Low flow estimation
in the
North West Water region
Draft report
1988

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Preface

This report describes the results of a low flow study of the North West region commissioned by North West Water and carried out by the Institute of Hydrology. The main objective of the study was to improve techniques for low flow estimation. The study was based on mean daily discharge data for 114 stations held on the UK surface water archive. The authors would like to acknowledge the contribution of North West Water, particularly Mike Knowles, to the development of the report and also the assistance and advice provided by Alan Johnstone and Ray Rushton in the classification of station data quality. The authors further acknowledge the contribution of Roger Moore and Ann Sekulin in the development and application of digital cartography techniques. This report is complementary to a national revision of low flow estimation procedures in the UK funded by the Department of the Environment (Water Directorate, Contract No. 7/7/135)

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SYMBOLS AND ABBREVIATIONS

ADF	average daily flow in cumecs
AREA	catchment area in km^2
BFI	base flow index
FALAKE	proportion of catchment covered by lake or reservoir
MAM(10)	mean annual 10 day minimum
MODE(30)	weighted mid-point of the smallest discharge range to contain 30% of all discharge values
Q95(1)	1 day average flow exceeded by 95% of daily discharges
SAAR	standard period (1941-1970) average annual rainfall
TSL	total stream length
WRAP	winter rainfall acceptance potential

1. BACKGROUND TO THE STUDY

1.1 INTRODUCTION

The Low Flow Studies report (Institute of Hydrology 1980) developed a national design procedure for low flow estimation at the ungauged site. Regional relationships were established between key low flow indices - Q95(10), MAM(10) - and catchment characteristics at 626 gauging stations in the United Kingdom. Within the regional relationships, low flow indices were expressed as a fraction of average daily flow to enable comparison of values between catchments of different area. The key catchment characteristic in determining low flow patterns was shown to be the Base Flow Index (BFI), a measure of the proportion of total runoff derived from stored sources. The procedure for estimating low flows at the ungauged site requires an estimate of BFI at the site of interest using local data to provide gauged values of BFI and the inspection and interpretation of soil and geology maps. The derived BFI value is then applied to the appropriate equation to obtain estimates of each low flow measure.

Historical perspective

The period since the final data collection phase of the Low Flow Studies report in 1974 has been marked by several extreme low flow events at a national scale. The summers of 1976 and 1984, in particular, yielded well-below normal rainfall resulting in summer low flows with minima estimated to occur only once in every 250 years. The North West Water region has experienced an increased frequency of rainfall deficiencies since 1970 compared with the period 1945-1970. This trend is represented by the increase in both the persistence and magnitude of rainfall deficiency peaks at Thirlmere (Institute of Hydrology 1985), as shown in Figure 1. The rainfall deficiency index for each month represents the departure below the long-term average rainfall depth for that particular month, which may be added to the cumulative deficiencies in preceding months if a deficit series is present (Institute of Hydrology 1985). It is evident from the diagram that a prolonged period of rainfall deficiency occurred throughout the period 1970 to 1978.
The 1976 drought was less significant in the North West region than in southern England and Wales, although the Weaver basin in Cheshire experienced its lowest summer rainfall minima on record in that year. However, in 1984 a large part of the region experienced the lowest summer rainfall on record, with the April to August period receiving less than 50% of the long term average rainfall depth for the period. This rainfall minima is estimated to have a return period in the order of 300 years.

It is therefore appropriate to revise low flow estimation procedures to incorporate recent extreme events, whilst at the same time benefitting from the extension and increased density of available hydrological records.

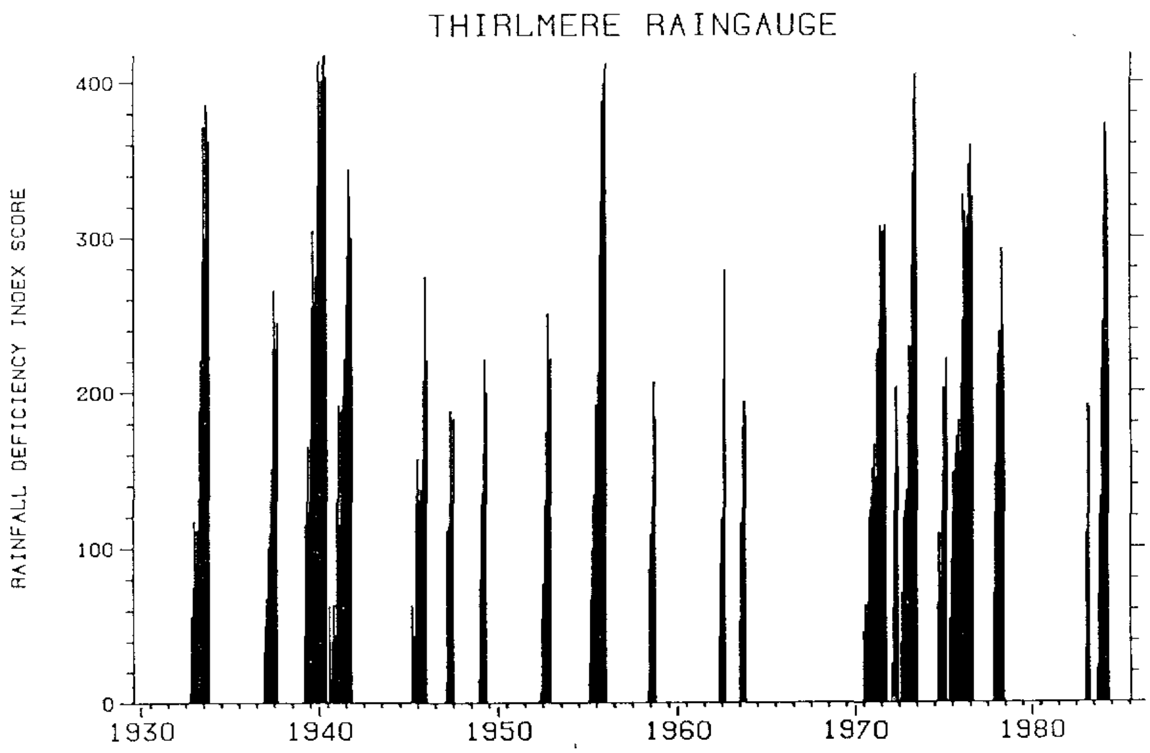


FIG. 1 Rainfall deficiency peaks at Thirlmere, 1930-1985.

Development of the modal flow index

Consideration of flow regime statistics suitable for water quality design has tended recently towards average flow conditions as well as low flow extremes. This has led to recommendations towards the incorporation into design procedures of a measure describing the most frequently occurring flow - the modal flow index. Although modal flow indices have been employed as flow statistics in previous studies, the index lacks a standard definition. The development of the most suitable algorithm for defining the modal flow is investigated within this report, and the different procedures are summarised in Appendix 2.

Developments in digital cartography

Regional hydrological techniques have benefitted greatly from recent developments in automated cartography and the production of data bases of hydrologically relevant data. Existing low flow estimation procedures rely on the interrelationships between low flow measures and catchment characteristics, which require estimation from thematic maps. Techniques for deriving catchment characteristics have been traditionally based on the catchment area above the site of interest. They require the user to delimit and overlay the catchment boundary on a series of thematic maps to derive catchment characteristic estimates. In addition, the derivation of BFI involves interpretation of local geology and soil maps. Such procedures based on catchment area can prove time-consuming and repetitious to the user, and require a local knowledge of the relationship between BFI and catchment soil and geology.

The recent availability of computerised data bases - including river networks, winter rainfall acceptance potential (WRAP) classification of soils, rainfall, and potential evaporation - are thus of considerable value to low flow estimation procedures in reducing the user commitment to catchment characteristic derivation. An automated procedure is developed in this report which generates estimates of BFI and other low flow estimates for all significant river stretches in the North West Water region. This is achieved by superimposing a data base of river networks upon thematic data bases. Catchment characteristics for each river stretch are derived from their relationship with the natural river network above the downstream node of each stretch rather than with their catchment area. This report shows that catchment characteristic values derived from the river network technique exhibit strong correlations with values derived from the traditional catchment area procedure.

1.2. SUMMARY OF REPORT

This project uses standard techniques of low flow regionalisation, employing the Base Flow Index as the dominant catchment characteristic, in an improved low flow estimation procedure for the North West Water region. The improvements upon previous design procedures are based on the

- specific attention to the estimation of low flow events in the North West Water region rather than the use of national equations
- increased data availability
- inclusion of recent extreme events
- revised classification of the hydrological response of soil series
- development and estimation of a modal flow index
- developments in automated cartography.

In this draft report, the five class Winter Rainfall Acceptance Potential (WRAP) map is employed as the basic hydrological response map. The second stage of the project will incorporate both a revised map based on a nine class division, and an interpretation of local soil and geological variations by staff of the Soil Survey of England and Wales.

This work in the North West Water region is complementary to a national revision of low flow estimation procedures in Great Britain at the Institute of Hydrology, funded by the Department of the Environment.

1.3 CATCHMENT SELECTION

Mean daily discharge data for 114 gauging stations held on the UK Surface Water Archive are used in the calibration of the low flow estimation procedure.

Records for 118 stations in the North West Water region were assessed for their suitability by the grading procedure described below, with the assigned grades presented in Table 1.

The catchment selection procedure adopted within this project assigns a two letter grade to each gauging station; the former describes the hydrometric quality of the flow records and the latter describes the degree of artificial influence exerted on the natural flow regime within the catchment above the station. Both of the quality grades range from A to C, and are defined as follows;

	Hydrometry	Artificial influences
A	Factorial standard error of estimate of check gaugings is less than 10% at the Q95 discharge, and the control is sensitive at low flows.	The gauged Q95/ADF differs by less than 20% from the natural Q95/ADF.
B	Factorial standard error of estimate of check gaugings is between 10% and 20% at the Q95 discharge, and the control is sensitive at low flows.	The gauged Q95/ADF differs from the natural Q95/ADF by between 20% and 50%.
C	Either the factorial standard error of estimate is greater than 20% at Q95 or the control is insensitive at low flows.	The gauged Q95/ADF differs from the natural Q95/ADF by more than 50%.

Extensive consultation with North West Water staff confirmed the grades assigned to each station.

Only stations which are graded either A or B for both hydrometry and degree of artificial influences are included in this study, although in this preliminary stage no discrimination is made in the use of A and B graded stations. C grade stations are omitted from low flow analysis but may be incorporated at the final stage of the project in the calibration of the procedure for average daily flow estimation at the ungauged site.

The 66 stations selected by this procedure were supplemented by 48 stations from neighbouring Water Authority regions, including Northumbrian WA (20), Severn-Trent WA (18), Yorkshire WA (7) and Solway River Purification Board (3). These supplementary stations were selected to represent underlying solid and drift geology types which occur both within and outside the North West Water region but which are better represented by discharge data inside other Water Authority regions within a similar range of mean annual rainfall.

Whilst the grading procedure described above was applied only to the 118 stations in the North West Water region, the 48 supplementary stations from other water administrative regions are known to possess long series of good quality, relatively natural flow records.

The reference number and name of each gauging station together with the period of record used are shown in Table 2. The location of the gauging stations is shown in Figure 2.

Table 1 Low flow data quality classification of North West Water gauging stations.

