used for rearing and some land is given over to forestry. Forestry is also found in the Dukeries and Sherwood Forest, although the majority of the land in this area is used for arable or dairy farming.

There are several major built up areas in the catchment. Most notable is the City of Birmingham, which, with its satellites West Bromwich, Walsall and Wolverhampton make up Britains second largest urban conurbation. Other prominent urban developments are the cities of Leicester, Nottingham and Derby and the adjoining towns of Newcastle, Stoke, Hanley and Burslem which are known collectively as the Potteries. These towns and cities have a profound effect on the hydrological cycle. Industrial abstractions and discharges, sewerage systems and the percentage and type of developed area all influence river flows. The effects can also change from day to day. For example, regular variations in flow may be observed due to reductions in abstractions and effluent returns seen at night or at weekends. Alternatively, changes may be more permanent due to changing industrial or sewerage development strategy. For example, in the 'Black Country' (Walsall, West Bromwich) many small water reclamation works which have historically discharged to small tributaries of the River Tame are being closed and all effluent is being transferred, by means of trunk sewers, to a single large works. This works then discharges to the River Tame at a single point many kilometers downstream from the source of the effluent. This and other urban influences on river flows are discussed and quantified in several subsequent sections.

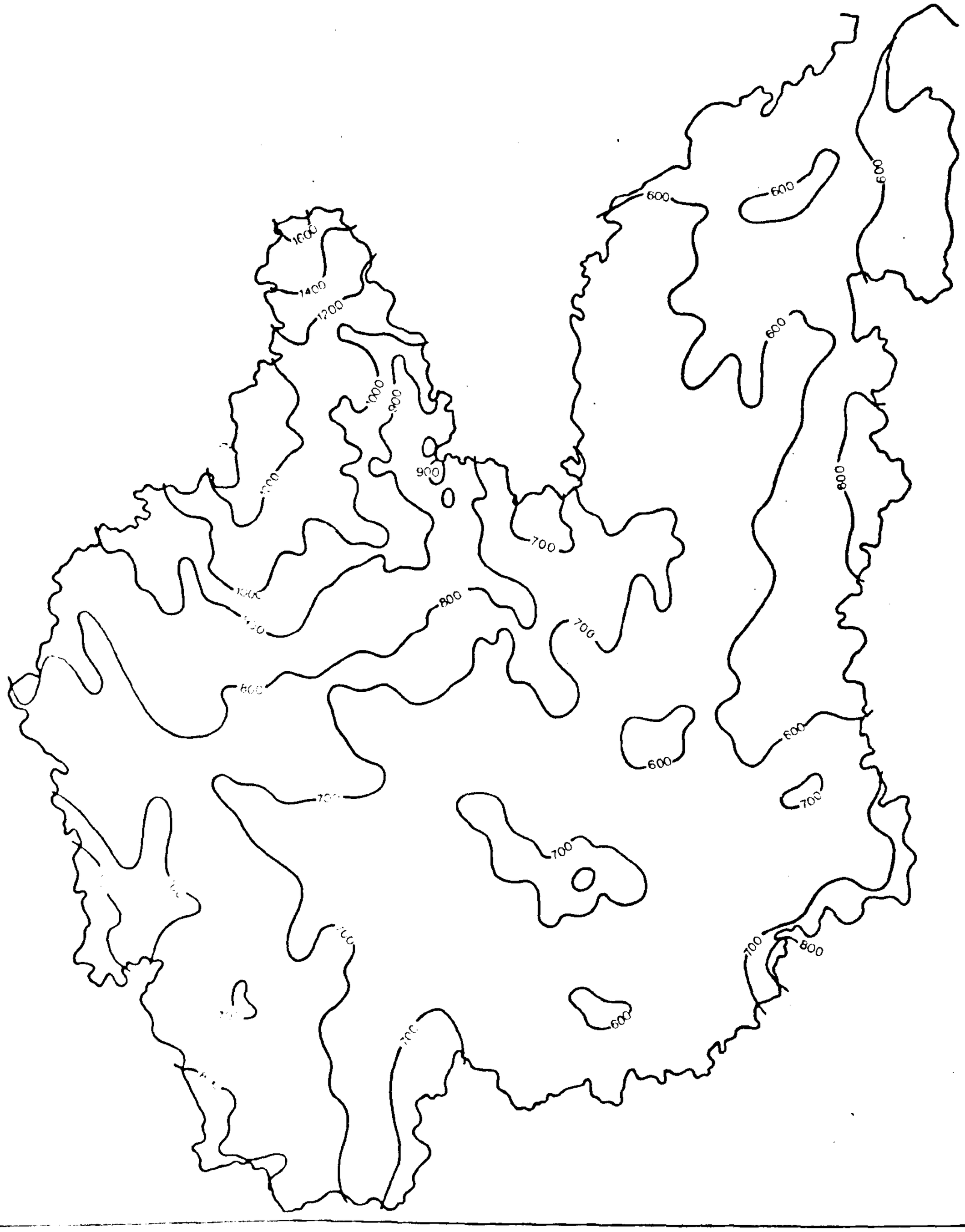
TRENT AREA

MEAN ANNUAL PRECIPITATION

FIG. 5

700 ISOHYETS IN MILLIMETRES PER ANNUM

0 10 20 30 Kilometres



3.4 PRECIPITATION, EVAPORATION AND EFFECTIVE PRECIPITATION

3.4.1 The runoff from any catchment is dependent on the relative magnitudes of the precipitation input and the losses due to evapotranspiration. Catchment physiography and geology have a major influence on the time distribution of runoff, but over a period of years, average flow is largely controlled by climatic factors. The only exception being catchments with a large groundwater component and in which there is natural or artificial transfer of water out of the catchment. This is the case in the River Idle catchment.

3.4.2 Mean annual precipitation in the Trent catchment varies from 1600mm in the uplands of the north and west to 600mm in the lowlands of the north-east. The majority of the Trent basin has an average annual rainfall of less than 900mm per annum. A map of mean annual precipitation is shown as figure 5.

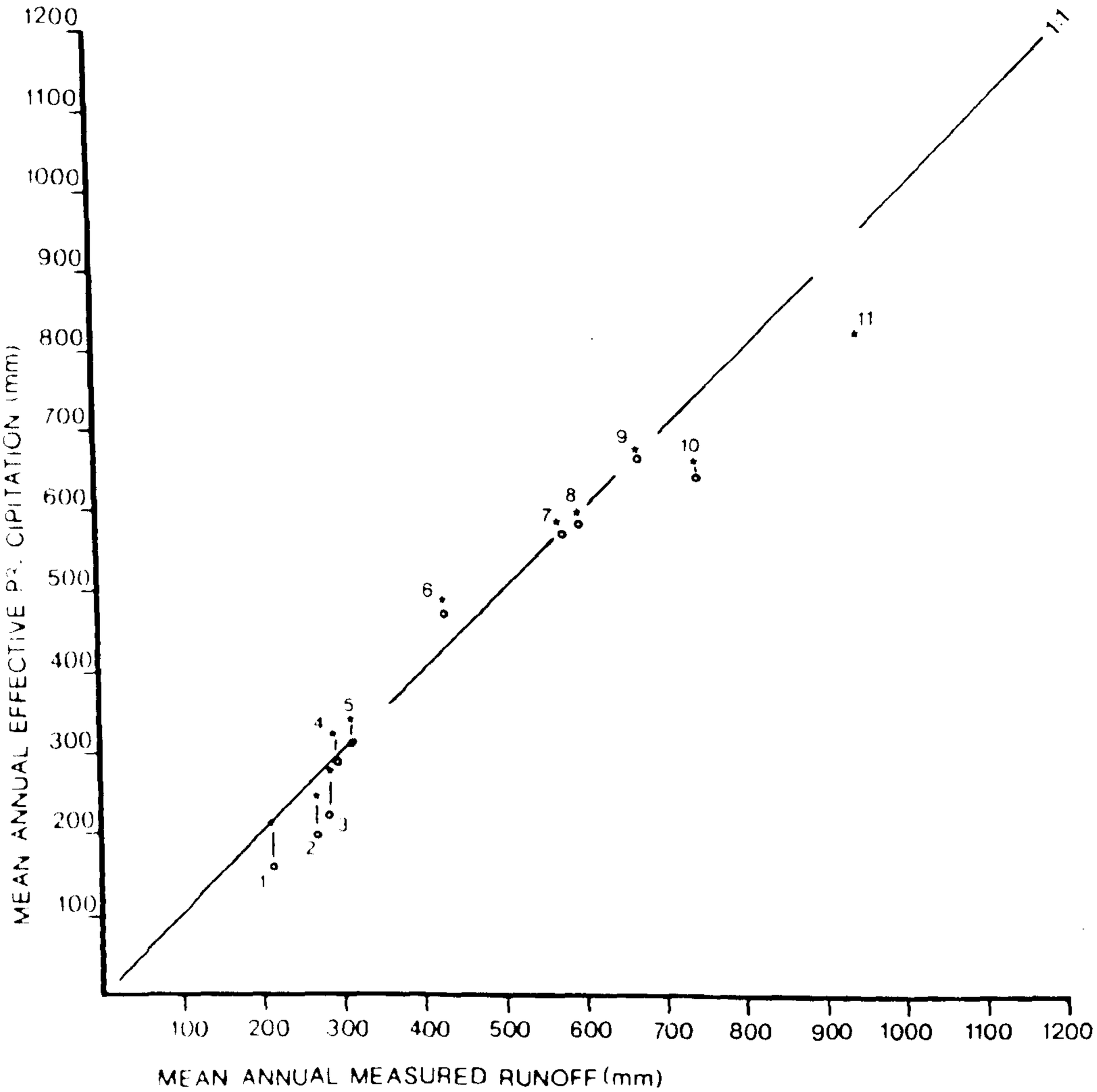
3.4.3 The spatial distribution of evaporation varies much less than precipitation. Meteorological Office estimates of potential evaporation (PE) for the Trent basin vary from 450mm per annum in the Peak District to 510mm per annum in the Vale of Belvoir and the central valley of the Trent. The distribution of PE thus varies inversely to rainfall. Theoretically, this is because evaporation is reduced in upland areas due to a higher proportion of cloud cover, a reduced temperature range and reduced sunshine (Manley, 1952).

In practice actual evaporation is often less than potential because of soil moisture depletion. The Institute of Hydrology (1980) has suggested a reduction ratio (R) by which actual annual evaporation may be calculated from potential. The distribution of R is related to annual average rainfall.

Average Rainfall (mm)	500	600	700	800	900	1000	1100
Ratio R	0.88	0.90	0.92	0.94	0.96	0.98	1.00

Comparison of effective precipitation and runoff

FIG. 6



1 Syston
2 Polesworth
3 Ratcliffe Culey
4 Blackbrook
5 Calthorpe Park
6 Rocester (Churnet)
7 Waterhouses
8 Rocester (Dove)
9 Izaak Walton
10 Ilam
11 Hollinsclough

• Adjusted using ratio(R)
o Potential evaporation

For catchments with an annual average rainfall in excess of 1100mm , actual evaporation is assessed to be equal to potential (R=1) because periods when actual evaporation is limited by a soil moisture defecit are compensated by periods when actual evaporation is in excess of potential. The greater loss rate can occur because potential evaporation is defined to relate to a freely transpiring grass surface but other vegetational types are able to exceed this rate of loss (Calder 1977). Thus, although PE is assessed to be greatest in lowland areas, actual evaporation is more likely to reach potential in upland areas. The overall effect being an actual evaporation of approximately 450-460mm throughout the catchment.

If the ratio R, the Meteorological Office estimates of PE, and measured rainfall (figure 5) are reliable, then on average, effective rainfall (rainfall minus actual evaporation, PE x R) should be equal to measured runoff from a catchment (given no artificial influences or water export). The twelve year average runoffs measured at Syston (R.Wreake), Polesworth (R. Anker), Ratcliffe Culey (R. Sence), Onebarrow (Black Brook), Calthorpe Park (R. Rea), Rocester (R. Churnet), Waterhouses (R. Hamps), Rocester (R. Dove), Izaak Walton (R. Dove), Ilam (R. Manifold) and Hollinsclough (R. Dove) were compared with calculated affective precipitation. (All station details are given in Appendix 1). Most of these data are not significantly effected by artificial influences but where necessary the flows were naturalised using Appendix 3 (section 5.3.9, latter). The results of the comparison are shown in figure 6.

In all but two catchments a good agreement is evident between measured runoff and effective precipitation. In the cases of the poor fits (R. Dove to Hollinsclough and R. Manifold to Ilam) both catchments are located in the Peak District and have a dissected upland topography. It is possible that the disagreement is due to the underestimation of rainfall rather than errors in the reduction ratio or potential evaporation.

600 ISOHYETS IN MILLIMETRES PER ANNUM

0 10 20 30km

TRENT AREA
MEAN ANNUAL EFFECTIVE PRECIPITATION
[ADJUSTED]
FIG.7

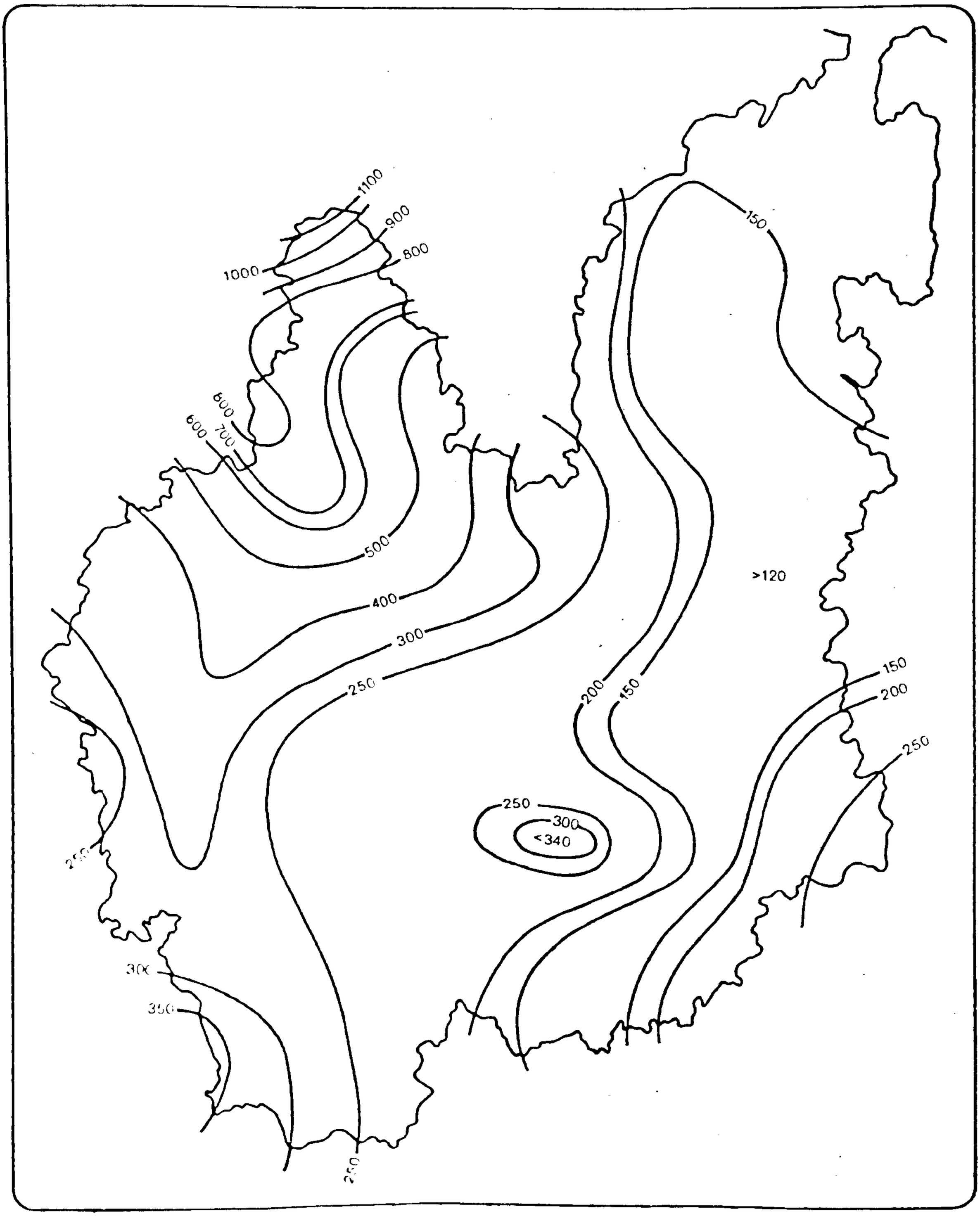


TABLE 3

RUNOFF CHARACTERISTICS OF THE TRENT BASIN

RIVER	LOCATION		FLOW AND YIELD (cumecs, cumecs/km^2)		
			Average	Dry Weather	Maximum
Trent	Stoke	(SJ 892 467)	0.71(.013)	3.20(.004)	18.5(.35)
Trent	Yoxall	(SK 131 177)	N/A	4.20(.004)	126 (.11)
Tame	Water Orton	(SP 169 915	5.82(.014)	2.85(.007)	106 (.26)
Tame	Elford	(SK 188 104)	18.9 (.013)	9.85(.007)	320 (.22)
Trent	Drakelow	(SK 239 204)	36.54(.012)	14.40(.005)	515 (.17)
Churnet	Rocester	(SK 103 389)	3.60(.016)	1.06(.004)	N/A
Dove	Marston	(SK 238 288)	18.40(.020)	3.48(.004)	160 (.32)
Derwent	Derby	(SK 356 363)	17.70(.017)	4.67(.004)	520 (.50)
Soar	Narborough	(SP 551 985)	N/A	0.32(.002)	24.5(.12)
Soar	Kegworth	(SK 498 240)	N/A	3.20(.002)	180 (.13)
Trent	Colwick	(SK 620 399)	83.50(.011)	28.00(.004)	C 1200 (.16)

Rodda (1967, 1970), Green (1969) and Brown and Peck (1962) have shown that rainfall may be undermeasured in upland catchments due to sampling errors and the inadequate performance of raingauges in windy conditions.

Figure 7 is a map of effective precipitation for the Trent basin calculated from measured precipitation (figure 5), Meteorological Office estimates of potential evaporation and the adjustment ratio R. The results of the comparison between measured runoff and effective precipitation suggest that figure 7 can be used to estimate mean annual flow for ungauged catchments in the Trent catchment.

3.5 RUNOFF

3.5.1 The net effect of the interaction of the climate, geology, surface deposits, physiography and land use of the Trent basin is to produce Britain's largest river. The long term average flow of the Trent at Cromwell Weir (the tidal limit) is 85.7 cumecs. This is 10% greater than the average flow in the Severn and 27% greater than the average flow in the Thames at their equivalent points (HMSO, 1978). This high average is maintained by a combination of a high level of effluent baseflow from the industrial West Midlands and substantial flood flows generated by high rainfalls in the uplands of the Peak District. This is evident from Table 3. For example, the Tame exhibits very high dry weather flows per unit area compared with the rest of the catchment whereas the Dove and the Derwent exhibit greatest peak flows per unit area.

3.5.2 The physical characteristics of the major tributaries of the River Trent reflect the regional variations in topography, geology and land use. Three types of river can be identified.

(i) Tributaries draining the southern Pennines. In the centre of this region, on the carboniferous limestone outcrop, surface drainage is restricted to a few deeply incised rivers; notably the Wye which crosses

the outcrop from west to east, and the Dove and Manifold which cut across the south west corner. These rivers flow in steep sided dales, at times 200m below the adjacent plateau surface. The deeply incised main streams have dewatered the limestone, giving rise to a complex network of dry valleys less deeply incised on the plateau. The water table in the limestone has also been lowered over large areas by long artificial drainage tunnels known as 'soughs' which were driven to facilitate mining. Flows still emanate from many of these tunnels even though mining has ceased. The other major river of the southern Pennines, the Derwent, also flows in a deeply incised valley. This is orientated in a north to south direction along the regional strike of the Millstone Grit. Because of the upland nature of all these rivers and the incised valleys, flow velocities are high and there is little flood plain storage. Floods therefore pass from the area quickly with little attenuation.

(ii) Tributaries draining the undulating and hilly catchments to the south and east of the Trent. These include the rivers Sow, Penk, Anker, Soar, Sence, Wreake and Idle. Most valleys are gently sloping with extensive washland storage. River velocities are lower than experienced in the southern Pennines and attenuation of flows are more common. In the Idle catchment, reductions in flow can also be attributed to losses to the Sherwood sandstone aquifer (Figure 12a, Section 5.3.8).

(iii) Tributaries draining the Birmingham conurbation. The characters of the Tame, Rea, Cole and Blythe are complex. Gently sloping reaches with extensive flood plain storage are intermingled with canalised man made channels with little or no washland storage. Natural tributaries also intermingle with storm drains from the impervious area.

3.5.3 River flow is continuously measured at 65 permanent gauging stations in the Trent basin. The first permanent sites were installed in 1905 (Yorkshire Bridge, SK 198 851) and 1937 (Hamstall Ridware, SK 109 192) but the majority were constructed between 1960 and 1970. The average length of station record is 18 years. Whilst there are some 1200 station years of recorded river flow data in the Trent basin not all data are of high quality. The most accurate measures of flow are normally associated with well maintained, purpose-built structures such as 'Crump' weirs. At these sites level is uniquely related to flow. Slightly less dependable than these, are permanent sites where river level is controlled by natural channel features, and flow is derived from river level by means of a rating equation based on current meter measurements. Sites such as these need considerable maintenance attention to maintain the quality of flow measurement, as weed growth or movement of the river bed can produce variations in flow for any given river level. This is particularly apparent at low flows when percentage errors can become very large if insufficient attention is paid to the stage-discharge rating. Calculations of an instantaneous flow, for these sites can vary in accuracy from better than $\pm$8% at a well maintained structure, to possibly worse than $\pm$20% at one of the poorer open channel stations. At each site, level is recorded every 15 mins, thus mean daily flow is the average of 96 individual readings. Over a sample as large as this, random errors in the overall flow computation will normally be eliminated, such that the expected accuracy of the data may be greater than values stated above. Systematic errors, such as those caused by weed growth in a channel, will remain however, and may still be large. At sites where levels are not continuously recorded, or where it is not possible to derive a stable stage-discharge rating, individual current meter gaugings are often taken to determine flows. At some sites, gaugings are taken regularly, perhaps once a week, where as other sites may be gauged once or twice a year. The accuracy of an individual current meter gauging will depend upon the physical nature of the site more than other factors but, given

a good site and good practice on the part of the gauger, will normally be of the order of ±8%.

3.5.4 The length of riverflow record required to define the runoff characteristics of a river basin vary according to the characteristic under consideration. It is possible that a single, well timed current meter gauging may be sufficient to define a specific index of low flow. In the case of fitting a high flow simulation model, three or four years of data may be sufficient to define the models parameter values. However, for the derivation of many other hydrological indices a longer record is required. Pirt and Douglas (1982) showed that 12 years of record are required to adquately define a 'Dry Weather Flow' or an equivalent percentile low flow. Ward (1968) suggested that 10 years of data would be adequate to determine the major runoff characteristics of British rivers. The majority of the records analysed in subsequent chapters are at least of 13 years duration. The exact quantity of data used in each analysis is specified in the relevant section.

Details of all stations used in the analyses along with their location and reliable measurement range are given in Appendix 1.

3.5.5 Table 3 (section 3.5.1) has shown that river flows vary due to mans activities as well as by natural causes. According to Tattersall (1980, page 3,4). "An industrial river is affected by man's activities almost from source to mouth. Its head waters often are reservoired and its effective source is compensation water issuing from a dam; it is subject to abstraction and effluent return by industry; it is weired and diverted from its natural course; it receives sewage effluents often exceeding its dry weather flow; it receives storm run-off from vast paved areas; it gets gulped into power stations; and it may be canalised for navigation."

In many cases data are available to quantify these artificial effects and thus naturalise flow data. In the Trent catchment the following data are available:

(i) Discharges from water reclamation works (Divisional Offices of Severn-Trent Water Authority)

(ii) Licensed abstractions (Directorate of Scientific Services, STWA)

(iv) Minewater discharges (Trent Area Unit, STWA)

(v) Reservoir compensation water and abstractions to supply (Divisional Offices, STWA)

(vi) Abstractions from, and discharges to, canals (Area Offices, British Waterways Board).

The general quality of measurement of artificial influences is not always good. In the cases of industrial and agricultural abstractions and discharges, many licence holders fail to fill in returns and many data, particularly for abstractions for spray irrigation, are estimates. Discharges from all but the largest water reclamation works are also often estimated. In contrast, measures of compensation water and supply from reservoirs are generally accurate. Because of the very large number of artificial influences, particularly abstractions and discharges in some industrial areas, it is unrealistic to analyse every single influence on natural flow. For the purposes of the investigations described in subsequent sections only those influences with a net effect in excess of 0.5 Mld have been considered in industrial areas. In some rural areas a large number of small abstractions for spray irrigation tend to be of local significance, and abstractions as small as 0.1 Mld have been considered.

4 QUANTIFICATION OF PHYSIOGRAPHY, GEOLOGY AND LAND USE

4.1 INTRODUCTION

Chapter 3 has described the topography, geology, landuse, climate and runoff characteristics of the Trent basin. Whilst it was possible to give a quantitative description of the climate and runoff of the basin, the descriptions of geology,landuse and topography were purely descriptive. Yet, if the hydrology of the catchment is to be adequately modelled, these facets must also be quantified. Horton (1932) provided the first quantitative analysis of this type. He outlined four factors for analysis: Morphologic factors, Soil factors, Geologic/structural factors, Vegetational factors (page 350).

"(i) Morphologic factors. These factors depend only on the topography of the land forms of which the drainage basin is composed and on the form and extent of the stream system or drainage net within it.

(ii) Soil factors. This group includes factors descriptive of the materials forming the groundwork of the drainage basin, including all those physical properties involved in the moisture relations of soils.

(iii) Geologic/structural factors. These factors relate to the depths and characteristics of the underlying rocks and the nature of the geologic structures in so far as they are related in groundwater conditions or otherwise to the hydrology of the drainage basin.

(iv) Vegetational factors. These are factors which depend wholly or in part on the vegetation, natural or cultivated, growing within the drainage basin."

This subdivision provided by Horton is meaningful and it provides a useful basis for a discussion of the many indic es which have been developed to describe drainage basins. Each

of the four factors are considered in the following sections, although vegetational factors have been included in a broader discussion of land use.

4.2 MORPHOMETRIC (MORPHOLOGIC) FACTORS

4.2.1 The first two major assessments of morphometric factors were undertaken by Horton (1932) and Langbein (1947). Horton outlined 10 descriptive indices by which catchment morphology could be described (form factor, compactness, mean elevation, general slope, mean slope, order of streams, drainage density, stream density, direction and length of overland flow) and Langbein eight (area, stream density, area - distance distribution, length, land slope, channel slope, area-altitude distribution and area of water surface). Since Horton and Langbein's work, the number of morphometric indices developed by geomorphologists have grown to well over 50. Such variety has arisen because catchments are complex three dimensional forms. Also, indices has been developed for a number of different purposes. Some analyses have simply described basin form (Horton, 1932), some describe the river and its valley (Wolman, 1967) and some basin process and form (Gray, 1965). A hierarchy of complexity of indices has also grown. Some indices are very simple, being absolute measures (eg catchment area), some are combinations of measures (eg slope) where as others are based on a derived method (eg basin elongation which according to Schumm (1956) can be expressed as the diameter of a circle with the same area as the basin, divided by basin length).

It is outside the scope of this project to provide a comprehensive review of catchment indices. Several such reviews are already available: Gregory and Walling, 1973; Newson, 1975; Vorst and Bell, 1977. The following sections will only be concerned with placing morphological indic es into a hydrological context and more importantly describing those indic es used in the analyses discussed in latter chapters.

4.2.2 In the United States, Government Agencies were early instigators of geomorphological research involving hydrology. In the 1950's and 1960's the Office of Naval Research considered drainage basin characteristics and their relationships with river flow (Miller, 1953; Melton, 1957; Morisawa, 1958). During the same period the Geological Survey conducted studies into the magnitude and frequency of flooding and their relationships to morphometric and other catchment characteristics. Prediction equations were produced for ungauged catchments (Benson 1959, 1962 and 1964). Also in the 1950's and 60's, Strahler (1952, 1957, 1964) conducted extensive research into river basin slope and in particular, found relationships between the angle of slope of valley sides and the magnitude of the mean annual flood. As well as these examples relating to high flows, extensive research linking low flows and morphological indic es has also taken place in the USA. The work of Thomas and Benson (1970), Osborn (1975) and Chang and Boyer (1977) having already been discussed in section 2.

In Britain, geomorphologists have shown interest in the relationships between morphology and climate (Chorley 1957, Gregory and Ovenden, 1979) and in the use of morphometric indices to compare drainage basins in different areas (Chorley and Morgan, 1962). Consideration has also been given to the variation of indices (drainage density in particular) within catchments (Gregory and Walling, 1968; Blythe and Rodda, 1973). However, river flow estimation studies including geomorphological parameters are very limited. The exceptions being the work of Nash (1960), Nash and Shaw (1966), Rodda (1969) and NERC (1975) who all considered morphological indices in relation to high flows. Wright (1970) and the Institute of Hydrology (1980) have considered morphological indices in relation to low flows. The hydrological studies which have incorporated morphological indic es have had variable degrees of success (as described in chapter 2). However, consideration of derived estimation techniques, indicates that any limitations in the estimation methods are more likely to be due to poor

descriptions of catchment geology and soils rather than to inadequate descriptions of morphology. The large number of available morphological indic es would seem to be sufficient for most purposes: A problem exists, however in selecting which and how many indices should be used in any analysis.

4.2.3 The selection of suitable indic es can be simplified if they are grouped according to purpose. Gray (1965) suggested that all morphometric indices fell into five groups: size and shape of the drainage area, density and distribution of water courses, general land slope, slope of channels and storage. Gregory and Walling (1973) have also suggested five groups of indices: area and stream order, density of the stream network, basin and channel length, basin network and channel shape, and channel network and basin relief. Dornkamp and King (1971) considered indices could be characterised into four groups: drainage network, basin geometry, measures of intensity of dissection and measures involving heights. Newson (1975) suggested three groups of indices: size (including shape), slope and channel network. How the authors have composed their groups depends on their interpretation of the inter- relationships between measures of area, length, shape and relief, and scale (basin, reach or cross section): The major differences being in the treatment of the channel in cross-section and storage. Newson, for example does not consider the dimensions of the stream channel in cross-section, thus he is able to characterise a basin solely by map analysis. This approach would seem to have drawbacks in a hydrological context where the volume of the channel may be of vital consideration in explaining process. However, the inclusion of measures of channel cross-section inevitably leads to field survey which may not always be feasible. Once a basis for grouping indic es has been identified, then a number of measures can be selected from each group in the knowledge that all the required facets of catchment morphology have been considered.

The importance of grouping indices and determining independent measures of catchment features is also pertinent

if 'regression' is to be used as a form of hydrological analysis. A prerequisite of multiple regression analysis is that variables should not show marked colinearity. Violation of this criterion can lead to unstable regression coefficients and to difficulties in the interpretion of the independence of variables in any resulting equations. Yet total independence is impossible to achieve as all processess in a catchment are related. For example drainage density has been correlated with each of rock type (Strahler, 1964), climate (Chorley and Morgan, 1962), relief (Slaymaker, 1968) and time (Ruhe, 1952).

For the study described in subsequent chapters, morphometric indices belonging to four groups have been selected for analysis:

(i) Measures of basin size and geometry, representing the catchment in plan.
(ii) Measures of intensity of dissection, representing the stream network in plan.
(iii) Measures of catchment and channel slope and relief, representing the catchment in cross section.
(iv) Measures of channel size and condition, representing the channel in cross section.

These choices reflect evidence presented by other workers, particularly the principal component analysis reported by Newson (1975) and a considerable degree of user intuition.

4.2.4 Measures of basin size and geometry, intensity of dissection, and catchment and channel slope and relief can be obtained from maps. However, the scale of the map used for measuring indices must be chosen very carefully as scale directly affects the values of many indices (Morisawa, 1957; Gregory, 1976; Newson, 1975; Ovenden, 1981; Burt and Gardiner, 1982). For example, Newson has calculated that drainage density as depicted on 1:25000 maps is approximately twice that shown on 1:63360 maps for the same region (Bristol Avon). The chosen map must also be widely available and depict stream channels

and contours clearly and accurately. In Britain, the most convenient map is the Ordnance Survey 1:25000 series. However, this choice is a compromise between general availability, user familiarity, clarity and accuracy. Dornkamp and King (1971, page 13) state "The fundamental failing of 1:25000 maps is that they do not allow a precise definition of the number or lengths of first order valleys and streams. Since the whole ordering system is dependent upon this feature it is important that it should be defined correctly. Once this has been done the definition of many other characteristics follow automatically. For example, the number of higher order streams is dependent on the number and location of first order streams, as is the assessment of total stream numbers and lengths. The bifurcation ratio between first and second order streams depends on the number of first order streams and the drainage density cannot be calculated unless the correct lengths of all streams are known. Stream frequency is derived from the number of streams in the basin, and thus depends on the correct assessment of the number of first order streams".

Thus whilst map analysis was of considerable importance in this study, field surveys were also undertaken to quantify channel size and condition. Although being much slower and more expensive to execute than map analysis, it was considered that the extra effort may improve high flow estimation because of the connections between channel size and storage, and roughness and velocity. For example, Cordery (1968) showed that improved estimates of synthetic unit hydrograph parameters could be made for eastern New South Wales by the inclusion of a channel roughness factor estimated from field surveys in the estimation equations.

4.2.5 The specific morphometric indices chosen for analysis are outlined in the following sections 4.2.6 - 4.2.10. As well as taking account of the groupings outlined in section 4.2.3 the choice was based on:

(i) Experience of other authors in relating morphology to hydrological measures. For example, Vorst and Bell (1977) showed that two geomorphic parameters are consistently significant in regression studies concerned with predicting flood response times or other hydrograph parameters. These are the distance travelled by the flood (length of main channel) and the gradient of the flood flows (slope of main channel).

(ii) Relative simplicity. The models are for use by practicing engineers and hydrologists. If they are to be accepted, parameters need to be relatively simple and be determined quickly.

(iii) Intuition based on practical experience.

4.2.6 Measures of Basin Geometry:

Nearly all expressions of outflow from a catchment are directly related to drainage basin area. Pilgrim et. al (1982, page 206) state that "Catchment size can be expected to influence runoff in a number of direct and indirect ways. Various aspects of runoff, such as total yield, flood peaks, direct storm runoff and losses, will be affected differently". For example, the peak discharge of a hydrograph is directly related to catchment area. As the size of the basin increases, the base length of the hydrograph also increases. Therefore, for a given rainfall excess, the peak yield (discharge per unit area) will decrease with area. The derivation of area (AREA) requires that the catchment boundary is assessed (in this study from a 1:25000 map) and the encircled area measured.

The distribution of catchment outflow in time is related to catchment shape. Given the same catchment area, slope and geology, a compact, near circular catchment will produce runoff at the outflow point much quicker than a long rectangular catchment. Catchment shape can be represented by

the ratio of catchment length to width. This parameter is referred to in subsequent sections as SHAPE.

$$SHAPE = L \div W$$

where L is catchment longest length measured in a straight line

and W is catchment longest width measured at 90° to the length line.

Some authors, (eg Miller, 1953) have used measures of circularity as indices of catchment shape. In some of the analyses described in subsequent sections 'C FORM' has been used for this purpose

$$C\ FORM = \frac{A}{P^2}$$

where A is catchment area in km^2

and P is catchment perimeter in km.

A commonly used index of catchment size and shape is main-stream length (Gray, 1961., NERC, 1975). In some cases this index has been taken as the actual length of blue line on a 1:25000 map and in others as the length of a straight line parallel to the drainage line. Some authors, (eg Brush, 1961) have also estimated an imaginary flow line joining the start of the blue line with the catchment watershed and included this distance in the measurement of main-stream length. The length of the actual sinuous blue line on 1:25000 maps has been used to define main-stream length (MSL) in the analyses described in subsequent sections because this approximates to the maximum distance water travels in a definite channel which provides both a pathway and storage.

The disadvantage of main-stream length as a catchment index is that it takes no account of the lengths of other stream

channels in the catchment. It is also possible that two catchments exhibiting the same main-stream length could have very different sizes, geometry and drainage pattern. For example a long thin catchment with a single main-stream could have the same main-stream lengths as a circular catchment with a dendritic drainage pattern. For some intercatchment comparisons total stream length would be a preferable index to main-stream length, but its derivation is very time consuming. In this study a parameter has been developed (LENG) that portrays variations in channel storage and catchment size in a similar fashion to total stream length, but it can be calculated much more quickly. This is the total length of channel of streams in a catchment which are greater than 3.6 km in length. (3.6 km was chosen as an arbitrary threshold as this is the approximate distance flood water will travel in a minor stream in one hour). The parameter proved to be a good index of catchment shape, size and dissection. For example, the River Dove (Main-Stream Length - 30.4 km) has no tributaries greater than 3.6 km in length, whereas the River Anker (MSL - 31.2 km) has 130.6 km of tributaries greater than 3.6 km. The Dove is an upland river with a long thin catchment and its runoff hydrographs are characterised by fast responses with very sharp rises and recessions (little routing/storage effect). In contrast the Anker is a larger, circular catchment with slower responses and more rounded hydrographs (portraying a pronounced storage/routing effect).

4.2.7 Measures of Intensity of Dissection

The pattern and arrangement of natural stream channels determines the efficiency of a drainage system. A well defined system reduces the distance water must move in overland flow and thus reduces the time of concentration of the system. Also, stream network intensity varies directly with the relative percentage of precipitation that appears in streams as surface runoff, and it may be indicative of larger floods and smaller low flows (Osborn 1976). The most commonly used measures of intensity of dissection are

drainage density and stream frequency. Drainage density, the length of stream per unit area, has often been favoured by geomorphologists for catchment analysis. However, it is a difficult and time consuming parameter to determine, yet its accuracy is still related to the quality and scale of the map used for analysis (4.2.4). Conversely, stream frequency, the number of stream junctions per catchment area can be determined relatively quickly, although the problem of map scale still applies. Melton (1958), Gardiner (1961) and Newson (1975) have shown that there is a very high correlation between the two indices and that the extra effort required to determine drainage density is not fully warranted. Stream frequency (STMFRQ) has been used in the analyses discussed in subsequent sections.

4.2.8 Measures of Slope and Relief:

General land slope has a complex relationship with runoff because of its influence on infiltration, soil moisture and vegetation. "The influence of land slope on hydrograph shape is manifested in the time of concentration of the runoff volumes in defined stream channels" (Newson 1975, page 18). After reaching the main channel the time necessary for water to pass downstream is then related to the length and slope of the main waterway.

Strahler (1952), Benson (1959) and Newson (1975) have shown that main stream slope and general catchment slope are correlated and that a single index is sufficient to represent all slopes in a basin. Taylor and Schwarz (1952) and Nash (1960) suggest complex methods of determining this slope involving the use of the Manning equation and an integration of the slope of the channel profile but Newson (1975) has shown that the slope of the main channel between the 10 and 85 percentiles of the mainstream length (SLOPE) is highly correlated with the more complex methods and is adequate for most purposes. This simple method of slope determination has also been successfully used by the United States Geological

Survey and by the Institute of Hydrology and has been adopted in this study.

Some authors (Chang and Boyer, 1977) have found that simple measures of relief are useful in estimating flows at ungauged sites. These measures may serve as indices of factors that cause basin to basin stream flow variation but which are difficult to evaluate. For example, vegetation and basin roughness may vary with elevation. Relief can be represented as a single absolute measure (ALT, mean catchment altitude) or as a ratio between the altitudes of the highest point on the watershed and the basin mouth (RELF) (Schumm, 1956). Both these measures have been considered in the following analyses. Catchment altitude was taken as the mean of the heights of each 1km grid square intersection on a 1:25000 map lying within the catchment boundary.

4.2.9 Measures of Channel Geometry:

River channels are shaped by process and therefore their dimensions should relate to the amount and distribution of streamflow.

For example outflow from a river reach (Q) relates to inflow (I) and change in storage (dS/dt).

$$\frac{dS}{dt} = I - Q \qquad (13)$$

thus $S = a\,Q^{b}$ (14)

where a and b are parameters which relate to the physical nature of the channel in question. If a channel reach of length L, has an average cross sectional area A, then the storage in the reach at any time is given by S = AL (or A = S/L). If S/L is substituted in the Manning equation (15) (Manning 1890, 1895)

$$Q = AV = A\ R^{2/3}\ s^{1/2}\ n^{-1} \qquad (15)$$

where A = cross sectional area (m^2)

V = velocity (m/sec)

R = hydraulic radius = $\frac{A}{\text{wetted perimeter}}$ $\Rightarrow$ $\frac{A}{w + 2d}$

w = channel width (m)

d = channel depth (m)

s = slope of the water surface

n = Manning roughness coefficient

then S can be represented by equation 16 (in the same form as equation 14)

$$S = \left(L\ \frac{n^{0.6}(w + 2d)^{0.4}}{s^{0.3}}\right)\ \ Q^{0.6} \qquad (16)$$

The storage equation 14 has been commonly used in rainfall runoff modelling (Mein et. al, 1974; NERC 1975; Douglas 1974) and the parameters a and b determined by optimisation (section 6.4.3). However equation 16 shows that if equation 15 is a perfect expression of discharge in a river, then the exponent of equation 14 has a universal value of 0.6 and the value of a is related to the slope, roughness and cross sectional geometry of the river channel. One of these indic es, slope, can be adequately determined from maps but cross sectional geometry and roughness require field assessment.