STATION	RIVER	LOCATION	GRADE	
68001	Weaver	Ashbrook	AB	
68002	Gowy	Picton	CA	
68003	Dane	Rudheath	CA	Pre-1978
			AA	Post-1978
68004	Wistaston Brook	Marshfield Bridge	CA	Pre-1980
			BA	Post-1980
68005	Weaver	Audlem	AA	
68006	Dane	Hulme Walfield	CA	Pre-1978
			AA	Post-1978
68007	Wincham Brook	Lostock Gralam	CA	Pre-1982
			AA	Post-1982
68010	Fender	Ford	BA	*
68011	Arley Brook	Gore Farm	AA	*
68015	Gowy	Huxley	CA	Pre-1979
			AA	Post-1979
68018	Dane	Congleton Park	Flood warning	
68019	Weaver	Pickerings Cut	CC	*
68020	Gowy	Bridge Trafford	BA	
69001	Mersey	Irlam Weir	CC	
69002	Irwell	Adelphi Weir	BC	
69003	Irk	Scotland Weir	BC	
69004	Etherow	Bottoms Reservoir	AC	Nat 45-69
69005	Glaze Brook	Little Woolden Hall	CC	
69006	Bollin	Dunham Massey	CC	
69007	Mersey	Ashton Weir	AC	
69008	Dean	Stanneylands	AA	*
69011	Micker Brook	Cheadle	BA	*
69012	Bollin	Wilmslow	BA	
69013	Sinderland Brook	Partington	AB	
69015	Etherow	Compstall	AC	
69017	Goyt	Marple Bridge	AB	
69018	Newton Brook	Fiddle 'I' 'Th' Bag	AA	*
69020	Medlock	London Road	BB	
69021	Stake Brook	Bacup	AA	*
69023	Roch	Blackford Bridge	CC	
69024	Croal	Farnworth Weir	CC	
69027	Tame	Portwood	BC	
69030	Sankey Brook	Causey Bridges	BC	Pre-1983
			AC	Post-1983
69031	Ditton Brook	Greenbridge	CC	
69032	Alt	Kirkby	CC	Pre-1977
			BC	Post-1977
69033	Alt	Sefton	CC	
69034	Musbury Brook	Helmsmore Intake	AC	

Table 1 (continued)

STATION	RIVER	LOCATION	GRADE	
69035	Irwell	Bury Bridge	CC	
69036	Eagley Brook	Longworth Clough	BB	*
69039	Medlock	New Viaduct Street		
69040	Irwell	Stubbins Brook	CC	Pre-1980
			BC	1980-1986
70001	Douglas	Rivington Reservoir	AC	
70002	Douglas	Wanes Blades Bridge	CA	Pre-1984
			BA	Post-1984
70003	Douglas	Central Park	CB	
70004	Yarrow	Croston Mill	BB	
70005	Lostock	Littlewood Bridge	CC	
71001	Ribble	Salmesbury (PGS)	BB	
		(FMS)	AB	
71002	Hodder	Stocks Reservoir	AC	
71003	Croasdale	Croasdale Flume	CA	
71004	Calder	Whalley Weir	CB	Pre-1970
			AB	Post-1970
71005	Bottoms Beck	Bottoms Beck Flume	CA	
71006	Ribble	Henthorn	AB	
71007	Ribble	Hodder Foot	CB	*
71008	Hodder	Hodder Place	AC	
71009	Ribble	New Jumbles Rock	//	
71010	Pendle	Barden Lane	BB	
71011	Ribble	Arnford	CA	Pre-1972
			AA	Post-1972
71013	Darwen	Ewood	BC	
71014	Darwen	Blue Bridge	BC	
72001	Lune	Halton	BB	
72002	Wyre	St. Michael's	BB	Pre-1976
			AB	Post-1976
72004	Lune	Caton	AA	
72005	Lune	Killington	AA	
72006	Lune	Kirkby Lonsdale		*
72007	Brock	Upstream A6	AA	
72008	Wyre	Garstang	BB	Pre-1969
			AB	Post-1969
72009	Wenning	Wennington	AA	
72010	Lune	Tebay		*
72011	Rawthey	Briggs Flatts	AA	
72809	Wyre	Scorton Weir	CC	
72811	Brock	Roe Bridge	//	
72814	Calder	Sandholme Bridge	//	
72817	Barton Brook	Hollowforth Hall	//	

Table 1 (continued)

STATION	RIVER	LOCATION	GRADE	
72818	New Mill Brook	Carvers Bridge	//	
72820	Burnes Gill	Tebay (M6)	//	
73001	Leven	Newby Bridge	BB	Pre-1971
			AB	Post-1971
73001	Leven	Newby Bridge	BB	Pre-1971
			AB	Post-1971
73002	Crake	Low Nibthwaite	AA	
73003	Kent	Burneside	AA	
73005	Kent	Sedgewick	AA	
73007	Troutbeck	Troutbeck Bridge		
73008	Bela	Beetham	AA	
73009	Sprint	Sprint Mill	AA	
73011	Mint	Mint Bridge	AA	
73013	Rothay			
73014	Brathay	Jeffy Knotts		
73015	Keer			
74001	Duddon	Duddon Hall	AB	
74002	Irt	Galesyke	AB	
74003	Ehen	Ennerdale	AB	
74005	Ehen	Braystones	BB	
74006	Calder	Calder Hall	AC	
74007	Esk	Cropple Howe	BA	
74008	Duddon	Ulpha	CB	
75001	St. John's	Thirlmere	CA	
75002	Derwent	Camerton	AA	
75003	Derwent	Ouse Bridge	AA	
75004	Cocker	Southwaite Bridge	BB	
75005	Derwent	Portinscale	CA	
75006	Newlands Beck	Braithwaite	BA	
75007	Glenderamackin	Threlkeld	BA	
75009	Greta	Low Briery	AA	
75010	Marron	Ullock	AA	
75016	Cocker	Scalehill	BC	
75017	Ellen	Bull Gill	BB	
76001	Haweswater Beck	Burnbanks	BC	
76002	Eden	Warwick Bridge	BA	
76003	Eamont	Udford	BC	
76004	Lowther	Eamont Bridge	BB	
76005	Eden	Temple Sowerby	BA	
76007	Eden	Sheepmount	AA	
76008	Irthing	Greenholme	AB	
76009	Caldew	Holm Hill	BA	

Table 1 (continued)

STATION	RIVER	LOCATION	GRADE
76010	Petteril	Harraby Green	BA
76011	Coal Burn	Coal Burn	AA
76014	Eden	Kirkby Stephen	AA
76015	Eamont	Pooley Bridge	AC
76805	Force Beck	Shap	//
77001	Esk	Netherby	BA
77005	Lyne	Cliff Bridge	BA

// denotes no grade yet assigned
* denotes no records available on Surface Water Archive

TABLE 2 Summary data of gauging stations used in the study

NO.	NAME	PERIOD OF RECORD
23002	Derwent at Eddys Bridge	1954-1965
23004	South Tyne at Haydon Bridge	1973-1986
23005	North Tyne at Tarset	1973-1986
23006	South Tyne at Featherstone	1966-1986
23007	Derwent at Rowland's Gill	1966-1969
23008	Rede at Rede Bridge	1968-1986
23009	South Tyne at Alston	1969-1983
23010	Tarset Burn at Greenhaugh	1970-1980
23011	Kielder Burn at Kielder	1970-1986
23013	West Allen at Hindley Wray	1971-1980
24003	Wear at Stanhope	1958-1986
24004	Bedburn Beck at Bedburn	1959-1986
24005	Browney at Burn Hall	1954-1986
24006	Rookhope Burn at Eastgate	1957-1980
24008	Weat at Witton Park	1972-1986
25002	Tees at Dent Bank	1956-1970
25003	Trout Beck at Moor House	1957-1980
25006	Greta at Rutherford Bridge	1960-1986
25011	Langdon Beck at Langdon	1969-1983
25012	Harwood Beck at Harwood	1969-1986
27024	Swale at Richmond	1961-1980
27034	Ure at Kilgram Bridge	1967-1986
27035	Aire at Kildwick Bridge	1968-1986
27043	Wharfe at Addingham	1974-1986
27051	Crimple at Burn Bridge	1972-1986
27061	Colne at Longroyd Bridge	1978-1986
27074	Spen Beck at Northorpe	1984-1986
28002	Blithe at Hampstall Ridware	1937-1944
28008	Dove at Rocester Weir	1953-1985
28018	Dove at Marston-on-Dove	1961-1985
28031	Manifold at Ilam	1968-1985
28033	Dove at Hollinsclough	1965-1982
28038	Manifold at Hulme End	1969-1982
28038	Manifold at Hulme End	1969-1982
28041	Hamps at Waterhouses	1968-1982
28046	Dove at Izaak Walton	1969-1985
28055	Ecclesbourne at Duffield	1971-1982
28058	Henmore Brook at Ashbourne	1974-1984
28070	Burbage Brook at Burbage	1965-1982
28075	Derwent at Slippery Stones	1979-1982
54041	Tern at Eaton-on-Tern	1972-1985
54044	Tern at Ternhill	1972-1985
54059	Allford Brook at Allford	1972-1984
54060	Potford Brook at Potford	1972-1984
54818	Roden at Northwood	1970-1975

TABLE 2 (continued)

NO	NAME	PERIOD OF RECORD
54822	Allford Brook at Allford Upper	1973-1976
68001	Weaver at Ashbrook	1965-1985
68003	Dane at Rudheath	1979-1985
68004	Wistaston Brook at Marshfield Bridge	1981-1985
68005	Weaver at Audlem	1953-1985
68006	Dane at Hulme Walfield	1979-1985
68007	Wincham Brook at Lostock Gralam	1983-1984
68015	Gowy at Huxley	1981-1985
68020	Gowy at Bridge Trafford	1981-1985
69012	Bollin at Wilmslow	1985-1986
69013	Sinderland Brook at Partington	1982-1985
69017	Goyt at Marple Bridge	1977-1985
69020	Medlock at London Road	1976-1985
70002	Douglas at Wanes Blades Bridge	1984-1985
70004	Yarrow at Croston Mill	1976-1985
70803	Newreed Brook at Slate Farm	1972-1973
71001	Ribble at Salmesbury	1960-1985
71004	Calder at Whalley Weir	1971-1985
71006	Ribble at Henthorn	1968-1985
71009	Ribble at New Jumbles Rock	1980-1985
71010	Pendle at Barden Lane	1971-1985
71011	Ribble at Arnford	1973-1984
72001	Lune at Halton	1959-1976
72002	Wyre at St. Michael's	1963-1985
72004	Lune at Caton	1959-1986
72005	Lune at Killington New Bridge	1969-1986
72007	Brock at Upstream A6	1985-1985
72008	Wyre at Garstang	1967-1985
72009	Wenning at Wennington	1981-1986
72011	Rawthey at Briggs Flatts	1986-1984
72811	Brock at Roe Bridge	1970-1976
72814	Calder at Sandholme Bridge	1971-1976
72817	Barton Brook at Hollowforth Hall	1972-1975
72818	New Mill Brook at Carvers Bridge	1972-1974
72820	Burnes Gill at Tebay (M6)	1972-1974
73001	Leven at Newby Bridge	1970-1976
73002	Crake at Low Nibthwaite	1963-1986
73003	Kent at Burneside	1981-1986
73005	Kent at Sedgewick	1968-1986
73008	Bela at Beetham	1969-1986
73009	Sprint at Sprint Mill	1981-1986
73011	Mint at Mint Bridge	1970-1986
74001	Duddon at Duddon Hall	1968-1986
74002	Irt at Galesyke	1967-1986

Table 2 (continued)

NO	NAME	PERIOD OF RECORD
74003	Ehen at Ennerdale	1974-1986
74005	Ehen at Braystones	1974-1986
74007	Esk at Cropple Howe	1977-1986
75002	Derwent at Camerton	1960-1986
75003	Derwent at Ouse Bridge	1968-1986
75004	Cocker at Southwaite Bridge	1967-1986
75006	Newlands Beck at Braithwaite	1968-1980
75007	Glenderamackin at Threlkeld	1969-1978
75009	Greta at Low Briery	1971-1984
75010	Marron at Ullock	1972-1977
75017	Ellen at Bull Gill	1982-1986
76002	Eden at Warwick Bridge	1966-1986
76004	Lowther at Eamont Bridge	1962-1986
76005	Eden at Temple Sowerby	1964-1986
76007	Eden at Sheepmount	1967-1986
76008	Irthing at Greenholme	1967-1986
76009	Caldew at Holm Hill	1968-1986
76010	Petteril at Harraby Green	1970-1986
76011	Coal Burn at Coal Burn	1967-1983
76014	Eden at Kirkby Stephen	1971-1986
76805	Force Beck at Shap	1973-1975
77001	Esk at Netherby	1963-1986
77002	Esk at Canobie	1962-1986
77003	Liddel Water at Rowanburnfoot	1973-1985
77004	Kirtle Water at Mossknowe	1979-1985
77005	Lyne at Cliff Bridge	1977-1986

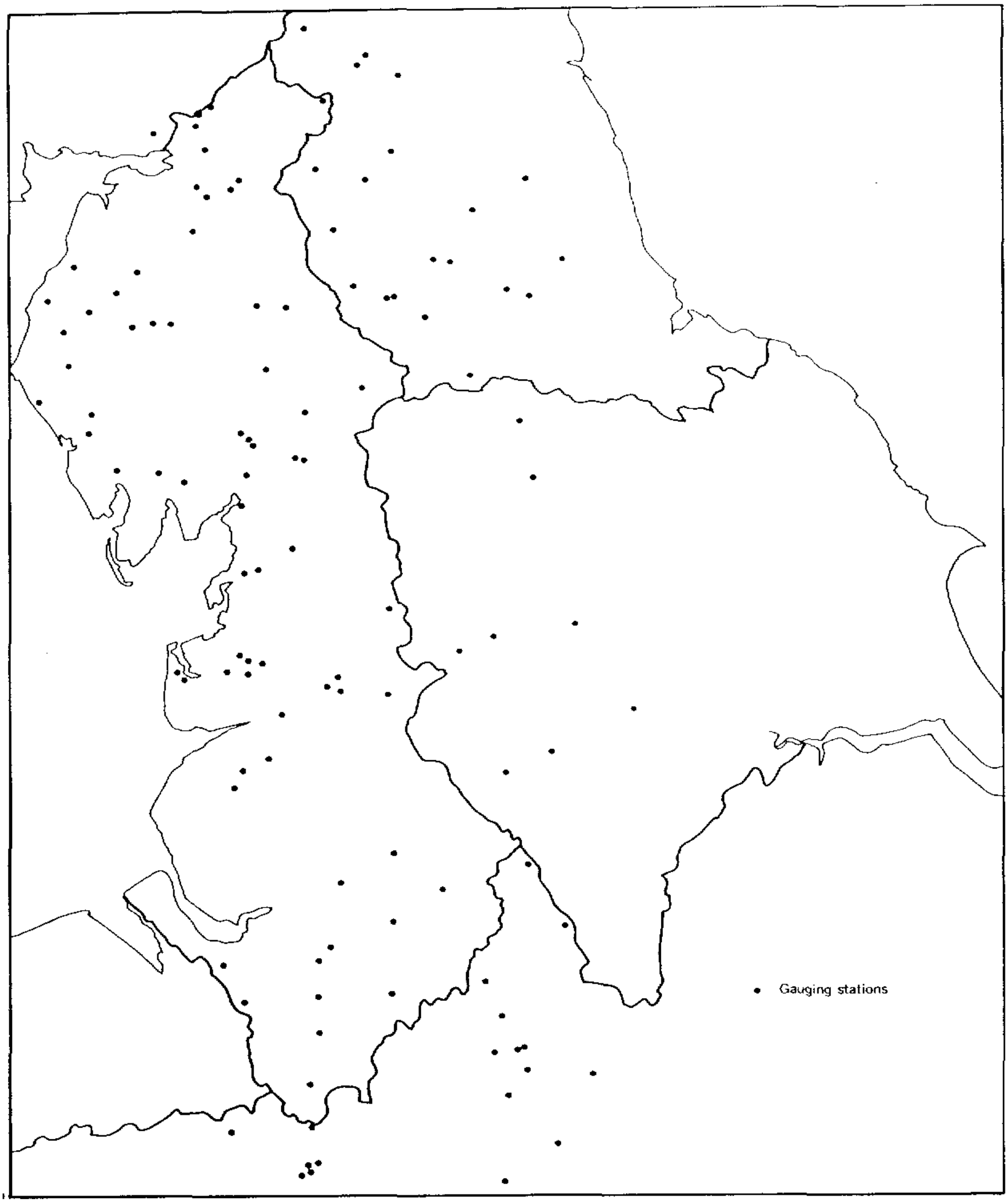


FIG. 2 Location of gauging stations used in the study.

2. Automated low flow estimation procedure

2.1 DIGITAL CARTOGRAPHY

The procedures for the estimation of low flow measures at the ungauged site proposed within the Low Flow Studies report (Institute of Hydrology 1980) necessitate the manual derivation of catchment characteristics from thematic maps. Estimates are required of catchment area or mainstream length, average annual rainfall, potential evaporation, the proportional extent of soil classes, and the extent of lakes and reservoirs. As discussed in the introduction, if a number of estimates are required at different sites then the derivation of the appropriate characteristics can prove to be a time-consuming and repetitive task, particularly for large catchments. The improvement of procedures for catchment characteristic derivation by employing automated cartographic techniques is a key area of current development in regional hydrology.

The dominance of a single catchment characteristic, the Base Flow Index, in controlling low flows facilitates automated estimation procedures. By reflecting variations in response from different geology and soil associations, the distribution of the Base Flow Index may be viewed as the key variable in determining regional patterns of low flow measures.

One important development to assist hydrologists in low flow estimation has been the production of a Base Flow Index map of Scotland (Gustard et al 1986, Institute of Hydrology 1988) which separates river stretches into 12 BFI classes. Visual inspection of the map yields a BFI value for any river site of interest which may be employed in equations for estimating other low flow measures. Although this approach circumvents the user requirement to interpret relationships between low flows and soil and geology, the cartographic procedure faces two main drawbacks;

- production of BFI maps involves the manual incorporation of locally recorded BFI values or an estimate of the extent of soil classes above each river stretch (in the order of 5000 stretches in Scotland). Errors may be introduced by the manual interpolation of data.

- use of the graphical procedure yields low flow estimates only as a percentage of the average daily flow, with no procedure for rescaling to absolute units of discharge.

The development of computer-accessible data bases of hydrologically relevant data enables both of these problems to be resolved and thereby reduces the workload of low flow estimation imposed upon the user. Data bases are now available for all catchment characteristics necessary for the Low Flow Studies Report estimation procedure. Techniques are currently being developed for the most appropriate method of automated extraction using the existing data base of river networks. North West Water Authority and the Institute of Hydrology each possess an archive of digitised river stretches for the study region. The derivation of catchment characteristics employing the digitised river networks is described in detail below. The developed river network procedure overcomes previous problems of manual procedures based on catchment area because

- *catchment characteristics are* automatically calculated and stored for each river stretch. This removes the need to delimit catchment areas and to interpret soil and geology maps for each ungauged site;

- catchment characteristics are automatically applied to the appropriate equations to estimate Q95(1), MAM(10) and the modal flow at each river stretch;

- low flow estimates are rescaled to absolute discharge units.

Further developments of estimation techniques will be based on Digital Terrain Models (DTM's) which comprise a gridded data base of land surface altitude. The principal advantage of DTM's over alternative procedures is the ability to automatically delimit catchment boundaries for ungauged sites and then derive estimates of catchment area. Catchment area is the essential characteristic in the rescaling of low flow estimates from a fraction of the average daily flow to absolute discharge units. *Knowledge of the catchment boundary* is required for the derivation of catchment characteristics. However, such procedures are not yet widely available although a national DTM is presently under development.

2.2 DIGITISED RIVER NETWORK DATA BASE PROCEDURE

In common with most parts of the United Kingdom, a data base of the regional river network is available for the North West Water area. The source of the data base is the 1:50,000 O.S. maps, from which the main river network was digitised and archived. The archiving system holds the river network as a series of digitised "stretches", where a stretch is a length of river to which a unique line identification number (LID) is assigned. Generally, each stretch comprises the river length between two consecutive confluences and which does not possess any influent tributaries. Stretches meet when their end coordinates are identical. By storing all stretches in a structured way, with the downstream coordinates (or node) first, it is possible to trace to the river network upstream or downstream from any given stretch.

The Institute of Hydrology has digitised national maps of standard period average annual rainfall (SAAR) isohyets and of the areal extent of WRAP (NERC 1975) classes. For each catchment characteristic, the resulting data have been transformed to a grid of values over the U.K.. The 5 class WRAP map is held on a $100m^2$ grid and SAAR is held on a $1km^2$ grid with a rainfall depth resolution of 1mm, to an accuracy in the order of 10% of SAAR recorded at rain gauges.

A technique was developed whereby superimposition of the river network onto the gridded data bases enables the extraction of catchment values. This procedure is based on a preliminary stage in which the length of each river stretch *(resolution is one metre)* overlying grid squares of different values is identified and stored. Values of WRAP class and SAAR were calculated for each individual river stretch within the region.

The second stage of the procedure involves the identification, for each river stretch, of all the river stretches lying above it. This is made possible by the internal structure of the archiving system. Identification of the river network above each point of interest enables the calculation of the length of the river network overlying each unit division of the thematic data bases. For a particular river stretch, the length of river within each thematic class division may then be expressed as a proportion of total river length above the stretch to give, for example, the relative proportion of five soil classes within the catchment. Alternatively, a mean catchment value of SAAR may be calculated from the sum of rainfall per metre for each metre of the river length divided by the total river length.

2.3 DIGITISED RIVER NETWORK IN THE NORTH WEST WATER REGION

The source map from which the North West river network was digitised is the First Series Ordnance Survey 1:50,000 map. The digitised network represents approximately 50% of the depicted network on the 1:50,000 maps. The policy for selecting which streams were to be digitised followed two broad aims; firstly, to digitise all streams incorporated within the River Quality Survey, England and Wales (DoE 1975), for which the threshold was all stream reaches with summer flows in excess of 0.05 cumecs; secondly, to include additional streams of interest to North West Water. Criteria for the latter point include streams in receipt of significant polluting discharges, statutory main rivers, and "any stretches of general hydrological interest".