For the purposes of this study, representative river cross sections were measured at 20%, 40%, 60% and 80% of the distance between the point at which flow is determined and the source of the river as indicated by the blue line on a 1:25000 map. Where major tributaries were present in a catchment, cross sections were also taken on the tributaries at 50%, or 25% and 75% of the distance between the tributary source and the confluence with the main river, depending on tributary size. This particular sampling distribution was

TABLE 4

CHANNEL INDICES CORRELATION MATRIX

	XSEC	WETP	HYDR	XSWP	MANN	PCIF
XSEC	1.0					
WETP	0.889	1.0				
HYDR	0.949	0.826	1.0			
XSWP	0.930	0.695	0.939	1.0		
MANN	0.387	0.412	0.262	0.302	1.0	
PCIF	0.381	0.012	0.279	0.560	0.119	1.0

XSEC = mean reach cross sectional area

WETP = mean reach wetted perimeter

HYDR = mean reach hydraulic radius

XSWP = XSEC ÷ WEPT per reach

MANN = Manning roughness coefficient

PCIF = Inbank routing factor (section 6.3)

chosen arbitarily. Whilst it is probable that a greater number of cross sections may have given more accurate information, account was also taken of possible future applications. Any method which requires extensive field analysis will not gain acceptance from practising engineers and hydrologists. The cross section measured was that part of the channel which was presumed to be underwater when the river is flowing at bankfull discharge. In many cases bankfull can be precisely defined at the point where the vertical river bank changes to horizontal flood plain. However, in some upland rivers with narrow steep sided valleys, the precise location of bankfull has to be estimated by eye. From the cross sections, a number of catchment indicies were determined. The simplest was mean bankfull cross sectional area (XSEC). XSEC was also combined with LENG (4.2.6) to provide a catchment storage volume (CHAN), (CHAN = LENG x XSEC). As LENG is not a measure of total stream length, CHAN is only an index of channel volume within a catchment. However, it was felt that like absolute measures of total channel volume (Gregory, 1976; Gregory and Ovenden, 1979) it may prove a useful morphological index. For example, as drainage networks are composed of several types of channel, two areas which have identical drainage densities may have very different volumes and hence storage/runoff properties.

Channel hydraulic radii (cross sectional area ÷ wetted perimeter) were also calculated by two methods. XSWP, being the mean reach cross sectional area ((XSEC) divided by mean reach wetted parameter (WETP)) and HYDR the mean of the hydraulic radii calculated at each individual site in the catchment. XSWP was used in the analyses described in subsequent sections because it generally proved to have a higher correlation with dependent variables. Consider for example, table 4, here the correlation matrix between PCIF, the inback routing factor of the conceptual model outlined in Chapter 6, and a number of channel indices is shown. The correlation between PCIF and XSWP was 0.560 compared with 0.279 between HYDR and PCIF.

Unlike channel slope, channel roughness cannot be measured directly. Values can be obtained indirectly by measuring discharge, hydraulic radius and slope and solving the Manning equation for n. However, more commonly, roughness values are estimated. Bailey and Ray (1966) suggested that roughness coefficients can be estimated with an accuracy of plus or minus 15% under most conditions. There are three commonly used methods:

(i) A look up table of typical values based on general channel descriptions is consulted (Chow, 1959)

(ii) Standard photographs are consulted (Barnes, 1967)

(iii) The individual factors that affect roughness are considered and a value determined according to the relative importance of each parameter in each river situation. Chow (1959) suggests ten interdependent factors which affect roughness: surface roughness, vegetation, channel irregularities, channel alignment, silting and scouring, obstructions, size and shape of the channel, stage and discharge seasonal change, suspended material and bedload. However, it is improbable that all these facets could be considered in any estimation equation. Alternatively, Cowan (1956) considered that roughness could be described by five primary factors: irregularities of the surface of the channel sides and bottom, variations in shape and size of cross section, obstructions, vegetation and meandering of the channel. Using these factors, Cowan derived an estimation equation. The procedure is to select a basic value of roughness for a straight, uniform smooth channel in the natural materials involved, then through critical consideration of the five primary factors affecting roughness select a modifying value associated with each factor. The modifying values are added to the basic value to obtain roughness for the channel under consideration using equation 17.

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)\ n_5 \qquad (17)$$

Respective values of 'n' are given in Appendix 2. The advantage of this approach over the use of reference tables and photographs is that it is universally applicable. However, some familiarity with the method is required before the exact distinction between some of the factors becomes apparent. For example, in diferentiating between 'degree of irregularity' (pools and riffles in the bed) and 'variations in cross section' (convergance of the banks). Using this method a roughness value was derived for each of these sites at which cross sections were measured (section 4.2.9) and a mean value (MANN) calculated per catchment.

4.3 GEOLOGICAL INDICES

4.3.1 The influence of catchment geology on runoff has long been recognised. In 1922 (page, 109), Thompson suggested "The variability of streams is more profoundly influenced by the character of the underlying rock than by any other factor." Also Ward (1968) showed that in Britain "The main factors influencing relationships between rainfall and runoff are geology and the increasing effectiveness of evapotranspiration towards the south and the east ..... Hard old crystalline rocks with little groundwater storage encourage the rapid transmission of precipitated water into stream channels. Conversely porous, sedimentary, water bearing rocks encourage infiltration, percolation and the subsurface storage of precipitated water and its gradual slow release into stream channels" (page, 368).

The effect of lithology on streamflow is particularly apparent at times of low flow when the entire discharge in a river system may come from underground resources. This dependence is well reported in the literature. McMahon (1976) lists 38 references where the influence of geology on low flows has been reported. In contrast, discussions of the effect of solid geology on high flows are less well reported, yet, catchment geology would intuitively seem to be a major influence on flood runoff. Newson (1975) in

selecting catchment indices for analysis during the Flood Studies Project suggested that "Permeable rock shows strongly" as a factor in influencing runoff and "It appears that geology is moderately independent of other basin characteristics and thus may be used in further analyses" (page 25). However, an index of solid geology did not appear in the subsequent 'Flood Studies Report' (NERC 1975). One particular rock type which may be expected to influence runoff throughout the full range of flow is Carboniferous Limestone (Dinantian). In areas where Karst is strongly developed surface drainage may disappear altogether at times of low flow and be greatly reduced during high flows. For example much of the flow of the River Manifold disappears underground at Wettern Mill (SK 095 558) before reappearing downstream. Atkinson and Drew (1974) considered that 70% of flow re-emerging from limestones has been underground for a considerable period of time, but 30% is very short term water passing through conduit systems. These conduits may act in a manner similar to urban storm drains during periods of heavy rainfall.

4.3.2 Whilst the influence of catchment geology on flow and in particular, on low flow, has been widely reported, the TASK Committee of the US Society of Civil Engineers (1980) considering the characteristics of low flows concluded that the effect has very rarely been adequately quantified.

Any expression representing geology has to be multipurpose in dealing with porosity, the ability of the rock to store water; permeability, the capacity to yield water; and local structural effects. One possible type of index is an ARBITRARY SCALE of the type derived by Wright (1970, 74) where a rock is assigned a number according to its expected performance in producing specific flows. Wright derived his scale by analysis of low flows in Southern Scotland and South-West England. Another direct measure is to assume that one property is dominant, for example PERMEABILITY and assign values according to reported field tests. Many standard references (eg Chorley, 1969) give approximate values of permeability for a variety of rock types.

TABLE 5a

WRIGHTS ARBITRARY GEOLOGICAL INDEX

Geology	Index	Geology	Index
Peat	0.8	Alluvium	3.0
Igneous Rock	1.9	Boulder Clay	4.2
Sand and Gravel	1.9	Sandstone	4.7
Limestone	2.5	Chalk	5.0
Shale	2.5		

TABLE 5b

DERIVED GEOLOGICAL INDICES

Rock	Permeability	Arbitrary Scale
Mercia Mudstone (Keuper Marl)	0.00001	1.5
Lias	0.0001	1.5
Igneous/Metamorphic	0.0005	1.9
Westphalian (Coal Measure)	0.001	2.8
Namurian (Millstone Grit)	1.000	3.0-4.0
Sherwood Sandstones (Keuper Sst)	3.00	3.2
(Bunter Sst)	5.00	4.2
Oolitic limestone	8.00	4.8
Dinantian (Carboniferous Limestone)	10.00	5.0

In the regression analyses described in Chapter 5 permeabilities were ascribed log values. The value ascribed to Namurian rocks in the arbitrary scale depended on the type of 'Grit' shown on geological maps.

In some cases indirect measures of catchment geology have been used. These include MORPHOMETRIC INDICES. Jacob (reported in Carlston (1963)) established a theoretical relationship between drainage density and transmissibility and Carlston (1963) established a theoretical relationship between drainage density and base flow.

Vladimirov (1966) and Browne (1981) have used the rate of change of flow as illustrated by RECESSION CURVES to reflect permeability and thus geology of a catchment. The Institute of Hydrology 'Low Flow Study' (1980) used a similar indirect index, the BASE FLOW INDEX. This is a measure of the proportion of baseflow under a flow hydrograph and is reported to be related to catchment lithology. Both recession curve and base flow indices rely on continuously measured data in the catchment of interest or the transposition of indices using analogue catchments. Transpositions of this type are not generally practical. For example, the Base Flow Indices vary nearly as much within one lithological type (limestone 0.20 to 0.75) as they do over the whole series of lithological types (0.14 for Clays to 0.98 for Chalk).

4.3.3 For the purposes of this study, both base flow and the recession curve indices have been rejected as suitable 'measures' of geology. A method is required that is more suited to the needs of ungauged or infrequently catchments. Also rejected were morphological indices such as stream frequency as these parameters are not necessarily specific only to geology. Measures which have been considered are permeability (PERM), an arbitrary geological scale (GEOL) and the Dry Weather Flow yield (DWFY or DWFI (DWFY x 100)). Estimates of permeability are based on values given in several standard texts (Chorley, 1969; Davis and De Wiest, 1966; Read and Watson, 1961). The chosen values are shown in table 5b. The values accorded to rock types in the Arbitrary Scale were developed from Wrights analyses (1970, 74). Wrights original scale is shown in table 5a. Rocks were ascribed an index in the range 0.8 to 5.0 to indicate their

FIGURE 8a

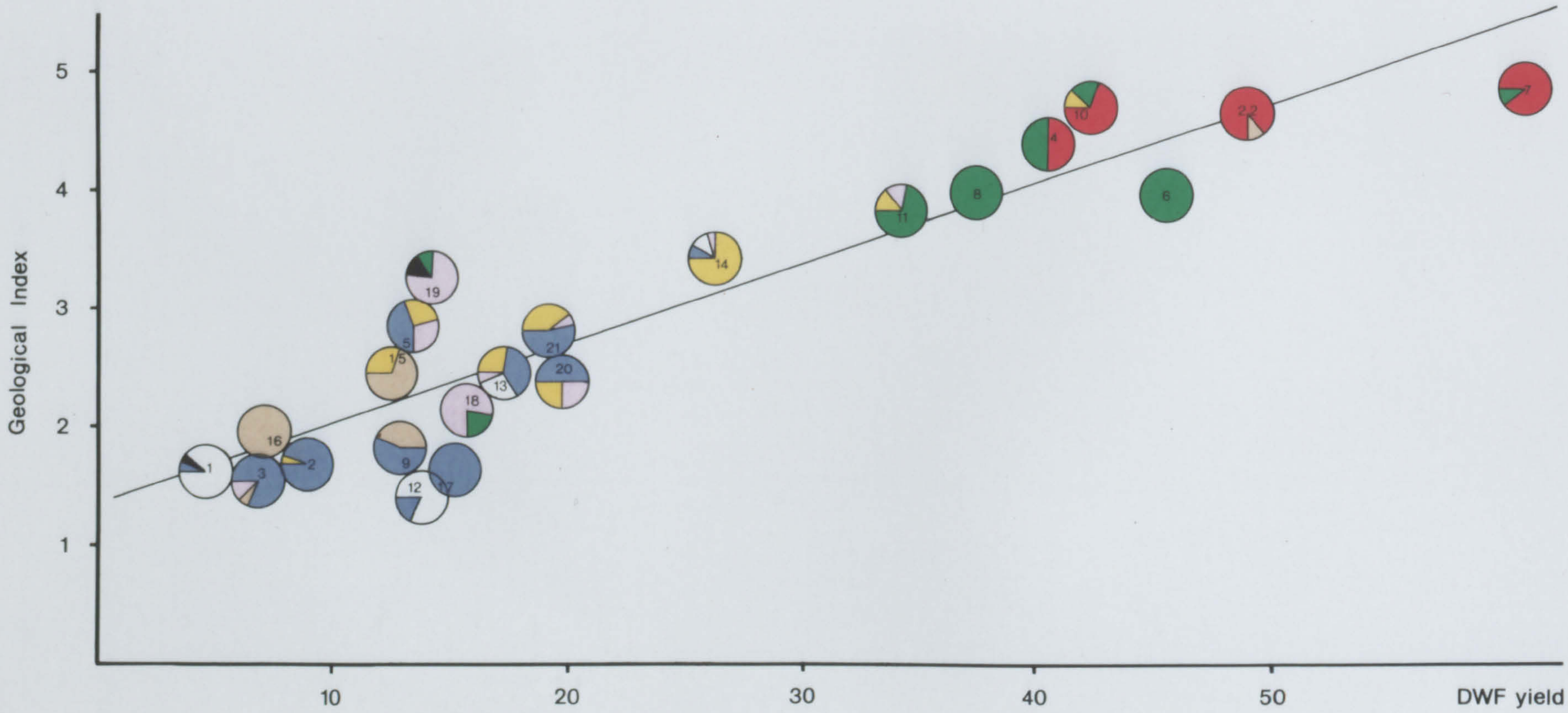
STATION REFERENCE NUMBERS (FIGURE 8)

1	Syston	12	Coleshill
2	Ratcliffe Culey	13	Stoke
3	Polesworth	14	Wingfield Pk
4	Ilam	15	Penkridge
5	Calthorpe Pk	16	Gt Bridgford
6	Yorkshire Bridge	17	Ashford
7	Izaak Walton	18	Stareton
8	Hollinsclough	19	Roddington
9	Black Brook	20	Walcott
10	Rocester (D)	21	Tenbury
11	Rocester (C)	22	Rhos-y-Pentref

In catchments of mixed geology all indices were apportioned according to the areal extent of different rock types.

Keuper Marl
Lias
Metamorphic/Igneous
Coal Measures
Millstone Grit
Sandstone
Oolitic Limestone
Carboniferous Limestone

FIG.
ARBITRARY GEOLOGICAL INDEX 8



water producing potential in periods without rainfall. Hard crystalline rocks with little porosity and/or permeability were ascribed low numbers whilst sedimentary rocks with high porosity and/or permeabilities were ascribed high numbers. For the purposes of this study the scale has been expanded to included a greater number of rock types. Values were chosen after trial and error optimisations of the index against measured dry weather flow runoff for 22 catchments. The values of the index were adjusted until a best fit straight line relationship was obtained between catchment mean index and the measured flow. This relationship is shown in figure 8 and 8a. The index values are given in table 5b.

The reasons for the choice of Dry Weather Flow yield (DWFY or DWFI) as the third geological index is given in section 5.3.10.

4.4 INDICES OF SUPERFICIAL DEPOSITS AND SOILS

4.4.1 The influence of superficial deposits and soils on runoff from a catchment has been stressed by many workers. Wright (1970, page 468) stated that "River Flow characteristics of the area (Lothians, Scotland) are largely dependent on the nature of the surface deposits". Ambruster (1976) showed that an index of soil infiltration was significant in estimating the flow characteristics of rivers in the Susquehanna River basin in the United States. By the inclusion of infiltration of soils in his analysis, Ambruster reduced the standard errors of estimate of his flow equations by between 11 and 66 percent. Rodda (1967) emphasised the importance of surface deposits by reporting a lack of success in predicting flood flows using morphological characteristics due to a failure to incorporate soil indices in his analysis. Farquaharson et al, (1975) found as an index of the interface between rainfall and river flow, soil was the most important variable in explaining percentage volume of runoff and in Australia, Klassen and Pilgrim (1975) found that baseflow characteristics are more strongly related to

the occurence of alluvium along the stream channel than to the general geology over the catchment.

4.4.2 Infiltration rate has been the soil property most commonly used for hydrological classification. The U.S. Soil Conservation Service used the results from small watershed experiments to group soils according to their minimum infiltration rate. The classification is described by Musgrave (1955) and has been incorporated in hydrological design by the United States Soil Conservation Service (1964) and U.S. Bureau of Reclamation (1965, 1974). A version of this classification formed the basis for the first large-scale attempt at soil mapping for hydrological purposes in England and Wales (Painter 1971). Painter's map has been used for hydrological prediction by Painter himself and by Herbertson et al. (1971). However, the transfer of the United States class boundaries for infiltration rates to British soils is described as 'only tentative' by Edmonds et al. (1970). Also, Farquaharson et. al (1978) suggested that the numerical accuracy of Painters classification was unwarranted in view of the complexity of the process and the measurement involved. They also considered there to be more influences on runoff generation than the infiltration rate alone. As an alternative, Farquaharson et al. (page 6) stated "The combinations of soil properties controlling winter runoff and in particular runoff likely to cause flooding from rivers can be summarised by the expression Winter Rainfall Acceptance Potential".

In deriving the index Winter Rainfall Acceptance Potential Farquaharson et al placed soils into classes according to:

(i) The soil water regime.
(This is a 3 class system outlined in the Soil Survey Field Handbook, 1974)

(ii) The depth to an impermeable horizon.
(A 3 class system: $>$80cms, 80-40cms, $<$40cms)

(iii) The permeability above the impermeable horizon.
(A 3 class system; rapid, medium, slow)

(iv) Slope.
(A 3 class system: $< 2°$, $2-8°$, $> 8°$).

The above properties are combined to produce 5 classes of Winter Rainfall Acceptance Potential ranging from very high to very low (or conversely runoff potential from very low to very high).

A catchment runoff potential is calculated from equation 18. The constants in the equation were derived by the Institute of Hydrology using runoff data from 150 study catchments (NERC, 1975).

$$SOIL = 0.15\ S_1 + 0.30\ S_2 + 0.40\ S_3 + 0.45\ S_4 + 0.50\ S_5 \quad (18)$$

where S_1 - S_5 are proportions of total catchment area and relate to the differing soil types.

Whilst the Winter Rainfall Acceptance Potential soil index would seem by its title to relate only to flood runoff, it is also likely to be a useful tool in estimating low flows, since soils which produce large amounts of rapid response runoff from rainfall have small storage volumes, and are thus poor contributors to river flows during dry periods. In addition, these soils commonly have shallow water tables and impermeable layers close to the soil surface. There is, therefore, little scope for recharge of any soil storage reservoir. Conversely, soils which generate low percentage storm runoffs have good storage characteristics, high infiltration capacities and thus retain a large volume of rainfall capable of maintaining low flows. However, Farquaharson et al suggest, that before the application of equation 18 to low flows, the rainfall acceptance potential classes 4 and 5 are reversed because the upland peaty soils of class 5 have been shown to sustain low flows better than clay soils of class 4.

Group 1

2

3

4

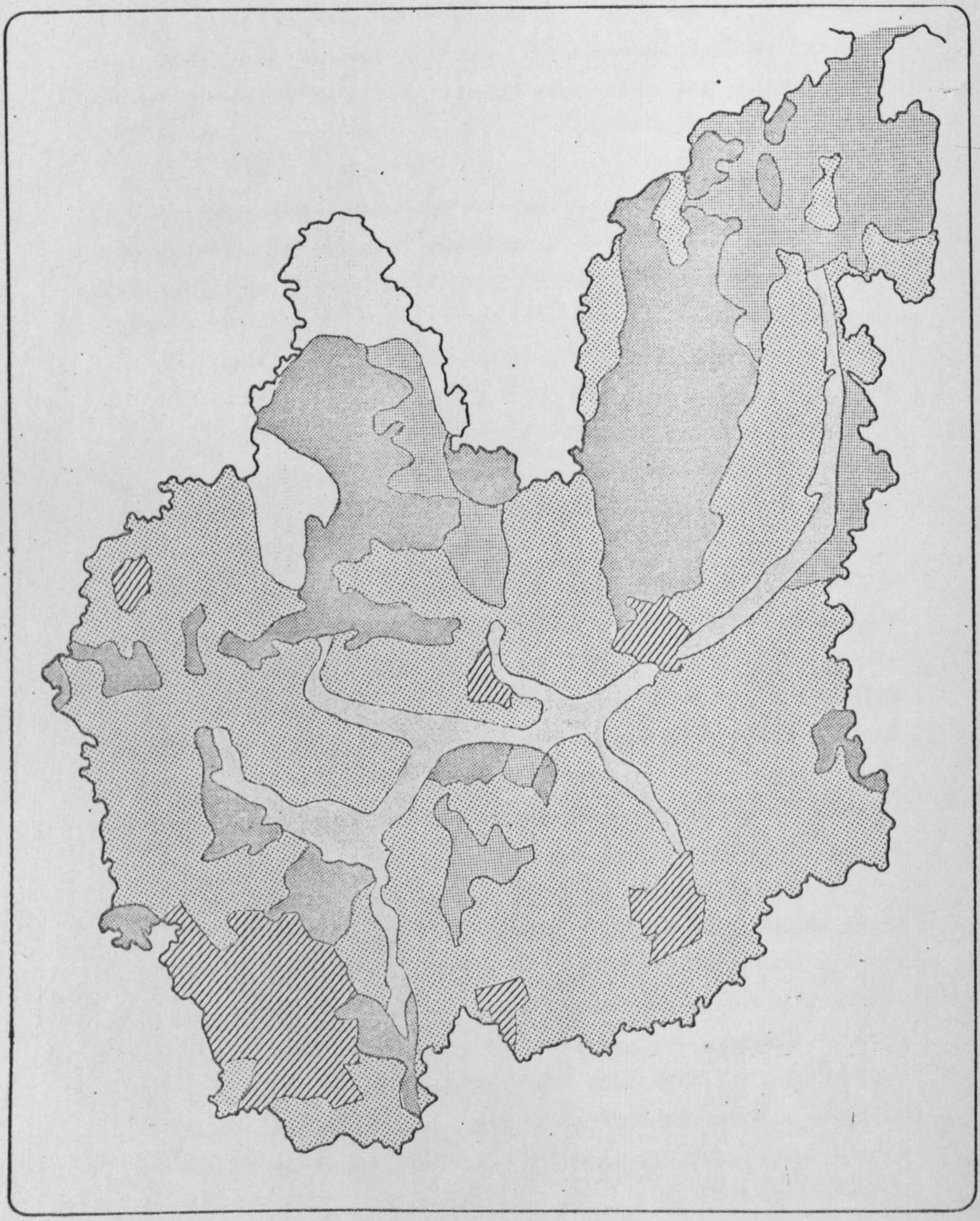
5

URBAN (6)

SOIL INDEX

(after Mackney 1977)

FIG. 9



4.4.3 The concept of Winter Rainfall Acceptance Potential proved very effective in the studies undertaken for the 'Flood Studies Report' (NERC, 1975) and the Institute of Hydrology 'Low Flow Study' (1980) and it is the most suitable index of soils and surface deposits available for use in England and Wales. However, a drawback with the approach would seem to be that there is no special account taken of the surface deposits of major urban conurbations. The same five soil classes are applied regardless of the percentage of built up area because where there was no specific soil survey data available, the classification relies on the correlation between geology and soil type. This simplification can be challenged and it can be argued that storm runoff is greater in some urban areas than rural areas due to the impermeable nature of large areas of ground. Also, in some urban areas low flow discharges may also be enhanced as a result of leakage from distribution and sewers systems. However, more commonly, low flows in urban areas are diminished by the reduced infiltration. (See section 4.5.1)

To account for the urban effect, a further soil class (number 6) was added to equation 18. A constant of 0.55 being arbitrily selected to account for higher runoff and lower base flow potentials. The index 'SOIL' has been calculated from Equation 19 (high flows) and equation 20 (low flows) for use in subsequent analyses.

$$S = 0.15\ S_1 + 0.30\ S_2 + 0.40\ S_3 + 0.45\ S_4 + 0.50\ S_5 + 0.55\ S_6 \quad (19)$$

$$S = 0.15\ S_1 + 0.30\ S_2 + 0.40\ S_3 + 0.50\ S_4 + 0.45\ S_4 + 0.55\ S_6 \quad (20)$$

By the inclusions of class 6, the soil index assessment equations are probably also indirect measures of land use (section 4.5) . The proportions of S_1 - S_6 can be determined from figure 9.

4.5 LAND USE AND LANDUSE CHANGES

4.5.1 In any catchment the use which is made of land influences riverflows. There are 3 major factors to be considered: agriculture and forestry, reservoir development and urban development.

(i) Agriculture and Forestry:

One of the most important aspects of recent changes in farming practices from the point of view of water yield, has been the installation of field drains to improve drainage in existing fields and to help in the reclamation of large tracts of agricutural land constrained by water logging. Field drainage has the effect of substantially increasing the density of drainage lines within the affected area by an amount depending on the type of drainage adopted. Such increases in drainage density must inevitably lead to and quickflow increased streamflow within the fluvial system. Howe et al. (1966) have attributed recent increases in flooding along the upper reaches of the Rivers Severn and Wye in mid Wales in part to the effects of land drainage. Variations in agronomic practice also effects runoff. Such activities as pasture improvement, crop rotation and changes in type and stocking density of grazing animals all have an effect. The greatest influence is on evapotranspiration which is reduced by the replacement of deep rooted vegetation, and by measures such as fallowing and over-grazing when the density of vegetation is reduced. As a consequence, the groundwater table may rise and runoff is increased.

One form of land-use change which has affected most countries is forestry activity, either in the form of removing existing forests for timber, land clearance or development, or in the form of afforestation for timber, flood and erosion control, or to improve scenic attractiveness and amenity value. Both forms of

activity can have marked effects on the fluvial system, (Park, 1981). The effect of afforestation on water yields in British catchments was first evaluated by Law (1956) around the headwaters of the River Hodder in Lancashire, using lysimeter observations, and since then the problem has been studied in a variety of areas, with conflicting findings. Green (1973) examined the hydrological impact of afforestation (1960-65) of 40 per cent of the Brenig catchment in North Wales by comparing changes in the relationship between precipitation and streamflow during the pre and post planting phases. In the post planting phase, flow increased by 10 per cent. The Institute Hydrology has instrumented the headwaters of the River Severn (forested) and the River Wye (grassland) at Plynlimon in mid Wales since 1968 to determine the differences in water and sediment yields between the two types of land use. Analyses of the data available for the period 1970-75 (IOH, 1976) showed that the mean annual water loss for the Wye is about 18 per cent of the annual precipitation, whereas the Severn showed a mean annual loss of about 38 per cent.

(ii) Reservoir development:

Some of the most apparent man-induced fluvial changes are associated with reservoir development. Beaumont (1978) has pointed out that during the period 1900-1970, major changes in the runoff regimes of many of the larger river systems of the world were brought about by reservoir development. In North America and Europe between 15 and 20 per cent of the total stream runoff is regulated by reservoirs. Clearly the impact of a particular reservoir will relate to the size and purpose of the reservoir because these will affect the timing, nature and magnitude of runoff.

(iii) Urban development:

Leopold (1972) evaluated many of the hydrological aspects of urban land use. He identified four major areas of urban impact. Three areas related to: sediment yield, effluent and amenity, but on the subject of river flow he suggested that modified runoff patterns are brought about by increases in the relative amount of drainage basin area which is made impervious, and by increases in the speed at which water is transmitted into channel systems across urban floodplains, through storm drains and other installations. The general effect is an increase in the volume of streamflow, characterized by decreased base flows but marked increases in peak flows. There have also been other analysis of runoff and changing runoff in urban areas. Gregory (1974), observing progressive urbanisation in a suburb of Exeter recorded a twofold increase in peak discharge, a 50 per cent decrease in lag time, and an increase in overall runoff volumes of up to 300% during urbanisation. Espy and Winslow (1974) provide evidence of increases in flood peak discharge of between 0 and 200 per cent, in urban areas depending on the recurrence interval of the particular event. They point out that in many cases the increase in peak discharge through urban development apparently decreases at flows with recurrence intervals of between 2 and 5 years because this is the range of design frequency for storm sewer systems. Hollis (1974, 1975) has synthesized a wide range of results of studies of the effects of urban development on floods of different recurrence intervals, and he concluded that the relative effect declines as the recurrence interval of the event increases. Also, he considered that whilst summer floods are very greatly influenced by urban effects, the influence is almost non existant in winter months.

4.5.2 Whilst it is possible to generalise the possible effects of land use and land use change on riverflows, with the exception

of reservoir area and volume the selection of measures to portray intercatchment variations is difficult. To date, successful analyses of land use variations have been small, localised studies with extensive instrumentation which take little account of mapped data.

In Britain, land use classification maps are available at a scale of 1:625,000 but they refer only to 'good', 'poor' etc. classes of land. Similarly the Ministry of Agriculture's on-going Agricultural Land Classification map (1:63,360) is based on potential not actual use, as are the Soil Survey's maps of land-use capability based on soil series. Mapped information is therefore insufficient to precisely differentiate between different types of agronomic, land drainage and forestry practice within the Trent basin. Similarly, extents of urban development can be approximated from topographic or soil maps but no information is given as to the type and age of the development or to the location of storm drains and overflows.

As the variations in drainage, forestry and agronomic practices are not great within the basin, and most land use variations are related to topography and soil (section 3), it was decided to rely on the soil index and morphological variables (eg. relief) to account for the effects of land use on runoff. However, because the urban effects were likely to be more pronounced an extra 'soil class' was added to the soil index equation. This has been discussed in section 4.4.3.

4.6 CONCLUSIONS

The opening paragraph of this chapter described four factors which Horton (1932) suggested were descriptive of a drainage basin as related to its hydrology: morphology, soils, geology and vegetation. Today, this remains a meaningful description of a river catchment although vegetation should be considered under a more general description of land use. Each of these factors has received variable degrees of attention from hydrologists and gemorphologists. For example, over 50

indic es now exist to describe the shape, topography and stream network within any basin: These being sufficient for most purposes. Catchment morphology has received more attention than any of the three other factors because it is the simplest feature to quantify and because there is an abundance of base data in the form of topographic maps. The numerical description of geology is much more complex as any index has to account for unseen permeability, porosity and structure. In water bearing rocks in particular, two formations ascribed the same geological name and with broadly similar lithologies many have very different hydrologies because of different structural influences. Simple indic es of the type developed by Wright (1973), where a rock is classified according to its expected water releasing potential, are useful in some circumstances but there will always be exceptions to the rule. For reliable flow estimation, another form of geological index is required which integrates the total hydrological effect of a catchment. (Such an index is considered in lat er chapters). The effect of surface deposits (including soils) on riverflows are also important. The effects have been considered in both the USA and Britain and a useful index, the Winter Rainfall Acceptance Potential (WRAP) has been developed by the Institute of Hydrology/Soil Survey (Farquaharson et al. 1978). WRAP has been used to good effect in the 'Flood Studies Report' (NERC, 1975) and to a lesser degree in the 'Low Flow Study' (IOH, 1980) and is advocated for use herein. The influences of land use on runoff are complex and occur on several scales. The smaller effects being connected with agronomic practice and largest with urban and reservoir development. Very few of these influences can be quantified and it is unlikely that a reliable index of land uses can be developed without very extensive field survey and possibly the use of air photography. In this study the correlation of land use with soils and topography is relied upon to provide an indirect index.

The indices described in this chapter, plus a further index of geology (derived in chapter 5), have been combined with

measures of precipitation, evaporation, artificial influences on riverflows, and measured runoff to derive a number of flow estimation techniques for ungauged areas. These analyses are described in the following chapter 5 (low and average flows) and chapter 6 (flow hydrographs).

5 THE ESTIMATION OF LOW FLOWS IN UNGAUGED AREAS OF THE TRENT BASIN

5.1 INTRODUCTION

Section 2.2 has shown that there are severe limitations to most of the methods currently used by hydrologists to estimate low flows for ungauged catchments. Nevertheless, professional engineers, scientists and research workers regularly require river flow data for ungauged areas.

The most important requirement is for a method by which a single, precisely defined index of low flow can be determined for any location. The method should be applicable to urban as well as rural catchments. There are further requirements for methods by which flow frequency and flow duration distributions may be estimated for ungauged areas.

The following sections outline the development of a number of techniques by which flows can be estimated for ungauged river reaches and catchment areas in the Trent basin.

5.2 ALTERNATIVE INDICES OF LOW FLOW

There is a whole range of flow conditions which can be broadly be described as low. One such condition, which is clearly of importance, is the lowest flow ever experienced. This condition is not easily defined, but must in practice be very similar to the flow experienced immediately before the end of the droughts of 1933, 1959 and 1976. The minimum flow at any site is thus directly related to the length of record used in its determination. As the minimum flow is an imprecisely defined and rare event, interest is more often centred on low flows of a more common nature. In the past, much emphasis has been placed on the 95% exceedence flow; that is the flow which is exceeded 95% of the time, or on average, on all but 18 days per year. For instance, Cross (1949, page 564) suggested that the 95% exceedence flow could be considered as a dry weather index and as being "Sustained

by seepage from groundwater resources." The majority of British Water Authorities have based their surface water licencing policies on the 95% exceedence flow.

The 95% exceedence flow has been shown by Pirt and Douglas (1982) to be an unstable statistic, dependent upon the length of record used in its calculation, unless that length exceeds twelve years. For short records which contain one very dry spell, flow may be below the 95% value only during the dry spell. For example during a three month drought in a five year record.

An alternative measure of average low flow has been developed by Hindley (1973). This measure, the '<u>Dry Weather Flow</u>', is the average of the annual series of the minimum weekly (seven consecutive days) flows. This can be likened to the driest week in an average summer. Unlike the 95% exceedence flow, the Dry Weather Flow (DWF) gives equal weight to each year. The seven day period covered by the DWF is important as it eliminates the day to day variations in the artificial component of river flow, notably the reduction in abstractions and effluent returns often seen at weekends.

This statistical definition of Dry Weather Flow should not be confused with others used in the design of sewerage or in general hydrological discussions. For example, Thompson (1922, page 108) suggested "If no further rainfall intervenes, a point is eventually reached, below which the rate of flow is nearly constant. This is known as the dry-weather flow, the decrease of which is so slow, that the stream is replenished by the next flush long before the channel has run dry." The Water Resources Board (1970) also used the term Dry Weather Flow loosely. Their publication TN12 'Dry Weather Flows' was simply a catalogue of lowest gauged river flows. No frequency or duration was ascribed to the data.

Dry Weather Flow as defined by Hindley, (the annual average seven day low flow) is a flow frequency statistic. The 95%

exceedence flow is a flow duration statistic. The difference between and the importance of these distributions are discussed in Sections 5.4.2 and 5.4.3.

5.3 DRY WEATHER FLOW IN THE TRENT CATCHMENT

5.3.1 In 1980, Tattersall, the Assistant Director of Resource Management of the Yorkshire Water Authority suggested that "Most (resource) management decisions hinge on the assessment of a river's dry weather flow at any point along its length and it will be apparent that many factors other than the natural phenomenon of dry weather will affect it" (page 3, 4). However, he also felt that "With so many artificial influences on a river, classical hydrological techniques for the study of its behaviour are not applicable. Time series analysis for the study of low flows has little validity and relationships between rainfall and run-off are almost impossible to establish."

Lloyd (1968) has suggested a technique that can be developed to provide a regional picture of Dry Weather Flow information. "The Mersey and Weaver River Authority has devised for this purpose a method of river analysis which is based on long-term records of river flows and effluent discharges, and upon information now becoming available from the licencing system. The method has been adapted to make full use of data processing equipment and computer technique. It will be further refined and better applied to practical conditions in the light of experience, and by using the more reliable information yet to be obtained from the licencing system and the hydrometric scheme. The results are presented graphically in the form of a simple residual flow diagram which can be used for forecasting the effects of changed artificial interferences during drought conditions with various return periods. These diagrams open up the way for the planning and cost/benefit analysis of schemes for using a river system for bulk water distribution, in addition to the traditional uses for land drainage and other in situ purposes. They may be looked upon, therefore, as one of the

new tools to be used in preparing the Periodical Surveys, as well as for day-to-day use in dealing with licence applications" (page 372).

5.3.2 A residual flow diagram is a snapshot of the flow throughout a river system, including an assessment of the quantity and quality of the natural and artificial components of flow at any point. For a chosen condition (eg Dry Weather Flow) all information on river flow and artificial influences are collected and combined to give a catchment wide snapshot of river conditions, thus meeting Tattersalls data requirement (5.3.1). Residual flow diagrams also meet a more general data requirement specified by Riggs (1972, page 16). "Flow characteristics should be presented in such a way that the reader can find information at or close to his site of interest rapidly".

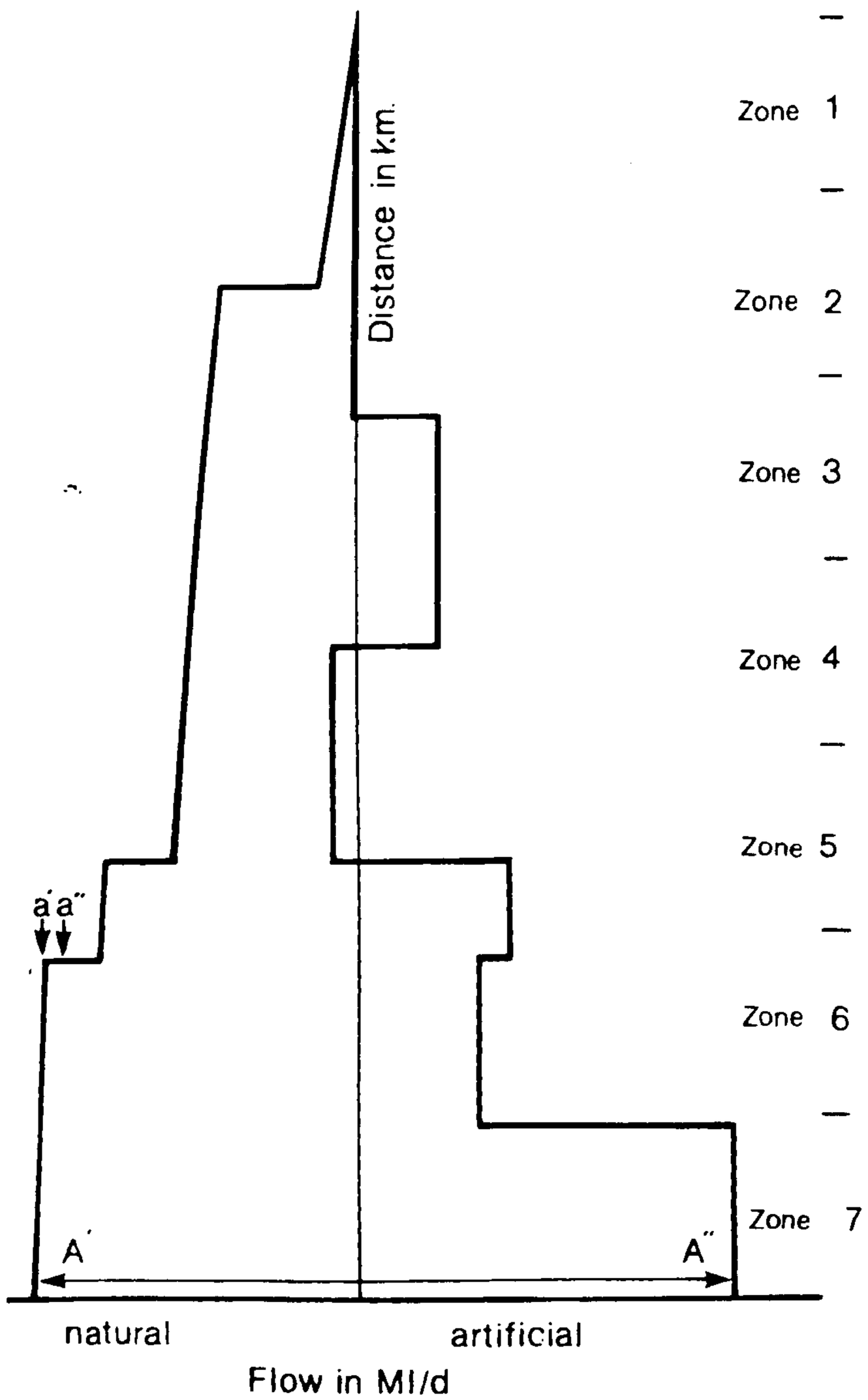
5.3.3 A problem with the snapshot residual flow diagram approach, is the assumption that the flow condition being described, existed simultaneously throughout the whole catchment. A catchment the size of the Trent may be expected to give inconsistent flow patterns. However, an analysis of a number of gauging station records representing each major subcatchment in the basin showed that conditions approximating to the Dry Weather Flow existed throughout the whole of the Trent catchment during the period 5-13 September 1977.