The main canal systems within the region were also digitised as a component of the natural river network, including the following canal systems;

Shropshire Union Canal (and Llangollen Branch)
Trent and Mersey Canal (and Middlewich Branch)
Bridgewater Canal
St. Helens Canal
Leeds and Liverpool Canal
Ashton Canal
Rochdale Canal
Manchester, Bolton and Bury Canal
Huddersfield Canal
Peak Forest Canal
Macclesfield Canal
Manchester Ship Canal
Lancaster Canal

For the purposes of this study, the North West digitised network was "naturalised" to exclude the canal systems from the stream network procedure. This was undertaken to prevent canals from artificially increasing both catchment area and/or drainage density and so to restore the digitised stream network to the natural network structure. This aim was set so that any estimates at the ungauged site are related to the natural network and so users consistently commence from a common base in the consideration of artificial influences.

The naturalisation procedure encompassed two stages. It first involved the *discrimination of the canal systems* listed above from the natural network structure. The LIDs associated with the canal systems were identified and assigned a discriminatory flag which distinguishes them from the natural stream network. Secondly, in cases where a tributary stream is dissected by a canal and no longer reaches its natural river confluence, missing links between the canal confluence and the natural stream confluence were reinstated to establish the natural stream network. This was achieved by interpreting the natural relief from 1:50,000 O.S. maps. Again, these inserted links are assigned a discriminatory flag. The use of codes enables the digitised network to be manipulated in order to restore or exclude canal systems and/or interpolated links.

The Manchester Ship Canal provided a particular problem in its lower reaches. The Ship Canal comprises a canalised section of the Lower Irwell in its upper reaches above Irlam Weir, and further downstream a canalised section of the River Mersey. As a canalised section, the Ship Canal in these two reaches constitutes a section of the natural river network. Downstream of Woolston, the Mersey bifurcates into the natural channel of the Mersey and the Manchester Ship Canal. At this point, a component of the flow is diverted into the Ship Canal by a series of weirs and sluices to maintain an adequate draught for navigation within the Ship Canal. This lower section of the Ship Canal was therefore flagged as an unnatural section of the network in parity with the other canal systems.

The basic structure of the complete naturalised network is 42 separate networks which comprise a combined total of approximately 7,000 individual river stretches.

2.4 ESTIMATION OF CATCHMENT CHARACTERISTICS

The procedure for transferring estimates derived from low flow analyses at gauged sites to each individual river stretch employs catchment characteristics estimated from the naturalised digitised river network. The terms to describe the catchment characteristics derived by this procedure are those employed in the Low Flow Studies report prefixed by the letter R.

Transfer of low flow estimates to the ungauged site was based on regression relationships between BFI and the proportion of catchment area contained within each of five soil class. These classes are termed SOIL 1, SOIL 2 .... SOIL 5 and are based on the five class WRAP division. The current procedure using the digitised stream network employs estimates of soil class based on the proportional extent of each soil class overlain by the river network, as calculated by the procedure described above. These classes are termed RSOIL 1, RSOIL2 .... RSOIL 5. Each soil class was calibrated by a BFI value derived from the regression relationship between soil class and BFI in the 114 study catchments (section 3), enabling a catchment BFI estimate to be calculated from the proportional extent of each soil class. The catchment

BFI index was then employed as an independent variable in regression relationships for the estimation of low flow variables of the form

Q95(1) = a + b BFI + c RSAAR

Estimates of SOIL 1 .... SOIL 5 and RSOIL 1 .... RSOIL 5 for 66 catchments in the North West region were compared to investigate the efficiency of the network approach in estimating soil class extent. Figure 3 presents plots of proportional soil extent from the two procedures for each soil class. Correlation of the estimates from the two procedures are all significant at the 0.1% level.

The main difference in the estimates from the two procedures arises from low drainage densities associated with reclassified (see Section 3.1) limestone geologies in RSOIL 5. The occurrence of lower drainage densities on limestone areas gives less weight to RSOIL5 by the network method than by areal extent. This phenomenon is reflected in the relatively lower estimates of RSOIL 5 than SOIL 5. The association of WRAP class 5 with class 4 in limestone catchments means that this phenomenon is reflected in higher values of RSOIL 4 than would be estimated from areal extent (SOIL 4).

Figures 4 and 5 show the strong relationships that exist between estimates of the standard period average annual rainfall (SAAR) by the two procedures and between catchment area and Total stream length. Table 3 presents the calculated catchment characteristics for each of the 114 study region basins.

The strong correlations revealed by these comparisons validate the use of the estimates derived from the stream network procedure. Although problems are introduced by variations in drainage density with geology in particular cases, no significant bias is introduced by sampling soils or rainfall in the valley bottom alone.

Values of RSOIL1, RSOIL2, ... ,RSOIL5, RSAAR and Total Stream Length (TSL) were calculated for each individual river stretch and linked to the appropriate LID in the archiving system.

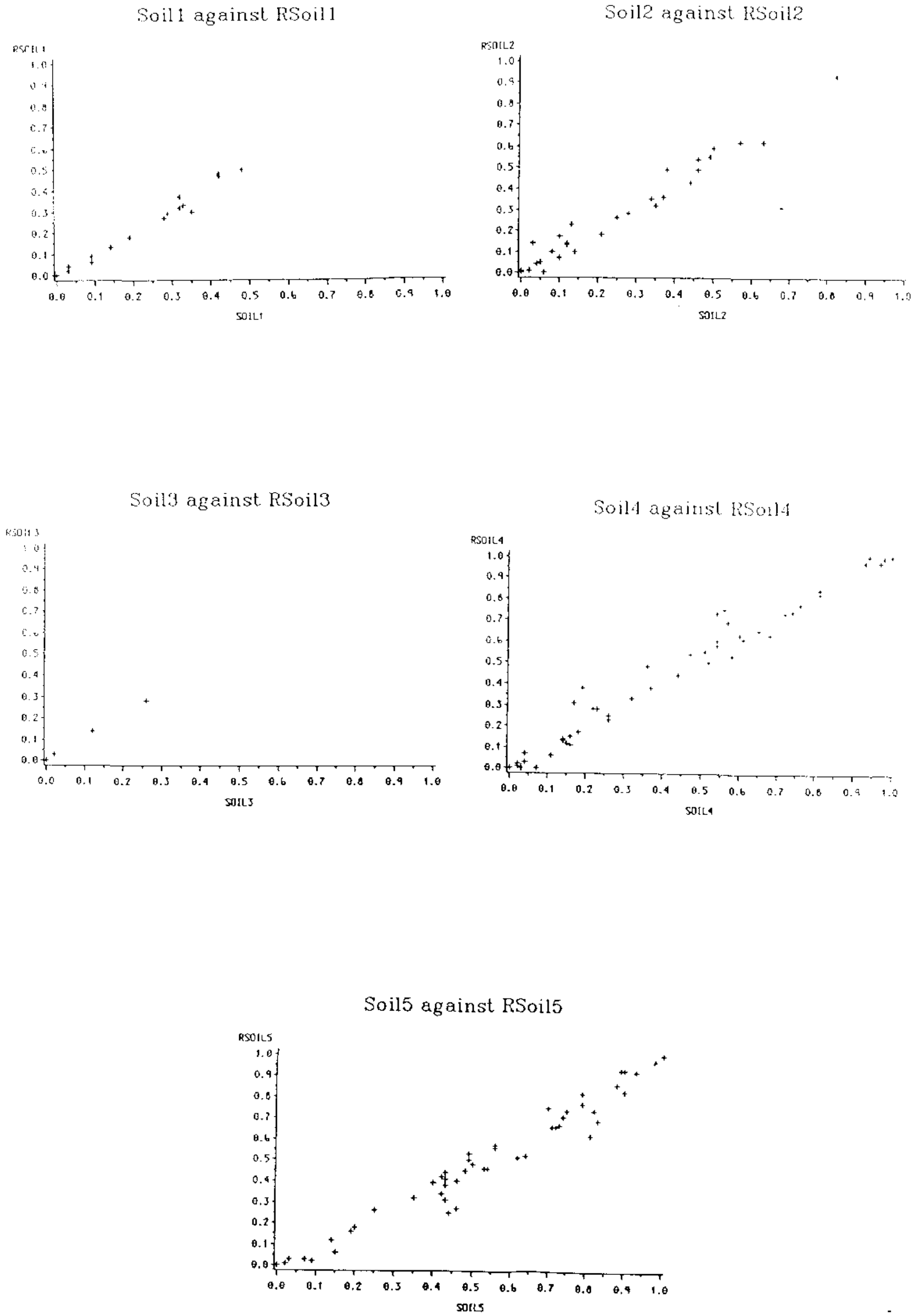


FIG. 3 Comparison of proportional soil class estimates from area and river network procedures within gauged catchments

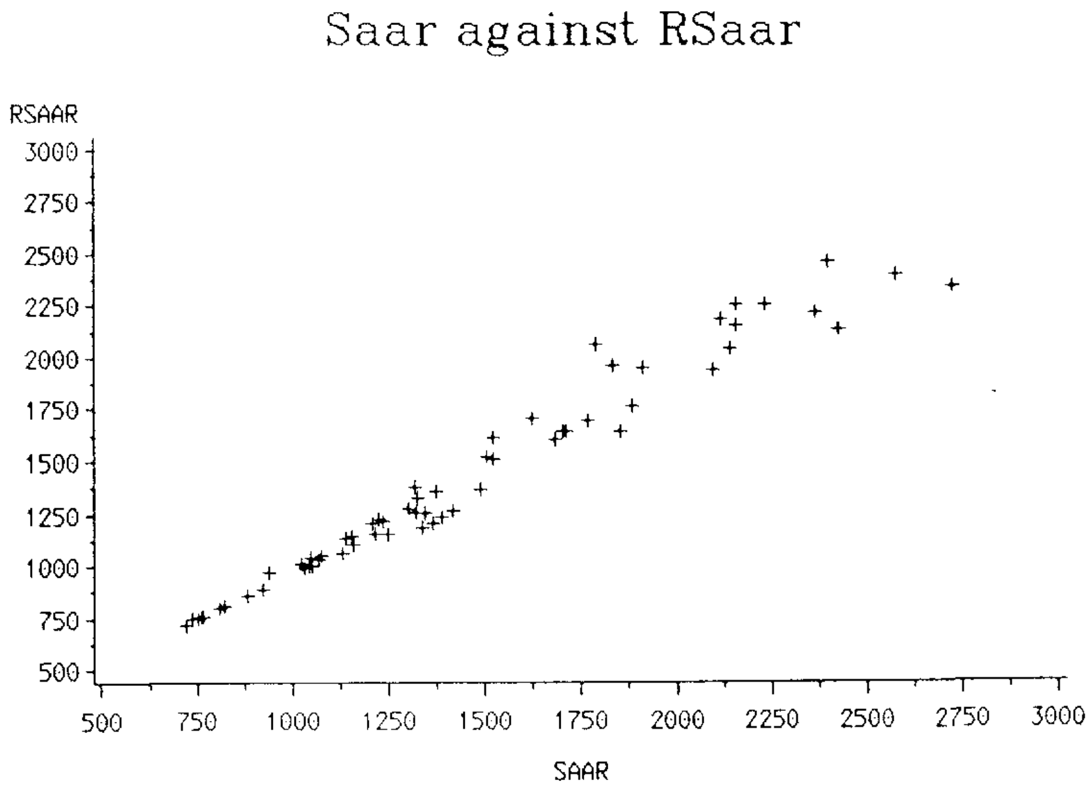


FIG. 4 Comparison of standard period average annual rainfall from area (SAAR) and river network (RSAAR) procedures within gauged catchments.

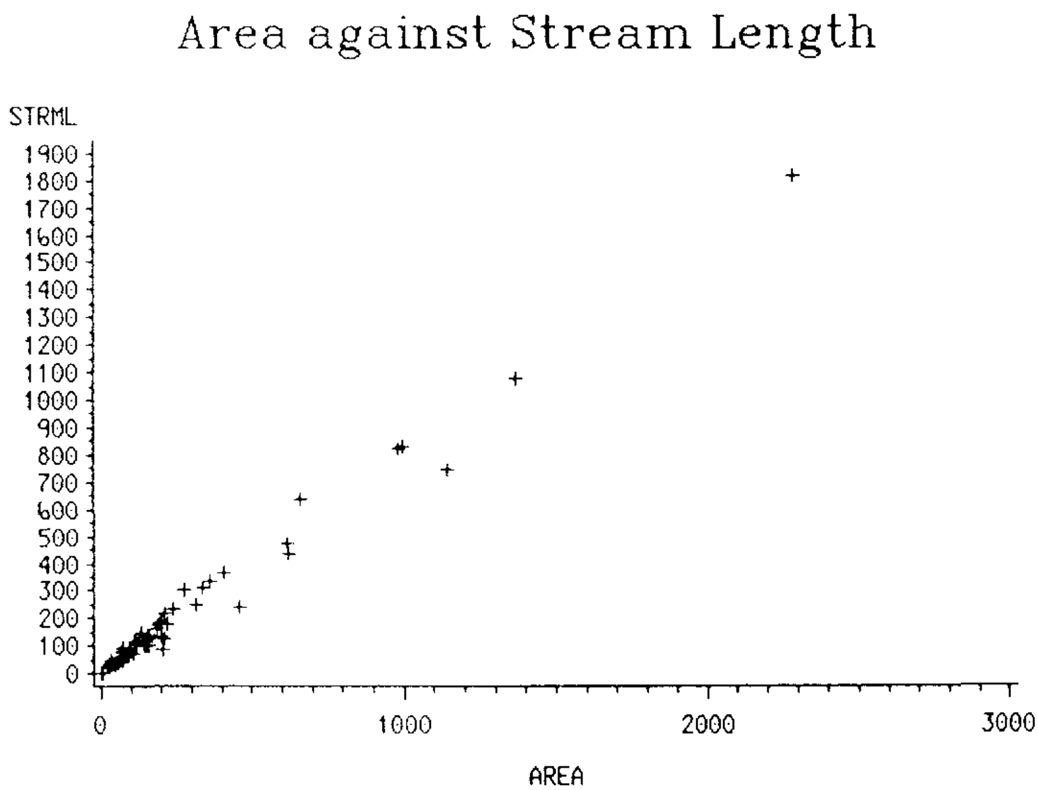


FIG. 5 Comparison of catchment area and Total Stream Length of the digitised stream network within gauged catchments.

TABLE 3 Catchment characteristic values at gauged sites

STATION	AREA	TSL	SOIL1	RSOIL1	SOIL2	RSOIL2	SOIL3	RSOIL3	SOIL4	RSOIL4	SOIL5	RSOIL5	SAAR	RSAAR	FALAKE
23002	118.07		0.00		0.00		0.00		0.03		0.97			962	0.000
23004	749.78		0.00		0.00		0.00		0.09		0.91			1234	0.000
23005	283.29		0.00		0.00		0.00		0.00		1.00			1322	0.000
23006	324.10		0.00		0.00		0.00		0.00		1.00			1464	0.000
23007	245.11		0.00		0.00		0.00		0.49		0.51			868	0.001
23008	346.76		0.00		0.00		0.00		0.00		1.00			1022	0.002
23009	118.24		0.00		0.00		0.00		0.00		1.00			1710	0.000
23010	95.54		0.00		0.00		0.00		0.00		1.00			1063	0.000
23011	58.43		0.00		0.00		0.00		0.00		1.00			1401	0.000
23013	78.51		0.00		0.00		0.00		0.01		0.99			1253	0.000
24003	173.19		0.00		0.00		0.00		0.01		0.99			1316	0.002
24004	74.72		0.00		0.00		0.00		0.41		0.59			950	0.000
24005	176.33		0.01		0.00		0.00		0.98		0.01			752	0.000
24006	36.93		0.00		0.00		0.00		0.01		0.99			1221	0.000
24008	454.5		0.00		0.00		0.00		0.65		0.35			1070	0.000
25002	219.79		0.00		0.00		0.00		0.04		0.96			1758	0.000
25003	11.41		0.00		0.00		0.00		0.00		1.00			2027	0.000
25006	86.99		0.00		0.00		0.00		0.00		1.00			1259	0.000
25011	13.19		0.00		0.00		0.00		0.00		1.00			1457	0.000
25012	24.46		0.00		0.00		0.00		0.00		1.00			1753	0.000
27024	388.45		0.00		0.00		0.00		0.23		0.77			1302	0.000
27034	505.48		0.03		0.04		0.00		0.38		0.55			1346	0.000
27035	264.95		0.08		0.00		0.00		0.57		0.35			1134	0.004
27043	474.6		0.19		0.00		0.00		0.13		0.68			1400	0.000
27051	7.97		0.00		0.00		0.00		1.00		0.00			866	0.000
27061	73.82		0.00		0.44		0.00		0.05		0.51			1296	0.000
27074	46.51		0.00		0.02		0.00		0.57		0.00			818	0.000
28002	166.73		0.16		0.00		0.00		0.84		0.00			777	0.000
28008	394.5		0.47		0.00		0.01		0.21		0.31			1020	0.000
28015	379.58		0.26		0.00		0.06		0.49		0.18			934	0.000
28031	149.02		0.30		0.00		0.30		0.02		0.38			1085	0.000
28033	8.17		0.00		0.00		0.00		0.00		1.00			1363	0.000
28036	45.23		0.00		0.00		0.00		0.00		1.00			1197	0.000
28041	35.51		0.02		0.00		0.00		0.01		0.97			1067	0.000
28046	54.04		0.71		0.00		0.00		0.03		0.26			1141	0.000
28053	51.1		0.08		0.17		0.00		0.75		0.00			841	0.000
28058	39.43		0.21		0.00		0.00		0.79		0.00			870	0.000
28070	8.82		0.00		0.17		0.00		0.00		0.83			985	0.000
28075	16.24		0.00		0.00		0.00		0.00		1.00			1511	0.000
54041	202.65		0.62		0.00		0.00		0.38		0.00			754	0.001
54044	95.64		0.60		0.00		0.00		0.40		0.00			796	0.000
54059	10.8		1.00		0.00		0.00		0.00		0.00			697	0.000
54060	24.44		1.00		0.00		0.00		0.00		0.00			680	0.000
54818	19.85		0.01		0.37		0.00		0.62		0.00			745	0.000
54822	5.0		1.00		0.00		0.00		0.00		0.00			713	0.000
68001	622.00	434	0.28	0.27	0.00	0.00	0.00	0.00	0.72	0.73	0.00	0.00	758	765	0.003
68003	407.10	362	0.14	0.13	0.12	0.15	0.00	0.00	0.61	0.61	0.14	0.12	861	883	0.001
68004	92.70	76	0.42	0.47	0.00	0.00	0.00	0.00	0.58	0.53	0.00	0.00	757	766	0.003
68005	207.00	126	0.19	0.18	0.00	0.00	0.00	0.00	0.81	0.82	0.00	0.00	746	756	0.017
68006	151.30	142	0.03	0.04	0.02	0.01	0.00	0.00	0.60	0.63	0.35	0.32	1003	1053	0.003
68007	148.00	118	0.09	0.06	0.37	0.36	0.00	0.00	0.54	0.58	0.00	0.00	802	813	0.004
68015	49.00	42	0.48	0.50	0.00	0.00	0.00	0.00	0.52	0.50	0.00	0.00	747	739	0.0
68020	156.0	125	0.35	0.30	0.00	0.00	0.00	0.00	0.65	0.65	0.00	0.00	718	725	0.0
69012	72.50	54	0.42	0.48	0.34	0.35	0.00	0.00	0.14	0.14	0.09	0.02	892	924	0.0
69013	44.5	37	0.00	0.00	0.63	0.62	0.00	0.00	0.37	0.38	0.00	0.00	812	824	0.0
69017	183.0	165	0.03	0.02	0.35	0.32	0.00	0.00	0.14	0.13	0.49	0.53	1130	1143	0.0
69020	37.5	37	0.00	0.00	0.00	0.00	0.00	0.00	0.93	0.97	0.07	0.03	1002	1046	0.0
70002	198.0	136	0.00	0.00	0.04	0.04	0.00	0.00	0.76	0.77	0.20	0.18	994	1032	0.0
70004	74.4	65	0.00	0.00	0.00	0.00	0.00	0.00	0.97	0.97	0.03	0.03	1008	1023	0.0
70803	5.75		0.00		0.05		0.00		0.95		0.00			966	0.0
71001	1145.0	743	0.00	0.00	0.00	0.00	0.00	0.00	0.57	0.69	0.43	0.31	1253	1322	0.004
71004	316.0	252	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.60	0.46	0.40	1205	1211	0.0
71006	456.0	241	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.73	0.46	0.27	1259	1345	0.00
71009	1053.0														0.00
71010	108.0	74	0.00	0.00	0.00	0.00	0.00	0.00	0.47	0.54	0.53	0.46	1213	1237	0.009
71011	204.0	99	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.38	0.81	0.62	1365	1491	0.00
72001	994.6	329	0.00	0.00	0.05	0.05	0.00	0.00	0.23	0.28	0.72	0.66	1512	1522	0.00
72002	275.0	305	0.00	0.00	0.08	0.10	0.00	0.00	0.51	0.55	0.42	0.34	1152	1251	0.002
72004	983.0	325	0.00	0.00	0.05	0.05	0.00	0.00	0.22	0.28	0.73	0.67	1514	1525	0.001
72005	219.0	178	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1707	1625	0.001
72007	32.0	34	0.00	0.00	0.03	0.14	0.00	0.00	0.15	0.12	0.82	0.74	1206	1368	0.0
72008	114.0	120	0.00	0.00	0.00	0.00	0.00	0.00	0.36	0.48	0.64	0.52	1263	1418	0.005
72009	142.0	101	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.75	0.44	0.25	1383	1318	0.00
72011	200.0	191	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.98	0.97	1646	1705	0.00
72811	37.3	38	0.00	0.00	0.13	0.23	0.00	0.00	0.16	0.11	0.71	0.66	1181	1338	0.00
72814	18.5	23	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.31	0.83	0.69	1240	1392	0.00
72817	31.9	47	0.00	0.00	0.06	0.00	0.00	0.00	0.94	1.00	0.00	0.00	1049	1078	0.004
72818	64.5	50	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	1045	1048	0.002
72820	0.72		0.00		0.00		0.00		0.00		1.00			1634	0.00
73001	241.4	230	0.00	0.00	0.10	0.07	0.00	0.00	0.00	0.00	0.90	0.93	2254	2233	0.077
73002	73.0	92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	2042	2143	0.071
73003	73.6	79	0.00	0.00	0.21	0.18	0.00	0.00	0.00	0.00	0.79	0.82	1767	1887	0.0
73005	209.0	217	0.00	0.00	0.44	0.43	0.00	0.00	0.00	0.00	0.56	0.57	1692	1769	0.004
73008	131.0	145	0.00	0.00	0.82	0.93	0.00	0.00	0.02	0.01	0.15	0.06	1277	1301	0.01
73009	34.6	35	0.00	0.00	0.10	0.17	0.00	0.00	0.00	0.00	0.90	0.83	1942	2099	0.00
73011	65.8	79	0.00	0.00	0.57	0.62	0.00	0.00	0.00	0.00	0.43	0.38	1599	1683	0.002
74001	85.7	60	0.00	0.00	0.12	0.14	0.00	0.00	0.00	0.00	0.88	0.86	2217	2369	0.003
74002	44.2	36	0.00	0.00	0.25	0.26	0.00	0.00	0.00	0.00	0.75	0.74	2336	2727	0.07
74003	44.2	35	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.44	0.56	0.56	2397	2577	0.0
74005	125.5	122	0.00	0.00	0.00	0.00	0.00	0.00	0.81	0.84	0.19	0.16	1638	1852	0.0
74007	70.2	75	0.00	0.00	0.38	0.49	0.00	0.00	0.00	0.00	0.62	0.51	2129	2428	0.0
75002	663.0	634	0.00	0.00	0.28	0.28	0.00	0.00	0.32	0.33	0.40	0.39	1951	1914	0.028
75003	360.0	336	0.00	0.00	0.46	0.49	0.00	0.00	0.04	0.03	0.50	0.48	2258	2159	0.03
75004	116.6	112	0.00	0.00	0.14	0.10	0.00	0.00	0.16	0.15	0.70	0.75	2154	2158	0.063
75006	33.9	40	0.00	0.00	0.46	0.54	0.00	0.00	0.00	0.00	0.54	0.46	2459	2401	0.00
75007	64.5	64	0.00	0.00	0.50	0.59	0.00	0.00	0.07	0.00	0.43	0.41	1956	1833	0.00
75009	145.6	127	0.00	0.00	0.49	0.55	0.00	0.00	0.03	0.00	0.48	0.45	2181	2118	0.0
75010	27.7	30	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	1641	1712	0.0
75017	96.0	87	0.00	0.00	0.00	0.00	0.00	0.00	0.98	0.99	0.02	0.01	1145	1157	0.0
76002	1366.7	1078	0.33	0.33	0.00	0.00	0.00	0.00	0.18	0.17	0.49	0.50	1325	1327	0.0
76004	158.5	132	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.06	0.89	0.93	2060	1788	0.0
76005	616.4	471	0.32	0.32	0.00	0.00	0.00	0.00	0.26	0.25	0.42	0.42	1154	1216	0.00
76007	2286.5	1816	0.29	0.29	0.00	0.00	0.02	0.03	0.26	0.23	0.43	0.44	1225	1225	0.0
76008	334.6	310	0.09	0.09	0.00	0.00	0.12	0.14	0.00	0.00	0.79	0.77	1033	1070	0.008
76009	147.2	105	0.00	0.00	0.00	0.00	0.00	0.00	0.74	0.74	0.25	0.26	1615	1524	0.00
76010	160.0	100	0.32	0.37	0.00	0.00	0.00	0.00	0.68	0.63	0.00	0.00	975	942	0.001
76011	1.52	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1100	1163	0.00
76014	69.4	46	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.07	0.93	0.92	1354	1376	0.00
76805	4.1	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1516	1508	0.00
77001	841.7		0.00		0.00		0.36		0.00		0.64			1449	0.0
77002	494.7		0.00		0.00		0.39		0.00		0.61			1507	0.0
77003	319.0		0.00		0.00		0.27		0.00		0.73			1401	0.0
77004	72.0		0.00		0.00		0.97		0.00		0.03			1133	0.0
77005	191.0	180	0.00	0.00	0.00	0.01	0.26	0.28	0.00	0.00	0.74	0.71	1062	1133	0.00