All available hydrological data were collated for this period. These included the records from 50 permanent gauging stations, the results of 316 current meter gaugings and the returns from every water reclamation works, licensed abstraction and discharge in the basin. This involved the analysis of the records of several thousand water users. The sources of these data and their quality have been discussed in sections 3.5.3 and 3.5.5.

5.3.4 Whilst Lloyd (1968) championed the case for residual flow diagrams and examples have since appeared in the reports of

Simplified Residual Flow
Quantity Diagram

FIG. 10



several Water Authorities (for example, STWA 'First Survey of Water Services', 1980) there is no widely recognised technique by which the diagrams are constructed. For the purposes of this study two types have been considered; a quantity diagram and a quality diagram.

5.3.5 Quantity Diagrams

A 'quantity' residual flow diagram shows the total quantity of water in a river or stream at any point by dividing it into its natural and artificial components. Figure 10 is a simplified version of such a diagram. The vertical axis of the diagram represents distance downstream from source, and the horizontal axis, rate of flow. The horizontal axis is split into two sections by the vertical axis, the left hand side represents natural runoff to the main river and the natural component of runoff from any tributary. The right hand side represents the artificial component of flow; in other words, it shows man's effect. The most important point is that in every case the total flow in the channel is represented by the distance between the natural and artificial lines (eg A' - A"). Any change in flow must be considered in net terms and both sides of the diagram observed. If at any time the artificial line crosses the central axis this indicates that total flow at that point is less than the natural flow would have been in an 'untouched' river.

Figure 10 illustrates a number of features of this type of residual flow diagram.

Zone 1 - Natural flow only is shown. Flow at any point is the distance between the natural line and the central axis.

Zone 2 - Similar to Zone 1 but with a tributary included. The tributary has no artificial component in its flow.

Zone 3 - The first artificial component is shown in the form of a discharge. This could be from a water reclamation works, industry or perhaps compensation water from a reservoir. Total flow is now the distance between the artificial and natural lines.

Zone 4 - An abstraction is shown from the main river which could be to public water supply or to industry.

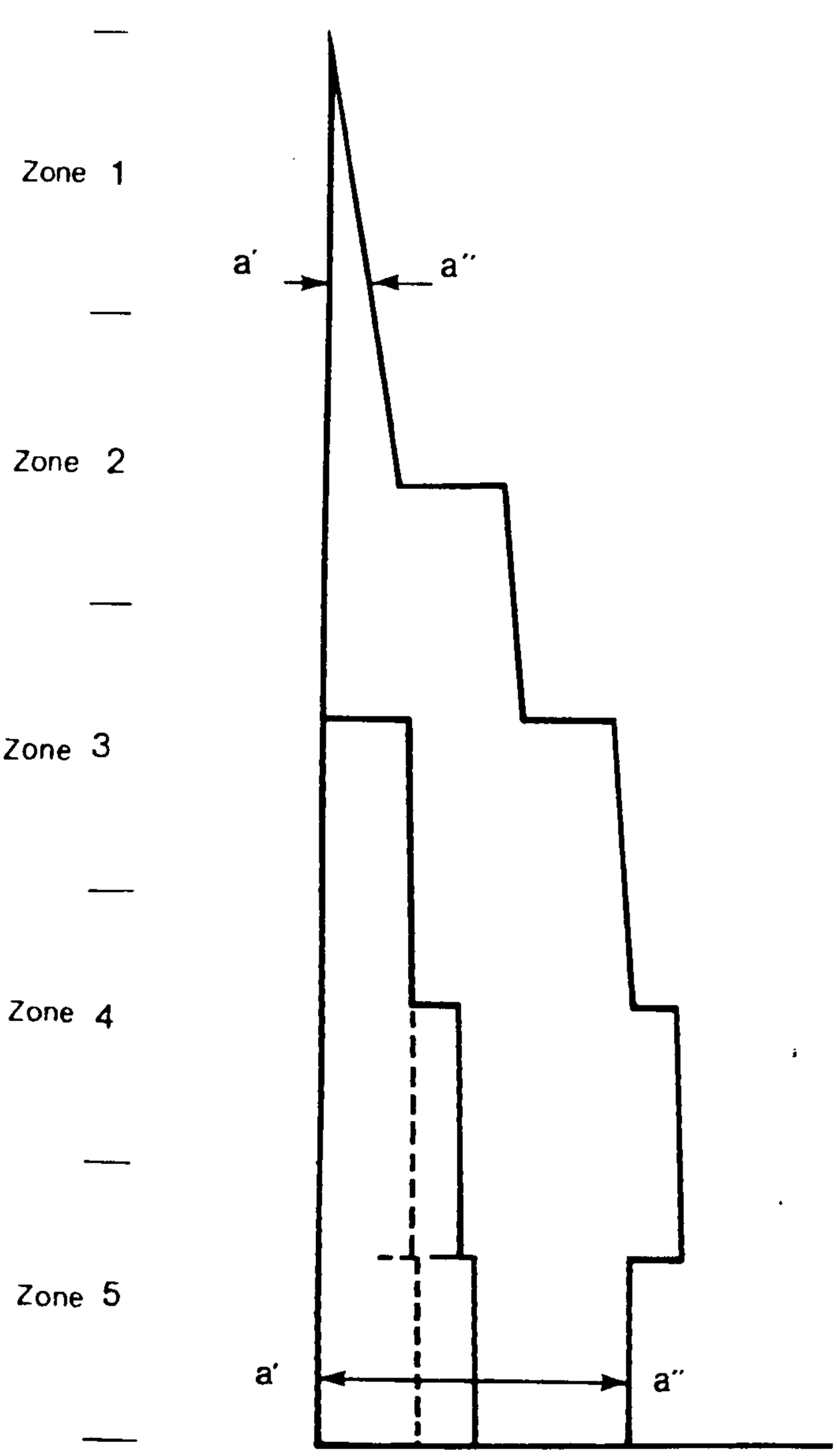
Zone 5 - In this section a major tributary has joined the river. The main river flow is increased on both the artificial and natural sides by the same quantities as the artificial and natural components of the tributary.

Zone 6 - In this section one of the most difficult concepts is introduced. This is how to show an abstraction in a tributary, ie. water lost from the catchment which would have reached the main river. The solution adopted is to show the abstraction on the artificial side at the point of tributary entry and also to adjust the natural side by the same amount. This shows how much natural input there would have been and how much was actually removed, yet at the same time maintaining no overall net change in the main river. Any other natural inflow or artificial discharge entering the main river can be superimposed on this effect, for example distance a'-a".

Zone 7 - This section shows a large increase in artificial flow. The final flow in the example river is equivalent to the distance A'-A".

Simpified Residual Flow
Quality Diagram

FIG.11



x y

y total (sewage, industrial and thermal) effluent
x sewage and industrial effluent

5.3.6 Quality Diagrams

The diagram outlined in the previous section says very little about the composition of water at any point. This is because of the way abstractions from rivers are subtracted solely from the articial component of flow, rather than in proportion to the composition of flow at the abstraction point. In order that the residual flow diagrams can be used to gain an impression of the composition of flows, a second set of diagrams, the 'quality' diagrams, have been produced using a different method of computation.

Figure 11 shows a stylised presentation of a quality diagram. This type of diagram does not show the total natural runoff at any point, only total flow is drawn, to the right of the vertical axis. The quantity of water which has been affected by man is shown in two ways, making the distinction between water reclamation works and industrial effluent discharges, and discharges of cooling water which are at a higher temperature than the receiving watercourse but otherwise of unimpaired quality. In Figure 11

Zone 1 - The distances a'-a" is the total flow and is equivalent to any distances A'-A" in the quantity diagram.

Zone 2 - Depicts a tributary input which is totally natural.

Zone 3 - Depicts an artificial discharge which is totally sewage and industrial effluent.

Zone 4 - Depicts an artificial discharge of cooling water. This is only indicated on the total effluent and total flow lines. The sewage and industrial effluent quantity remains unchanged.

Zone 5 - Depicts an artificial abstraction and discharge. The total net abstraction is monitored on the

total flow line. Lines x and y are altered by an amount related to the proportions of effluent in the river at that point. Taking the abstraction first, the amount of effluent removed from the river, is, in both cases, calculated from the ratio of effluent flow to total flow. For example:

Before abstraction:

Total flow = 20 Ml/d

Total effluent = 5 Ml/d

Sewage and industrial effluent = 4 Ml/d

Abstraction = 6 Ml/d

Therefore after abstraction:-

Total flow = (20 - 6) = 14 Ml/d

Total effluent = $5 - (\frac{5}{20} \times 6) = 3.5$ Ml/d

Sewage and industrial effluent = $4 - (\frac{4}{20} \times 6) = 2.8$ Ml/d

For a discharge at the same site, the total flow quantity is amended by the discharged quantity, as is the total effluent value. The amendment to the sewage and industrial effluent line is dependent upon the composition of the discharge.

In a complex case it is possible that the discharge may be classed as part thermal, part sewage and industrial. For example, 3 Ml/d of the original 6 Ml/d abstraction may be discharged, which is said to be 50% thermal, and 50% sewage and industrial. In order to calculate the resultant sewage and industrial

effluent quantity the 3 Ml/d must be divided into two separate parts. The first is equal to the original value of the net sewage and industrial abstraction ie.

$$\left(\frac{4}{20} \times 6\right) = 1.2 \text{ Ml/d}$$

The second portion is equal to the remaining part of the 3 Ml/d discharge, ie 1.8 Ml/d, which is itself divided into sewage and industrial effluent, and thermal effluent in the ratio 50:50. The resulting value of 0.9 Ml/d is added to the above 1.2 Ml/d to give a total sewage and industrial discharge of 2.1 Ml/d. This means that the resultant quantity of sewage and industrial effluent in the river downstream of the abstraction point is 4.9 Ml/d.

For example:

Discharge = 3 Ml/d, 50% thermal, 50% sewage and industrial effluent.

After discharge:-

Total flow = 14 + 3 = 17 Ml/d

Total effluent = 3.5 + 3 = 6.5 Ml/d

Sewage and industrial effluent = 2.8 + 1.2 + (1.8 x 0.5)

= 4.9 Ml/d.

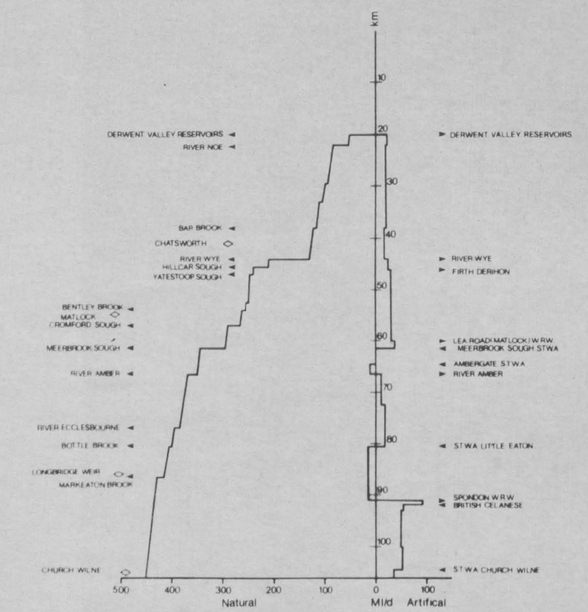
Hence the final quantity of sewage and industrial effluent discharged at any point is related not only to the industrial process, but also the quality of river water upstream.

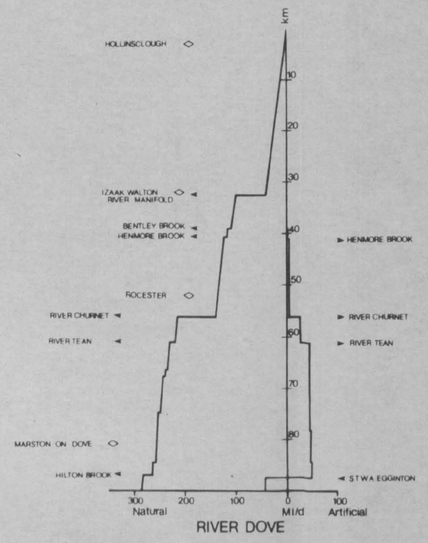
5.3.7 In constructing residual flow diagrams the quality of all data has to be carefully assessed. When considered individually, the accuracy of parts of both the river and artificial flow data are poor (Section 3.5.5). However much greater reliability can be placed on the data collectively

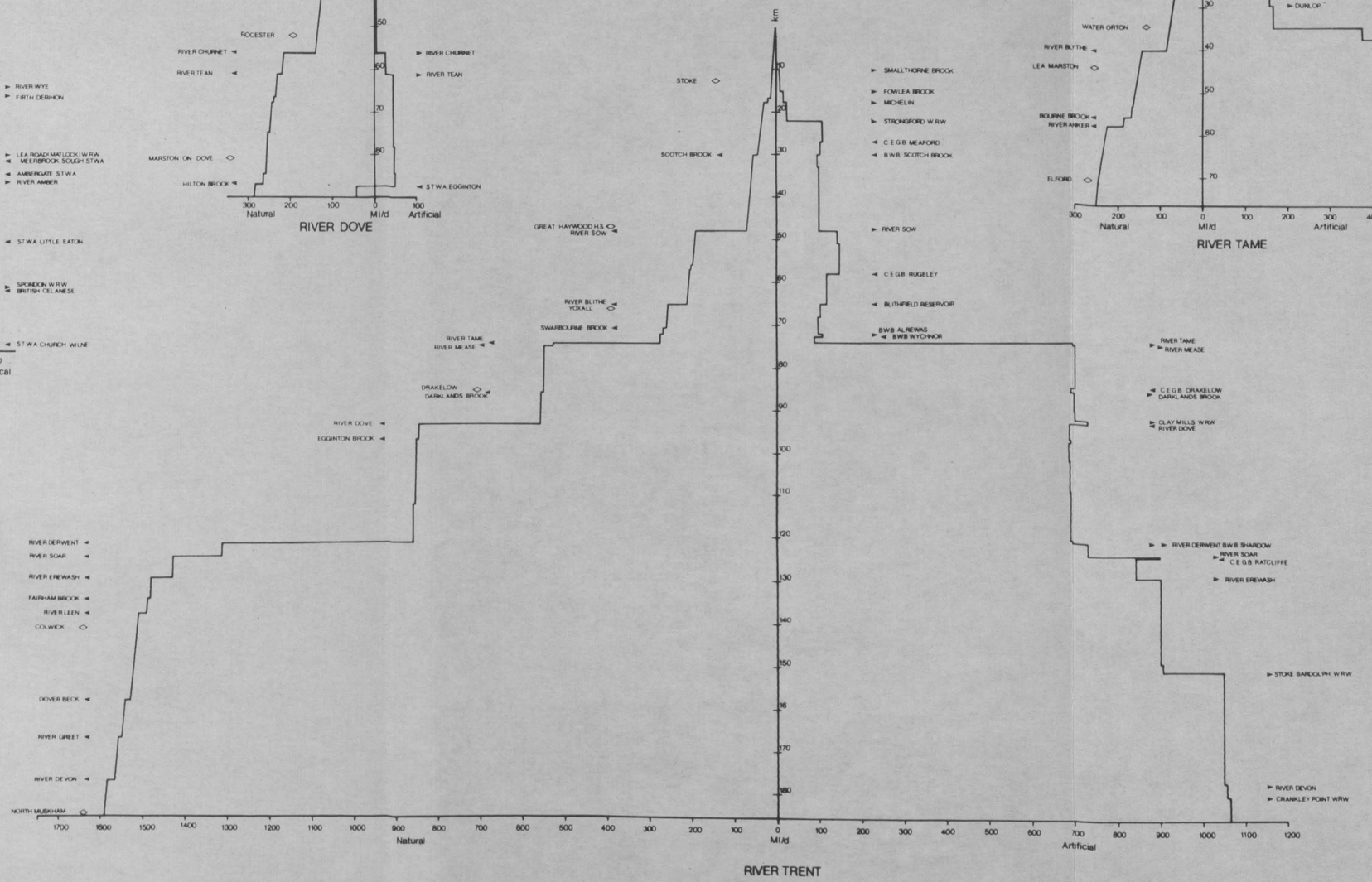
RESIDUAL FLOW DIAGRAM
DRY WEATHER FLOW CONDITIONS

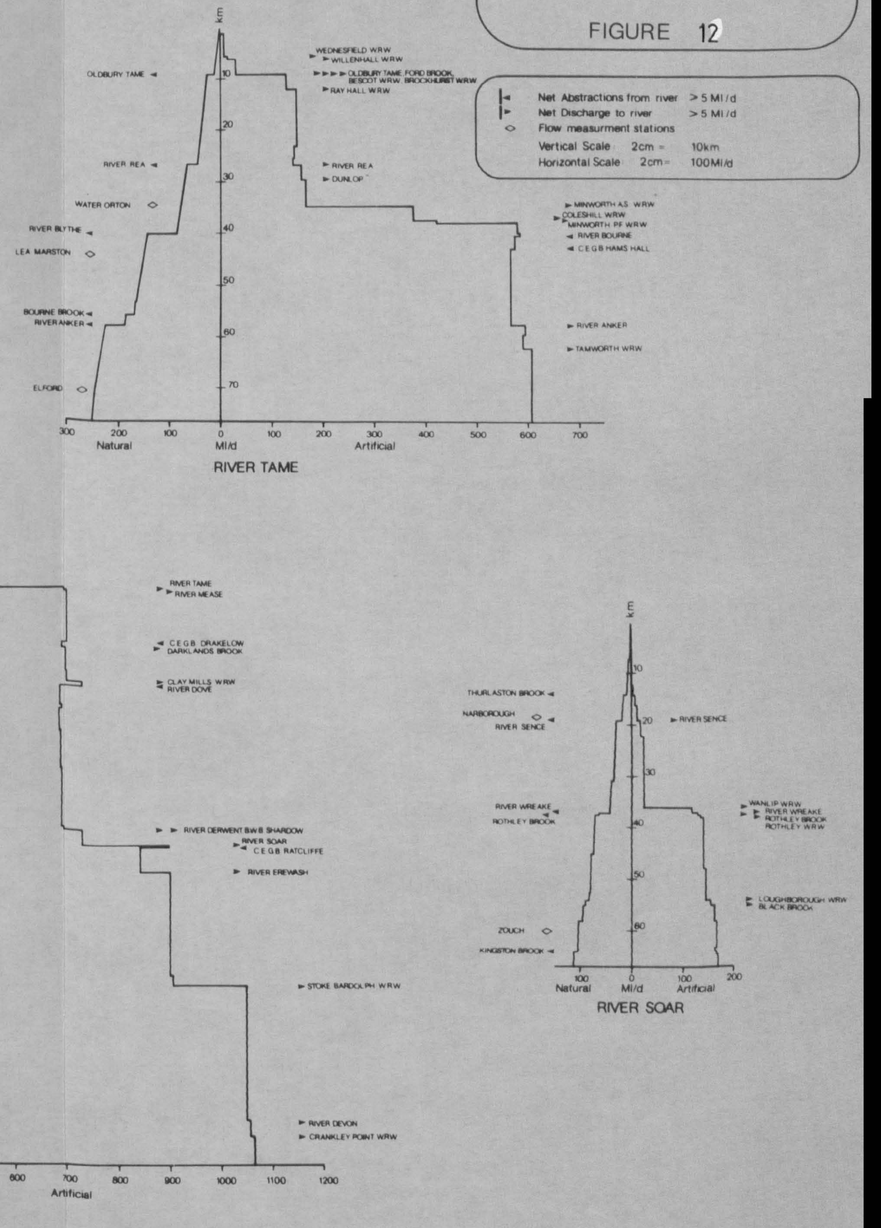
FIGURE 12

Net Abstractions from river > 5 Ml/d
Net Discharge to river > 5 Ml/d
Flow measurment stations
Vertical Scale 2cm = 10km
Horizontal Scale 2cm = 100Ml/d





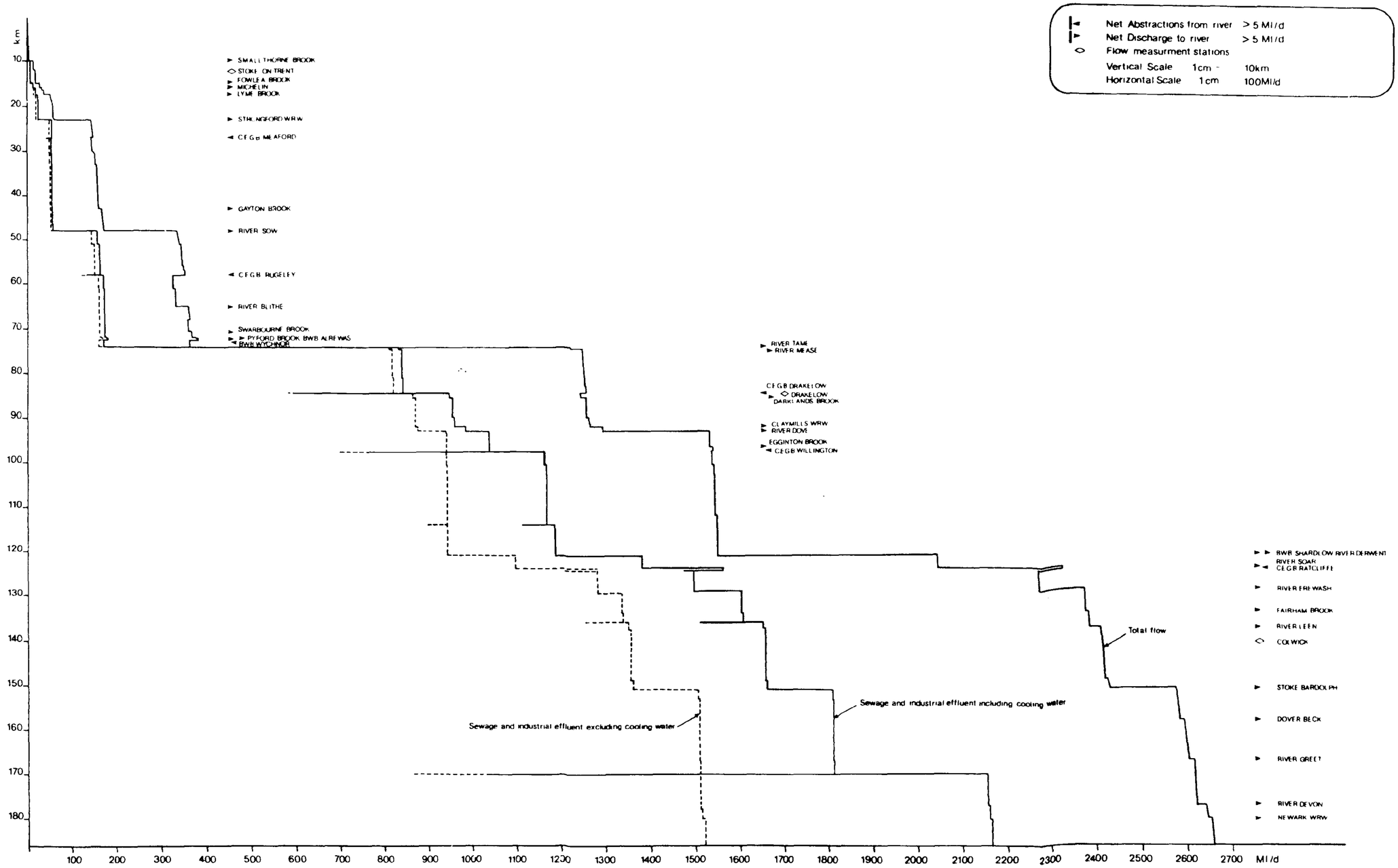




RESIDUAL FLOW DIAGRAM
DRY WEATHER FLOW CONDITIONS
RIVER TRENT

FIG.13

Net Abstractions from river > 5 Ml/d
Net Discharge to river > 5 Ml/d
Flow measurment stations
Vertical Scale 1cm - 10km
Horizontal Scale 1cm 100Ml/d



J.P. 1980

than on any of the individual components. This is because all the values have been considered in relation to each other as part of the recursive calculations necessary to construct the diagrams. Each tributary and each discharge has to fit a general pattern controlled by the gauging station network. Spurious values emerge and each has to be checked. This validation procedure has shown a number of errors in the data. In some cases river velocities were too low for worthwhile stream gauging, in others, water depths were inadequate for gauging and in some extreme cases it is obvious that the wrong watercourse was gauged. Where a choice of data was available, those which best fit the overall pattern have been used. These recursive calculations are the most tedious part of understanding the pattern of low flows and of producing residual flow diagrams. They are also the most important and give, overall, a high quality result.

5.3.8 A complete set of Dry Weather Flow 'quantity' and 'quality' residual flow diagrams for the Trent basin are presented as Figures 12 to 18. Figures 12 and 12a are quantity diagrams, Figures 13-18 are quality diagrams (Figures 12 and 13 are included in the text). The data used to prepare the diagrams are tabulated in Appendix 3. The following information is given in the Appendix:

(i) A tabulation of each major 'event' on a river (e.g. a tributary confluence, water supply reservoir, industrial abstraction, reclamation works discharge), its position in kilometres from the source of the river and its location on the National Grid.

(ii) The catchment area to any gauging point in km^2. A tributary catchment area is prefixed by a + sign and a suffix * depicts that not the whole tributary area was gauged.

(iii) The subcatchment natural runoff and the running total main river natural runoff in Ml/d.

(iv) The quantity of artificial abstraction (-) and discharge (+) at any location in Ml/d. The running total artificial flow (according to the quantity method).

(v) The running total sewage and industrial flow according to the quality method. The running total sewage, industrial and thermal flow.

(vi) The running total, total flow (natural plus artificial) in Ml/d.

(vii) The natural runoff yield per square kilometre (see Section 5.3.10).

(viii) A number of comments, giving the source of the data (eg. PF = processed flow, CMG = current meter gauging) or the type of water (eg. CD = colliery discharge, CF = canal feeder). Also shown where applicable is the licensed daily abstraction or discharge if this is different from the observed quantity. A full list of all abbreviations is given as Appendix 4.

5.3.9 The figures and tables discussed in the previous sections meet both Rigg's requirement (5.3.2) for flow characteristics that can be found at or close to the site of interest rapidly and Tattersall's need for an assessment of a river's Dry Weather Flow at any point along its length. A variety of resource management decisions can be made using this data. For example:

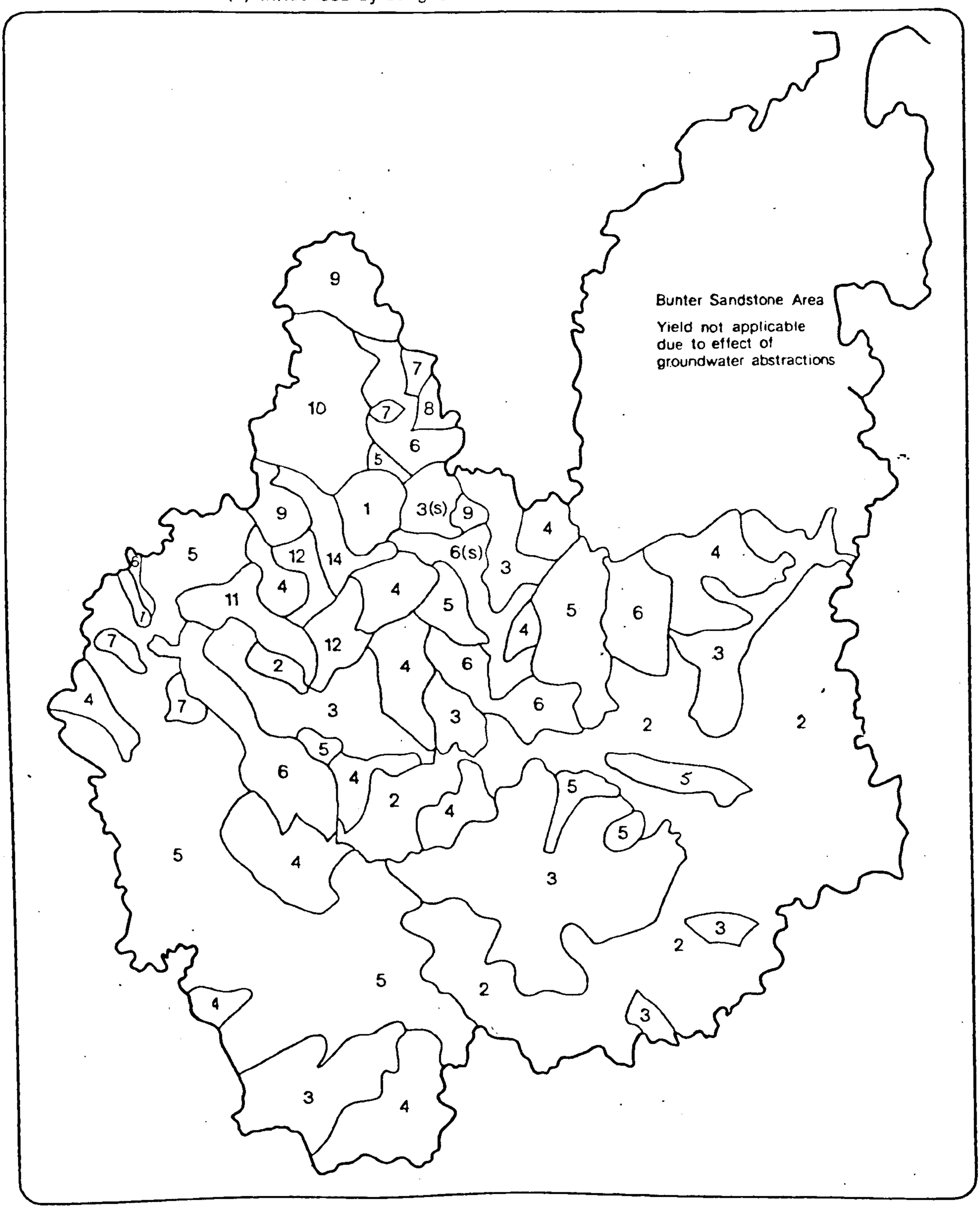
(i) The quantity diagrams and tables give information on the absolute and relative magnitudes of river flows and artificial influences in a basin. This data can be used by engineers and scientists engaged in abstraction licensing, formulating consents to discharge, designing water reclamation works and fishery management. It is interesting to note for example, that the Dry Weather Flow of the River Soar

1	0·01 - 0·04	Mld/km²	8	0·35 - 0·39
2	0·05 - 0·09		9	0·40 - 0·44
3	0·10 - 0·14		10	0·45 - 0·49
4	0·15 - 0·19		11	0·50 - 0·54
5	0·20 - 0·24		12	0·55 - 0·59
6	0·25 - 0·29		13	0·60 - 0·64
7	0·30 - 0·34		14	0·65 - 0·7

(s) influenced by soughs

TRENT AREA

RUNOFF COEFFICIENTS
DRY WEATHER FLOW CONDITION
FIG 19



(area = 1388km^2) is less than the output from a single water reclamation works in another basin (Minworth, R Tame, SP 160 924).

(ii) The diagrams and tables show the relative water quality of the various rivers. For example, the Dove and the Derwent are virtually unaffected by man where as sections of the River Soar and River Tame have a high proportion of used water. This ready supply of river quality data can reduce the requirement for water quality monitoring and analysis.

(iii) River flows are often analysed on the assumption of no trend. This is not the case, due to an ongoing increase in the quantity of the artificial component. Residual flow diagrams can highlight and solve this problem.

(iv) The detailed analysis of the artificial component of flow provides information which can be used to naturalise river flows on a regular basis and thus increase the accuracy and reliability of other types of hydrological analysis.

5.3.10 In the residual flow 'quantity' diagrams described in Section 5.3.5, (Figure 10), the portion of the diagram to the left of the central axis represents natural runoff in the main river and the natural component of runoff from any tributary. By dividing the net addition to natural runoff between any two points by the contributing catchment area, natural runoff yield per unit area can be calculated. These calculations have been performed and the results tabulated in Column 12 ('natural yield') of Appendix 3. The yields lie in the range 0.01 to 0.70 Mld per km^2. Figure 19 depicts the distribution of the yields throughout the Trent catchment. In the figure the yields are represented by 14 groups each with a range of 0.05 Mld/km^2. It can be assumed that all subcatchments lying within a zone depicted by a single coefficient have the same runoff yield.

Figure 19 can be used to estimate the Dry Weather Flow of any points of interest in the Trent basin not covered by the residual flow diagrams. The method can be outlined by means of an example. The Dry Weather Flow of the Fairham Brook, a small tributary of the Trent on the outskirts of Nottingham, is calculated by:

(i) Determining the catchment watershed on a 1:25000 map.

(ii) Calculating the catchment area in Km^2.

(iii) Determining the catchment runoff coefficient using Figure 19. Figure 3 (in Volume 2), the transparent overlay showing main watercourses and the national grid is a useful aid. In catchments where more than one yield applies, a composite yield is derived from the relative proportions of catchment area lying within each yield zone.

(iv) Multiply yield by area and include any known artificial inputs

Area of Fairham Brook to SK 562 338		= 63.8	km^2
Runoff coefficient, DWF		= 0.09	
Natural DWF = 63.8 x 0.09		= 5.74	Ml/d
Artificial inputs,	Keyworth WRW + 1.3 Ml/d		
	Gotham WRW + 0.4 Ml/d		
		+ 1.7	Ml/d
Total DWF at NGR SK 562 338		= 7.4	Ml/d

(NB. The technique may not apply to very small catchments ($<5km^2$) because local effects such as springs may have more influence on flow than general catchment yield).

The advantages of this simple approach to the estimation of low flows in ungauged catchments are:

(i) The method makes optimum use of all available gauged data.

(ii) No numerical quantification of catchment geology is required hence avoiding many of the pitfalls of other low flow estimation techniques (Section 4.3).

(iii) It is quick and simple to use. Low flow assessments can be made quickly and accurately without resort to time consuming stream gauging. These 'instantaneous answers' may be invaluable to farmers or industrialists considering applications for licences to abstract or consents to discharge water. The applications may be assessed without a major hydrological investigation.

5.3.11 One of the suggested advantages of the method of estimating Dry Weather Flow described in 5.3.10, is that there is no requirement for a numerical index of catchment geology. However, it is recognised that geological indices are fundamental to many other types of hydrological model. A number of indicies used in other studies have been described in Section 4.3. As an alternative to these indices, it is possible that Dry Weather Flow yield as defined in 5.3.10 can be used as an index of catchment geology.

A comparison of Figure 19 and the geological map for the Trent basin (Figure 4) shows that low flow yield is very closely correlated with geology. For example, rocks of the Lias type generally have a yield of 0.05 to 0.09 Mld/km^2, Marls 0.10 to 0.24 Mld/km^2, Westphalian 0.15 to 0.24 Mld/km^2 and Namurian 0.34 to 0.44 Mld/km^2. Further, it is possible that these yields are not specific just to the Trent basin. For example, Schneider (1965) analysing the 1.9 year return period low flow for the Swarta Creek basin in Pennsylvania, found that although precipitation differed for the various geologic zones in the basin, there was no evidence of a cause-and-effect relationship between the differences in precipitation and the differences in base

TABLE 6

COMPARISONS OF DRY WEATHER FLOW YIELDS

	Swarta	Trent	Yorkshire
Ordovician Shales (shale with some sandstone)	0.01-0.09	0.05-0.09	N/A
Devonian (sandstone and shale)	0.05-0.19	0.10-0.19	0.13
Pennsylvanian (coal measures)	0.09-0.29	0.15-0.24	N/A
Triassic (sandstone, shale and limestone)	0.29-0.38	0.34-0.44	0.34-0.41
Ordovician and Cambrian (crystaline limestone)	0.90	N/A	N/A

(units :- $Ml/d\ km^2$)

flows between zones. In fact, highest sustained base flows occurred in the area of lowest precipitation, indicating that in the basin geology rather than precipitation was the major controlling factor over the low flows. Table 6 is a comparison of low flow yields for the Swarta Creek basin (1500 km^2) and the equivalent Dry Weather Flow yields for the Trent. The geology of the Swarta basin is complex and the comparison is based on approximate lithologies rather than specific stratigraphic units. Nevertheless, there is very close agreement between the yields calculated for each general rock type.

Analysis of Yorkshire Water Authority 'River and Rainfall Statistics, Updated to 31.12.81' (Clark, 1982) has also provided a small quantity of Dry Weather Flow yield information. This is also shown on Table 6 and confirms that each general rock type may have a charactistic yield.

Allowing for the major differences between the locations, ages, sizes and complexities of the sampled catchments, the low flow yields are very similar for each rock type. Rocks therefore have a general characteristic low flow hydrology and for this reason Dry Weather Flow yield (DWFY) (Figure 19) can be used as an index of catchment geology in some hydrological analyses within the Trent basin.

5.4 FLOW DISTRIBUTIONS

5.4.1 The major drawback of the residual flow diagrams and tables presented in Section 5.3.9 and the Dry Weather Flow runoff coefficients presented in Section 5.3.10 is that they refer to a specific flow condition. For some hydrological purposes flow of other frequencies and durations are required. For gauged catchments flow frequency and flow duration curves can be derived to provide this information.

5.4.2 A FLOW DURATION CURVE shows the relationship between any given discharge and the percentage of time that the discharge is exceeded. It is a means of combining in one curve the

FIGURE 20

FLOW DURATION CURVE ANALYSIS FOR R DERWENT AT YORKS BRIDGE (NAT)

FOR PERIOD 1.69 TO 11.81

ALL MONTHS ANALYSED

CLASS INTERVAL : FLOW IN CUMECS	NUMBER OF OBSERVATIONS	ACCUMULATED NO OF OBS	% TIME LOWER LIMIT EXCEEDED
<0.05	2	4717	100.000
0.05 TO <0.10	1	4715	99.958
0.10 TO <0.20	4	4714	99.936
0.20 TO <0.30	5	4710	99.852
0.30 TO <0.35	10	4705	99.746
0.35 TO <0.40	22	4695	99.534
0.40 TO <0.45	20	4673	99.067
0.45 TO <0.50	45	4653	98.643
0.50 TO <0.70	163	4608	97.689
0.70 TO <1.00	368	4445	94.234
1.00 TO <2.00	1208	4077	86.432
2.00 TO <3.00	763	2869	60.823
3.00 TO <5.00	968	2106	44.647
5.00 TO <10.00	754	1138	24.125
10.00 TO <15.00	227	384	8.141
15.00 TO <20.00	86	157	3.328
20.00 TO <30.00	52	71	1.505
30.00 TO <40.00	8	19	0.403
40.00 TO <50.00	7	11	0.233
50.00 TO <70.00	3	4	0.085
70.00 TO <80.00	1	1	0.021
GREATER THAN 80.00	0	0	0.000

MEAN FLOW FOR PERIOD = 4·090 CUMECS

NO OF DAYS FLOW LESS THAN OR EQUAL TO ZERO 0

flow characteristics of a stream through the full range of discharge.

Flow duration curves can be derived from daily flow data by assigning average daily discharges to class intervals and counting the number of days within each interval. The proportion of the total number of days above the lower limit of any given class interval is then calculated and plotted against the lower limit of the interval. An example of such an analysis is given in Figures 20 and 25.

5.4.3 A LOW FLOW FREQUENCY CURVE shows the proportion of years, or equivalently the average interval between years (return period), in which a river flow falls below a given discharge. Thus whilst a flow duration curve gives information about the statistical distribution of all streamflows for a period of years (in which the data may be serially dependent) the flow frequency curve gives specific probability information about unrelated data.

Low flow frequency curves for gauged sites may be constructed by:

(i) Finding the lowest consecutive D day flow in each year of the stream flow record, where D is the period under consideration.

(ii) Ranking the resulting series of data in order from highest to lowest.

(iii) Plotting the ordered discharges on suitable probability paper. In the following analyses Gumbel paper and the Gringorten plotting position were used. These particular types of probability paper and plotting position (equation 21) are suited to independent data with more than 10 observations. Good fits can be obtained with low variance (Simpson, 1977; Cunnane 1976).