3. Base Flow Index estimation

3.1 INTRODUCTION

Base Flow Index is a key variable in linking low flow measures and catchment soils and geology because it expresses the proportion of catchment yield which derives from stored sources. Catchments experiencing a high WRAP value are normally associated with high BFI values due to the relatively greater contribution to stream flow from stored sources. This relatively high base flow component maintains summer low flows to a greater degree than catchments which are dominated by a more rapid response.

At present, the United Kingdom WRAP map employs a five-division classification, with Class I associated high WRAP values and WRAP values decreasing through to Class V, in which catchments typically experience a rapid runoff response. Future estimates of BFI will use the improved hydrological response map of the United Kingdom which is based on the hydrological properties of soil types (Gustard and Hollis 1986).

The existing five class WRAP classification for the North West Water region and the surrounding area is presented in Figure 6.

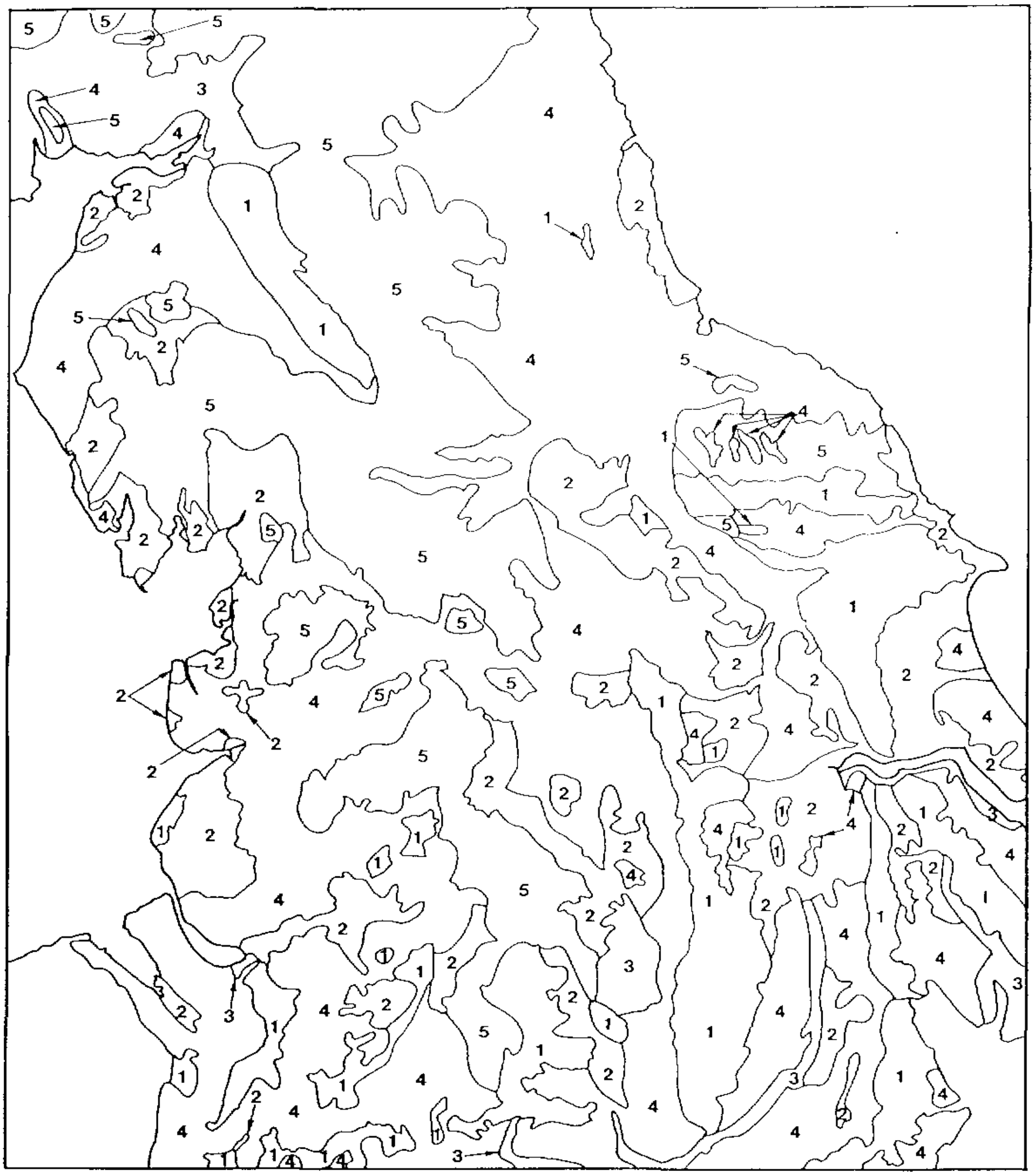
The regional classification presented in Figure 6 incorporates a local re-interpretation of the first edition of the national WRAP map. Analysis of potential runoff data (Boorman 1985) and local hydrological evidence (Gustard 1981) revealed that a set of catchments on the Carboniferous Limestone of North-West England differed from their assigned WRAP Class 1 response. The very rapid catchment response resulting from both the low soil moisture storage in the associated shallow calcereous soils and the quick response via the fissure permeable limestone led to a reclassification of the soil association as WRAP Class 5 (Flood Studies Supplementary Report No 17 1985).

3.2 RELATIONSHIP OF BASE FLOW INDEX WITH CATCHMENT SOIL AND GEOLOGY

The mean BFI amongst the 114 study catchments is 0.40. The lowest BFI values in the sample region is 0.15 (Trout Beck at Moor House, gauged by Yorkshire Water) draining upland peat overlying Carboniferous Limestone and Millstone Grits. The highest BFI values of 0.7 - 0.76 occur in the basins of the rivers Dove and Tern, gauged by Severn Trent Water Authority, draining typical brown earths overlying Triassic sandstones. The highest BFI value within the North West region is 0.65, from the river Bollin and Wistaston Brook, each draining stagno-gleys and brown earths overlying Triassic mudstones and Permo-Triassic sandstones.

Regressions were carried out between BFI and soil class employing data from the 114 catchments. The proportion of soil class within each catchment was

Winter Rainfall Acceptance Potential



Class 1	Very high
Class 2	High
Class 3	Moderate
Class 4	Low
Class 5	Very low

10 0 10 20 30 km

FIG. 6 Map of the WRAP classification for the North West Water region and surrounding areas indexed by RSOIL1, RSOIL2 ...RSOIL5. The resultant coefficients are presented in Table 4, along with the estimated coefficients from the United Kingdom as a whole (Hollis and Gustard 1986).