FIG. 21

FLOW FREQUENCY CURVES

(DERWENT, WREAKE)

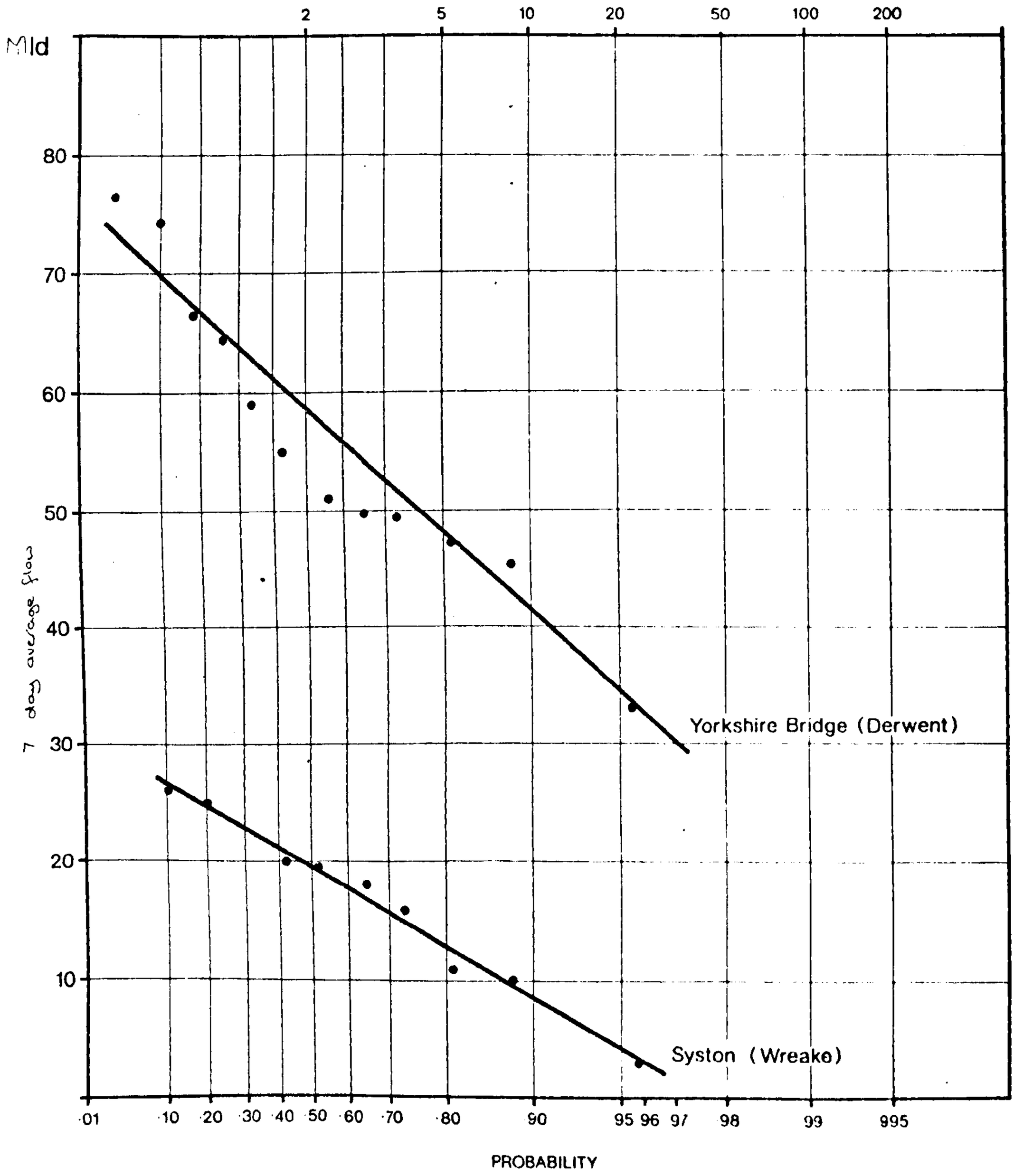


FIG. 25
FLOW DURATION CURVES
(DERWENT, WREAKE, REA)

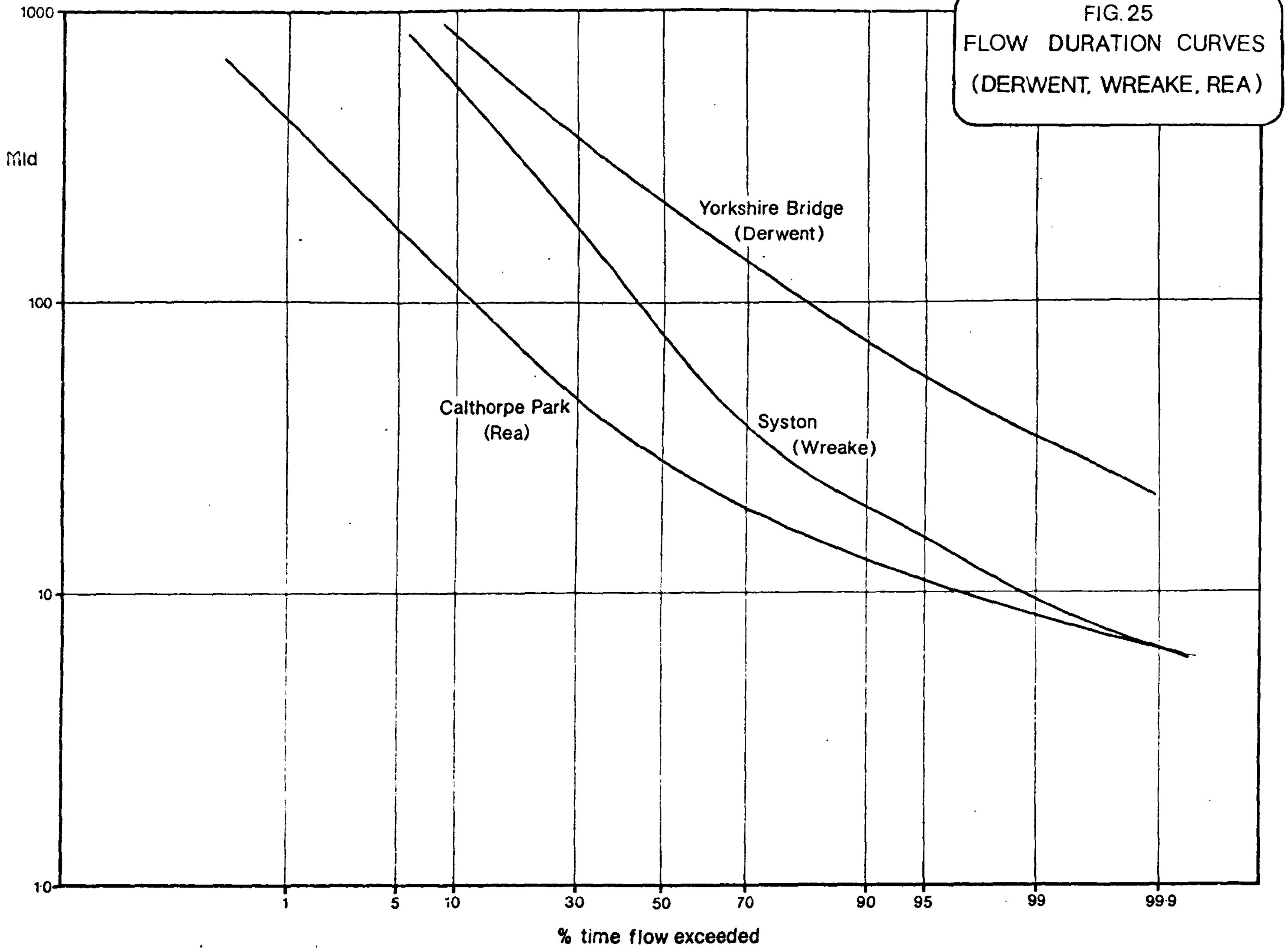


TABLE 7

COMPARISON OF LOW FLOW STATISTICS

RIVER	STATION	DWF $Q_{7,2.33}$	RETURN PERIOD $Q_{7,2.33}$	$Q_{95\%}$	$Q_{7,10}$	$Q_{7,MIN}$	RETURN PERIOD 7,MIN	$Q_{24,2.33}$	% 14>7
REA	CALTHORPE PK	8.2	2.9	8.2	6.0	4.3	22	9.7	18
SENCE	RATCLIFFE CULEY	16.0	2.2	16.0	8.0	2.0	38	17.6	10
ANKER	POLESWORTH	24.0	2.6	23.0	11.0	4.0	20	26.7	11
MANIFOLD	ILAM	60.5	2.3	54.2	39.0	29.5	20	63.2	4
DOVE	HOLLINSCLOUGH	3.2	2.0	3.1	1.9	1.5	19	3.4	6
DOVE	IZAAK WALTON	50.0	2.5	47.5	36.0	26.0	21	51.3	4
DOVE	ROCESTER	167.5	2.0	161.9	110.0	85.5	20	173.9	3
HAMPS	WATERHOUSES	5.9	2.2	5.9	2.9	2.0	28	6.0	1
CHURNET	ROCESTER	81.7	2.0	65.5	53.0	38.0	22	86.5	5
DERWENT	YORKSHIRE BRIDGE	55.6	2.5	55.0	41.0	33.8	22	64.6	16
WREAKE	SYSTON	18.3	2.5	15.9	9.7	3.0	22	19.6	7
Average			2.3				23		7.7

Explaination:- $Q_{x,y}$ relates to flow of duration x (eg 7 day) of Return Period y (eg 2.33) years)

Flows are naturalised, units:- Mld

Return period in years

$$\text{Plotting position} = \frac{n - 0.44}{N + 0.12} \qquad (21)$$

where n = rank number

N = total number of observations

(iv) drawing a smooth line through the plots (Figure 21).

In Section 5.2.1 a case was made for a seven day data base. This was to eliminate the day to day fluctuations caused by variations in the artificial components of river flow; notably the reduction in abstractions and effluent returns often seen at weekends. To maintain continuity, the flow frequency curves considered in this report are also based on seven day data (D = 7), although some consideration has also been given to fourteen day period means.

5.4.4 To consider the properties of flow frequency curves and flow duration curves, the records from 11 flow measuring stations were analysed and curves produced according to the method outlined in 5.4.2 and 5.4.3. The particular stations were chosen because they represented the longest available, accurate, homogenous data set that could be naturalised, using information given in Appendix 3. A standard period of 13 years (1969-81 was used in each case).

The derived curves are shown as Figure 21 to 28: 21-24 are flow frequency, 25-28 flow duration (Figures 21 and 25 are included within the text). Table 7 summarises the analyses made of the two sets of curves. The following points are evident:

(i) The flow frequency data approximated to Gumbel (1958) type 1 distributions (e.g. Figure 21), i.e. straight line fits were obtained in every case. By assuming straight line (type 1) distributions, a zero flow is obtained for each catchment. However, this interception point is generally at a return period of 200 years or more. It was considered that a

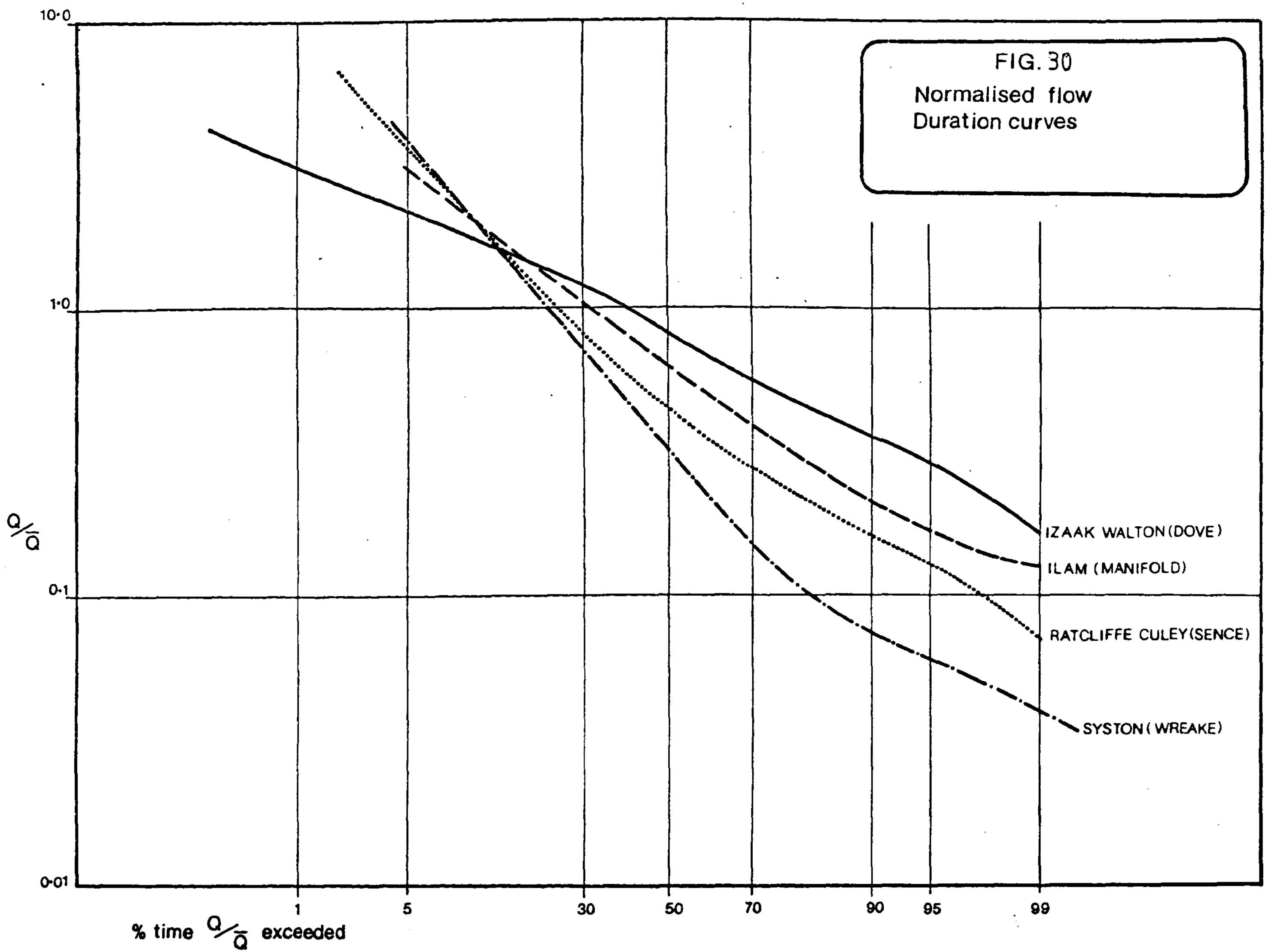
distribution covering 200 years provided sufficient hydrological information for most purposes and there was no need for more complex asympotic distributions.

(ii) Dry Weather Flow as defined in 5.2.1 is the average of the annual series of the minimum weekly (seven consecutive days) flows. Thus it is effectively the mean of the data set used to derive the frequency curves. As such Dry Weather Flow has a return period of 2.33 years. (Both statistically and analytically, see column 3 of Table 7.)

(iii) The return period of the 'minimum' seven day flows as determined from the distributions varied from 19 to 38 years, with an average of 23 years. These minimum flows were generally the lowest 7 day average flows recorded during the 1976 drought. This 'event' consistently fits the tails of the distributions even though this drought was known to be an exceptional event, in certain parts of Britain (Hamlin and Wright, 1978).

To further assess if the return period of the drought in the Trent basin was of the order of 23 years, the two longest flow records in the catchment that could be naturalised, were analysed. These were the Derwent at Yorkshire Bridge (50 year record) and the Churnet at Rocester (27 year record). Unfortunately both these records are liable to error. The catchment to Yorkshire Bridge is largely reservoired and flows require naturalisation using records of reservoir level, overflow, compensation and supply. In the case of Rocester the measurement structure is inadequate, particularly at high and low flows. Nevertheless the analysis was still considered worthwile. The distributions were plotted for record lengths increasing by ten and five years respectively (ie. for Yorkshire Bridge the 10, 20, 30, 40 and 50 year distributions and for Rocester the 5, 10, 15, 20 and

FIG. 30
Normalised flow
Duration curves



25 year distributions). This analysis showed that although 1976 is the most extreme event for a shorter record of, say, 10 years; over a longer record there are other events with smaller flows, notably 1959. The return period of the 1976 event is therefore reduced, in the case of Yorkshire Bridge to about 15 years for a 50 year record, and at Rocester, 12 years for a 27 year record.

This analysis shows that in the Trent basin the drought of 1976 was not very extreme and that short records can be used to assess the order of magnitude of its return period.

(iv) Flow frequency curves were also produced from the same 11 stations based on 14 consecutive day data. An example is given as Figure 29 (Volume 2). On average, the 14 day mean annual flows were 7.7% greater than the 7 day mean annual flows, and there was no improvement in the fit of the distributions of 14 day flows over those fitted to the 7 day flows.

(v) The curvature of the flow duration curves varied substantially from catchment to catchment (figures 25-28). All flow duration curves are asymmetrical as there are more days with flow below the mean than above, but catchment precipitation, morphology and geology also affect the shape of the curves. Figure 30 shows the influence of geology and morphology. The flow duration curves for Syston and Ratcliffe Culey (both clay and marl catchments) and Ilam and Izaak Walton (limestone and grit catchments) have been normalised (divided by mean daily flow) to remove the effect of catchment area, evapotranspiration and precipitation. The resulting differences in curvature are due to catchment morphology and geology. The catchments with an important groundwater component give flat curves whereas the clay and marl catchments exhibit steep curves.

5.5 THE ESTIMATION OF FLOW FREQUENCY CURVES FOR UNGAUGED CATCHMENTS

5.5.1 The analysis of flow frequency curves for gauged catchments (5.4.4) showed that Dry Weather Flow has a return period of 2.33 years. Thus Figure 19 is a map of 2.33 yield. As such, the map leads directly to one point on a probability (frequency) curve. Since the form of this relationship has been shown to be a straight line (property (ii), Section 5.4.4), all that is required to complete the distribution is the slope of that line.

The literature review undertaken in Section 4.3 has indicated that river flow, averaged over a period of years, in any catchment, is controlled by climatic factors, but the distribution of flow throughout a year is strongly influenced by drainage basin characteristics, including the geology. At times of lowest flows, when streams are totally composed of water from the ground, it may be that the distribution of these flows is wholly dependent on the nature of the solid geology.

Frequency distributions were constructed for 18 catchments using the method outlined in Section 5.4.3 (a list of stations used in the analysis is given in Appendix 5 and, station details are given in Appendix 1) . A standard period of 1968-80 (13 years) was used in every case and the data were naturalised according to the information given in Appendix 3. A stepwise linear regression analysis was undertaken to find an expression of the slope of frequency distributions.

The slope of the flow frequency line (QDIF), the dependent variable, was represented by the difference between the discharge per unit area of 2.33 year return period ($Q_{2.33}$) and the discharge per unit area of 20 year return period (Q_{20}) on the measured flow frequency lines. The value QDIF is thus a normalised representation of the slope of the frequency line.

TABLE 8

FLOW FREQUENCY CORRELATION MATRIX

	QDIF	DWFI	GEOL	SOIL	MAEP	ALT	STMFRQ	SLOPE	PERM
QDIF	1.0								
DWFI	0.9602	1.0							
GEOL	0.949	0.9082	1.0						
SOIL	-0.2735	-0.1883	-0.3194	1.0					
MAEP	0.5701	0.602	0.5229	0.1877	1.0				
ALT	0.64	0.6888	0.6072	0.2465	0.962	1.0			
STMRFQ	0.3175	0.392	0.3032	0.4644	0.7731	0.7644	1.0		
SLOPE	0.3867	0.3531	0.3060	0.4664	0.7293	0.7563	0.5694	1.0	
PERM	0.7864	0.7359	0.8054	-0.6346	0.2054	0.2672	-0.1355	-0.1057	1.0

Eight catchment indic es were considered as independent variables: Arbitrary geological scale (GEOL), permeability (PERM) and Dry Weather Flow yield X100 (DWFI) (all representing geology), winter rainfall acceptance potential (SOIL), altitude (ALT), catchment slope (SLOPE), stream frequency (STMF$\hat{Q}$) and mean annual effective precipitation (MAEP). (Each of these measures and indic es have been discussed in Chapters 3 and 4).

The first stage in regression analysis is to produce a correlation matrix of the independent variables. This is a pre-requisite as none of the independent variables should be highly correlated amongst themselves. Violation of this criterion can lead to unstable values for the regression coefficients, and to difficulties in interpreting the effectiveness of the independent variables included in the equation. Although a set of morphological, geological and climatological variables that are entirely independent of each other would be preferable, this is not possible because nearly all the characteristics exhibit some degree of interdependence.

Table 8 shows the correlation matrix of PERM, GEOL, STMFRQ, DWFI, SOIL, MAEP, ALT and SLOPE. The correlation matrix shows that GEOL and PERM, and GEOL and DWFI are, as expected, highly correlated. As DWFI had the highest correlation with the dependent variable (0.96), the other geological indices (PERM and GEOL) were omitted from the final stepwise regression. MAEP and ALT were also highly correlated. ALT was included in preference to MAEP. The index ALT highlighted the problem of interdependence. As well as being highly correlated with rainfall it was also moderately correlated with slope, stream frequency and geology. None of the other indices were correlated.

The prediction equation obtained from the regression analysis at the 95% significance level was:-

$$QDIF = 36.60\ DWFY + 1.6083 \quad (22)$$

(note: DWFI = DWFY x 100)

The R^2 value for equation 22 was 0.922. The regression program calculated that no other variables were significant. Thus as the Dry Weather Flow is related to catchment geology and the slope of the flow frequency line is related to Dry Weather Flow, catchment geology is the major influence on low river flows. If Dry Weather Flow yield maps can be constructed for an area, they will provide all the information that is required to estimate flow frequency curves within that area.

5.5.2 To estimate flow frequency curves for ungauged catchments within the Trent basin, the following method applies:

(i) Calculate Dry Weather Flow by multiplying the relevant runoff coefficient (DWFY) on Figure 19 by catchment area

(ii) This value is the 2.33 year flow and is plotted accordingly on Gumbel type probability paper.

(iii) Calculate QDIF using equation 22 and multiply by catchment area ÷ 100.

(iv) Subtract the value of QDIF x AREA from the value of the Dry Weather Flow and plot the total at probability 0.95 (20 years) on the Gumbel paper.

(v) Draw a straight line through the two points.

5.5.3 The low flow correlation matrix, Table 8, showed that DWFI and the Arbitrary Geological Index (GEOL) were correlated (0.908). Thus GEOL could be used in an equation to calculate Dry Weather Flow in areas without yield maps. A stepwise linear regression was undertaken to determine the exact form of the relationship, using DWFI as the dependent variable and

GEOL, STMRFQ, SOIL, MAEP and SLOPE as the independent variables.

The resulting equation at the 95% significance level was

$$DWFI = 12.888\ GEOL - 15.254 \quad (23)$$

$$(R^2 = 0.825)$$

$$DWF = (DWFI \times AREA) \div 100 \quad (24)$$

The regression program calculated no variables other than geology to be significant. Thus, although the value of R^2 is not particularly high and the constant is large, it is possible to estimate Dry Weather Flow for catchments without DWFY maps and thus extend the concept of Section 5.5.2 to areas outside the Trent basin.

5.5.4 Estimates of flow frequency curves were made for four flow measurement sites within the Trent basin using the method outlined in Section 5.5.2. The catchments chosen had not been used in any way to derive the regression equations 22 or 23. The areas of these catchments varied from 37 km^2 to 129 km^2, and their geological type ranged from Lias (Clays) to mixed lithologies of Dinantian (Carboniferous Limestones) and Namurian (Millstone Grit). In each case the record length was shorter than had been used in the analysis (6 to 9 years). The curves were then compared with measured data for the same catchments.

The method described in Secton 5.5.3, by which Dry Weather Flow could be estimated from geology, was also tested against measured data from the same four sites. Estimates were also made for two catchments located in the Yorkshire Water Authority area (the Snaizeholme Beck to Low Houses, NGR SD 832 883 and the River Derwent to Buttercrambe, NGR SE 731 587). These catchments provided a stringent test of the method of estimation as they represented a small catchment (10 km^2) of a single geology (Dinantian (Carboniferous Limestone)) and a large catchment (1600 km^2) of very mixed geology.

COMPARISON OF FLOW
FREQUENCY CURVES – BLABY

FIG. 31

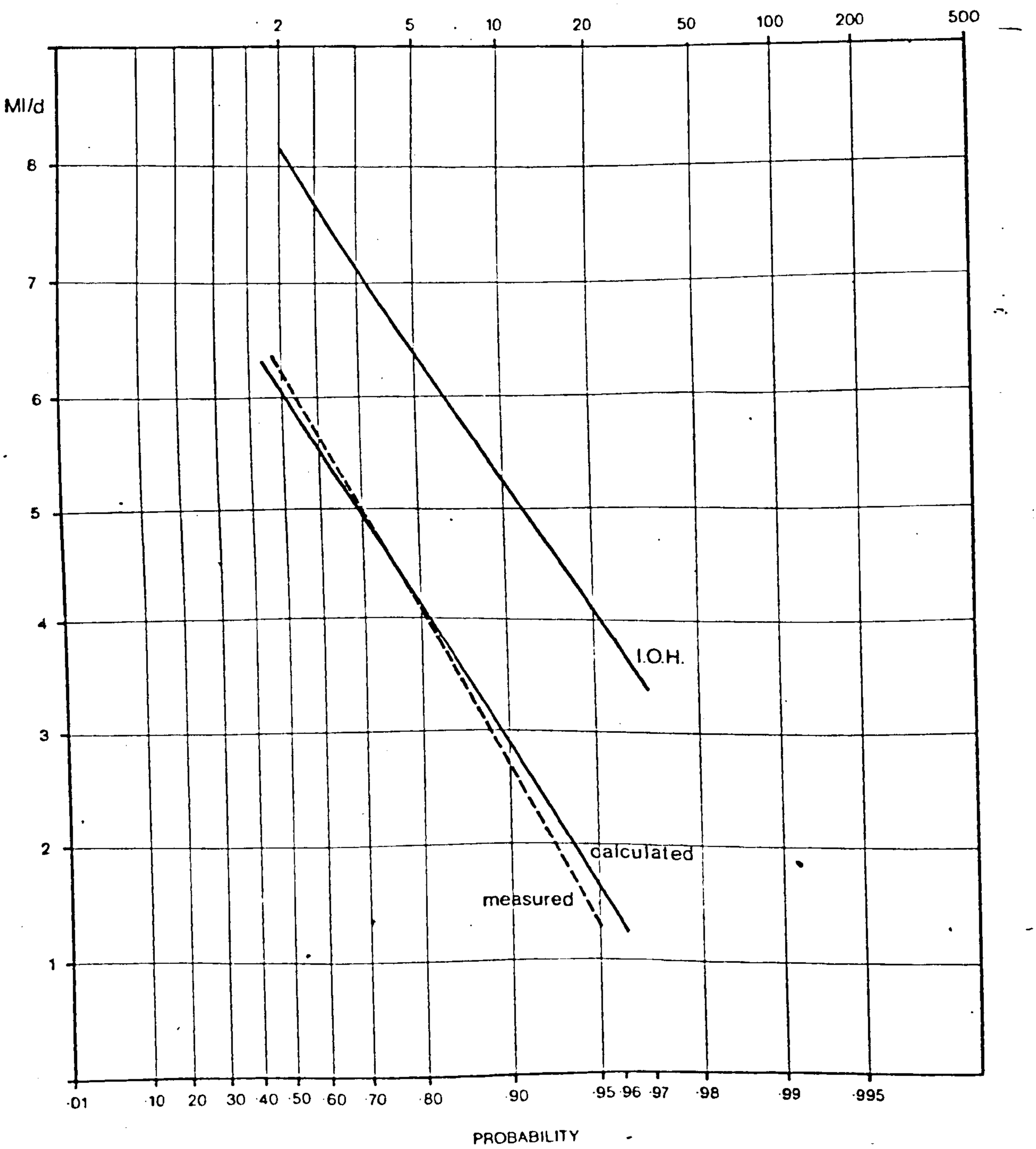


TABLE 9

RESULTS - FLOW FREQUENCY

RIVER	STATION	DWF ESTIMATE	DWF MAP METHOD		IOH METHOD		MEASURED DATA	
			DWF	Q_{20}	DWF	Q_{20}	DWF	Q_{20}
R. SENCE	BLABY	5.3	5.9	1.7	8.0	4.1	6.0	1.5
HENMORE BK	ASHBOURNE	10.8	5.7	3.0	7.8	4.5	5.5	2.9
ROTHLEY BK	ROTHLEY	4.5	7.5	3.1	1.6	0.7	7.5	1.8
R.ECCLESBOURNE	DUFFIELD	11.8	10.2	5.7	6.4	3.4	10.3	4.9
SNAIZEHOLME BK	LOW HOUSES	5.0	-	-	9.0	-	2.2	-
R. DERWENT	BUTTERCRAMBE	492.3	-	-	427.4	-	384.7	-

The calculated and measured flow frequency curves are shown in Figures 31 to 34. (Figure 31 is included within the text).The results are summarised in Table 9. There is good agreement between the measured flow frequency curves and those constructed by the method outlined in 5.5.2. This is particularly true of the estimates for Blaby and Ashbourne where the errors in the estimate of the mean annual low flow, and the 20 year low flow are 2% and 13% and 4% and 3% respectively. However the use of equations 23 and 24 to estimate Dry Weather Flow from geological maps gave estimates of variable accuracy. Some estimates are reasonable, Blaby (-11%) and Duffield (+14%) whereas others are poor, Snaizeholme Beck (+127%). The method given in 5.5.3 suffers from the same drawbacks as all other methods which include indirect measures of geology. Whilst rocks may have a general hydrology, local structural or lithological effects may greatly effect the yield. This problem is assumed to have affected the calculations for Snaizeholme Beck. The catchment is 100% Dinantian (Carboniferous Limestone) for which the regression equation suggests a DWFY of 0.5 Mld/km yet the measured DWFY is 0.22 Mld/km^2. This runoff yield is very much lower than for the other Dinantian (Carboniferous Limestone) catchments analysed. The yield is most probably affected by local structural or lithological effects.

5.5.5 Section 2.2.2 has shown that the most comprehensive analysis of low flows in British catchments is the 'Low Flow Study' (Institute of Hydrology, 1980). Report 2.2 of that publication outlines a method by which flow frequency curves, and hence the 2.33 year 7 day flow (Dry Weather Flow), can be estimated for ungauged catchments. These methods were applied to the same catchments as discussed in the previous section. An example of the 'Low Flow Study' computational procedure is given in Appendix 6. The results are also given in Table 9 and Figures 31 to 34. The estimates of flows obtained using the 'Low Flow Study' method are inferior to those derived in 5.5.4 with errors in the estimate of $Q_{2.33}$

(Dry Weather Flow) of up to 310%, and in the estimate of Q_{20} of up to 173%.

5.5.6 The combination of Dry Weather Flow Yield maps and the regression equation 22 (5.5.1) provides a reliable method of estimating flow frequency curves for ungauged catchments. The method is more accurate for all the sites examined, than that advocated in the Institute of Hydrology's 'Low Flow Study'. The major advantage of the Dry Weather Flow method is that it includes a direct integration of the effects of geology and surface deposits within a catchment, whereas most alternative methods of estimating flow frequency curves include only indirect geological indices. Indirect measures at these very low flows, may work in some cases, as indicated by the use of equations 23 and 24 (5.5.3), but can be unreliable in other cases due to local lithological and structural effects.

5.6 THE ESTIMATION OF FLOW DURATION CURVES FOR UNGAUGED CATCHMENTS

5.6.1 Section 5.4.4 has shown that the degree of curvature exhibited by flow duration curves is related to catchment climate, geology and morphology. If flow duration curves are to be estimated for ungauged catchments, then an expression of this curvature has to be found in terms of measureable catchment indic es.

5.6.2 Flow duration curves were constructed from measured flow data for 25 catchments. (A list of stations used are given in Appendix 5, and station details are given in Appendix 1). Fifty percent of the data were from the Trent Basin and 50% from the neighbouring Severn catchment. (Data from the Severn being introduced to improve the quality of the analysis). The curves were constructed according to the method outlined in Section 5.4.2. A standard period of 11 years (1970-80) was used in every case and where necessary the records were naturalised using data from Appendix 3.

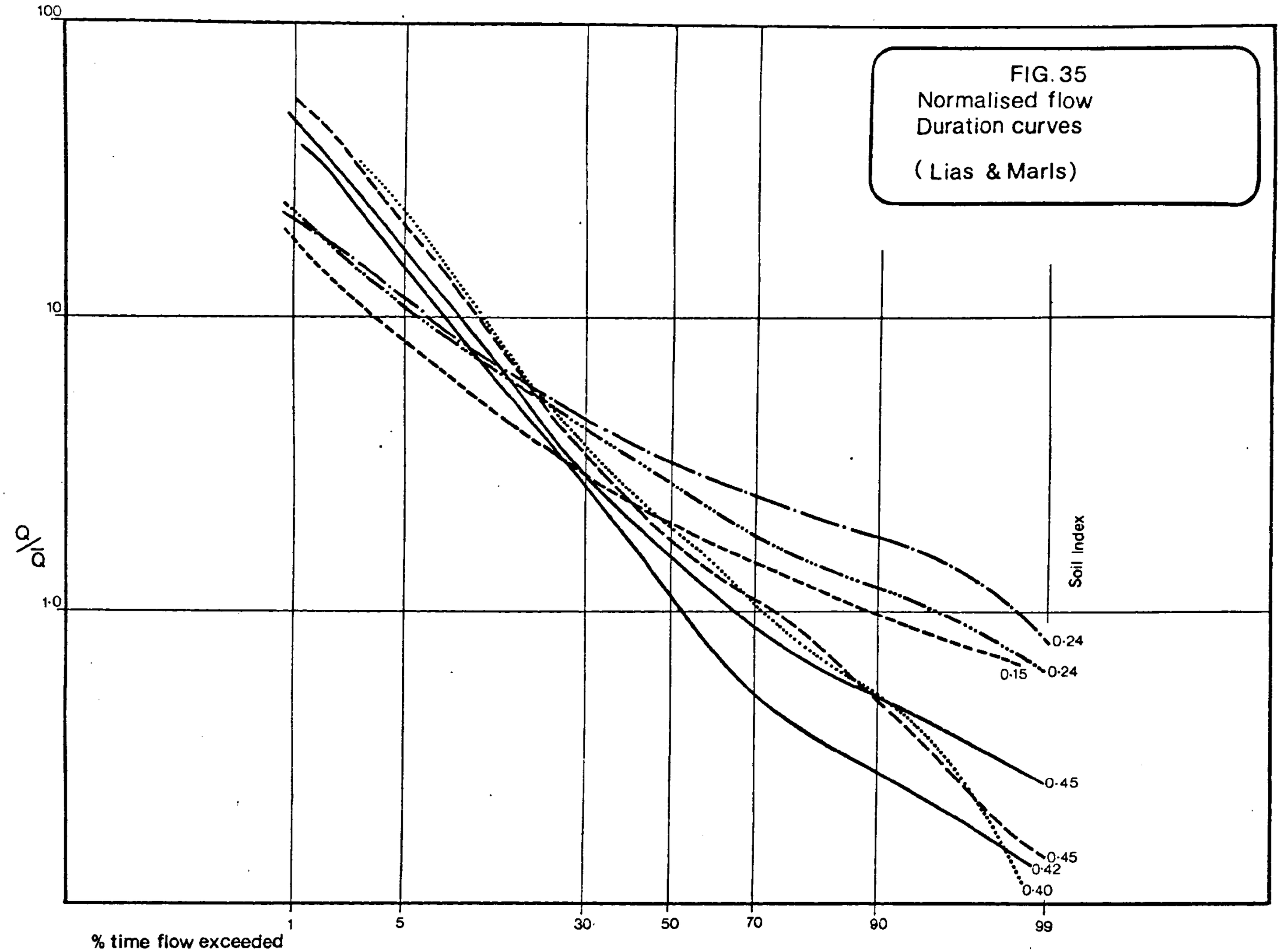
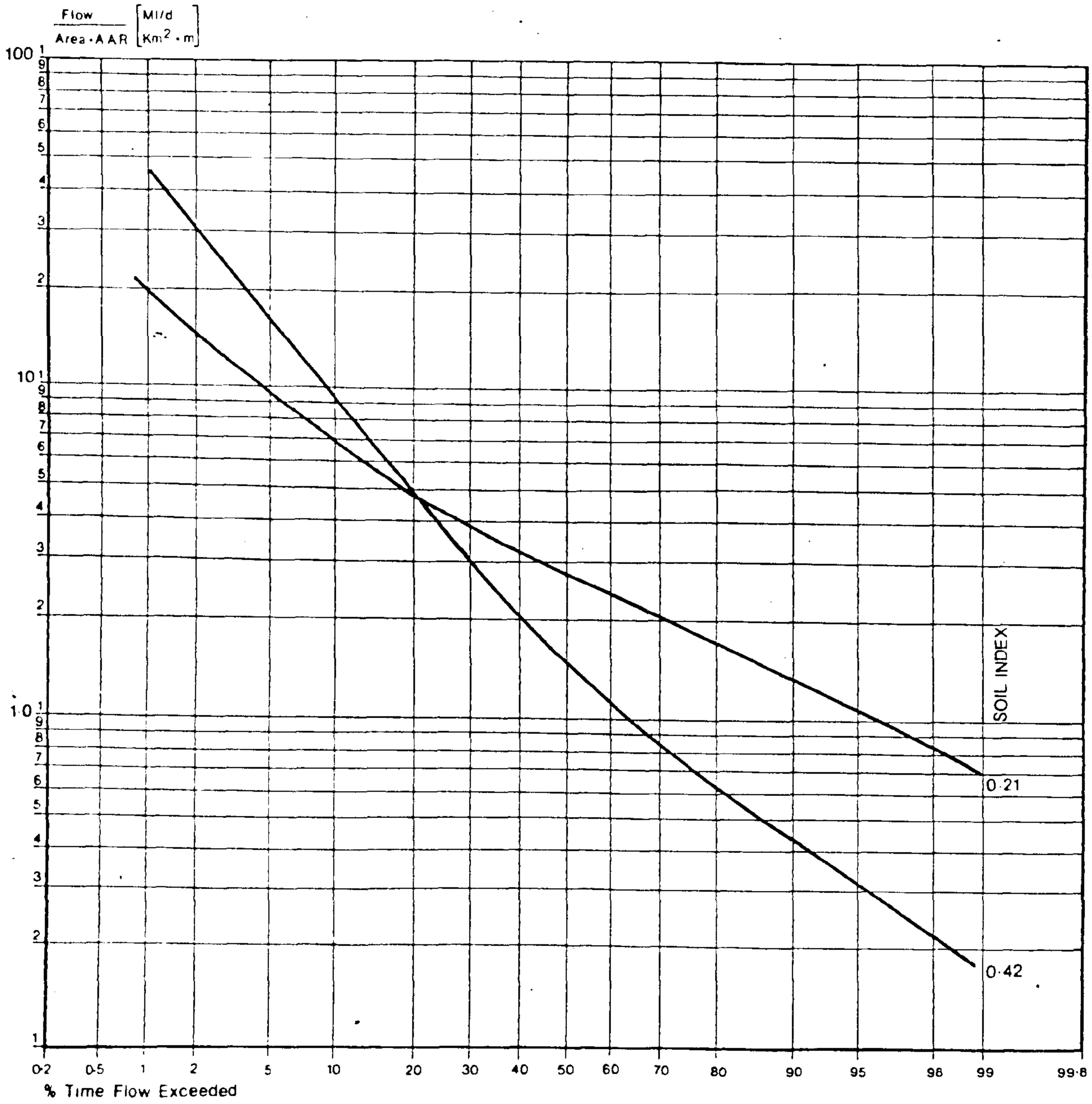


FIG. 35
Normalised flow
Duration curves
(Lias & Marls)
100
10
1·0
Q/Q̄
Soil Index
0·24
0·15
0·24
0·45
0·45
0·42
0·40
1
5
30
50
70
90
99
% time flow exceeded

Normalised Base Curve
Lias & Keuper Marl

FIG.37



To allow direct comparison of the curves obtained for each catchment, normalisation of the records is required. Normalisation of gauged data is usually achieved by dividing observed flows by the mean annual average flow thus accounting for variations in catchment size and precipitation. However, for a technique that is specifically applicable to ungauged catchments, an alternative normalisation factor is required. Section 3.4.3 showed that catchment adjusted annual effective precipitation derived from Figure 7 is a suitable replacement for mean annual flow in the normalisation procedure.

The 25 sets of flow duration data were normalised using catchment adjusted annual effective precipitation. The resulting curves were plotted on logarithmic probability paper (eg. Figure 30, Section 5.4.4). In this normalised form the upper portions of the duration curves could be approximated by straight lines, but the low flow sections (>70% time exceeded) showed variable degrees of curvature. Therefore the data set did not readily lend itself to a regression analysis of the type described in Section 5.5.1 (flow frequency procedures).

To further the analysis, the normalised curves were plotted in groups according to catchment geology (Figure 35, is an example for, Lias and Marl catchments). For each geological type there was a resulting family of curves indicating that factors other than effective precipitation, area and solid geology affect the shape of flow duration curves. However, when the calculated winter rainfall acceptance potential (soil index) for each catchment was considered in relation to the curves, a semblance of order was evident in each geological group. High values of winter rainfall acceptance potential were associated with steep curves whilst low values were associated with flat curves. Using this property it was possible to mean and smooth the 25 normalised curves (Figures 36 to 40, Figure 37 (included in the text) relates to Figure 35). Thus, averaged over a period of years effective precipitation, area, geology and soil are the four dominant

factors effecting the quantity and distribution of flow from a catchment. If maps of effective precipitation, geology and soil can be produced for any area, then figures 36 to 40 can be used to estimate flow duration curves for ungauged areas.

5.6.4 To estimate flow duration curves for ungauged catchments the analytical procedures described in 5.6.3 are reversed. The following method applies:

i Measure catchment area to the site in question (km^2) on an ordnance survey map (1:25000).

ii Calculate mean annual effective rainfall (m) from Figure 7. Figure 3, the transparent overlay is useful for this and the next two stages.

iii Define geological type from Figure 4.

iv Calculate the soil index using Figure 9 and Equation 20.

v Select the appropriate master curve from Figures 36 - 40.

vi Multiply a number of selected points on the curve by mean annual effective precipitation and by catchment area to give a naturalised flow duration curve.

vii Adjust for any artificial effects.

5.6.5 To assess the reliability of the method of estimating flow duration data outlined in 5.6.4, curves were estimated for a number of catchments with permanent flow measurement stations and the estimates compared with gauged data. As all the long standing good quality flow records within the Severn-Trent Water Authority area had already been assimilated into the study, data were used from neighbouring Authorities. In all, data from five sites were provided by the Yorkshire and North West Water Authorities. Each curve presented by these

TABLE 10

RESULTS - FLOW DURATION

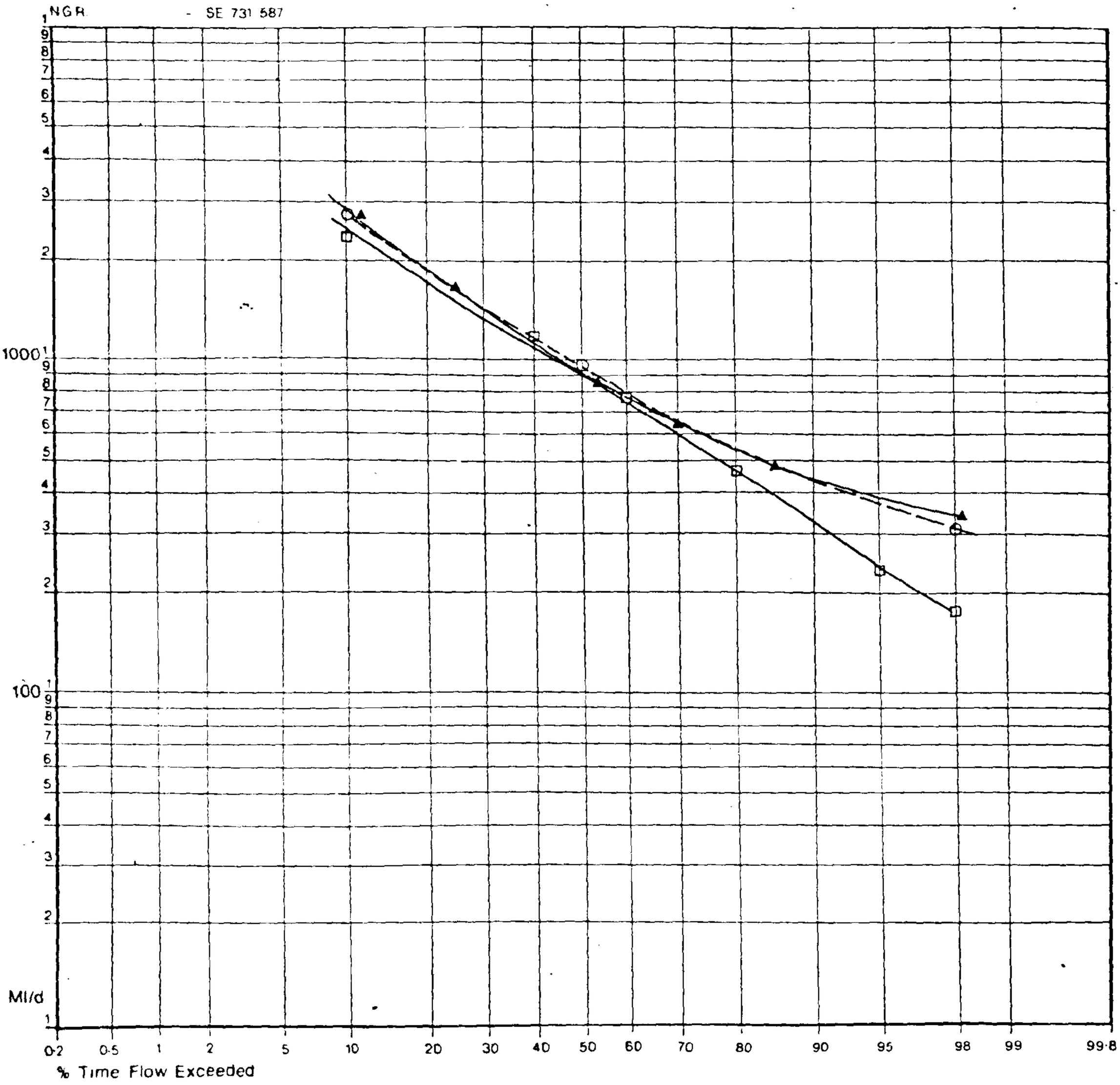
Station	Reference Percentile	% Difference between measured flows and calculated flows	
		Method as outlined in Section 5.6.4	I.O.H. Low Flow Study Method
Kildwick	91%	+58	+104
	50%	+27	+59
Buttercrambe	91%	+2	-26
	50%	-2	-4
Low Houses	91%	+17	+74
	50%	0	+35
Kilgram	91%	+12	+37
	50%	+5	+15
Garstang	91%	0	+43
	50%	+25	+33

In this comparison the reference levels of 91% & 50% were chosen to represent the approximate D.W.F. and median flow.

COMPARISON OF METHODS
R. Derwent
Buttercrambe (Y.W.A.)
FIG.41

Section 5
Measured
IOH

Catchment Area - 1586 km^2
Measurement Type - Crump Weir
Catchment Geology - Mixed (Corallian Limestone, Shales, Clay & Gravels)
NGR - SE 731 587



Authorities was for a basically natural catchment. The largest catchment used was the River Derwent (Yorkshire) at Buttercrambe (NGR, SE 731 587) with an area of 1600 km^2 and a very mixed geology and the smallest the Snaizeholme Beck (to NGR, SD 832 883) with an area of 10 km^2 and a uniform geology. The results of the comparison are shown in Figures 41 to 45 and are summarised in Table 10 (Figure 41 is included in the text). All relevant station details are given on the figures. There is a good agreement between estimated and observed curves. The mean error of estimate at the 90 and 50 percentile levels were 18% and 11% respectively. For Buttercrambe, Low Houses and Kilgram, the mean errors at these reference levels were much less, being only 2%, 8% and 9% respectively. These results are particularly pleasing when it is considered that the technique was tested for locations outside the area for which it was derived.

5.6.6 Flow duration curves were also estimated for the same six catchments using the 'Low Flow Study', Report 2.1, Flow Duration Procedures (IOH, 1980). These results are also summarised in Table 10 and Figures 41 to 45. There is poor agreement between measured and estimated curves using this method. The mean error of estimate at the 90 and 50 percentile levels are 57% and 29% respectively and in the case of Kildwick, the errors were 104% and 59% at these reference levels. Only the estimates for Buttercrambe (26% and 4%) were acceptable using this method.

As was the case in flow frequency estimation (Section 5.5.5), the method advocated in this report for the estimation of flow duration curves for ungauged catchments is superior to the equivalent method in the 'Low Flow Study' for application in the Trent Basin. The large errors obtained using the 'Low Flow Study' method, particularly at very low flows, may be because the Institute of Hydrology approximated flow duration curves by straight lines to facilitate regression analysis. Alternatively, the simple graphical approach advocated herein, by maintaining the observed curvature, may be more

applicable to this type of distribution. This conclusion is similar to one reached by Searcy (1959, page 31) "A synthetic duration curve based on an estimated variability index and an estimated median flow may be accurate for the portion of the flow-duration curve that plots as a straight line on log-probability paper" but "The end points of the flow-duration curve cannot be accurately determined from the slope of the straight portion of the flow-duration curve."

5.7 CONCLUSIONS

Sections 5.3.1, 5.3.10, 5.5.2 and 5.6.4 have described four methods by which flow information can be estimated for ungauged catchments. These are Residual Flow Diagrams, Dry Weather Flow Yields Maps, Flow Frequency Curves and Flow Duration Curves. The methods have been shown to be superior to the Institute of Hydrology 'Low Flow Study' (1980) for application in the Trent catchment, the area for which they are primarily intended, and a limited number of other catchments in the north of England.

It is considered that the methods make optimum use of all river flow data which are collected at discrete and regular intervals by regional water authorities. The derivation of residual flow diagrams and the Dry Weather Flow yield map are particularly useful as they provide both a method of low flow estimation and an integration of regional geology. Most water authorities have sufficient flow information to derive similar diagrams and maps for many more areas and hence remove the need for empirical low flow estimation equations and inaccurate indic es of geology.

6 THE SIMULATION OF CATCHMENT RESPONSE TO RAINFALL

6.1 INTRODUCTION

Section 2.3 has shown that there is a requirement for a simple catchment model that will predict and/or forecast the response to rainfall in ungauged catchments. The theoretical and practical difficulties of applying unit hydrograph models in ungauged areas have been outlined in sections 2.3.4 and 2.3.5 and the case for an alternative strategy, conceptual modelling, has been made in section 2.3.6. The following sections describe the development of such a model for application in the Trent basin.

6.2 CONCEPTUAL MODELS

6.2.1 A model is a simplified representation of a complex system. Mathematical models represent the behaviour of systems using sets of equations, and possibly logical statements, which express the relationships between variables and parameters. A variable is a measurable characteristic of a system which assumes different numerical values when measured at different times; a parameter is a quantity characterising a hydrological system, and which remains constant in time.

6.2.2 The process linking rainfall and river flow is deterministic, in that it is governed by definite physical laws. The ideal model would specify completely the properties of, and the processes that occur in all the relevant components of a catchment. Present knowledge does not permit all the properties and processes to be completely represented mathematically. Nevertheless, the fact that a basin is not a random assembly of different parts, but a geomorphological system whose parts are related to each other by a long common history, has encouraged the hope that simplified conceptual models may be developed which adequately describe the process of converting rainfall to runoff in a basin. If, in addition, the relation between this process and the physical

FIG. 46
Schematic representation of the general catchment model

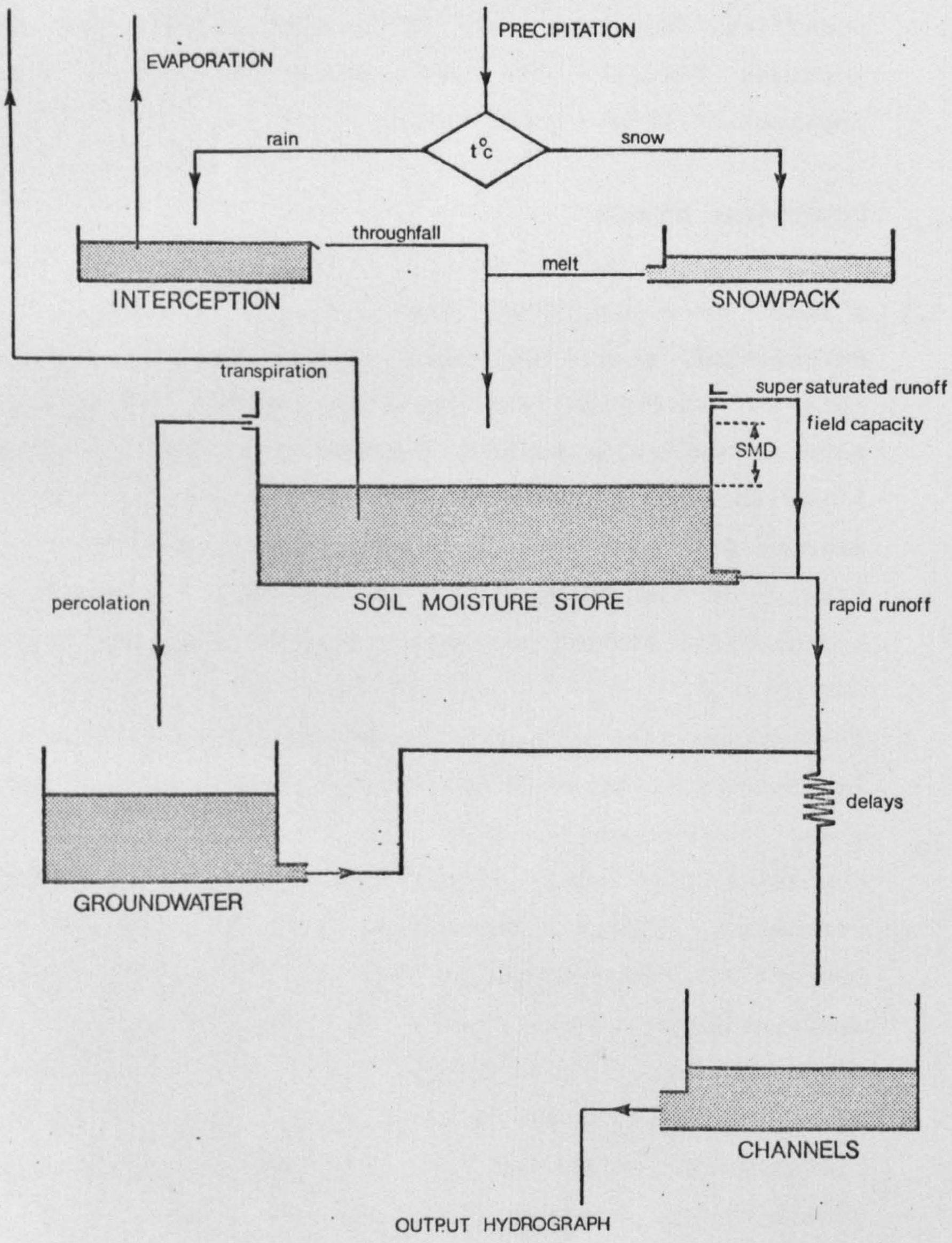


TABLE 11

RAINFALL RUNOFF MODEL PARAMETERS

PCIN	Capacity of interception storage
PSRC	Runoff percentage at zero SMD
PSRS	Exponential decay rate in ROP/SMD function
PRPM	Nominal maximum runoff percentage
PSST	SMD at which ROP reaches maximum value
PMPC	Max, percolation rate
PDRF	Supersaturated catchment drainage factor
PDRX	Supersaturated catchment drainage exponent
PGWF	Groundwater reservoir factor
PLAG	Time delay before initial hydrograph rise
PDUR	Duration of hydrograph response
PIEF	Interception store evaporation factor
PETF	Potential transpiration factor
PSET	Max. SMD for unrestricted transpiration
PDET	SMD above which transpiration at minimum
PETM	Min. transpiration factor
PCIF	In-bank channel routing factor
PCIX	In-bank channel routing exponent
PCOF	Out-of-bank channel routing factor
PCOX	Out-of-bank channel routing exponent
PCBF	Channel bank-full capacity

features of the catchment can be recognised, then the operation of ungauged catchments might be forecast from a study of these features.

6.2.3 It is the explicit soil moisture accounting function of some conceptual models that many believe to be their strongest asset. Sittner (1976, page 208), summarising a World Meteorological Office intercomparison of forecasting models, states "Explicit soil mositure accounting models are worthwhile if the user is obliged to work in any area other than one which is continuously humid" (their) "Superiority may be noted during and immediately after a long dry spell." There is also a belief (Manley et al, 1980) that non linear conceptual models, because of their hydrological reality, offer the best hope for forecasting extreme floods, and in particular flows greater than those to which the model has been fitted.

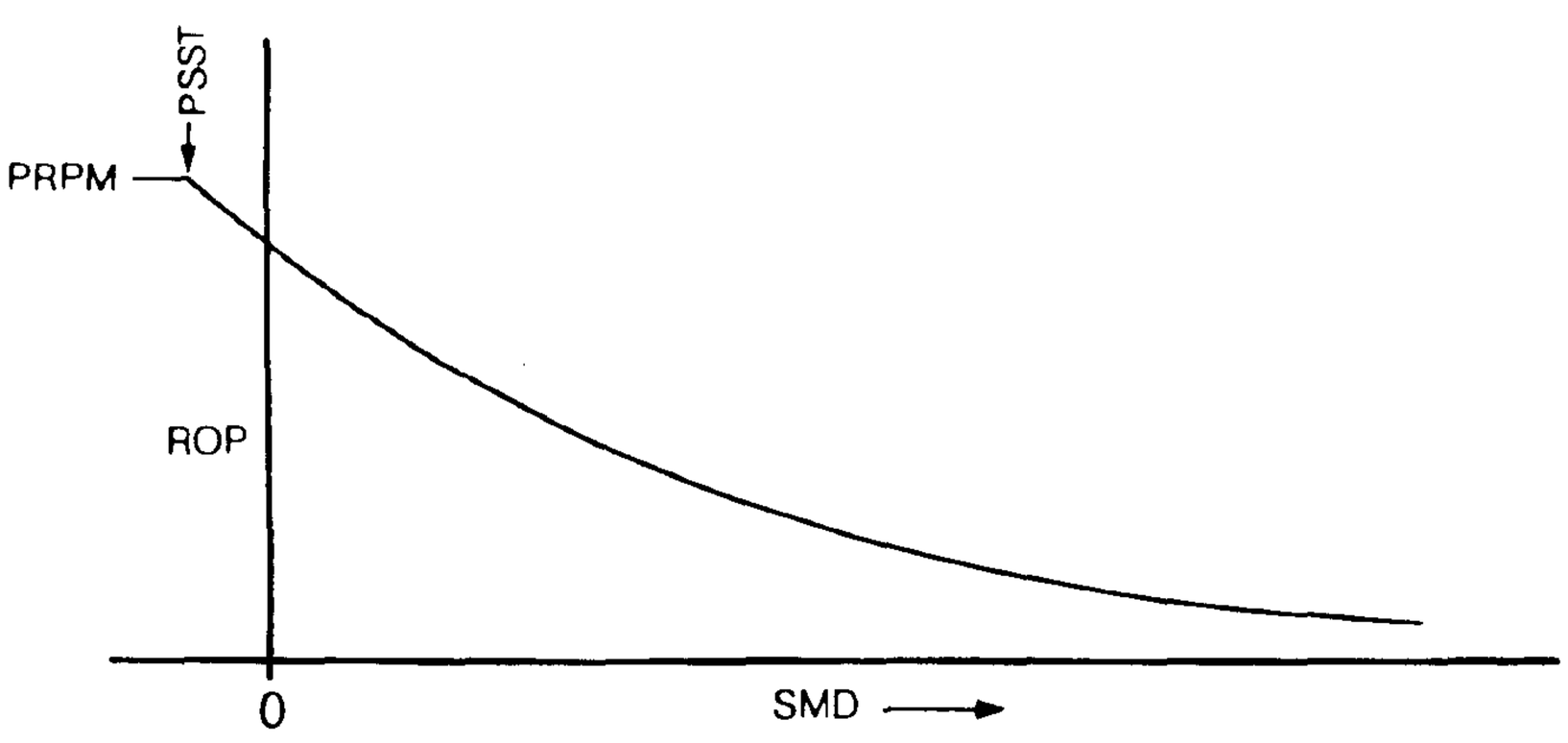
6.3 A GENERAL CATCHMENT CONCEPTUAL RAINFALL - RUNOFF MODEL

6.3.1 The approach chosen to produce a rainfall - runoff model for application in ungauged catchments was not to derive a completely new model; there are a large number of existing models covering a wide range of approaches, Nash and Sutcliffe (1970), Douglas (1974), Manley (1978); but to adapt an existing proven model for the ungauged case.

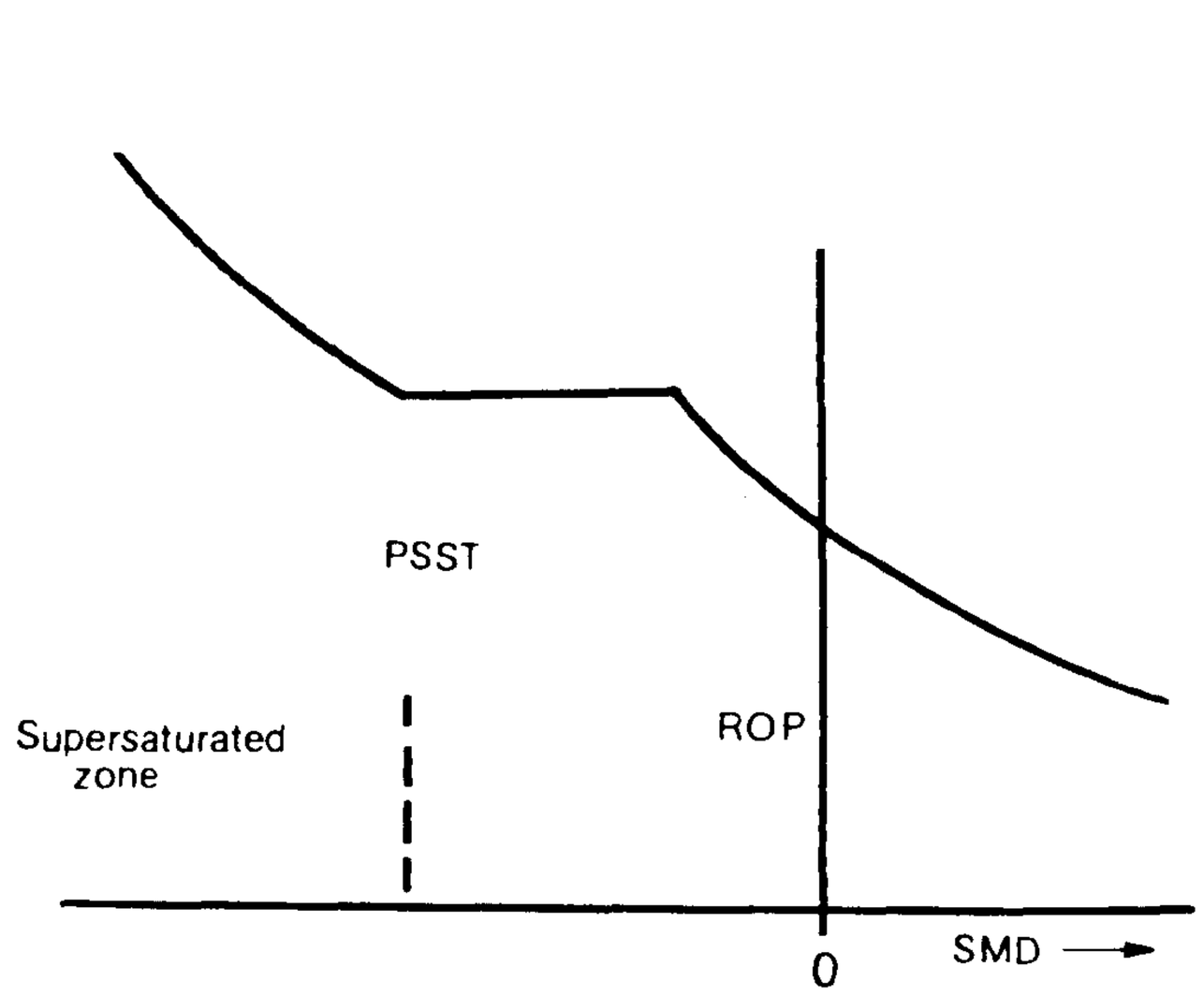
6.3.2 The rainfall runoff model selected for analysis and fitting was developed at the Institute of Hydrology (Dickenson and Douglas, 1972; Douglas, 1974) and amended in operational use at the Northumbrian and Severn Trent Water Authorities. The model is shown schematically in figure 46 and a computer listing of the computational sections of the model is given in appendix 7. It comprises of 27 parameters (table 11) split between five storage elements: interception, snow pack, soil moisture, groundwater and channel routing (this study is only concerned with rainfall-runoff, and neither snowpack nor snowmelt are given further consideration, the six snowmelt parameters are not therefore included in table 11).

FIG. 47

Functional relationships within the soil moisture component of the rainfall – runoff model

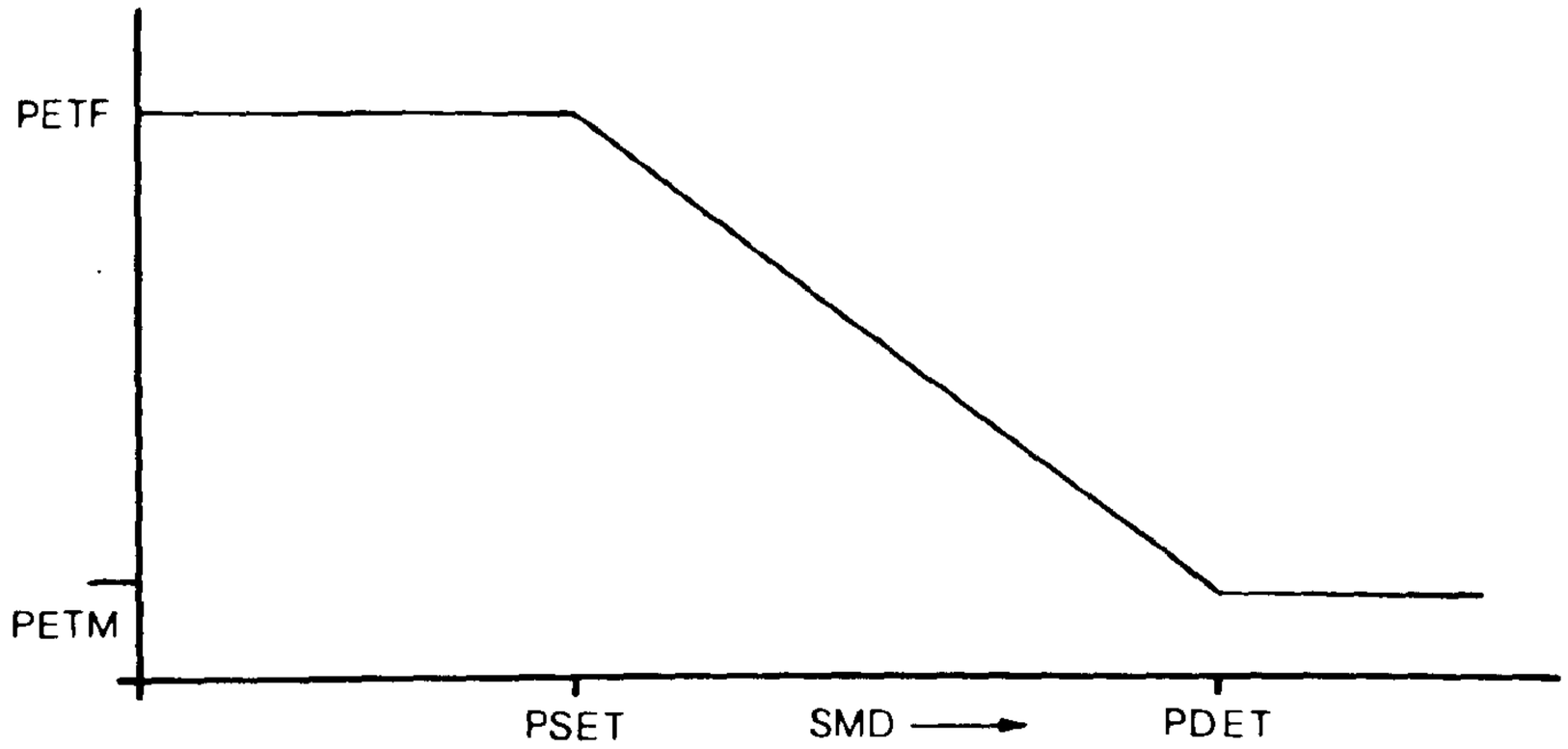


(a) Loss to streamflow

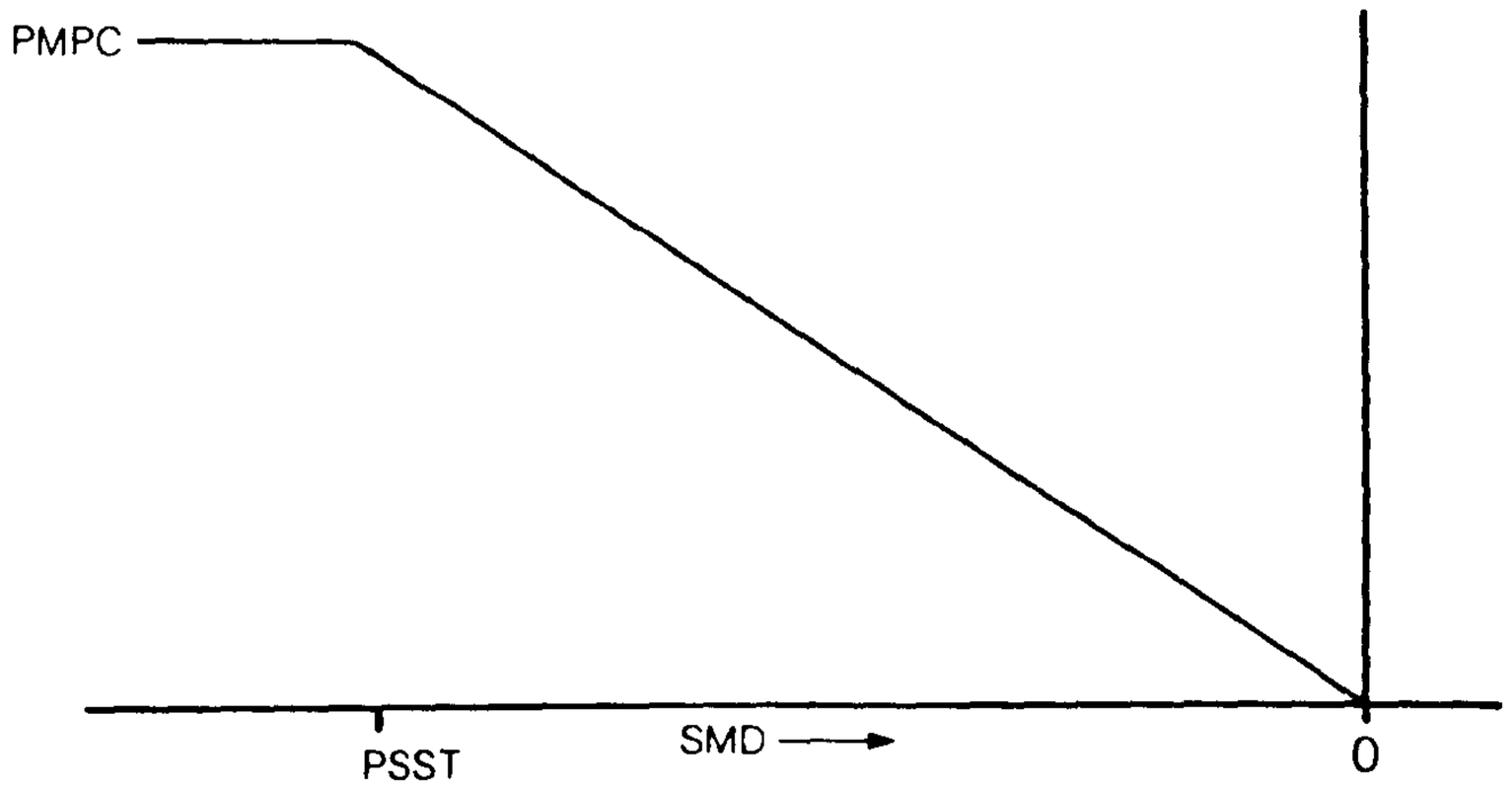


(b) Supersaturated loss

Fig.47(continued)



(c) Loss to transpiration



(d) Loss to groundwater

The model functions according to the following general principles (the actual functions are highlighted on the computer listing (appendix 7)):

Interception store:

This is a shallow storage element, with capacity PCIN, into which all rain falls. Only when the store is full, does any incoming rain overflow into the soil moisture store as net rainfall. Water is lost from interception storage by evaporation. Any evaporative demand remaining when the storage has been emptied is passed on to the soil moisture storage.

Soil Moisture Store:

The soil moisture store is the hub of the model. It accepts net rainfall (and snowmelt) as inputs, against which it balances losses to transpiration, streamflow and percolation to groundwater. The rates of these losses are related to the existing contents of the store. The functional relationships are shown in Figure 47.

The most important output from the store is to the river channel. This is considered to be a function of both the existing contents of the store and the net rainfall input, such that outflow is given as:

$$\text{Outflow} = \text{ROP} \times \text{NET RAIN} \qquad (25a)$$

ROP is a function of the soil moisture deficit and two parameters (PSRC and PSRS) (Figure 47(a)).

$$\text{ROP} = \text{PSRC}\ e^{-\text{SMD PSRS}} \qquad (25b)$$

Input which is not immediately lost to outflow reduces the deficit.

Goodhew (1970) suggested that SMD was not a good indicator of potential flood risk in winter because it was always close to zero. This problem is circumvented as the model allows SMD to become negative after the soil reaches field capacity, and thus the runoff percentage continues to increase (Figure 47(a)). If the SMD becomes a large negative number, that is, the catchment is "very wet" (> PSST), then further enhanced runoff occurs to the stream at a rate controlled by PDRF and PDRX, the supersaturated drainage factor and exponent. (Figure 47 (b).

$$ROP = PDRF\ e^{-SMD\ PDRX} \qquad (25c)$$

Transpiration, or water used by vegetation, is also taken into account in the soil moisture store. This takes place at a rate controlled by the residual evaporative demand and the current moisture deficit. The relationship is shown in figure 47(c)). The fourth outflow from the soil moisture storage is deep percolation to groundwater storage. This occurs at a rate which is also related to soil moisture storage. Percolation begins at zero SMD increasing to a maximum at PSST (Figure 47(d)).

Groundwater store:

The groundwater store receives water by percolation from the soil store. The only loss from the store is as baseflow to the stream, at a rate which is a function of the contents of the groundwater store and the rate of inflow.

$$\text{Outflow} = \frac{\text{Groundwater Store Vol}}{\text{PGWF}}^{1.5} \qquad (26)$$

Delays:

The total output from the soil and groundwater reservoirs is delayed by a time shift, PLAG and the time base of the hydrograph is adjusted by a parameter, PDUR. The flow then enters a channel routing reservoir.

Channel Routing reservoir:

This is conceived as a non-linear reservoir from which output (Q) is related to the reservoir contents (S).

$$Q = PCIF \quad S^{PCIX} \tag{27a}$$

No losses are allowed from the reservoir but if the flow ordinate is greater than the bankfull capacity (PCBF) a further non linear routing reservoir becomes effective.

$$Q = PCOF \quad S^{PCOX} \tag{27b}$$

Inbank and out-of-bank routed flow are combined to give total catchment outflow.

6.4 FITTING RAINFALL - RUNOFF MODELS TO MEASURED FLOW DATA

6.4.1 To particularise the model described in section 6.3.2, or in fact any model, to any catchment, the terms of the model must be made specific to that catchment. This is done by assigning numerical values to the parameters that control the operation of the model (and which are assumed to be catchment dependent) such that the simulated outputs match the performance of the given catchment. Tests are then made using measured input and output data to assess if the optimum parameters have been chosen.

Testing (fitting) of this type requires an index of agreement or disagreement between observed and computed discharges. The form of the objective criterion chosen will affect the values of the fitted parameters, because each measure of fit places a different emphasis on the difference between measured and calculated runoff values.

Linear regression analysis suggests a sum of squares criterion such as:

$$F^2 = \sum_{i=1}^{n} (q_i - q_i^1)^2 \tag{28}$$

where F^2 is the index of disagreement and q and q^1 are the observed and computed discharges at corresponding times. The sum is taken over all q's at intervals Δt. F^2 is analogous to the residual variance of a regression analysis.

A feature of this index is that it places greater emphasis on individual large errors than on a series of relatively small ones. This is useful if the model is required to predict flood flows, but may be undesirable if, for example, it is to be used only to predict baseflow in a groundwater-fed stream. The magnitude of the model error, F^2, is, in itself, not a complete statement of error. Its magnitude is dependent not only on the goodness of fit of the model, but also on the magnitude and variation of the observed output data. Nevertheless, the smaller value of F^2 derived from two different runs on an identical data set, indicates the better fit. To express the error estimate in a form allowing comparison between different data sets, the error can be reconsidered in relation to the proportion of the initial variance accounted for by the model.

Initial variance, F_o^2 is:

$$F_o^2 = \sum_{i=1}^{n} (q_i - \bar{q})^2 \qquad (29)$$

where $\bar{q}$ is the mean of the observed q's.

As F^2 is the final variance, R^2, the efficiency of the model is:

$$R^2 = \frac{F_o^2 - F^2}{F_o^2} \qquad (30)$$

FIG. 48

The optimum value of one parameter

(after Douglas, 1974)

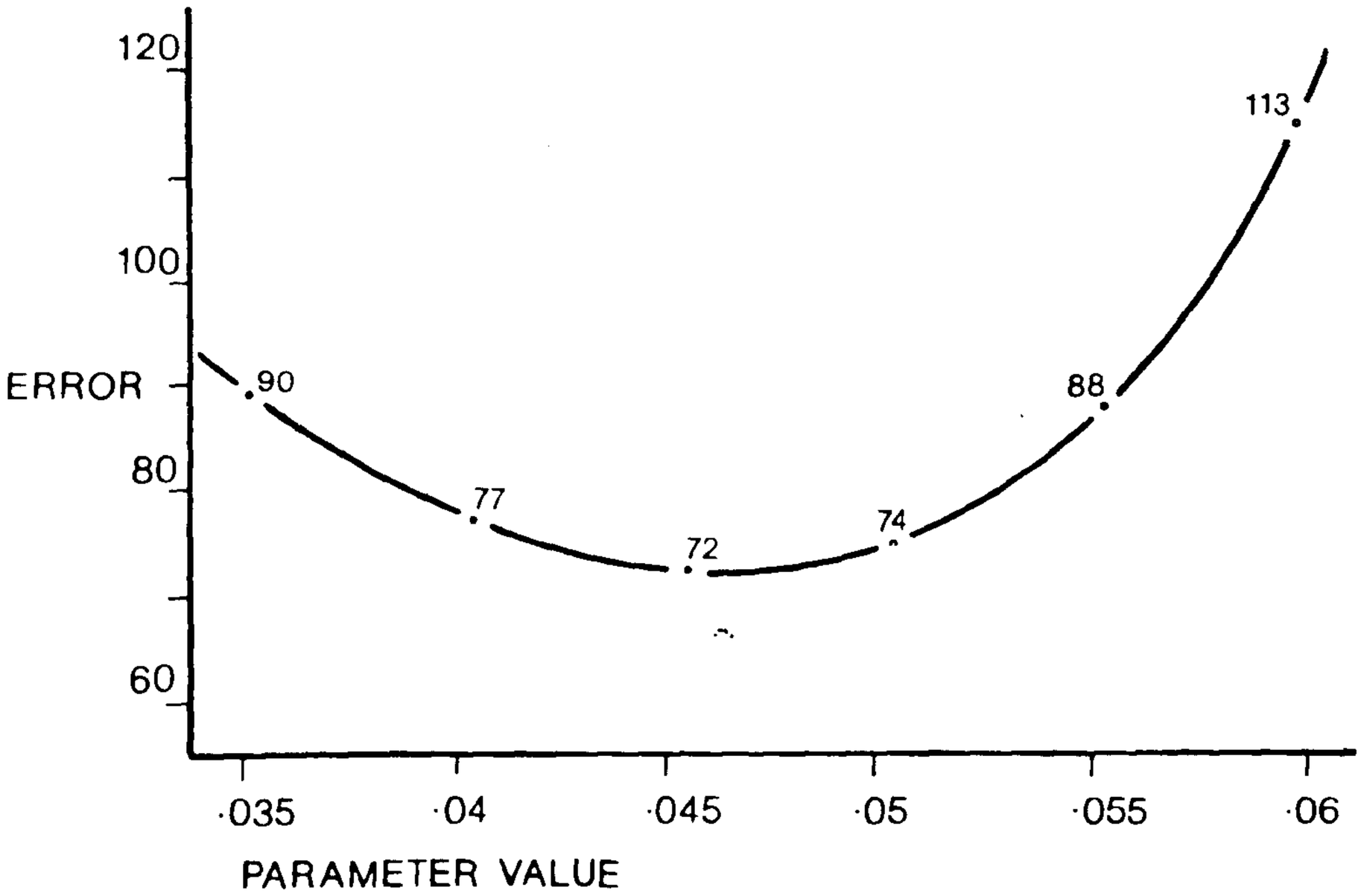
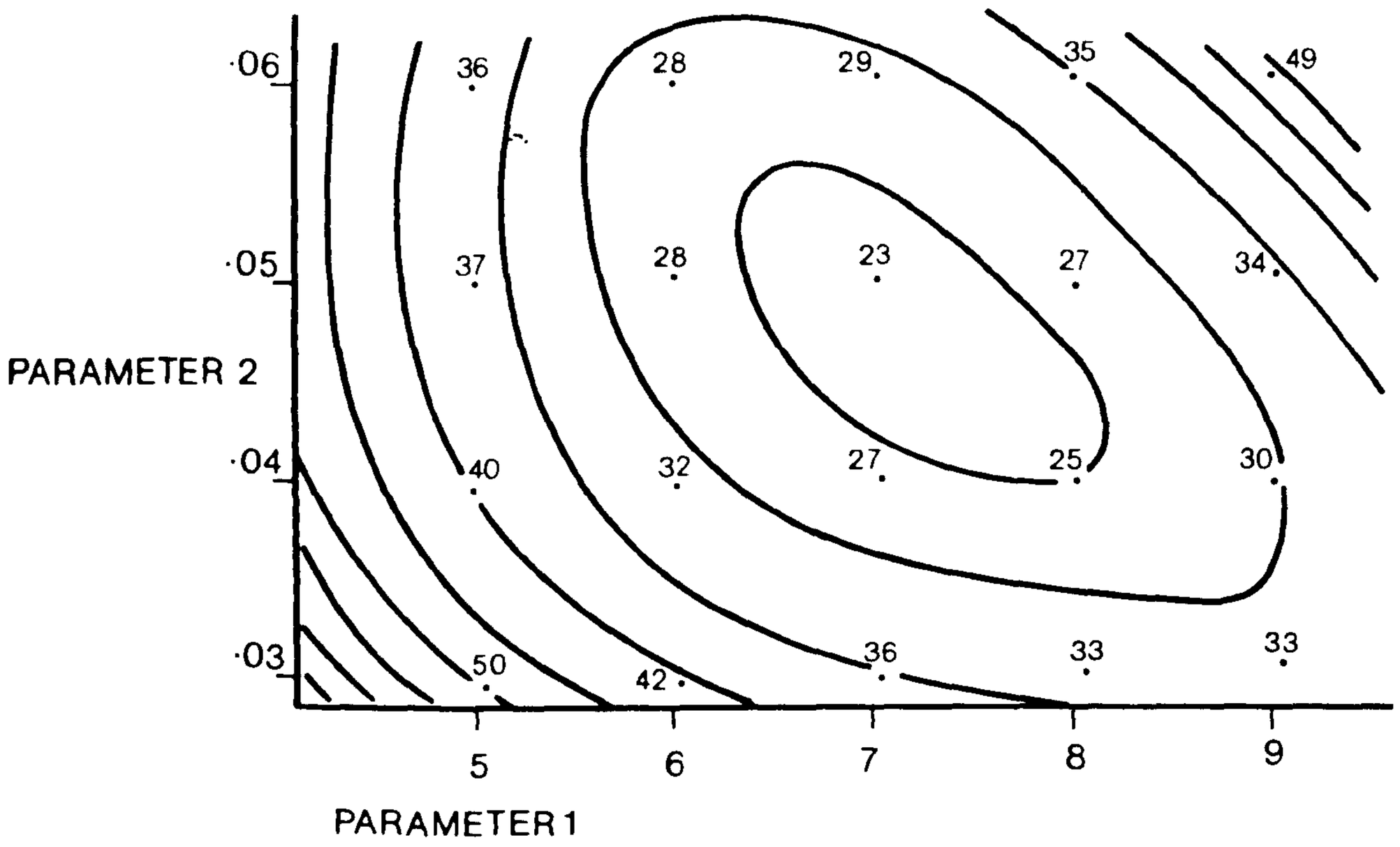


FIG.49

Error function surface for two parameters

(after Douglas, 1974)



The value of R^2 can range from $-\infty$ to +100%. An efficiency of 100% indicates that there is no error, and that the output computed by the model is exactly equal to that observed.