TABLE 4 Estimated BFI for 100% coverage of each WRAP class

	Class 1	Class 2	Class 3	Class 4	Class 5
NWW and supplementary stations	0.77	0.51	0.33	0.43	0.31
			s.e. = 0.094	R^2 = 0.549	
NWW only	0.75	0.51	0.35	0.40	0.31
			s.e. = 0.101	R^2 = 0.324	
UK	0.83	0.57	0.48	0.43	0.39
			s.e. = 0.13	R^2 = 0.430	

The decreasing trend in BFI with increasing WRAP Class exists within the North West region, with the exception of Class 3 for which an estimate of 0.33 was calculated. Soil associations assigned to WRAP Class 3 occur in only 3 gauged catchments in the North West region and do not exceed 25% of catchment area. The soils in this group largely comprise reddish till and reddish till with glaciofluvial drift, with small areas of glaciofluvial drift and blanket peat. The occurrence of these Class 3 soils is restricted to the lower reaches of the rivers Lyne, Irthing and Eden, in the vicinity of Carlisle. In the absence of adequate gauged data on these soil types, the U.K. estimate of 0.48 is used for Class 3 soils.

Differences are evident between the North West regional estimates and the U.K. national estimates of BFI. This is most likely attributable to the dominance of each Class by regionally extensive soil associations which may occur less frequently within the Class at the national scale. For example, the lower North West Water estimate for Class 1 is most likely attributable to the domination of the Class by sandstones within the North West Water region in contrast to the dominance of more permeable chalk in the national equation.

Extensive natural surface water reservoirs occur within the North West Water region, primarily in the Lake District and to a lesser extent within the Cheshire meres. The regulatory influence of natural storage reservoirs on the estimated BFI values was investigated by excluding those catchments in which natural storage bodies represent in excess of 1% of the basin surface area (FALAKE = 0.01) from the BFI estimation procedure. The resultant BFI coefficients remained stable and within the standard error of the estimates from the full data set. Consequently, no revision due to lakes and meres was applied to the estimates discussed above.

The BFI estimates employed for the purposes of this preliminary study are presented in Table 5;

TABLE 5 Base Flow Index values applied to soil classes in the current study

Class 1	Class 2	Class 3	Class 4	Class 5
0.77	0.51	0.48	0.43	0.31

3.3 DRAFT BASE FLOW INDEX MAP

The estimated BFI coefficients presented in Table 5 were employed to calibrate the digitised river network map. For each individual river stretch the proportion of each WRAP Class, retermed RSOIL class, in the catchment above the downstream end of the stretch was calculated and stored. The BFI value associated with each stretch was then calculated from the equation;

$$BFI = 0.77\ RSOIL1 + 0.51\ RSOIL2 + 0.48\ RSOIL3 + 0.43\ RSOIL4 + 0.31\ RSOIL5$$

The draft BFI map is the basis for the estimation of Q95(1), *MAM(10)* and MODE(30%).

4. Estimation of low flow indices

4.1 CALCULATION OF LOW FLOW INDICES AT GAUGED SITES

The estimation of flow statistics in this report is directed towards the following indices;

1. Average daily flow - ADF

2. One-day 95 percentile exceedance flow - Q95(1)

3. Mean annual ten-day minimum flow - MAM(10)

4. Modal flow index - Mode(30)

Definitions of ADF, Q95(1) and MAM(10) are contained within Low Flow Studies report, along with procedures for their calculation from recorded flow data. Each low flow index is expressed as a percentage of the average daily flow to remove the scaling effects of catchment area and average annual rainfall.

Particular attention is directed within this project towards the definition and derivation of a modal flow index. Five different procedures were investigated for defining the mode from recorded daily flow series in order to discover the relative merits and drawbacks. The most appropriate modal index is considered to be the weighted mid-point of the smallest class range to contain 30% of all daily flow values. A discussion is presented in Appendix 2 of

- general problems of modal definition
- a review of previous use of modal flow indices
- a description of six approaches to modal definition
- the advantages and disadvantages of each of the five approaches
- the selection of Mode(30) as the most appropriate modal index
- a definition of the procedure for the calculation of Mode(30) from recorded flow data

Table 6 presents calculated ADF, Q95(1), MAM(10) and Mode(30) for each of the 114 catchments included in the study.

TABLE 6 Low flow indices at gauged sites

STNNO	ADF	BFI	Q951	MAM10	MODE30
23002	1.89	0.43	10.03	14.95	26.6567
23004	17.02	0.34	11.59	11.09	20.1846
23005	7.88	0.35	11.11	12.46	28.3049
23006	10.34	0.32	13.04	12.88	24.8586
23007	3.35	0.49	28.80	26.87	43.3923
23008	5.74	0.33	10.29	10.50	18.5436
23009	3.88	0.30	10.06	10.24	20.5161
23010	1.76	0.27	8.07	7.82	16.1869
23011	1.82	0.34	15.25	15.13	28.8029
23013	1.65	0.27	3.58	4.02	14.3620
24003	3.57	0.34	13.70	13.84	25.6775
24004	1.19	0.46	14.53	15.24	27.6167
24005	1.73	0.52	19.20	22.32	34.4320
24006	0.78	0.35	9.46	12.06	25.2896
24008	7.42	0.44	15.84	15.11	26.9520
25002	7.81	0.21	7.99	7.32	19.8626
25003	0.55	0.15	5.03	4.96	13.6918
25006	2.22	0.21	5.72	5.42	14.4763
25011	0.42	0.20	5.94	5.23	13.1640
25012	0.97	0.22	6.33	6.00	15.6918
27024	10.46	0.35	12.09	13.46	30.9148
27034	14.83	0.33	7.16	6.93	22.2986
27035	6.02	0.37	8.49	7.63	17.1815
27043	14.51	0.32	10.21	9.78	21.3379
27051	0.12	0.31	5.85	5.25	10.6587
27061	1.56	0.38	20.36	22.32	33.3441
27074	0.76	0.59	38.35	37.47	47.2475
28002	1.58	0.49	21.85	21.84	31.5129
28008	7.42	0.61	22.23	26.62	43.1593
28018	13.88	0.60	26.82	30.14	55.3328
28031	3.53	0.53	18.76	20.49	37.6352
28033	0.25	0.45	14.39	16.35	32.9878
28038	1.19	0.31	7.79	7.30	20.2891
28041	0.73	0.35	8.20	8.49	19.7181
28046	1.93	0.78	29.66	32.96	54.2848
28055	0.70	0.49	17.84	18.21	29.7117
28058	0.51	0.46	12.20	12.96	21.1317
28070	0.19	0.45	13.37	13.02	28.8576
28075	0.64	0.37	15.44	10.35	28.9642
54041	1.76	0.71	43.96	44.95	57.1731
54044	0.07	0.76	50.31	52.05	65.3755
54059	0.28	0.70	5.87	50.74	16.3864
54060	0.12	0.76	36.48	41.37	58.7994
54818	0.08	0.57	33.18	29.04	42.5318
54822	0.01	0.62	.	8.12	28.3008
68001	5.63	0.53	20.15	24.96	43.2019
68003	5.47	0.52	18.84	22.02	38.9391
68004	0.79	0.65	31.96	28.91	49.5777
68005	1.61	0.50	18.67	16.38	26.8176
68006	2.80	0.55	16.67	32.33	40.3249
68007	1.86	0.26	.	12.27	13.5356
68015	0.40	0.51	23.42	24.52	37.3773
68020	1.25	0.47	22.41	23.32	31.0533
69012	1.06	0.65	.	.	67.3933
69013	0.44	0.59	.	.	48.0149
69017	3.79	0.50	20.14	20.44	32.6529
69020	0.88	0.54	32.54	32.68	50.9587

TABLE 6 (continued)

STNNO	ADF	BFI	Q951	MAM10	MODE30
70002	3.27	0.58	.	.	55.7240
70004	1.90	0.42	24.68	24.16	34.2843
70803	.	0.26	.	.	.
71001	33.14	0.32	13.24	13.36	26.4501
71004	8.28	0.44	22.36	19.86	34.1463
71006	13.36	0.29	8.14	8.63	18.8969
71009	35.85	0.30	11.71	11.22	21.7557
71010	2.60	0.43	22.55	22.42	33.1980
71011	8.22	0.25	5.60	6.90	35.9383
72001	33.71	0.32	9.26	10.67	30.6086
72002	6.56	0.34	8.21	8.62	22.4012
72004	34.70	0.32	8.87	9.98	20.1177
72005	8.49	0.34	8.68	9.7[illegible]	23.6032
72007	0.86	0.34	.	.	25.2721
72008	3.34	0.31	9.71	10.05	23.5719
72009	4.15	0.30	6.44	6.64	18.3793
72011	8.03	0.23	9.65	7.63	12.1781
72811	0.79	0.31	6.11	.	.
72814	0.29	0.24	7.51	.	
72817	0.77	0.20	3.71	.	.
72818	1.00	0.16	4.48	.	.
72820	0.02	0.26	.	.	.
73001	12.33	0.48	7.09	9.36	28.4635
73002	4.03	0.57	12.45	13.02	52.7973
73003	3.61	0.30	4.71	6.83	15.4651
73005	8.33	0.45	14.05	14.48	41.6072
73008	3.29	0.50	14.38	15.26	31.7519
73009	1.76	0.36	6.61	7.29	20.4520
73011	2.28	0.38	7.30	7.95	26.9838
74001	4.86	0.28	8.24	8.21	20.0335
74002	3.20	0.46	13.92	13.84	39.2952
74003	2.35	0.31	16.01	14.78	19.2931
74005	5.07	0.38	15.10	15.35	26.3987
74007	4.48	0.28	5.97	7.13	22.6363
75002	25.35	0.48	13.02	15.41	33.2041
75003	15.70	0.49	11.17	10.50	31.5020
75004	4.95	0.42	13.35	15.10	27.9045
75006	1.67	0.32	4.22	4.27	27.1549
75007	2.26	0.30	8.76	8.23	20.5497
75009	4.89	0.35	11.70	10.81	23.5968
75010	0.80	0.48	14.87	12.66	30.1600
75017	2.36	0.48	11.31	11.02	24.6747
76002	33.43	0.48	19.36	21.71	36.9106
76004	3.44	0.42	18.59	21.25	33.3606
76005	14.20	0.37	13.99	14.51	27.1994
76007	48.20	0.50	19.35	22.76	15.9609
76008	6.58	0.32	14.07	18.02	25.2005
76009	4.34	0.49	18.32	17.91	34.1056
76010	1.94	0.46	14.59	13.51	23.8678
76011	0.05	0.18	2.71	1.14	14.7544
76014	2.44	0.24	5.39	7.00	15.9080
76805	0.14	0.26	4.87	0.03	.
77001	23.71	0.36	12.29	13.23	18.6994
77002	16.23	0.38	.	12.57	27.5026
77003	9.76	0.33	.	9.65	19.1403
77004	1.81	0.29	.	6.24	14.3280
77005	4.30	0.29	7.84	4.76	18.4899

4.2. LOW FLOW ESTIMATION AT THE UNGAUGED SITE

A set of multiple regression models were calculated to estimate ADF, Q95(1), MAM(10) and Mode(30) at each river stretch, employing the low flow statistics at gauged sites as the dependent variables and BFI and RSAAR as independent variables. The availability of RSAAR within the NWW region only restricted the data set used in the calibration of the regression equations to the 66 North West Water stations. The most suitable transformation for the data prior to deriving the regression equations was found to be the square root transform, which was applied in each case with the exception of estimating ADF. The presented equations were calculated from the data set assembled from gauged sites of flow statistics (Table 6) and catchment characteristics estimated from the river network procedure (Table 3).