6.4.2 The significance of selecting correct model parameter values is shown by the application of equation 31.

$$\text{Runoff} = \text{Rain} \cdot e^{-\text{Para}_1 \cdot \text{SMD}} \qquad (31)$$

If equation 31 is an expression representing outflow from a catchment, then it is clear that different values of parameter 1 will give different outflows. If the catchment SMD is 10mm and $para_1$ = 0.035 then a 10mm rainfall input will give 7.1mm runoff. Alternatively if $para_1$ = 0.06, then 10mm of rainfall gives 5.5mm of runoff.

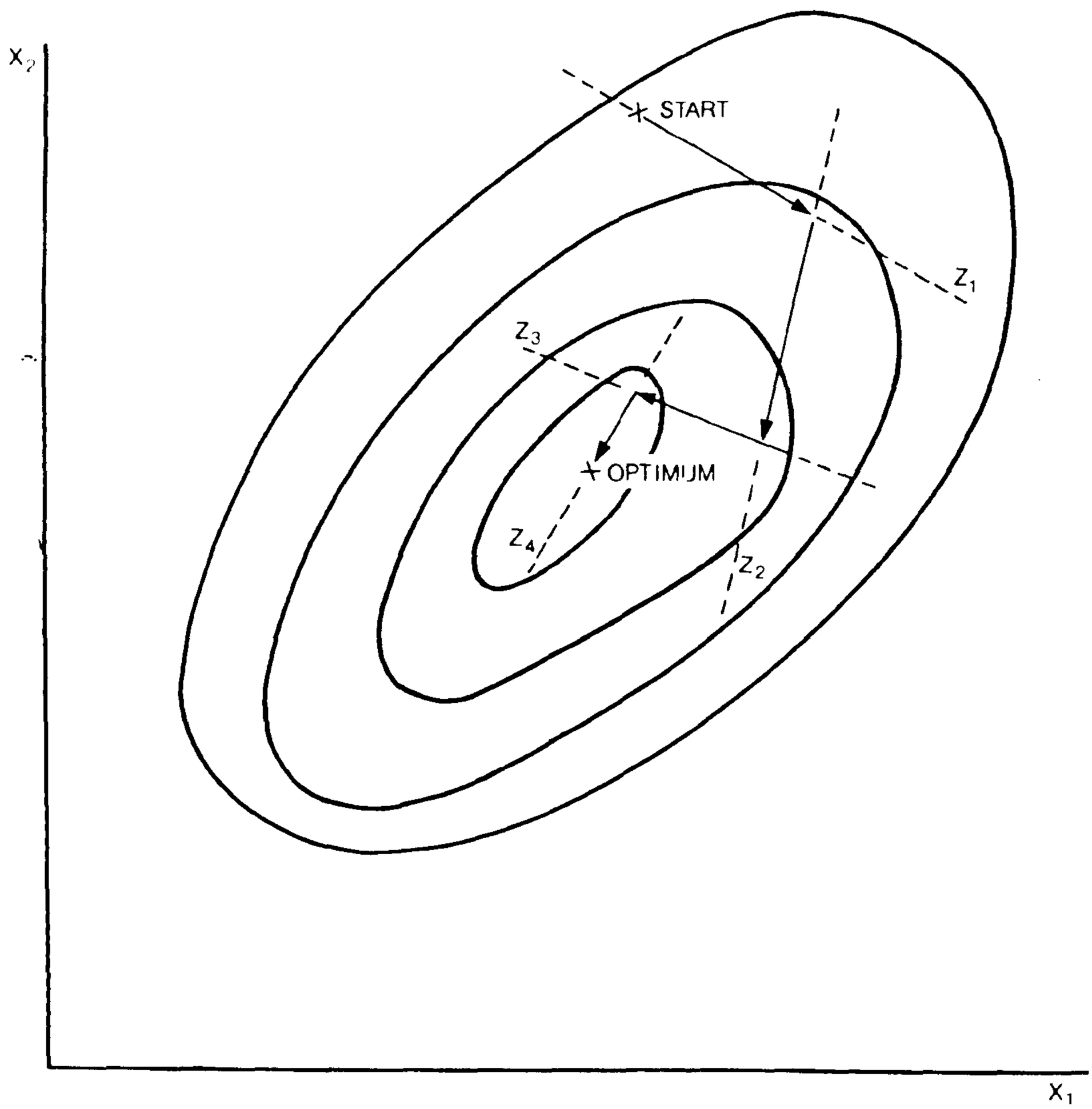
In practice, the optimum value of $parameter_1$ is found by trial and error fitting. The value selected is that which produces the smallest difference between observed and simulated runoff (lowest F^2). This is illustrated in Figure 48 where the error resulting from several runs of the model is plotted against each different value of the parameter. The optimum value of $parameter_1$ in the example is 0.046.

If the error in a model run is dependent on the values of more than one parameter, the problem of finding the best combination of values becomes more difficult. The problem is illustrated in Figure 49, where the error resulting from running a model with various combinations of values of two parameters are plotted. Contours have been drawn linking points with the same error, producing the error function surface for these two parameters.

A similar picture could be visualised in 3 dimensions, representing the error produced by running the model with

FIG. 50

General Pattern of Search
for Optimum



different combinations of values of 3 parameters. With more than 3 parameters, it becomes difficult to visualise the error function surface, although there is no limit to the number of parameters whose multi-dimensional surface can be studied mathematically. Multiparameter fitting is a problem which lends itself to the speed of the modern computer. There are a number of computer techniques available (optimisation routines) which will perform this task.

6.4.3 Optimisation seeks to minimise the value of an objective function by trial alterations in the values of the parameters. Successful trials are those which cause a reduction in the value of the objective function. Fig. 50, shows using a map, how this operates for a two parameter example. The parameter axes are shown as x_1 and x_2. Equal values of the objective function F form the contours of the response surface for F. A straight line (or direction) passing through a given starting point is defined, e.g. z_1. The search for the optimum point is carried out by evaluating the objective function at various points along such a line. When the line optimum (lowest objective function) has been found, a new search direction Z_2 is defined and the process is repeated. How the search directions are defined, and how each line is searched, give rise to different fitting methods. Ibitt and O'Donnell (1971) tested nine different optimisation methods and concluded that the rotating co-ordinate method of Rosenbrock (1960) suitably modified for hydrological models (Ibbitt, 1970) was the most appropriate for fitting conceptual rainfall-runoff models. Rosenbrock's method was adopted in this study. There are however a number of problems of automatic parameter estimation

(i) When a model has only one parameter, it is clear that it is not difficult to find the value of the parameter for which the model most efficiently predicts the output sequence. When there are two or more parameters, there may be an additional problem; that of interdependence of parameters. For example the

equation 31 given in 6.4.2 may be made more complex by the addition of a second parameter ($para_2$).

$$Runoff = Rain \cdot Para_2 . e^{-Para_1 . SMD} \quad (32)$$

For all positive values of SMD, there is no unique solution to this equation. For example, if the SMD = 10.0mm, the model gives the same runoff for $Para_1$ = 0.025 and $Para_2$ = 0.50, as if $Para_1$ = 0.032 and $Para_2$ = 0.70.

It depends on how the model is to be used, as to whether this interdependence is a problem, or not, since any of the pairs of values may be an optimum, and the resulting output sequence is unaffected by interdependence. However, if any meaning is to be attached to individual parameter values, (if, say, parameter values are to be correlated with catchment characteristics) the values obtained from such an optimisation may be meaningless. This problem is considered further in section 6.8.1.

(ii) A second problem with automatic computer optimisation is that any such routine is unable to reason hydrologically. The objective is to minimise the measure of fit regardless of the realism of the parameter values. If in equation 32 SMD is assigned a value of 0.0, then the equation can be rewritten as:

$$ROP = Rain.para_2 \quad (33)$$

this is because $e^{-Para_1 \times 0.0} = 1.0$

In automatic fitting, $para_2$ may become a number greater than unity to achieve a perfect fit between forecast and observed hydrographs, and thus satisfy

the criterion that the objective function reaches a minimum. At the same time the parameter would have no hydrological meaning. A value of $para_2$ of greater than unity in equation 32 and 33, implied that the runoff percentage is greater than 100, which clearly is not possible. Automatic optimisation therefore needs careful control otherwise fitting will take place at the expense of the conceptuality of the model.

6.5 ASSESSMENT OF THE CHOSEN CONCEPTUAL RAINFALL - RUNOFF MODEL

6.5.1 Section 6.3 described the principles behind the selected rainfall runoff model. Section 6.4 discussed how the model can be fitted to any catchment for which measured input and output data are available. In its original form there are 21 parameters (table 11) to be estimated for any one catchment. However from the description of the model it is obvious that some parameters are more fundamental to the estimation of high flows than others. The relative merits of the various parameters were quantified using a sensitivity analysis.

6.5.2 The majority of the sensitivity tests were made using data from two historic rainfall-runoff events. One represented a flood of approximately 1 in 5 year return period when the soil was at field capacity. The second event had a much smaller peak flow occurring during a period of very high soil moisture deficit (100 mm). Testing was undertaken on two catchments. For most parameters these were the River Trent to Stoke and the River Dove to Izaak Walton. The former has a catchment area of 53 km^2 and the geology is predominantly Westphalian (Coal Measures) and the latter an area of 83 km^2 and the geology Dinantian (Carboniferous Limestone). River flows in both catchments are measured at 'Crump' triangular profile weirs to a high standard of accuracy.

Out of bank routing parameters were tested on two different events and two alternative catchments. These were the River Wreake to Syston and River Amber to Wingfield Park which are

TABLE 12
SENSITIVITY ANALYSIS

PARAMETER	EVENT SMD 100								EVENT SMD 0								Catch-ment
	V_1		V_2		F_1		F_2		V_1		V_2		F_1		F_2		
PCIN cap interception store.	0.50		0.50		145		145		0.50		0.50		542		542		1
	0.50		0.51		72		71		0.50		2.00		106		96		3
PSRC Runoff Percent	0.200		0.426		218		141		0.200		0.426		856		354		1
	0.300		0.100		385		18		0.300		0.131		956		101		3
PSRS ROP exponent	0.060		0.021		360		153		0.060		0.078		332		312		1
	0.090		0.032		29		15		0.090		0.004		3057		97		3
PRPM max runoff Percent	NR				NR				0.55		0.55		542		542		1
	NR				NR				0.55		0.50		102		102		3
PSST SMD at max runoff	NR				NR				2.00		0.00		425		394		1
	NR				NR				5.00		23.00		449		93		3
PMPC max percolation rate	0.300		0.300		146		146		0.200		0.326		310		226		1
	0.540		0.540		69		69		0.540		0.820		318		92		3
PDRF supersat. drainage factor	NR				NR				2.00		1.87		523		522		1
	NR				NR				10.00		100		468		99		3
PDRX supersat. drainage exponent	NR				NR				1.00		0.10		537		526		1
	NR				NR				1.00		0.92		85		84		3
PGWF groundwater reservoir	35000		13670		145		136		35000		13670		573		336		1
	20000		100000		69		48		10000		10400		73		71		3
PLAG delay before rise	25		14		272		91		25		3.5		2222		448		1
	30		0.0		94		29		30		4.2		1733		102		3
PDUR duration of hydrograph	30		21		106		82		30.0		13.6		764		449		1
	30		79		55		36		30		4.3		401		91		3
PIEF Int. store evap.	5.00		5.14		163		163		5.0		0.1		599		528		1
	6.0		10.0		39		37		6.0		5.3		97		96		3
PETF Pot. transpiration	0.50		0.50		145		145		0.50		0.50		541		541		1
	0.50		0.50		69		69		0.50		0.50		102		102		3
PSET max SMD transp	50		50		146		146		50		50		542		542		1
	50		50		69		69		50		50		106		106		3
PDET min SMD transp	30		30		146		146		10		10		542		542		1
	50		50		69		69		10		10		106		106		3
PETM min transpiration	0.20		0.20		146		146		0.20		0.20		542		542		1
	0.20		0.20		69		69		0.20		0.20		106		106		3
PCIF Inbank routing factor	0.40		0.60		138		133		0.40		0.07		1120		627		1
	0.35		0.00		359		39		0.35		0.06		67		235		3
PCIX Inbank routing exp.	6.00		6.90		118		114		6.00		1.50		2020		545		1
	6.00		0.10		430		22		5.00		1.90		864		317		3

TABLE 13
SENSITIVITY ANALYSIS

PARAMETER	EVENT SMD 100								EVENT SMD 0								Catchment
	V_1	V_2	F_1	F_2	V_1	V_2	F_1	F_2	V_1	V_2	F_1	F_2	V_1	V_2	F_1	F_2	
PSRC	0.450	0.783	191	144					0.450	0.410	347	329					1
PSRS	0.030	0.030							0.030	0.042							
					0.300	0.142	18	10					0.300	0.127	2084	101	3
					0.030	0.025							0.030	0.020			
PDRF									40.00	1.01	542	484					1
PDRX									1.60	0.60							
													40.00	100.00	79	88	3
													1.60	1.30			
PCIF	0.020	0.490	151	111					0.020	0.003	850	536					1
PCIX	2.50	5.23							2.50	2.40							
					0.060	0.001	295	19					0.060	0.003	718	264	3
					3.00	2.87							3.00	2.42			

TABLE 14
SENSITIVITY ANALYSIS

PARAMETER	EVENT SMD 0.0								EVENT SMD 3.0								Catchment
	V_1	V_2	F_1	F_2	V_1	V_2	F_1	F_2	V_1	V_2	F_1	F_2	V_1	V_2	F_1	F_2	
PCOF	0.004	0.001	353	336	0.005	0.093	43567	3123	0.004	0.016	221	212	0.005	0.056	18311	2916	4 5
PCOX	1.76	0.32	352	339	0.660	1.950	43567	9767	1.76	0.10	221	217	0.66	1.62	18311	3536	4 5
PCBF	10.00	16.71	696	363	10.00	43.90	54443	11961	16.70	12.20	213	107	46.00	35.70	7769	5895	4 5
PCOF PCOX	0.004 1.76	0.001 0.37	353	331	0.005 0.660	0.098 0.615	43567	3023	0.004 1.76	0.015 0.10	221	193	0.005 0.660	0.054 0.703	18711	2857	4 5

both prone to washland flooding. Outflows from both catchments are adequately measured by 'Crump' weirs.

The sensitivity testing was performed with the aid of the Rosenbrock optimisation routine. The method was:

(i) For each event in each catchment, all but one of the parameters were assigned realistic values. These values were fixed.

(ii) The one remaining parameter was assigned an unrealistic value. Upper and lower limits were also set for that parameter.

(iii) The single parameter was optimised for the two individual events on the two catchments. The extent to which the parameter was able to influence each modelled output was monitored.

(iv) The parameter was returned to a realistic value and another parameter chosen for testing.

All parameters were considered in turn and those which were known to influence each other were also tested in groups.

The results from the sensitivity analyses are given in tables 12, 13 and 14. For each test catchment and event, both the initial and optimised parameter values (V_1 and V_2) are shown as are the initial and final measures of fit (F_1 and F_2). In most cases F^2 reduced as the value of the parameter reached an optimum (eg the values of PSRS in table 12). However in some cases both the starting and final values of V and F^2 remained virtually the same (eg PCIN in table 12). No change in the values indicates that the optimisation routine has searched for an improved fit but regardless of how it altered the parameter value along its search directions virtually no improvement in fit was obtained.

The sensitivity tests show that PSRC and PSRS have the most important function within the model. The position at which the runoff proportion becomes a maximum, PRPM, and PSST, the SMD at maximum runoff are also important. PLAG, the delay before the hydrograph rise was significant in all cases where as PDUR, the duration of the hydrograph is slightly less signficant. PCIF and PCIX the inbank routing factor and exponent are both significant, particularly when used collectively. All three parameters relating to out of bank flows, PCBF (bankfull discharge), PCOF (out-of-bank routing factor) and PCOX (out-of-bank routing exponent) influence the shape of simulated hydrographs. Other parameters which showed some measure of significance during the sensitivity tests were: PMPC, the maximum percolation rate, PDRF and PDRX, the supersaturated drainage factor and exponent, and PGWF the groundwater reservoir factor.

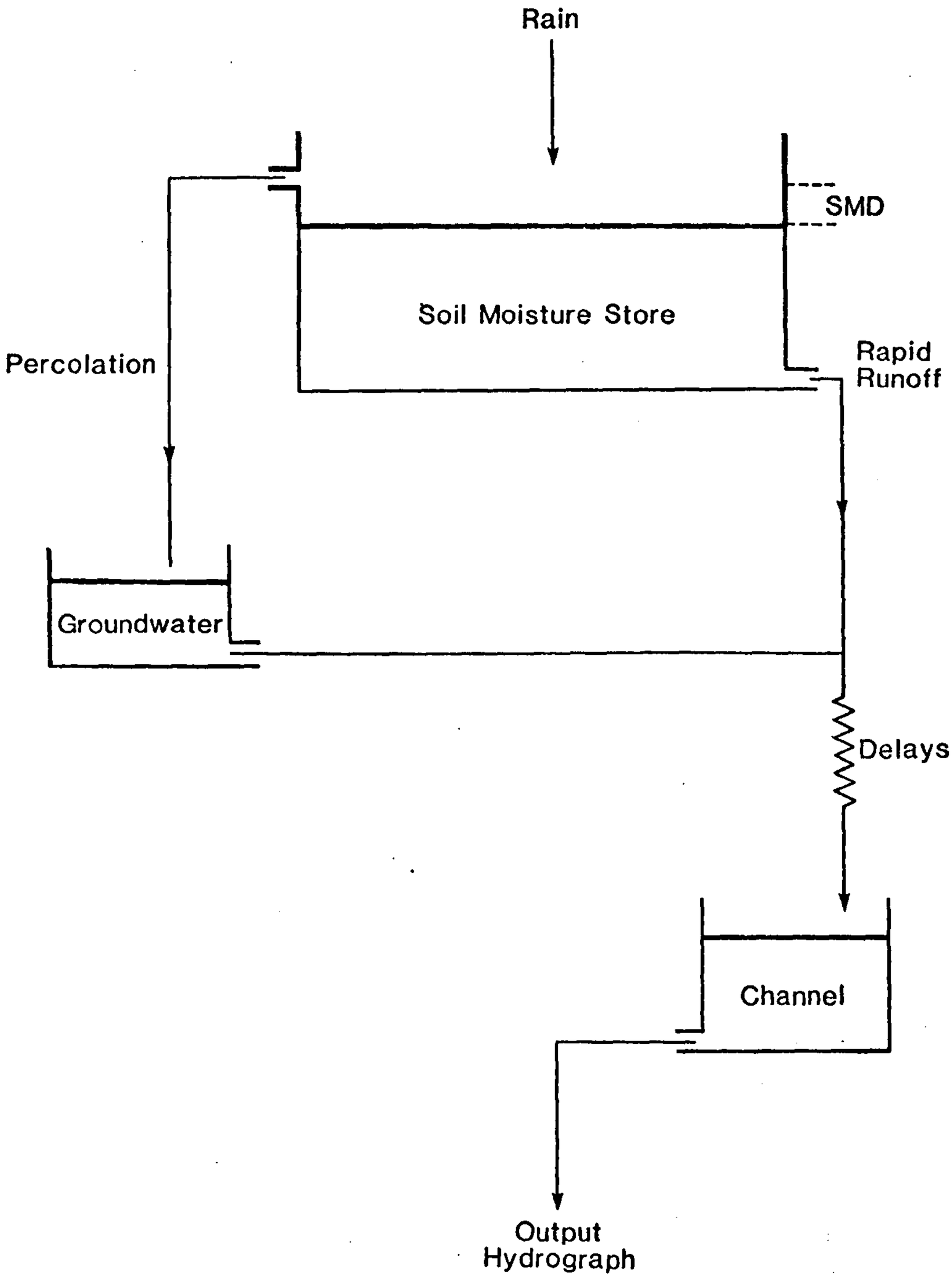
6.5.3 The sensitivity tests outlined in Section 6.5.2 have shown that six of the models 21 parameters have little or no influence on the simulation of isolated flood hydrographs. Their function is in the calculation of longer term changes in the soil moisture status and in the estimation of losses from the small surface store. Further, the relevance of some of the other parameters which did have an influence on the sensitivity testing can be questioned in relation to the ungauged case. PDRF and PDRX, the supersaturated drainage factor and exponent, which provide enhanced runoff when a catchment is very wet will influence a very limited number of hydrographs. In some catchments the mechanism is never activated because of the nature of the soil and the geology (this is illustrated by figures 78 and 81, derived in section 6.8.1). In other catchments where the relationship could be made to apply, the supersaturated state will only be reached in occasional events. Even then the inter relationship between PSRC, PSRS, PRPM and PSST is very complex (Figure 47b). Also, because of the concept of negative SMD's a form of supersaturated runoff can already be simulated for most events. To have even further enhanced supersaturation (above the value of PSST), possibly expressed by a stepped

relationship of the type shown in Figure 47b, seems unwarranted, particularly in a simple model, applicable in ungauged catchments.

If the parameters PDRF and PDRX are removed, then the runoff proportion element of the model is simplified considerably. Three parameters, PSRC, PSRS and PRPM require fitting. PSST can be calculated from PRPM in the simpler case (figure 47a). If the other parameters in the surface processes element of the model which showed little or no influence in the sensitivity analysis (PIEF, PETF, PSET, PDET, PETM and PCIN) are also removed then the whole runoff generation element can be represented by two reservoirs representing soil moisture and groundwater with six parameters (PSRC, PSRS, PRPM, PSST, PMPC and PGWF).

It is possible to also make reductions in the size of the routing sections of the model. Section 4.2.9 has shown that if the storage equations within the model (equation 27, section 6.3.2) are solved using the Manning equation, then the exponents of the equations could be represented by universal constants. Using the solution given in 4.2.9, PCIX and PCOX have a value of 1.66. (Note:- the storage equations used in the model, (equation 27, Section 6.3.2) are transposed from the equations used in the solution in section 4.2.9, thus the vaules of PCIX and PCOX are the reciprocal of the values given in 4.2.9). The use of constants for the routing exponents will make little difference to the efficiency of the model. Because the routing factor and exponent are interdependent, variation of the value of the factor has much the same effect as the variation of value of the exponent. A constant exponent could also solve many of the problems of automatic parameter estimation outlined in section 6.4.3. Several other authors including O'Donnell and Mandeville (1972), Mein et al, (1974) and Brakensick (1963) have used models with similar storage equations and constants for the exponents.

Figure 51
UCM Rainfall
Runoff Model



The routing element of the rainfall - runoff model could thus be reduced to 3 or 5 parameters depending on the nature of the flow. PLAG, PDUR and PCIF being required for inbank flow and possibly PCBF and PCOF for out of bank flows.

6.5.4 By making the adjustments described in the previous section to the model outlined in section 6.3.3, a simple 9, 10 or 13 parameter version of the model can be derived for application to isolated events (i.e. single or connected storms, with no requirement for day to day moisture budgeting). Figure 51 is a schematic representation of the nine parameter version of this model and a complete computer listing is given in Appendix 8. In this form the model is half way in complexity between the General Catchment Model (6.3.2 figure 46) and the Isolated Events Model (Section 2.3.6, Figure 2). The tenth parameter for inclusion is PCIX in place of the constant routing exponents, and 13 parameters being made up by a second (out of bank) routing reservoir. In its simplest form the model functions according to the following principles:

All input rainfall enters a surface soil moisture store. Within this store there are three levels of activity.

(i) If there is a soil moisture defecit (ie SMD > 0mm) then a percentage of the input rainfall imediately emerges from the store as rapid runoff. The functional relationship is shown in figure 47a. That water which does not runoff reduces the soil moisture defecit.

(ii) If the calculated soil moisture defecit is less than zero but greater than PSST (SMD at maximum runoff) the functional relationship shown in figure 47a still applies. However, at the same time a proportion of the input rainfall also infiltrates to the groundwater reservoir. This relationship is shown in figure 47c.

(iii) For values of SMD equal to or greater than PSST, rapid runoff and percolation both take place at their maximum rate (PRPM and PMPC).

Any water leaving the surface soil moisture store as percolation enters the groundwater store. Output from this store is to streamflow and the rate is governed by the contents of the store (SGRW) and the groundwater reservoir factor (PGWF). The functional relationship is:

$$V(4) = \frac{SGRW^{1.5}}{PGWF} \quad (34)$$

Flow from the groundwater store (V4) is combined with rapid runoff to give total runoff volume (V5).

Total runoff volume (V5) is then subjected to a two stage routing procedure:

(i) The volume is delayed by PLAG and the base length of the hydrograph is adjusted by PDUR. These parameters account for the time it takes input rainfall to appear as flow at the catchment outflow point.

(ii) The effect of channel storage(s) on the shape of the flow hydrograph is achieved by the application of either equation 35 or 35a.

$$Q = PCIF \; S^{1.66} \quad (35)$$

$$Q = PCIF \; S^{PCIX} \quad (35a)$$

If out-of-bank routing is required (ie flow > PCBF) then a second equation of the form of either equation 35 or 35a with a factor PCOF and an exponent of PCOX or 1.66 can be applied. The relevance of the out-of-bank routing equation is considered further in sections 6.5.5 and 6.8.1.

This simple model (UCM, ungauged catchment model) requires as inputs Q_o an inital, pre rainfall, runoff at the outflow station; SMD, an estimate of catchment soil moisture deficit prior to rainfall, and the storm rainfall. Output is in the form of discharge (cumecs) at the outflow site. Initial

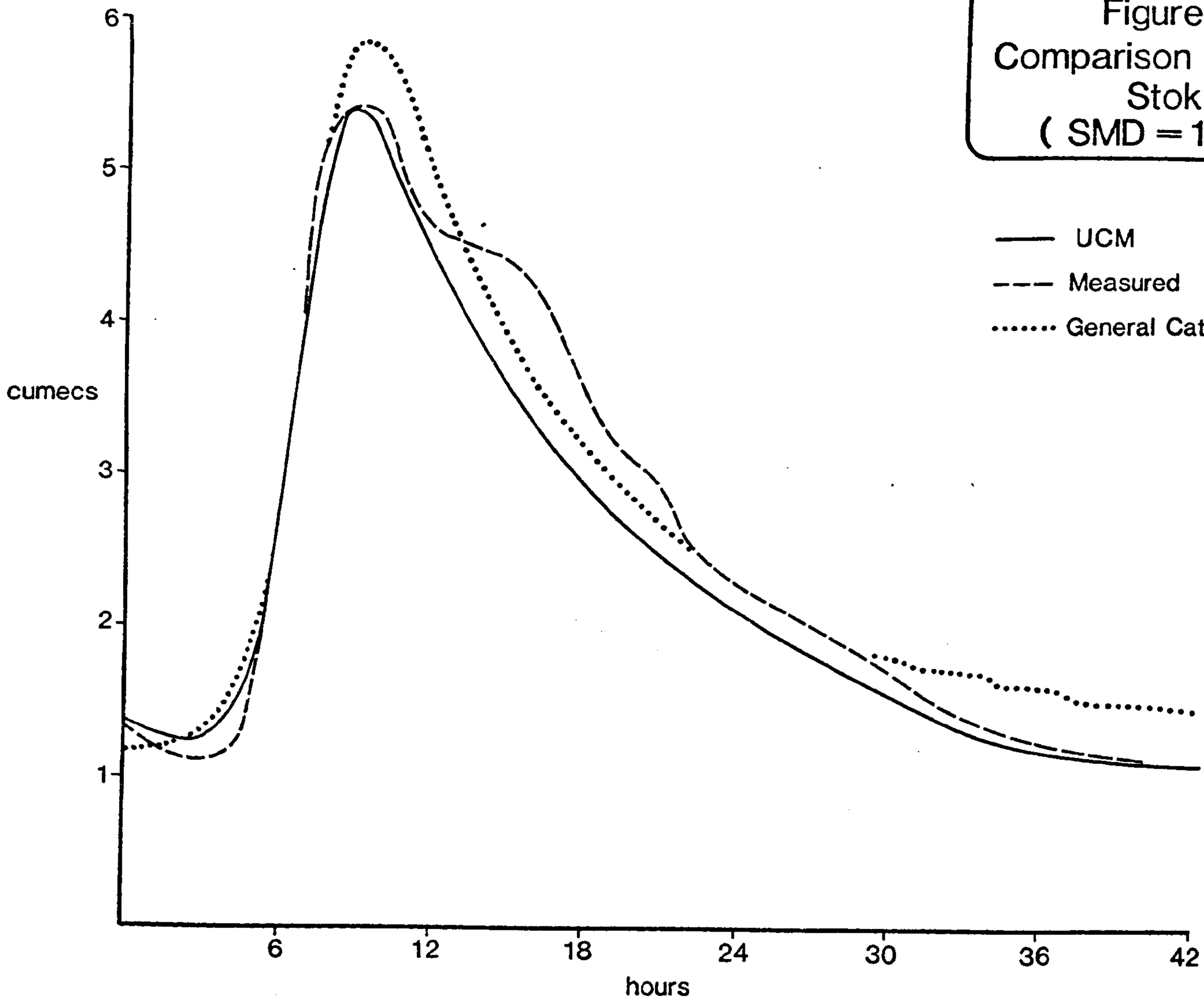


Figure 52
Comparison of Models
Stoke
(SMD = 18mm)

—— UCM

– – – Measured

····· General Catchment Model

TABLE 15

COMPARISON OF GENERAL CATCHMENT MODEL

AND THE UNGAUGED CATCHMENT MODEL

EVENT	OBSERVED PEAK FLOW	GENERAL MODEL		UCM		OBSERVED PEAK TIME	GENERAL MODEL		UCM	
		PEAK FLOW	% OF OBSERVED	PEAK FLOW	% OF OBSERVED		PEAK TIME	± HOURS OBSERVED	PEAK TIME	± HOURS OBSERVED
FIG 52	5.45	5.80	+ 6%	5.40	- 1%	9.0	9.0	0	8.5	- 0.5
FIG 53	13.60	13.40	- 1%	13.60	0	28.5	30.0	+ 1.5	28.0	- 0.5
FIG 54	20.0	21.0	+ 5%	19.9	- 1%	49.0	52.0	+ 3.0	52.0	+ 3.0
FIG 55	13.6	13.0	- 4%	13.5	- 1%	39.0	41.0	+ 2.0	40.0	+ 1.0
AVERAGE ERRORS			4%		1%			1.6 hrs		1.3 hrs

Units:- cumecs and hours

storage states are calculated within the model by the transposition of the equations 34 and 35 in relation to Q_o.

6.5.5 The accuracy of UCM in its simplest form (9 parameters) in forecasting flood flows, was assessed by comparison with the larger parent model and recorded flow data. Four very different flood events were forecast using both models. Both in-bank and out-of-bank flows were considered as well as events occuring during periods of both high and low soil moisture deficit. Four different gauging stations were also used; R Trent to Stoke, R Dove to Izaak Walton, R Sow to Great Bridgford and R Amber to Wingfield Park. The results of the comparisons are shown as figures 52-55 (figure 52 is included with the text) and summarised in table 15. There is little to choose between the models in simulating measured flow data. UCM is able to give superior representations of peak flow (1% error compared with 5%) where as the General Catchment Model produced better estimates of recessions (eg. figures 52 and 55). In general, both models proved capable of simulating runoff from rainfall in gauged catchments.

6.5.6 The comparisons undertaken in 6.5.5 indicate that for simulating peak flows in gauged catchments, the extra parameters of the general catchment model are of no specific advantage, where as the simplicity of UCM could be a virtue. A small model with a limited number of parameters can be used locally on small or desk-top computers thus making a viable alternative to the unit hydrograph technique as a design tool (section 2.3.4). Also, the model could be used for local flood forecasting purposes (2.3.6). The limited number of parameters, each with a concise function, make it probable that relationships may be found between the parameters and catchment indices and hence making the model also applicable to ungauged catchments.

6.6 FITTING THE UCM RAINFALL RUNOFF MODEL TO GAUGED CATCHMENTS

6.6.1 There are 14 gauged catchments in the Trent basin to which the UCM model can be fitted. These catchments are outlined in Appendix 9. Ten rainfall-runoff events were selected to fit the model to each catchment. Each event approximated to different conditions, and most eventualities were covered. These included, where possible, the highest flow on record, bankfull floods during both summer and winter, small winter floods, and flows resulting from moderate and heavy rain at times of medium and high soil moisture deficit. Meteorological records were checked to make sure no event included significant snowfall or smowmelt. For each catchment three types of data were collated: rainfall, river level and soil moisture deficit. The rainfall and river level data base was hourly, the SMD daily.

(1) Rainfall. 31 of the 65 autographic raingauges maintained by Severn-Trent Water Authority in the Trent catchment were relevant to fitting the model, together with 4 in the Severn catchment and one belonging to the North West Water Authority. On average three gauges were used per subcatchment (details are given in appendix 9). Each gauge, was weighted according to its degree of representativity in the particular catchment. Weightings ranged from one to four. The highest value was allotted to gauges lying well within the catchment; a value of three was given to those at the periphery; two to those outside, but close to the catchment or at its upstream or downstream end; and a value of one to those further away. The calculation of hourly rainfall included consideration of the annual average rainfall (A.A.R.) of each gauge and of the catchment, in order to account for the relative altitudinal and orographic influences on the gauged and catchment rainfall.

The calculation of catchment rainfall for an event is given by the following equation:

$$\text{Catchment rainfall} = \frac{\sum_{i=1}^{\wedge} \left(R(i) \times \left(W(i) \times \frac{CAAR}{GARR(i)}\right)\right)}{\sum_{i=1}^{\wedge} W(i)} \qquad (36)$$

where, for gauge (i)

R = hourly rainfall

W = weighting

GAAR = gauge average annual rainfall

and CAAR = catchment average annual rainfall

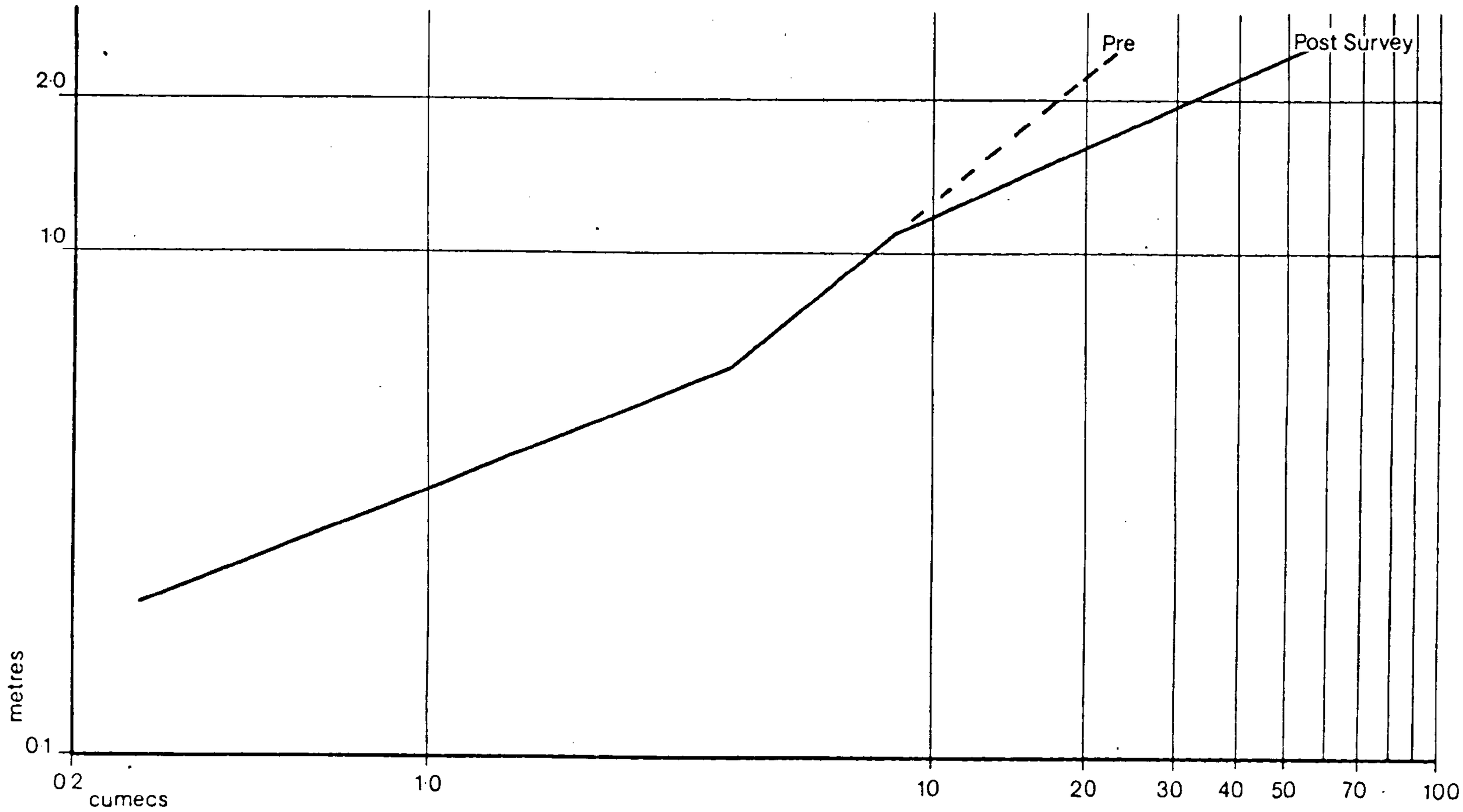
If for any timestep, data was missing for a particular gauge, the weighting factor was reduced to zero, thus effectively omitting the gauge from the analysis. If for any event, in any catchment, the quantity of data missing was such that the storm rainfall could not be adequately defined, then the whole event was removed from the analysis for that catchment.

(ii) River flow. Each catchment analysed has a rated, purpose built, gauging station at its outflow point. Levels are recorded at these sites every 15 minutes on punch tape recorders. 110 hourly levels were collated from the historic punch tape level record for each event. This was a sufficiently long period to define background conditions and monitor the whole hydrograph in every catchment for every event. The level records were then translated within the model to flow records (in cumecs) by specially derived rating equations. Improved rating equations were necessary as few gauging stations adequately measure all ranges of flow. Flow within bank is generally well defined by current meter gauging and/or model experiments but high flows and out-of-bank flows are generally poorly defined. To this end, the channel and complete flood plain cross section were surveyed at each measurement point. Velocities were then estimated for all points in the cross section which were not adequately

FIG. 56

River Soar - Narborough.

Rating Curve



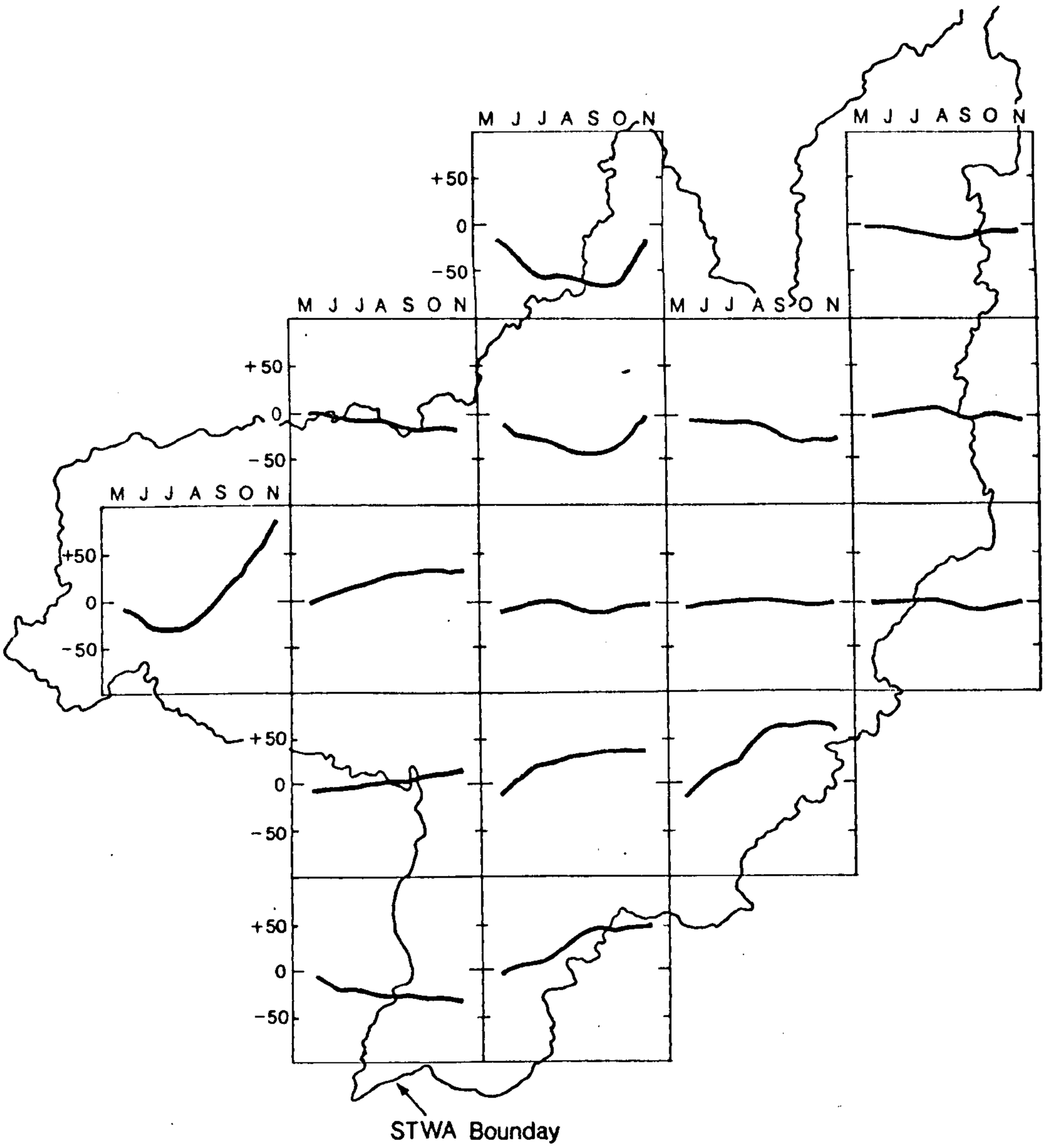
measured. The velocity estimates were based on current meter velocities measured in the channel and near the channel boundaries, from gaugings taken on any flood plain in the Trent area; and on the Manning equation. Advice was also obtained from the Hydraulics Research Station where there is considerable experience of the physical modelling of flows on flood plains (e.g. R. Trent tidal model). The improved high flow ratings were then derived from the estimated velocity-area distributions. In some cases estimates were made for very shallow water flowing across very wide flood plains, and in others very deep water flowing in narrow ar tifical channels. An example of pre and post survey ratings is given as figure 56.)

(iii) Soil Moisture Deficit. The soil moisture deficit (SMD) is the depth of water that is needed to restore the soil profile to field capacity. Field capacity is the moisture content of the soil profile when it is holding all the water it can against the force of gravity. Estimates of SMD are calculated from the cumulative difference between rainfall and evaporation. When evaporation exceeds rainfall, vegetation has to draw on the reserves of moisture in the soil to satisfy transpiration requirements and when this occurs a soil moisture deficit is initiated or increased.

The SMD pertaining to each modelled rainfall-runoff event was estimated by one of two methods. For those events occurring before April 1978 SMD values had been calculated by Severn Trent Water Authority. Measured rainfall from 38 stations had been balanced against Meteorological Office estimates of evaporation (Penman's (1949) method) and cumulative deficits derived. For those events occurring after April 1978 estimates of SMD were from MORECS, the Meteorological Office Rainfall and Evaporation Calculation System. This system is based on the work of Penman (1949) and

FIG. 57

Accumulated differences (mm) between actual & morecs rainfall May-Nov 1977 (after Pirt: et. al 1979)



Grindley (1967). Evaporation estimates are considered to be very realistic because of a complex soil model, real land use data and realistic mathematical representations of the physical processes involved. It is probable that the evaporation calculation procedures in MORECS are an improvement over the pre 1978 methods, but the associated rainfall measures are less accurate. MORECS uses CARP the Comprehensive Areal Rainfall Program (Salter, 1972) to estimate the precipitation input. However, in some areas there are insufficient raingauges to adequately define rainfall by this method. This is illustrated in figure 57, where cumulative errors of over 50 mm in rainfall totals are evident in many areas. The greatest errors are in the Welsh Mountins, but substantial differences between MORECS and actual rainfall also occur in the catchments of the Avon, Dove, Derwent and Churnet.

The Soil Moisture Deficit is an important input to many conceptual models but it may be a measure liable to considerable error, particularly in areas with greatly varied topography.

6.6.2 The model was fitted to the 14 catchments using the data from the 10 selected storms. Eleven parameters; PSRC, PSRS, PRPM, PMPC, RGWF, PLAG, PDUR, PCIF, PCBF, PCOF and PCOX were considered. PCFC, PCOF and PCOX were optimised at this stage because these parameters are site specific and although the comparison of models (6.5.5) indicated that in general, the model could function without them, there may be some sites where their inclusion could be advantageous. PSST was not optimised as its values can be calculated from other parameters. Fitting was achieved automatically using the Rosenbrock technique as outlined in section 6.4. The parameters were considered in groups of 3 or 4 until all had been optimised. After the first round of optimisation was complete attention was turned to the value of the soil moisture deficit ascribed to each event. This variable has a major effect on runoff volume and thus on the values of the

parameters defining the ROP curve. With all 11 parameters held constant at their optimum values, the value of the soil moisture deficit was optimised for each event. In so doing, improved simulations were obtained in many cases. An objective assessment was then made of each optimised SMD value. In some cases the optimised value was retained and in other cases the value was rejected. For example, a reduction in the value of the SMD from 110mm to 90mm for an August event was considered acceptable, particularly if meteorological records showed there had been rainfall prior to the event. Alternatively, an increase in the SMD from 1mm to 40mm for an event occurring during a wet January was not acceptable. Once the SMD values had been reassessed another round of parameter optimisation was undertaken. This was to account, where necessary, for the new SMD values.

6.6.3 All best fit parameters, SMD values and errors for the 10 events and 14 catchments are given in Appendix 10.

The model was able to simulate observed runoff adequately in nearly all cases. The average efficiency of all 131 runs was 93% (F^2 = 180). For some catchments runoff was simulated consistently well. These were the R. Soar to Narborough (R^2 = 95%, F^2 = 42) the R. Amber to Wingfield Park (R^2 = 95%, F^2 = 54), the R. Penk to Penkridge (R^2 = 96%, F^2 = 48) and the R. Sow to Great Bridgford (F^2 = 98%, F^2 = 18). For some catchments the simulations were only slightly poorer than these, R. Anker to Polesworth (R^2 = 98%, F^2 = 105), but in some cases the quality of the simulations were much more variable. The poorest simulations were for the R. Wye to Ashford (R^2 = 79%, F^2 = 115), R. Manifold to Ilam (R^2 = 91%, F^2 = 614), R. Churnet to Basford Bridge (R^2 = 80%, F^2 = 658) and the R. Rea to Calthorpe Park (R^2 = 86%, F^2 = 205).

In most cases the model simulated those events with large soil moisture deficits equally as well as those with zero soil moisture deficits. There were, however, exceptions. The worst simulations were for large SMD events occurring in

FIG 58

River Rea – Calthorpe Park
simulated and observed flow

SMD=50mm

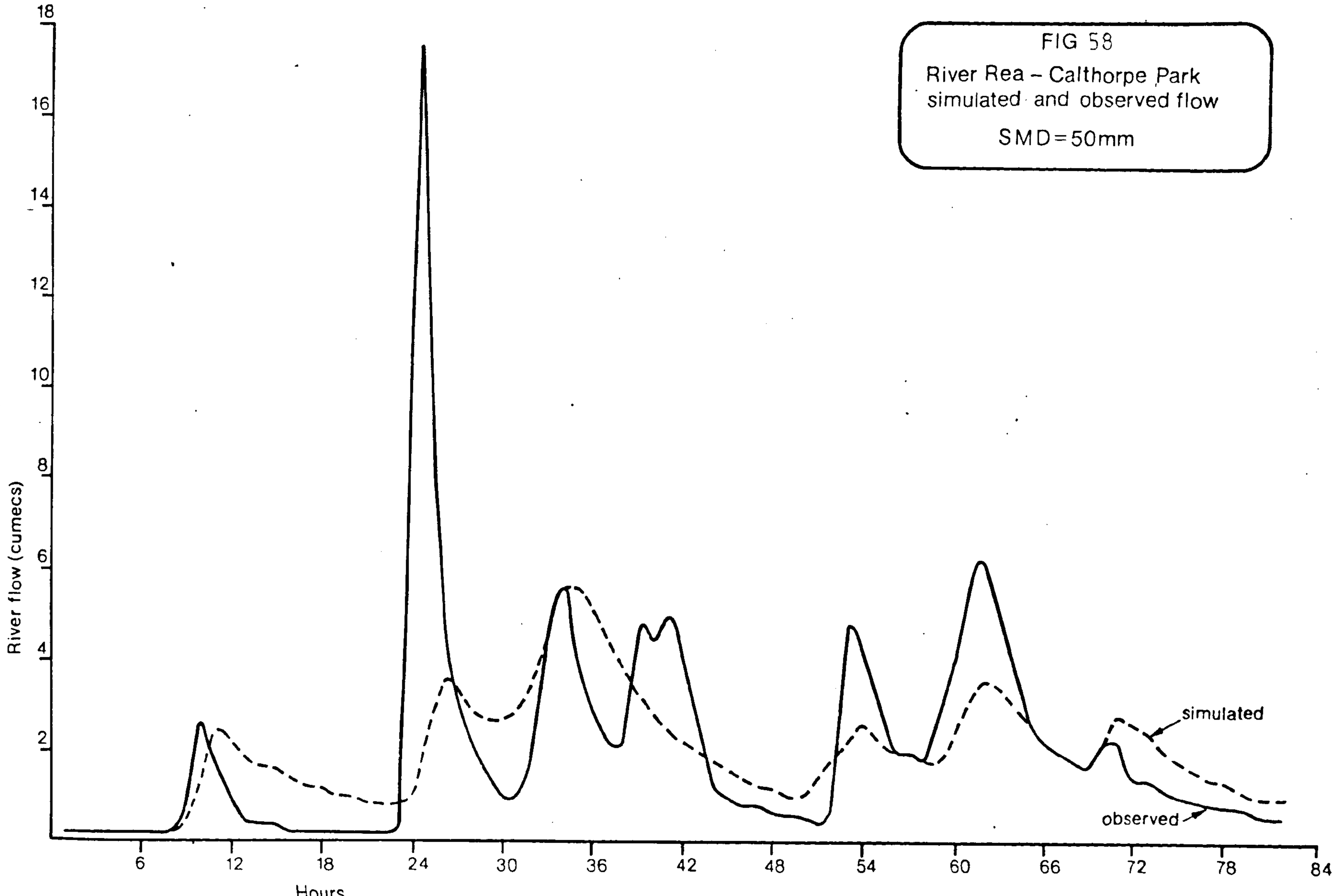


TABLE 16

PERFORMANCE OF THE MODEL IN URBAN CONURBATIONS

EVENT		MEASURE OF FIT (R^2) FOR DIFFERENT STARTING CONDITONS (SMD, mm's)		
		ACTUAL DEFICIT	NOMINAL/OPT DEFICIT	ZERO DERICIT
1	(REA)	(50 mm)	(5 mm)	(0 mm)
		27.4%	27.1%	26.7%
2	(REA)	(90 mm)	5 mm)	0 mm)
		84.8%	86.3%	80.3%
11	(REA)	(90 mm)	5 mm)	0 mm)
		90.5%	96.1%	72.5%
12	(REA)	(100 mm)	(40 mm)	0 mm)
		14.6%	34%	12.9%
14	(REA)	(120 mm)	(20 mm)	0 mm)
		67%	67%	55.1%
2	(COLE)	(90 mm)	5 mm)	0 mm)
		87.3%	91.8%	84.6%
11	(COLE)	(90 mm)	5 mm)	0 mm)
		89.1%	99.2%	83.1%
12	(COLE)	(100 mm)	11 mm)	(0 mm)
		91.4%	82.2%	91.1%
14	(COLE)	(120 mm)	10 mm)	(0 mm)
		87%	91%	80.8%

the catchments of the R. Rea and to a lesser extent the R. Cole where flows were often underestimated. Both these catchments drain parts of the Birmingham conurbation.

There are several reasons why some fits are superior to others. In those catchments where the simulations are good for all but one or two cases, the probable reason for the rogue events is spurious rainfall and/or soil moisture data. For those catchments where the simulations are consistently below average it is possible that the raingauge distribution is inadequate to define the precipitation input to the catchment, or the data from the flow measurement gauge is unsatisfactory. The latter is likely to be the case for the R. Wye to Ashford and the River Churnet to Basford Bridge. Ashford is an uncontrolled open channel gauging station, and Basford Bridge, although it has a structure, is known to suffer from variable backwater effects. The cases of poor simulations for events with high soil moisture deficits in urban areas may be due to a combination of problems.

6.7 PROBLEMS OF URBAN CONURBATIONS

6.7.1 Fitting the model to the R. Rea and the R. Cole was unsuccessful for summer events with high soil moisture deficits. The model failed to simulate the very fast rises and multi-peaked hydrographs recorded in these catchments. A typical example is shown in figure 58. In order to further investigate this lack of response, an extra two summer flood events (numbers 12 and 14) were fitted to the catchments by the method outlined in section 6.6.2. The results from the fitting are shown in table 16. The model again failed to simulate the correct response to rainfall.

6.7.2 There are a number of catchment features peculiar to urban areas which may effect the performance of any model. For instance, difficulties may be expected in the routing procedures due to the presence of storm drains and sewers. Drains may give a very fast response to rainfall, input large quantities of water at a single point or transport water out

of the catchment. In the case of the R. Cole and R. Rea, the problems of poor fitting were specific only to periods of large soil moisture deficit, therefore they were not connected with routing but with the one section of the model which has a seasonal element, the runoff proportion (ROP) curve.

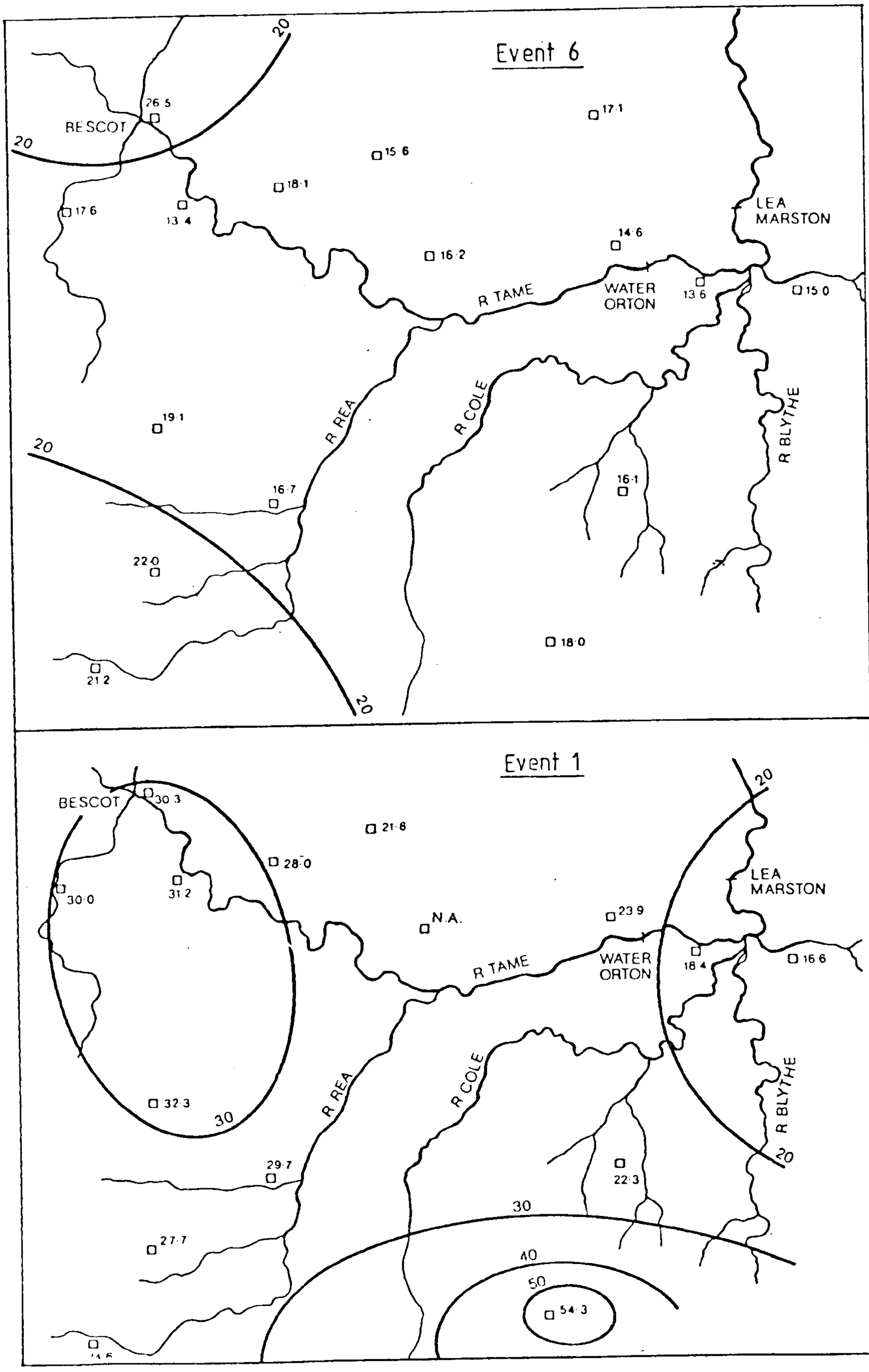
The application of a SMD controlled ROP curve in any catchment during periods of deficit has the effect of removing 30-60% of incoming precipitation, thus reducing the proportion of fast sharp rises simulated in summer months compared with winter months. However, as the Birmingham conurbation is predominantly an impervious area, it is possible that this concept of a catchment soil moisture deficit and its associated ROP curve may not apply. If this is the case, the model's performance may have been expected to be inversely proportional to the urban proportion present in any catchment. In fitting, the Rea, which has the greatest urban proportion, gave the worst simulations of all.

The hypothesis that the poor fits were related to the SMD-ROP problem was investigated. First, all five events with high SMD were reoptimised with a pseudo SMD of zero, thus inferring that built up areas do not have a soil moisture deficit. This approach greatly increased the runoff proportion of incoming rainfall but made no improvement to the hydrograph shape, or measure of fit (table 16 column 3). The five events were optimised a second time, this time using small pseudo SMD's representing the limited areas of undeveloped land in the catchments. For events 1, 2 and 11 small, nominal SMD values of 5mm were used and for events 12 and 14 optimised SMD values were derived (10 to 40mm) and used. For most events, in both catchments, the application of small SMD values gave slightly improved fits (table 16 column 2) but the level of improvement was insufficient to suggest a complete solution to the problem.

The second input to the runoff proportion concept which may also be seasonal, is rainfall. An undermeasurement of

Rainfall pattern
from daily raingauges.
Falls and isohyets in mm s

FIG. 59

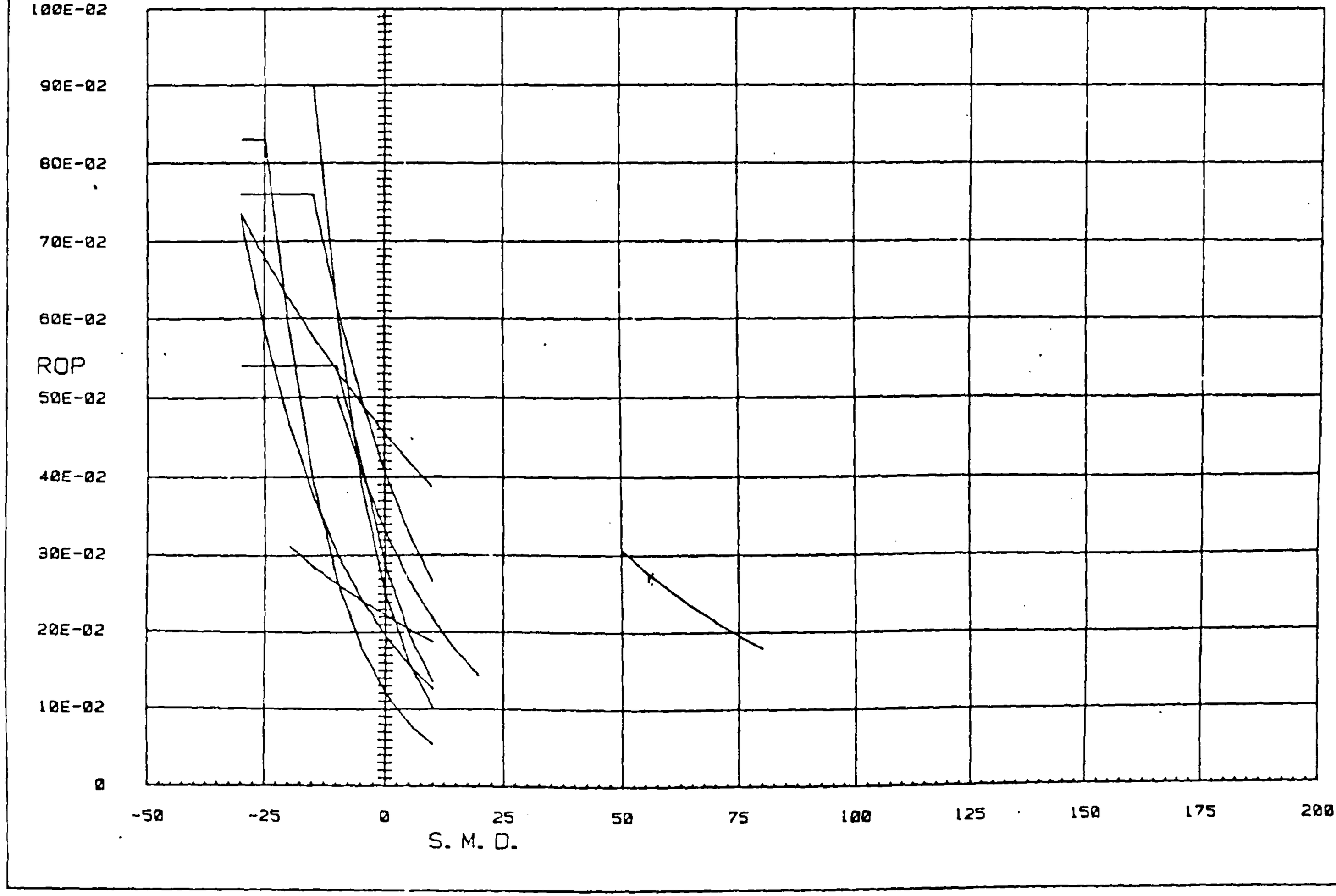


rainfall gives the same lack of response as an overestimation of SMD. Input rainfall to all 12 events as measured by the autographic gauges were checked against total storm rainfall measured at 20 daily rain gauges in the area of interest. Whilst the daily gauges are of little use in providing a rainfall profile, they do provide a check on the repesentivity of the limited number of gauges used to produce the profile. Maps of storm rainfall were produced for each of the 12 events. Examples are shown in figure 59. The maps indicated that the summer rainfall patterns were generally much more variable than those experienced in winter and in (nearly) all cases there was evidence of localised falls greater than observed at the autographic/interrogable sites. This implied the presence of localised convective storm activity. This was confirmed by the records of the Elmdon Airport Meteorlogical Office whose records showed that thunderstorms had occurred during four of the five summer events sampled.

The major problem in fitting a conceptual model to large urban areas, particularly in summer months, would seem to be one associated with precipitation sampling rather than with the structure of the model. By lumping rainfall inputs, lumped runoff outputs are produced. Summer rainfall, due to convective enhancement, needs to be measured by a much denser raingauge network. There may also be modelling problems related to the SMD concept, but these cannot be quantified separately from the rainfall problem. It is worth noting that for winter events, where adequate fits were obtained, the runoff proportions were 60-70% as in the case of rural catchments with similar base rocks. This would indicate that the hypothesis that riverflows are 200-300% greater in urban catchments (Gregory, 1974; Espey and Winslow, 1974) does not apply in Birmingham Conurbation. The results obtained from the Rea and Cole, if not conclusions drawn from them, are similar to those obtained by Hollis (1974) in Harlow. Hollis observed greatly increased summer flows but no influence in the winter following urbanisation. This effect Hollis suggested was due to an increased paved area.

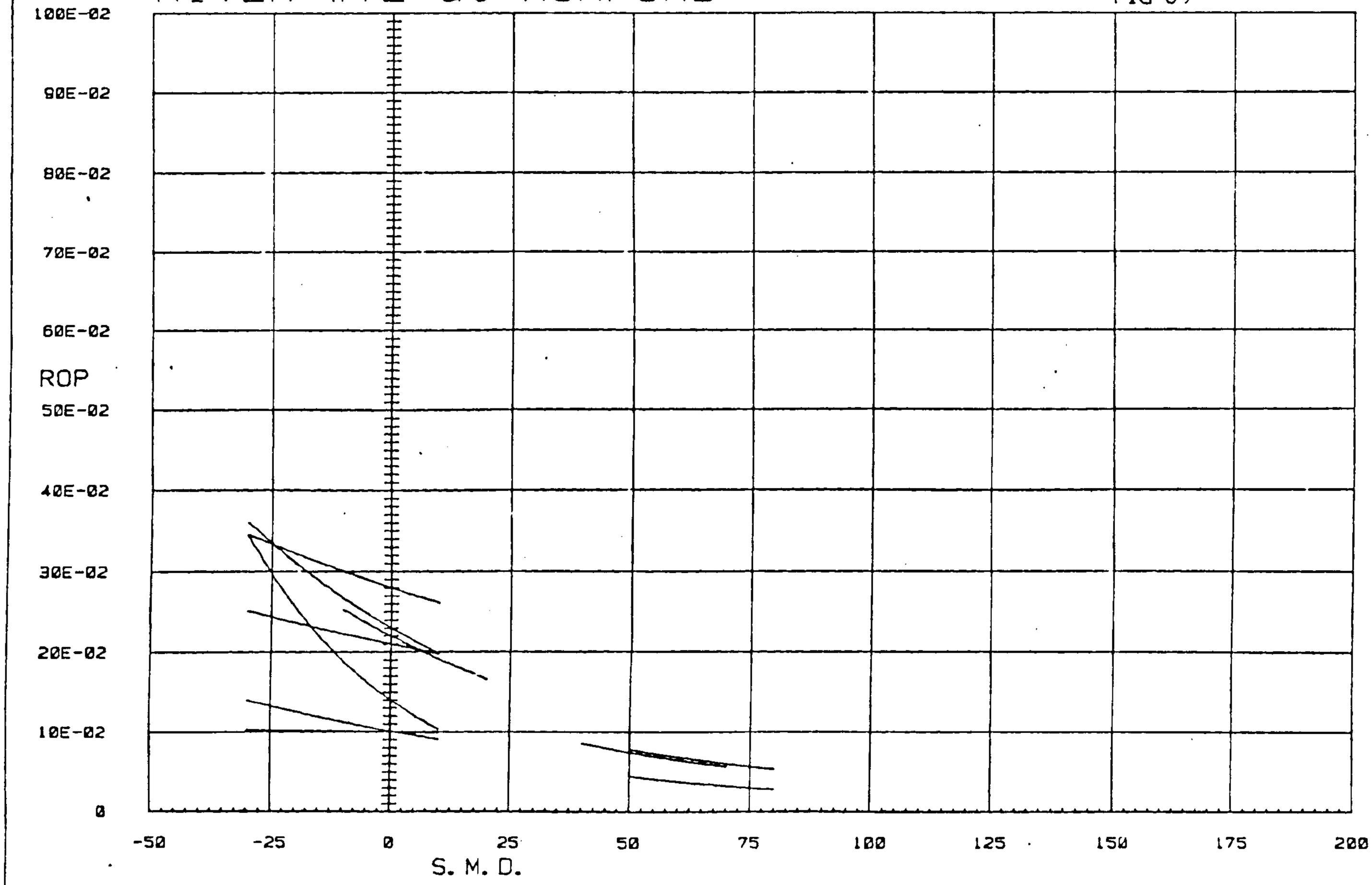
RIVER CHURNET at BASFORD BRIDGE

FIG 68

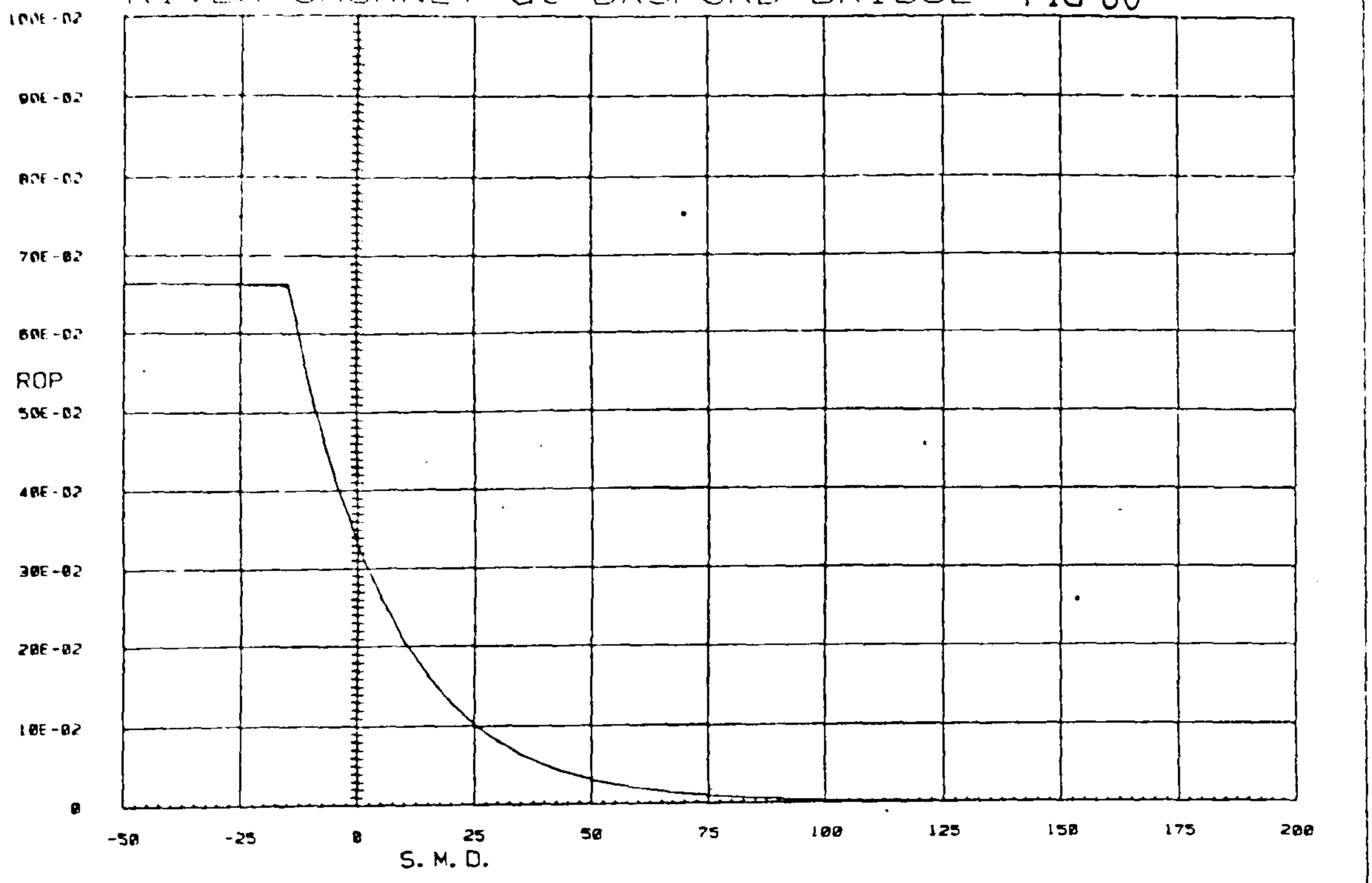


RIVER WYE at ASHFORD

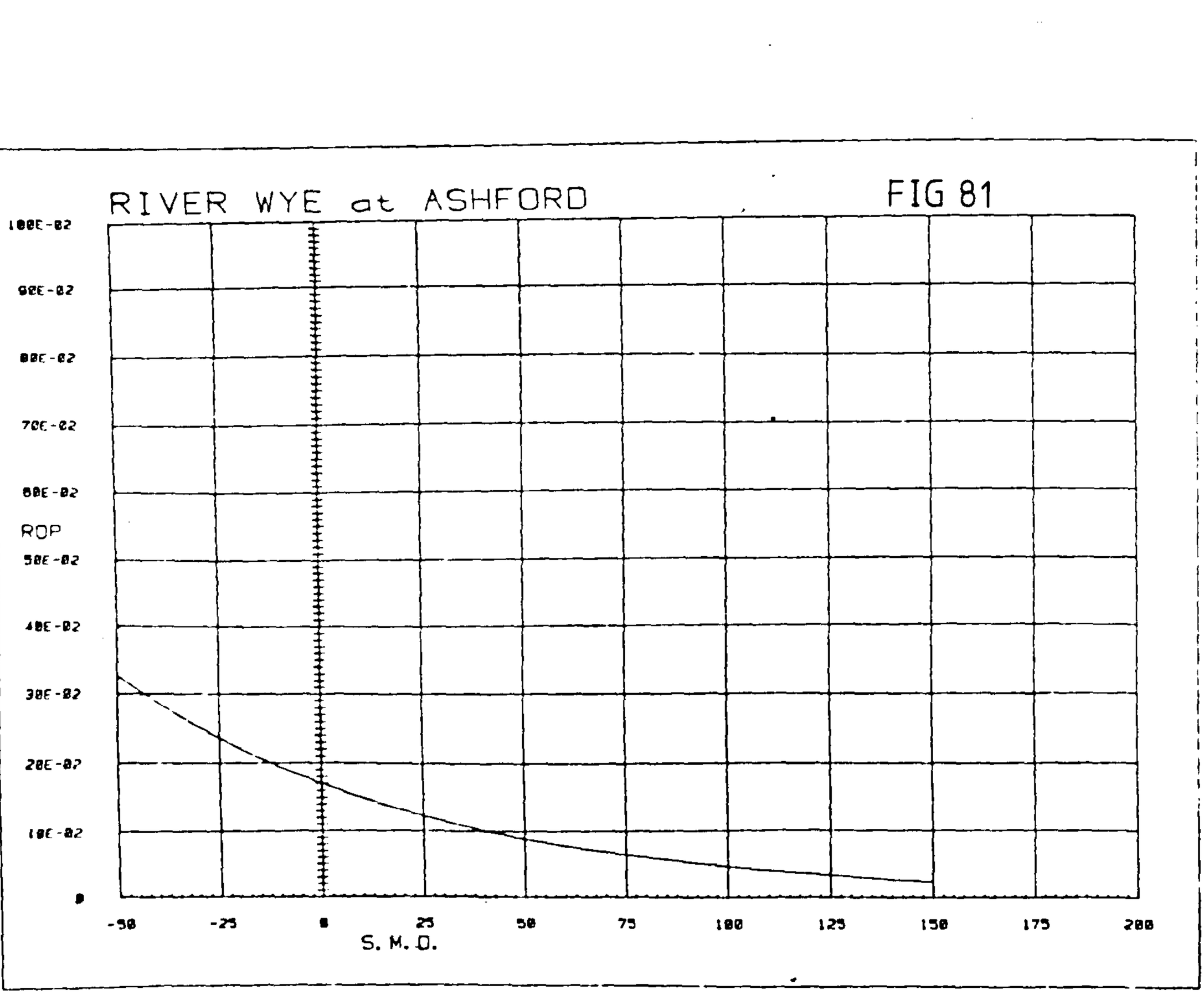
FIG 69



RIVER CHURNET at BASFORD BRIDGE FIG 80



RIVER WYE at ASHFORD FIG 81



6.8 THE ESTIMATION OF OPTIMUM CATCHMENT PARAMETER VALUES

6.8.1 The fitting procedures described in section 6.6.2 involved finding eleven best fit parameter values for up to 10 events for 14 catchments (1540 values). From the event optimum values, a single mean parameter set per catchment is determined. For the independent parameters (e.g. PLAG) the optimum values were easily determined. For each catchment in turn, every individual parameter value was assessed. If the parameter value was particularly unusual or related to a particularly poor fit then it was discarded. The justification being that rogue values are occasionally thrown up because of miss-measurement of rainfall (section 6.7.2) or errors in soil moisture defecit estimates (section 6.6.1). Much of the data from the Cole and the Rea comes into this category. The overall optimum parameter value for each catchment was taken as the arithmetic mean of the final number of optimised values.

When parameters are interdependent the problem of optimum parameter determination is more complex. Section 6.4.3 has shown that two different combinations of values of the same parameters can, in some circumstances, give similar representations of catchment response. In these cases the overall optimum parameter values are not necessarily the arithmetic means of the individual parameter sets. This is the case of the interrelated parameters PSRC, PSRS and PRPM. For fitting events with zero or a small SMD all three parameters are required to define the shape of the ROP curve, whereas for events with large positive SMD's, only two parameters are required to define the shape of the asymptotic portion of the ROP curve. To define their optimum values a computer program was written to plot graphically the actual portion of the ROP curve used in fitting any event. By overplotting the relevant portions of the curves for all 10 events in any catchment, a cumulative ROP curve can be drawn by eye through the part curves. The part curves for each catchment are shown as figures 60 to 73 and the derived optimum mean curves as figures 74 and 85 (figures 68, 69, 80

TABLE 17

OPTIMUM PARAMETER VALUES

STATION	PSRC	PSRS	PRPM	PMPC	PSST	PGWF	PLAG	PDUR	PCIF
Stoke	0.39	0.026	0.7	0.16	25.0	14570	0.34	7.28	0.062
Gt. Bridgford	0.25	0.028	0.63	0.24	35.0	20940	0.28	21.9	0.073
Penkridge	0.48	0.03	0.63	0.81	35.0	10430	1.89	12.64	0.005
Polesworth	0.59	0.03	0.6	0.78	5.0	19410	4.11	20.16	0.07
Izaak Walton	0.14	0.012	0.42	0.61	50.0	87830	2.78	4.58	0.046
Ilam	0.48	0.026	0.56	0.37	7.5	95380	3.82	1.85	0.033
Basford Bridge	0.33	0.047	0.65	0.34	17.5	85134	0.9	9.74	0.061
Ashford	0.17	0.013	0.50	0.83	50.0	85280	1.08	3.43	0.023
Wingfield Park	0.34	0.021	0.65	0.68	32.5	25650	0.78	8.94	0.039
Narborough	0.59	0.03	0.68	0.58	5.0	14390	0.49	19.91	0.072
Blaby	0.61	0.026	0.72	0.67	10.0	9020	2.02	13.63	0.046
Syston	0.71	0.026	0.72	0.67	10.0	4703	4.0	22.85	0.123

and 81 are included in the test). Figures 68 and 69 show the variation of runoff response between catchments. Figure 81 is for Dinention (limestone) catchment and Figure 80 a Namurian (Grit) catchments. The catchment optimum parameters are obtained from the figures. PSRC is the incercept of the curve and the x axis; PSST, is the position of the nick point in relation to the y axis. The measure of curvature, PSRS, is obtained by comparison with standard curve overlays (figure 88) derived by the same computer program.

The interconnecting parameters PCBF, PCOF and PCOX proved, as suggested in 6.5.5 a special case. Of all the events used to fit the model, bankfull discharge was considered to have been exceeded in 30% of cases. However, only 17% of the optimised estimates of these bankfull discharges (5% of all fitted events) were realistic. In most cases the optimisation package either failed to determine a bankfull discharge or infact recognised false bankfull discharges. In a few cases the out-of-bank parameters were falsely used for fine tuning of hydrograph shape, rather than reflecting out-of-bank flow. This situation arose because very few of the observed hydrographs exhibited any change of shape at or near bankfull discharge. Thus, in the catchments sampled, out-of-bank storage has little or nor influence on the rate of discharge at the outflow point. Extensive flood plain storage which influences hydrograph shape is more a feature of large mature rivers than small sub-catchments. For main river situations a completely different type of model with a specific routing element is required (e.g. Flout - A River Catchment Flood Model, Price (1980)). Rivers of this type are also generally gauged.

From the evidence of fitting UCM to the Trent Catchment it would seem that a single storage/routing equation and hence a 9 parameter model is adequate for simulating flows in catchments up to 300 km^2 in size.

The final optimum parameter set obtained from fitting the model to gauged catchments is given in table 17.

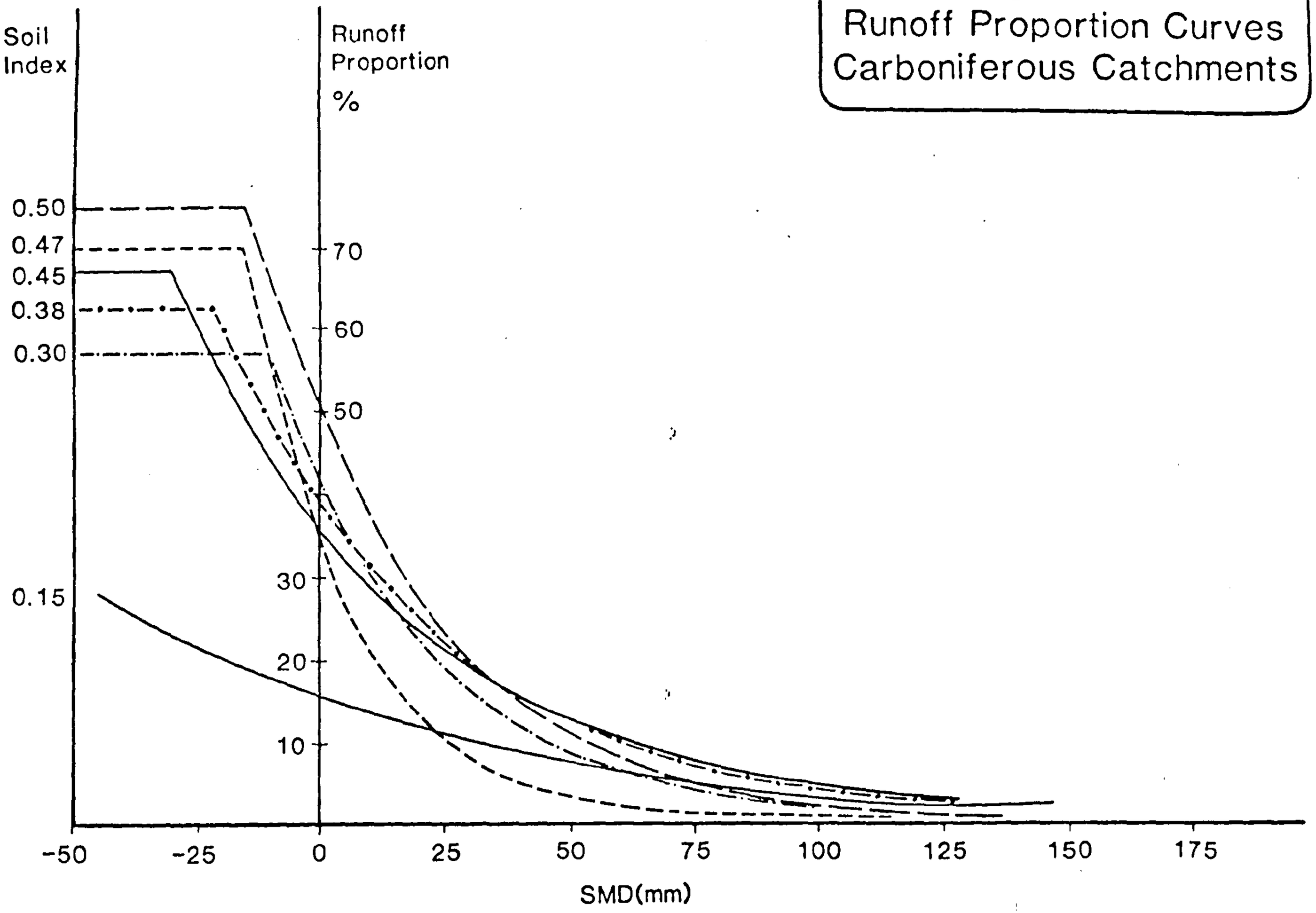


Figure 87
Runoff Proportion Curves
Carboniferous Catchments

6.9 THE ESTIMATION OF MODEL PARAMETERS FOR UNGAUGED CATCHMENTS

6.9.1 Section 6.8 has described how the simple conceptual rainfall - runoff model, UCM, was fitted to catchments in the Trent basin with gauged riverflow data. If the model is to be applied to ungauged catchments, relationships are required by which catchment parameters are estimated without recourse to runoff data. In introducing conceptual modelling (section 2.3.6) it was stated that river basins were not random assemblies of different parts, but geomorphological systems whose parts are related to each other by a long common history. If the relationships between these operations and the physical features of a catchment can be recognised, then the operation of ungauged catchments might also be forecast from a study of these features. A visual comparison of the shape of the runoff proportion curves, derived in section 6.8.1 suggest that such relationships exist. By grouping the runoff proportion curves according to catchment geology, it can be seen that geology has a primary effect and surface deposits have a secondary effect, on the relationship between percentage runoff and catchment soil moisture deficit. For example it can be seen from figures 87 and 88 that as the proportion of clay in the catchment decreases and the proportion of permeable rock increases the curvature of the ROP curve decreases.

A series of stepwise linear regressions were undertaken to quantify the relationships between 8 dependent variables; model parameters, PSRC, PSRS, PRPM, PMPC, PGWF, PDUR and PCIF; and many of the catchment indices (independent variables) described in sections 4.2, 4.3 and 4.4. (the ninth parameter, PSST, being calculated from other parameters). Seventeen independent variables were initially considered; GEOL, PERM, DWFI, SOIL, MSL, CFORM, AREA, SHAPE, RELF, ALT, SLOPE, STMFRQ, LENG, XSEC, XSWP, MANN and CHAN. These indices represented the four morphometric groups outlined in section 4.2.2: basin size and geometry, intensity of disection, catchment and channel slope and relief, channel size and condition, and catchment geology, superficial

TABLE 18

CATCHMENT INDICIES CORRELATION MATRIX

	DWFI	SOIL	MSL	CFORM	LENG	STMFRQ	SLOPE	ALT	XSEC	CHAN
DWFI	1.0000									
SOIL	-0.7753	1.0000								
MSL	0.0054	-0.1473	1.0000							
CFORM	-0.3803	0.1962	0.0875	1.0000						
LENG	0.5864	0.4296	0.6652	0.2635	1.0000					
STMFRQ	-0.0422	0.5024	-0.4686	0.0080	-0.2748	1.0000				
SLOPE	0.4321	-0.1948	-0.4739	-0.0861	-0.6761	0.5148	1.0000			
ALT	0.8905	-0.6296	0.0123	-0.2186	-0.5743	0.0952	0.7045	1.0000		
XSEC	0.1055	0.1002	0.6758	0.2411	0.4464	0.2041	0.0690	0.2860	1.0000	
CHAN	-0.4246	0.2260	0.7688	0.3265	0.8490	-0.1863	-0.4060	-0.3209	0.6263	1.0000

deposits and soils. During the regression analysis, the number of independent variables was reduced to 10 when account was taken of colinearity. For example ALT and RELF were never used in the same regression analysis nor were DWF, PERM AND GEOL. The correlation matrix for the most useful 10 independent variables is shown in table 18. Some inevitable cross correlation is evident in the matrix. Geology (DWFI) is related to soil and altitude, and all the variables representing channel size are partially correlated. Stream frequency shows some correlation with soil and slope. The most independent measure of the 10 variables included in table 18 is catchment shape.

In the regression, data from 12 catchments were used. Data from the River Cole and River Rea were not used because of the problems outlined in section 6.7. The derived regression equations are given below.

$$PSRC = 0.3693 - 0.0082\ DWFI + 0.01\ MSL \qquad (38)$$

$$MCC = 0.9144$$

$$PSRS = 0.018 + 0.0545\ SOIL + 0.455 \times 10^{-5}\ CHAN \qquad (39)$$

$$MCC = 0.8888$$

$$PRPM = 0.7347 - 0.0047\ DWFI \qquad (40)$$

$$MCC = 0.9124$$

$$PMPC = 0.9760 - 0.4134\ STMFRQ \qquad (41)$$

$$MCC = 0.8469$$

$$PGWF = 291.535\ RELF - 32891.45 \qquad (42)$$

$$MCC = 0.9380$$

$$PLAG = 0.176\ MSL + 0.0027\ RELF - 65.3631\ CFORM + 4.4293\ SOIL - 2.522 \qquad (43)$$

$$MCC = 0.9580$$

$$PDUR = 25.5768 - 0.0713\ ALT \qquad (44)$$

$$MCC = 0.8612$$

$$PCIF = 0.0682 + 0.1222 \times 10^{-4} CHAN - 0.0001 ALT \quad (45)$$

$$MCC = 0.8780$$

(All equations apply at the 95% significance level).

6.9.2 As DWFI, the geology index, appeared in two equations (38 and 40) UCM could only be applied to catchments with Dry Weather Flow maps. To give the model greater flexibility a second regression analysis was undertaken, this time with GEOL as an independent variable in preference to DWFI. Alternative versions of equations 38 and 40 were produced:

$$PSRC = 0.5258 - 0.1107 GOEL + 0.2253 XSWP \quad (46)$$

$$(MCC = 0.9255)$$

$$PRPM = 0.7222 - 0.0646 GEOL + 0.0959 STMFRQ \quad (47)$$

$$(MCC = 0.9035)$$

Thus UCM could be applied, if required, to catchments outside the Trent basin.

6.9.3 The high multiple correlation coefficients obtained for regression equations 38-47 give confidence that reliable estimates of parameter values may be obtained for ungauged catchments. However, it is equally important that the independent variables chosen for each equation are conceptually acceptable. For example an equation for PGWF, the groundwater reservoir factor, that included MANN, the channel roughness coefficient would not be acceptable regardless of the value of the multiple correlation coefficient. In the cases of equations 38-45 acceptable indices have been identified in all cases. Runoff proportion (ROP) which includes the parameters derived in equations 38-40, is primarily related to catchment geology and soil. The hydrograph 'lag' relates to catchment shape, relief and surface cover. The percolation rate to groundwater is inversely proportional to the number of streams in the catchment. The inbank channel routing factor is related to channel volume. One unexpected relationship is that between

the size of the groundwater reservoir, PGWF, and relief. A higher correlation was expected with geology. However RELIEF (as is ALT) is an imprecise variable which is partially related to geology and several other catchment characteristics such as vegetation, soil and slope. (The regression equation (48) obtained for PGWF if ALT and RELIEF are not included as independent variables is perhaps what may have been expected).

$$PGWF = 26024\ GEOL - 38114.5 \qquad (48)$$

$$MCC = 0.9139$$

Because of the high correlation coefficients and the conceptuality of the variables, the regression equations derived above can be confidently used to estimate parameters in the simple rainfall - runoff model outlined in section 6.5.4. The model can thus be used for flood prediction or flood forecasting purposes in ungauged catchments.

6.10 APPRAISAL OF THE UCM MODEL AS APPLIED TO UNGAUGED CATCHMENTS AND A COMPARISON WITH THE SYNTHETIC UNIT HYDROGRAPH TECHNIQUE

6.10.1 The accuracy and reliability of the UCM model as a means of forecasting flows in ungauged catchments were tested. Two catchments were chosen for consideration; the River Ecclesbourne to Duffield (SK 320 422) and the Kingston Brook to Kingston (SK 503 277). The Ecclesbourne is a Namurian catchment of 50.4 km^2 and Kingston Brook a Marl catchment of 58.7 km^2. Although similar in size, they are very different in terms of geology and topography and hence in runoff characteristics. The outflows from both catchments are measured by 'Crump' weirs, but historic flow data were not used to derive model parameter values. These were calculated from catchment indic es and the regression equations 38-45 (section 6.9.1). Flow forecasts were made using the UCM model, in its form given in appendix 8, for six rainfall events in psuedo real time. Three events were for each catchment and they represented a variety of conditions. For example, a storm in February 1977 was considered, which

Figure 92
Performance of UCM in Real Time Mode - Kingston

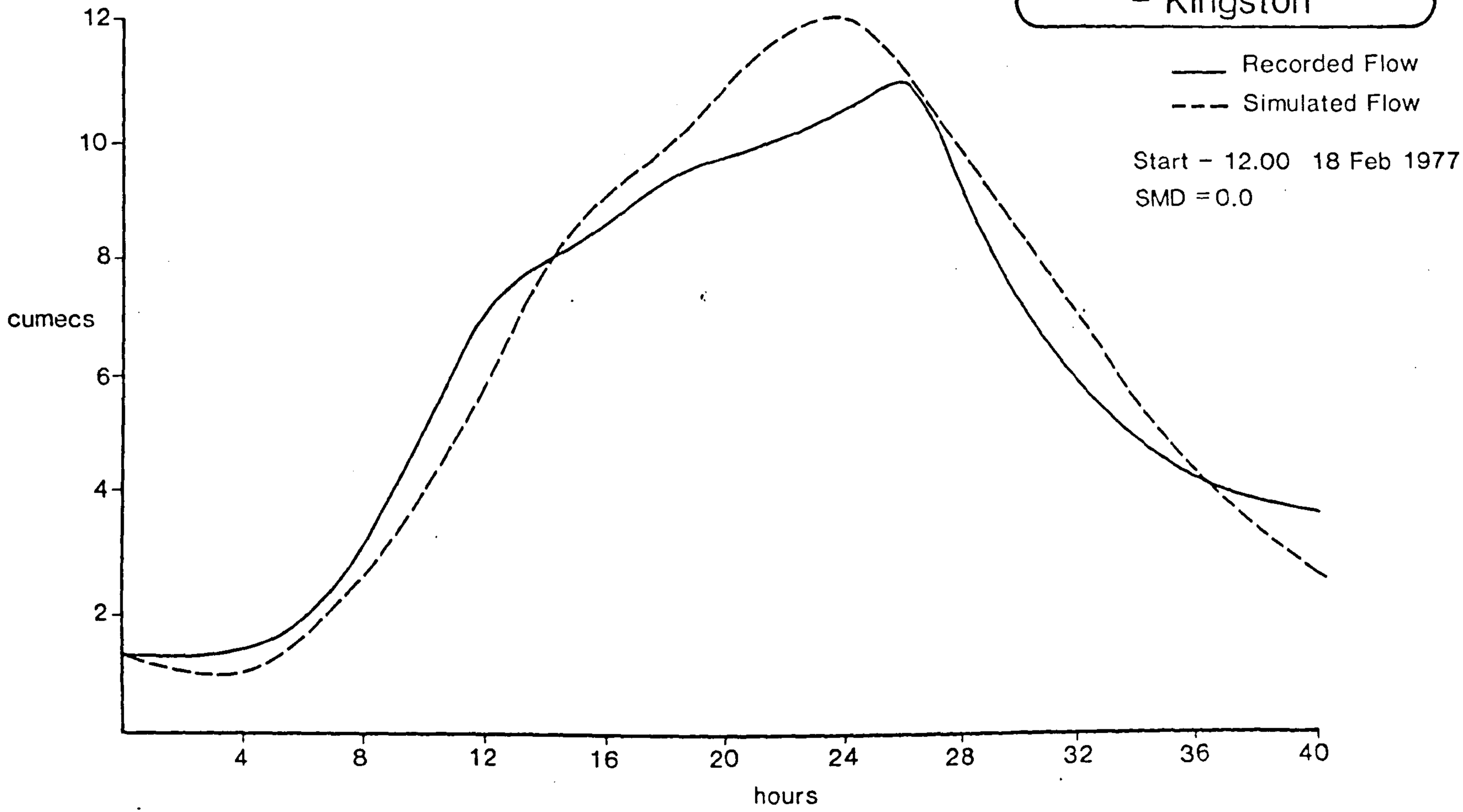


TABLE 19

RESULTS - REAL TIME FLOW SIMULATION

	ERROR max level mm's	ERROR max flow cumecs	ERROR max flow %	ERROR TOTAL VOL %	ERROR TIME TO PEAK (hrs)
89 DUFFIELD	10	+ 0.25	+ 3	+ 11	+ 5.5
90 DUFFIELD	24	- 9.50	- 35	+ 10	+ 3.0
91 DUFFIELD	9	+ 0.25	+ 3	+ 25	+ 3.0
92 KINGSTON	7	+ 1.00	+ 9	+ 2	- 1.5
93 KINGSTON	2	+ 0.10	+ 1	- 4	- 2.7
94 KINGSTON	0	0.00	0	- 14	0.0

gave regionwide flooding throughout the Trent catchment. Also considered, were intense local thunderstorms occuring during periods of soil moisture deficit. All rainfall and soil moisture deficit data for the test events are given in Appendix 11.

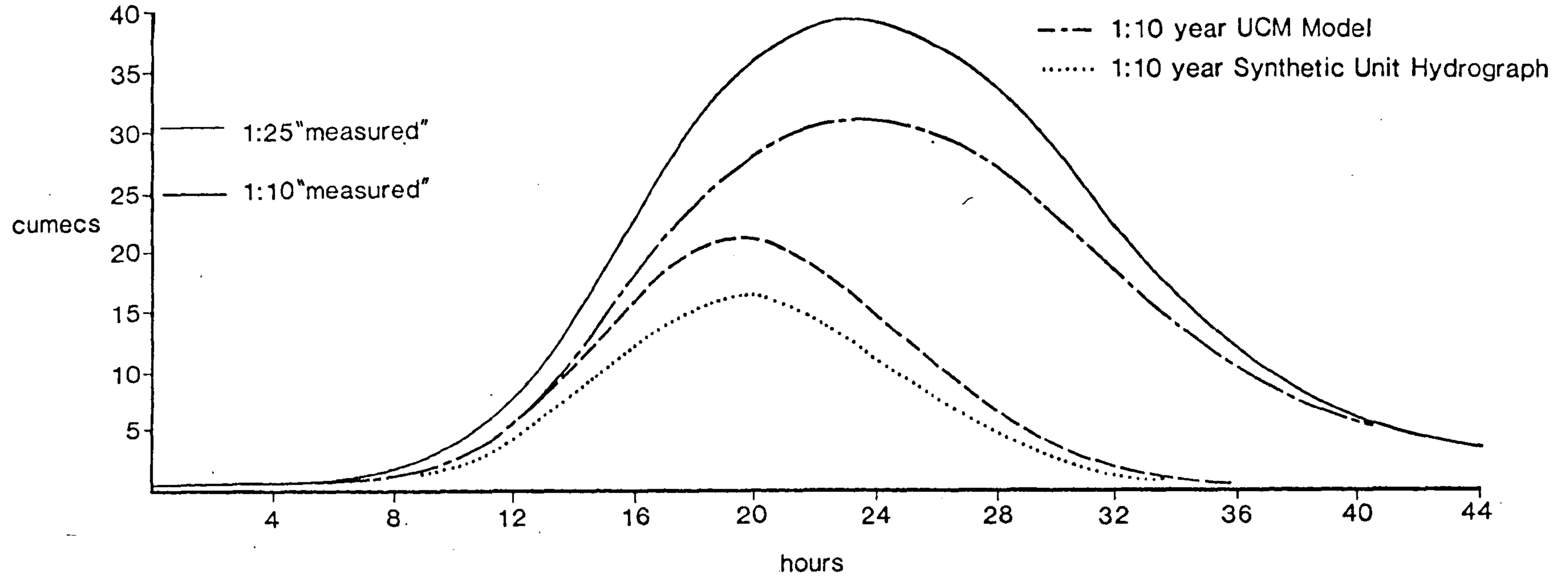
The flows forecast for the six test events are shown in figures 89-94, along with the actual measured runoff hydrographs. (Figure 92 is included in the text). The differences between observed and forecast flows are summarised in table 19.

The model simulated flows for the Kingston Brook well. The large floods of February 1977 (Figure 92) and May 1978 (Figure 93) were reproduced almost exactly and although the model did not reproduce two peaks for the May 1980 event (Figure 94) the overall representation of the maximum flow was good. Convective rainfall was the cause of this small event and the poor representation of overall shape is probably due to imprecise rainfall sampling, as in the case of the urban catchments discussed in section 6.7.

Representations of runoff for the Ecclesbourne catchment were less successful. The peak flows for the events of September and October 1981 (Figures 89 and 91) were accurately simulated but hydrograph shape and timing were not precisely defined. The poorest simulation of all was for the May 1979 event (Figure 90). In this case, as well as the shape and timing being in error, the peak flow was also underestimated. This misrepresentation of runoff volume was again probably due to poor rainfall sampling.

Of the two test catchments, the parameter values estimated for the Ecclesbourne were inferior to those estimated for Kingston Brook. The major discrepancies being in the estimates of PERC, PLAG and PCIF. However, overall, only one simulation could be termed very inaccurate, three were reasonable and two were very accurate. The average error in the peak and total flows being 8.5% and 11% respectively (ie

Figure 96
Comparison of UCM and Unit Hydrograph – Kingston



flows are estimated to a similar accuracy to which they are measured, Section 3.5.3) and perhaps of greatest significance to a real time flow forecasting model, is that the average error in peak level was only 9mm, when flows were reconverted to level using a stage - discharge relationship. By comparison, few models fare any better when fitted to gauged data. For example, the Severn-Trent Water Authority only expect one in three real time forecasts to be accurate when applying a 27 parameter conceptual model in fitted catchments (STWA, 1983). Similarly, when fitting the IEM4 model (Figure 2) to 21 gauged catchments, the Flood Studies Group obtained average errors in peak and total flow of 13.4% and 12.7% respectively. Thus by comparison, the UCM model with estimated parameters, performs adequately and it is considered that the model could be used for rainfall - runoff forecasting in ungauged catchments.

6.10.2 The reliability of UCM as a prediction tool was considered using synthetic design rainfalls as inputs. The Kingston Brook and the Ecclesbourne catchments were again used for the analysis. The 1 in 17 year and the 1 in 42 year storm rainfall profiles were derived from the 'Flood Studies Report', Volume II, Meteorological Studies (NERC, 1975). These rainfalls corresponding to 1 in 10 year and 1 in 25 year return period runoffs (Flood Studies Report, Volume I, Section 6.8.2). The hourly rainfall ordinates (given in Appendix 12 along with other starting conditions) were convoluted by both the 'Flood Studies Report' synthetic unit hydrograph technique (Volume I, Section 6.8.2) and the UCM model with estimated catchment parameters to produce hydrograph predictions. (A detailed example of the synthetic unit hydrograph method is given in appendix 13). The modelled outputs from both the UCM model and the unit hydrograph technique are shown in Figures 95-96. In all four cases, the unit hydrograph method predicted less runoff from the synthetic rainfalls than the UCM model. For Kingston Brook this was 63% and for the Ecclesbourne 14%. The estimates of hydrograph duration predicted for the Ecclesbourne by the two methods were similar, but for the

Kingston Brook, the synthetic unit hydrograph estimates of duration were much too short. This is confirmed by a comparison of Figure 96 and the measured hydrographs shown in Figures 92 and 93. For these two moderately large (less than mean annual flood proportions) events, the times to peak were 24 and 26 hours. Conversely the synthetic unit hydrograph method predicts a time to peak of 19 hours for both the 1 in 10 year and 1 in 25 year flows.

Annual maximum flow frequency analyses of measured data from the Ecclesbourne and Kingston Brook catchments were undertaken to ascertain the actual 1 in 10 and 1 in 20 year peak flows. Gumbel paper and the Gringorter plotting position (Section 5.4.3) were used (figures 97 and 98). Both records are relatively short (Ecclesbourne 11 years, Kingston, 7 years) and the highest flows at Kingston are also estimates as the weir drowns out at 11 cumecs. Nevertheless, the indications are that the UCM model is a superior to the synethetic unit hydrograph method for application within the Trent basin. In all cases, the UCM predictions were closer to the observed than those produced by the unit hydrograph method.

6.11 CONCLUSIONS

Section 6.5.4 has described a simple nine parameter rainfall - runoff model that will forecast or predict riverflows in ungauged catchments. Model parameters are estimated from catchment indic es and regression equations (Section 6.9.1). Most of the indic es can be derived from maps but some also require field measurement. The model has been shown (Section 6.10.2) to be a viable alternative to the synthetic unit hydrograph method (NERC, 1975) for hydrograph prediction in the Trent basin. Further, when used in real time (Section 6.10.1), the model provides reliable forecasts of catchment outflow from measured rainfall inputs. There is no other equivalent conceptual model which can be used for real time forecasting in ungauged areas in Britain. The model could be particularly suitable for providing flow

forecasts for single communities located at the outflow points of single uncomplicated catchments. For example, Skipton, in North Yorkshire, which has been flooded twice in the last five years, could be served by this model. The model does not supersede regional flood forecasting models of the type developed by many regional water authorities (for example Severn-Trent Water Authority, (Manley et. al 1980)) but could be used to complement them.

7 CONCLUSIONS

7.1 INTRODUCTION

Riverflows constitute both a major hazard to human activities and an important natural resource. If the magnitude and frequency of riverflows at any location are quantified then the hazards can be diminished and the benefits maximised. Whilst some of these data are measured, the majority have to be estimated. It is with the problem of riverflow estimation that this thesis is concerned.

Historically, riverflow estimation techniques have been categorised into two groups; estimates of low flows which include specific indic.es of base flow, flow duration curves and flow frequency curves, and estimates of high flows, comprising probable maximum peak flows, peak flows of particular return period and hydrographs resulting from specific storm rainfalls. Low flow estimation methods should be reliable, as baseflows are predominantly maintained by groundwater and their magnitude should be closely related to catchment size and geology. However in practice, the majority of currently available methods are inadequate for most purposes. The major problem with low flow derivation is in the representation of catchment geology in the estimation equations. Any expression of geology has to be multi-purpose in dealing with porosity, the ability of the rock to store water; permeability, the capacity to yield water; and local structural effects. There have been many indic es advocated to account for these processes, for example, Wright (1970, 1974) suggested an 'arbitrary scale', Carlston (1963) 'drainage density', Browne (1981) 'recession curves' and the Institute of Hydrology (1980) a 'base flow index'. However none of the indic es and hence none of the low flow estimation techniques have been totally successful (TASK, 1980., Pirt and Douglas, 1982., Pirt and Simpson, 1982).

High flow estimation techniques are of two specific types: estimates of peak flows, derived by means of parametric (regression) equations, and estimates of complete hydrographs derived by means of system synthesis. The parametric equation approach to peak flow estimation provides important information, but has two drawbacks; few of the equations derived to date are accurate (Francis, 1973., Simpson, 1977) and they give no information as to the shape of, or the total volume of, the flood hydrograph. Yet for most real time flood forecasting and design prediction purposes this information is generally required. Historically, hydrograph synthesis for ungauged catchments has been undertaken by the unit hydrograph approach (Nash, 1960., NERC, 1970) but many authors (Amorocho and Hart, 1961., Nash and Sutcliffe, 1970., Francis, 1973) agreed that this method has a basic weakness. Unit hydrograph theory treats catchments as linear systems (invariance and superposition of responses apply) where—as natural systems are non-linear and time variant. These simplifying assumptions can lead to estimation errors and it is considered herein that a more realistic (conceptual) treatment of catchment process offers an opportunity to realise more reliable results.

This thesis therefore has two prime objectives:

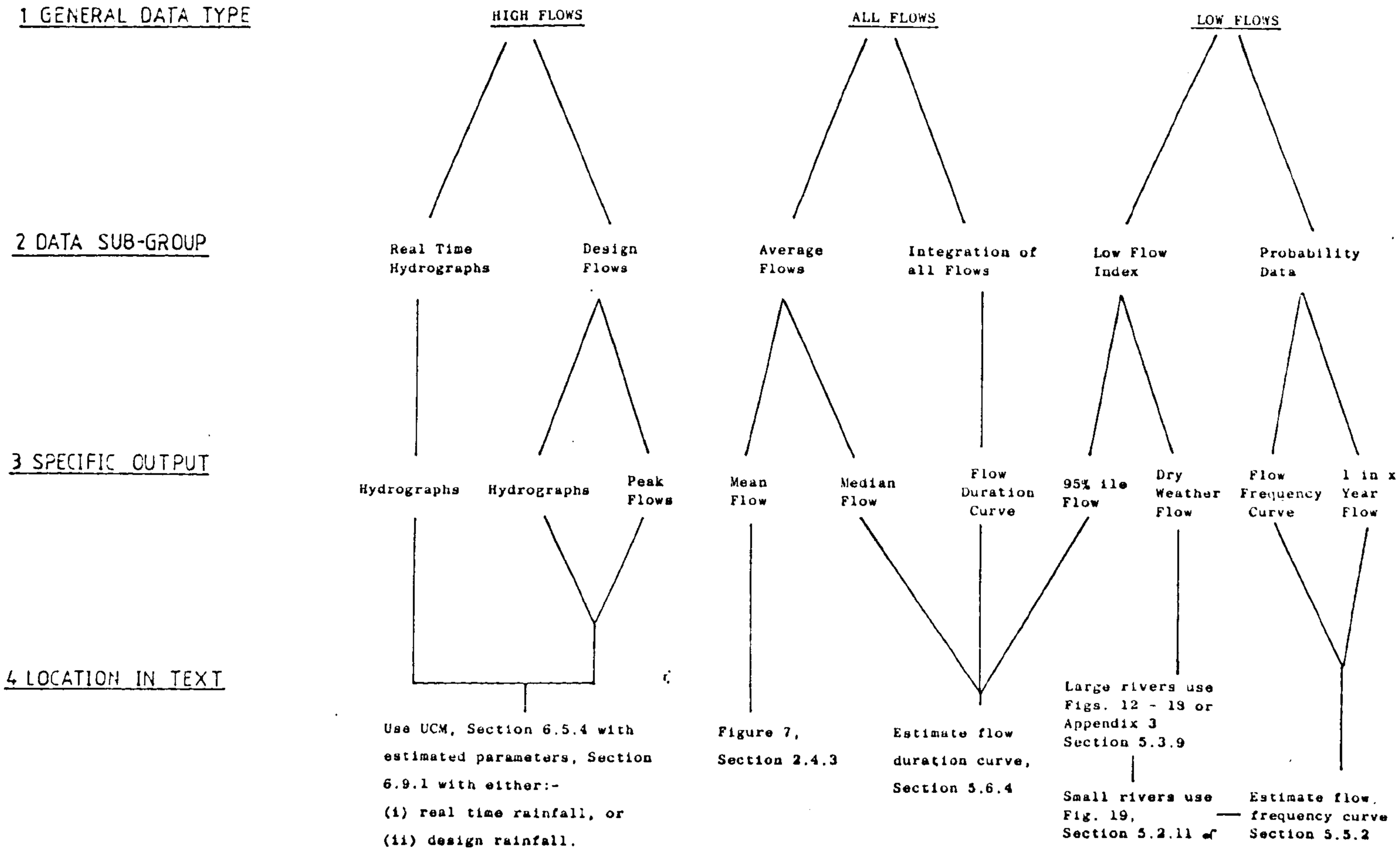
(i) The derivation of reliable methods of low flow estimation in which adequate account is taken of catchment geology.

(ii) The derivation of a non-linear conceptual hydrograph estimation technique that produces either predictions or forecasts (and thus by definition also provides estimates of peak flow).

The study has been based on the catchment of the River Trent and the methods derived are primarily for application in this area, however account has also been taken of the more general situation.

FIGURE 100

SUMMARY OF METHODS OF ESTIMATION



7.2 SUMMARY OF METHODS OF FLOW ESTIMATION

The derived methods of flow estimation for ungauged catchments are summarised in figure 100. Six data types can be identified: An index of low flow, flow frequency curves, flow duration curves, average flows, hydrograph forecasts and hydrograph predictions.

(i) An index of low flow:

The seven-day average 'Dry Weather Flow' is advocated for use as a design-flow in water resource management. This is a stable statistic which can be considered as a representation of the driest week in an average summer. A complete picture of Dry Weather Flow is presented for the Trent basin in two forms; residual flow diagrams and a runoff yield map. A residual flow diagram is a snapshot of the flow throughout a river system, including an assessment of the quantity and quality of both the natural and artificial components of flow at any point and as such is the most satisfactory mode of combining all occas ionally and continuously measured flow data to provide estimates of discharge for sites without gaugings. The distinction betwen artificial and natural flow is important and it is shown that in the R Trent, R Tame and R Soar the artificial component often exceeds the natural flow, where-as in contrast, the R Dove and R Derwent are almost totally natural. The Dry Weather Flow natural yield map itself is a by-product of the residual flow diagram approach. By dividing the net addition to natural runoff between gauged points on the diagrams, natural runoff yields per unit area have been calculated. These have been mapped and this can be used to estimate the Dry Weather Flow of any catchment of interest in the Trent basin which is not specified directly on the residual flow diagrams. It has also been shown that Dry Weather Flow yield is an excellent representation of

integrated catchment geology and as such can be used as a geological index. Other more general geological indic es and scales of the type developed by Wright (1970, 74) and the Institute of Hydrology (1980) are adequate in some instances but are totally unreliable in others due to the effects of unseen variations in structure and lithology. Nevertheless, for locations outside the Trent basin without DWF yield maps, a regression equation, based on an arbitrary geological index is presented to estimate Dry Weather Flow. The equation has a MCC of 0.91, but in application, it will never be totally reliable because of the geological problem.

(ii) Flow Frequency Curves (Probability Distributions):

An analysis of measured low flow probability distributions showed that , in general, the distributions form straight lines when plotted with the Gringorten plotting position on Gumbel paper. Moreover, the derived Dry Weather Flow was confirmed as having a return period of 2.33 years. One point on a flow frequency curve for an ungauged catchment can thus be determined by the methods described in (i) above. To complete the distribution, the slope of the straight line through the 2.33 year flow is determined from a regression equation based on catchment geology (the MCC is 0.96). In the Trent basin, geology is represented by the Dry Weather Flow yield and in other areas, by an arbitrary geological index.

(iii) Flow Duration Curves:

The properties of measured flow duration curves have been evaluated and the analysis demonstrated that, when normalised (÷ mean catchment annual effective precipitation) the distributions portrayed variable curvatures which related to catchment geology and surface deposits. This property has been used to

derive a graphical estimation method: flow duration curves may be estimated for many locations by the application of normalised base curves and measures of catchment effective rainfall and area.

(iv) Average flows:

A map of mean annual effective precipitation is presented for the Trent basin and for any area, average effective precipitation is shown to be a measure of average runoff.
The median flow (50% exceedence flow) can also be calculated for any area, see (iii) above.

(v) Predictions and Forecasts of runoff from storm rainfall:

A nine parameter, non-linear, conceptual rainfall - runoff model is used to represent natural catchments. Three catchment processes are simulated:

a) Surface runoff is calculated as a function of the soil moisture deficit.

b) Baseflow is calculated as a function of the contents of a groundwater reservoir.

c) Combined surface and baseflow runoff are routed through storage elements which influence the shape and timing of the runoff hydrograph.

The model has been fitted to measured data from 14 gauged catchments with an average efficiency of 93%. For ungauged catchments, estimation equations based on catchment indic es have been derived to estimate model parameter values (the average MCC of the equations is 0.90). The catchment indic es include geology, surface deposits, relief, shape, stream frequency and the dimensions and the length of the main stream

channels. The model can be used to forecast (real time) or predict (design) hydrographs for ungauged catchments using inputs of catchment rainfall, initial catchment soil moisture deficit and an initial discharge at the forecast outflow point. Both rainfall and soil moisture deficit data are potential sources of error and considerable care has to be taken in choosing these values. This is particularly true of rainfall in urban areas where convective enhancement may give variable rainfall patterns.

7.3 COMMENT

7.3.1 The derived flow estimation techniques have been shown to be accurate and reliable for application in the Trent basin. For example, the average error in predicting the 10 year 7 day low flow in four diverse catchments using the flow frequency estimation technique was 11%. Comparison of the techniques with gauged data from other areas in the north of England also showed that some of the methods, if not all the specific data, are suitable for more widespread application. In deriving flow duration curves for four catchments in Yorkshire and one in Lancashire the average errors in the estimation of the 50 (median) and 91 (approximate DWF) percentile flows were 12% and 17% respectively. The methods also proved superior to those advocated by the 'Low Flow Study' (IOH, 1980) for estimating dry weather flows, flow frequency curves and flow duration curves. The average error in predicting the 10 year 7 day flow for the same four Trent subcatchments using the 'Low Flow Study' method was 66% (compared with 11%) and similarly, the average errors in estimating the 50 and 91 percentile flows for the Yorkshire and Lancashire catchments were 29% and 57% (compared with 12% and 17%). The derived conceptual hydrograph simulation model also proved reliable. The average errors in forecasting peak and total flows for six 'real time' floods were 8% and 11% respectively. There is no other equivalent forecasting model to which these results can be compared. The model was also superior to the unit hydrograph losses model advocated by the

'Flood Studies Report' (NERC, 1975) in estimating design hydrographs for two catchments in the Trent basin. The unit hydrograph technique predicted 63% and 14% less runoff than the conceptual model for the 1 in 10 and 1 in 25 year design hydrographs for the Kingston Brook and Ecclesbourne catchments. Peak flow frequency analyses showed the conceptually modelled flows to be the most realistic.

There are three fundamental reasons why the estimation techniques developed herein are superior to other methods:

(i) The methods are, where relevant, conceptual and they describe the physical processes which occur in catchments.

(ii) They make optimum use of all hydrometric data. By the rigorous naturalisation process undertaken to produce the residual flow diagrams, all riverflow data (both discrete and continuous) are used to maximum effect.

(iii) The use of Dry Weather Flow yield as an index of geology is preferable to other indic es as it is an integration of all the properties of the rocks within a catchment.

7.3.2 Whilst the majority of data analysed in this study came from a single drainage basin, the Trent, it has been shown that all the techniques derived herein, could be further developed for application in other regions or counties. However, the application of the low flow estimation methods are better suited to areas with some gauged information. This is because of the significance of constructing residual flow diagrams, the natural yield map and the application of the yield map as an index of geology. In fact, the derivation of residual flow diagrams and yield maps would be a worthwile hydrological advance in all areas with adequate data (ie much of Europe and North America). Nevertheless, there will always be areas completely without gauged data and for these, estimation equations based on catchment indic es, of the type

derived in section 5.5.3 are required. The methods which do not rely heavily on numeric descriptions of geology: the flow duration curve estimation technique and the conceptual rainfall - runoff model, are more readily applicable to areas outside the Trent basin but these methods could also be improved by the inclusion of a wider range of data. In the case of flow duration estimation this would provide a greater number of base curves and in the case of the conceptual model, the analysis of further catchments would improve the regression equations by which parameters are estimated.

7.3.3 Whilst during the past decade there have been many improvements in data processing and hydrometric practices, including the development of electro-magnetic and ultra-sonic flow measurement techniques, the problem of estimating the magnitude and frequency of riverflows has not reduced in significance. In many cases, the application of new technology to riverflow measurement has brought associated higher costs, and this factor along with the world economic recession now means that in some areas, less flow data is collected than previously. Yet at the same time, water resource and flood protection development pressures continue to mount. The solution to this dilemma remains in the estimation of riverflows and it is hoped that the research described in this thesis constitutes an advance in this area.

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