Estimation of ADF

Estimation of ADF in this stage of the project involved the development of a linear regression between ADF and RSAARVOL. RSAARVOL is a measure of mean annual rainfall volume calculated from (RSAAR * Total stream length)

$$ADF = 0.1 + 0.0000239 \; RSAARVOL \qquad (5.1)$$

$R^2 = 0.949$ Standard error = 2.29

Estimation of ADF in the second stage of the project will be based on a water balance approach which incorporates estimates of actual evaporation losses. This approach is not adopted in the present study because the data base of potential evaporation is still nearing completion.

RSAARVOL was computed for each river stretch from archived values of RSAAR and Total stream length. Equation 5.1 was applied to computed RSAARVOL values to produce an estimate of ADF for each river stretch.

Estimation of low flow variables

The following equations represent the calculated relationships between the low flow indices and catchment characteristics at the gauged sites

$$\sqrt{Q95(1)} = -2.13 + 9.52 \sqrt{BFI} - 0.01 \sqrt{RSAAR} \qquad (5.2)$$

$R^2 = 0.336$ Standard error = 0.789

$$\sqrt{MAM(10)} = 1.88 + 6.51 \sqrt{BFI} - 0.066 \sqrt{RSAAR} \qquad (5.3)$$

$R^2 = 0.339$ Standard error = 0.888

$$\sqrt{MODE(30)} = 0.867 + 7.16 \sqrt{BFI} - 0.001 \sqrt{RSAAR} \qquad (5.4)$$

$R^2 = 0.165$ Standard error = 0.937

For each river stretch, archived values of BFI and RSAAR were applied to each of the above equations to compute an estimate of each low flow measure. Low flow estimates were converted to absolute discharge units by reversing the square root transformation to derive estimates expressed as a percentage of ADF, and then including the ADF estimate to compute low flow estimates in absolute discharge units (m^3/s).

4.3 LOW FLOW ESTIMATE STORAGE AND RETRIEVAL PROCEDURES

Low flow estimates are presented in two forms;

- hardcopy maps of the river network at 1:50,000 scale with each river stretch identified by a unique LID. This is accompanied by a listing of low flow estimates associated with each LID.

- data files of LID and low flow estimates in the format described within the Water Data Unit (DOE 1978) Water Archive User Manual. The relevant information for data storage, retrieval and adjustment of LIDs are presented in Appendix 1.

Two user procedures are therefore available and low flow estimates at the ungauged site may be derived from either of the two procedures;

PROCEDURE 1

- identify the river stretch which contains the site of interest on the appropriate 1:50,000 O.S. map

- identify the equivalent river stretch on the provided hardcopy maps of the river network and derive the unique LID

- refer the LID to the low flow estimate listing and extract the required low flow index

- where appropriate, adjust the low flow estimate for any extension of the network above the present canal system. Identify those river stretches in the catchment which are diverted into canal systems and abstract the appropriate low flow estimate for these stretches. Subtract the sum of any diverted flow from the low flow estimate at the site of interest.

In each case, the low flow estimates apply to the downstream node of each river stretch. It may be necessary to derive the low flow estimate at a site of interest from the upstream stretch, if for example the site of interest is located a short distance downstream of the upstream node of a long stretch.

PROCEDURE 2

The transfer of archived data to North West Water necessitated the creation of a new Water Archive system feature, called a low flow feature, with a feature type of "LOW".

The purpose of doing this was to locate the low flow data recorded against the system feature with respect to the river network.

Data items associated with the Feature File have been used as follows;

- Feature type code - LOW

- Feature Sub-type code has been filled according to the rules detailed in Appendix 1.

- User reference number contains the IH stretch reference number to whose downstream end the data relate. A table of IH stretch reference numbers is supplied in association with Procedure 1 above. From the North West Water point of view, this number may be treated as a unique identifier.

- Hydrological reference; to be computed by North West Water using Grid reference - to - HR conversion software together with the the table of User reference number to line end coordinates.

- National Grid reference; grid reference of downstream end of river stretch.

The Structured Feature file has been used to store the full values of low flow data as described in Appendix 1 (Item 1 = BFI, Item 2 = ADF, Item 3 = Q95(1), Item 4 = MAM(10), Item 5 = MODE(30)).

An example of the Feature Description Format File is presented in Appendix 1 together with examples of Feature File and Structured Feature File data.

5. Applicability of low flow estimation procedure in artificially influenced catchments

The low flow estimates derived within this report are those associated with the natural river regime. Clearly, extensive artificial influences are exerted upon the natural regime by water resource uses. An assessment of the applicability of the estimation procedure in artificially influenced catchments may be achieved by the following procedures;

- mapping the extent of artificial influences within the North West Water region to identify zones in which the present flow regime equates to the natural flow regime;

- incorporating artificially influenced gauged flow data to supercede natural low flow estimates;

- developing a data base of artificial influences, indexed by map reference, which are then assigned to the associated LID. This procedure would enable the manual or automatic adjustment of low flow estimates by the inclusion of identified artificial influences above the site of interest;

- the flexibility the digitised network facilitates the removal and inclusion of river stretches. In an interactive system, such flexibility would greatly facilitate the incorporation of artificial influences - for example, by the removal of tributaries which are bisected by a canal, or by the inclusion of artificial drainage channels. However, the current procedure requires the network to be selected prior to the calculation of catchment characteristics, and such flexibility is not therefore easily incorpoarted.

6. References

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Appendix 1 Low flow estimate Water Archive information

There are 13 files of data.

1. FORMAT FILE
2. FEATURE1 FILE
3. FEATURE2 FILE
4. FEATURE3 FILE
5. FEATURE4 FILE
6. FEATURE5 FILE
7. FEATURE6 FILE
8. STRUCT1 FILE
9. STRUCT2 FILE
10. STRUCT3 FILE
11. STRUCT4 FILE
12. STRUCT5 FILE
13. STRUCT6 FILE

Description of 'FORMAT FILE'.

These data follow the instructions for Input to the Feature Description Format File in the WDU manual.

Sample of the data..

```
**001  5ILOW
001 BFI                 N 3
002 ADF                 N 3
003 Q95(1 DAY)          N 3
004 MAM(10 DAY)         N 3
005 MODAL FLOW(30%)     N 3
```

Description of 'FEATURE FILE's.

These data follow the instructions for Input to the Feature File in the WDU manual.

The Feature Sub-type Code has been filled according to the following rules..

10 bins were set up for each item.

The limits were..

1.
0. to 1. in steps of .1 for item 1 (BFI)

2.
```
   lt. .31
    .31 to .62
    .62 to 1.25
   1.25 to 2.5
    2.5 to 5.
     5. to 10.
    10. to 20.
    20. to 40.
    40. to 80.
 gt. 80.
```
for item 2 (ADF). This conforms with the values on the map key we have here.

3.

0. to 15. in steps of 1.5 for item 3 (Q95)

4.

0. to 15. in steps of 1.5 for item 4 (MAM)

5.

0. to 30. in steps of 3. for item 5 (MODE)

The values of the items were assigned a bin number,and this was turned into a letter (1=A,2=B etc.),and the 5 locations of the Feature Sub-type Code filled in, Col 44 for item1,Col 45 for item2 etc.

Sample of data follows..

```
**0012
1LOW                                            IEIHJH          23992
2SV3271240198
**0022
1LOW                                            IFEAAA          23993
2SV3271240198
```

Description of the 'STRUCT FILE's.

These data follow the instructions for Input to the Structured Feature Description File in the WDU manual.

Sample of the data follows..

```
**001 2ILOW   23992
0118041988
02  1          443  2        66598  3        11739  4        13897  5        21132
**002 2ILOW   23993
0118041988
02  1          513  2         2906  3          635  4          749  5         1043
```

The following is a list of the stretches which were changed to 'naturalise' the network.

IFLAG=1 if stretch has been deleted.
IFLAG=2 if stretch is a new one produced by editting.
IFLAG=3 if stretch has been replaced by editting.For example
if a stretch was split into 2,it woul;d be replaced by
2 stretches with IFLAG=2.

REFERENCE	FLAG	COORDS OF FIRST 2 DOWNSTREAM				COORDS OF LAST 2 UPSTREAM			
23991	1	321000	403281	321038	403330	327100	402020	327129	401986
23999	1	338310	382510	338261	382466	337642	380012	337647	380005
24000	1	337647	380005	337685	379956	340484	377512	340505	377494
24008	3	343348	380001	343397	380035	346516	379997	346517	379997
24012	3	348336	380000	348380	380049	348779	381791	348783	381805
24017	3	352206	384092	352255	384098	356543	386672	356565	386670
24023	3	357549	386967	357563	386972	359984	386473	360000	386489
24024	3	360000	386489	360049	386506	361771	388142	361781	388173
24026	3	361781	388173	361806	388152	363734	388933	363752	388947
24031	3	364991	387894	365036	387884	369638	390340	369648	390360
24165	1	346403	377469	346447	377481	350201	379955	350207	379963
24167	1	350207	379963	350201	379970	350181	380005	350174	380004
24168	1	350174	380004	350137	380053	356516	384853	356542	384864
24170	1	356542	384864	356591	384887	359288	385812	359297	385815
24172	1	359297	385815	359346	385837	359946	386032	359995	386034
24173	1	359995	386034	360044	386040	360264	386108	360305	386134
24175	1	360305	386134	360354	386141	361647	386573	361652	386576
24177	1	361652	386576	361701	386589	364069	387447	364109	387466
24179	1	364109	387466	364158	387481	367612	388692	367633	388702
24181	1	367633	388702	367682	388707	368214	388883	368245	388894
24183	1	368245	388894	368250	388892	368285	388922	368289	388927
25430	1	383296	397492	383293	397509	384800	398130	384830	398142
25431	1	383296	397492	383288	397484	380036	396316	380017	396309
25432	1	380017	396309	379968	396290	379619	395581	379619	395573
25433	1	379619	395573	379570	395570	368833	399507	368832	399507
29997	1	368832	399507	368783	399502	360049	402055	360017	402092
25434	1	360017	402092	359968	402118	357874	404483	357879	404503
25435	1	379619	395573	379662	395524	366521	387006	366520	387006
29996	1	366520	387006	366495	387001	366520	387006	366495	387001
29998	1	366495	387001	366450	386986	360033	385182	360005	385185
25436	1	360005	385185	359956	385194	356713	381030	356713	380989
25437	1	356713	380989	356664	381025	351102	382916	351074	382918
25438	1	356713	380989	356713	380940	356972	380024	356992	379997
25439	1	356992	379997	357023	379948	359993	376584	360010	376575
25440	1	360010	376576	360054	376560	368308	370887	368328	370877
25441	1	368328	370877	368349	370862	373162	360214	373166	360174
25442	1	373166	360174	373171	360149	383556	354605	383575	354597
25443	1	383575	354597	383562	354556	390412	366542	390413	366548
25444	1	390413	366548	390433	366593	392918	379970	392919	379986
25445	1	392919	379986	392904	380027	396121	388372	396140	388386
25446	1	383575	354597	383624	354591	383742	354105	383737	354090
25447	1	384830	398142	384837	398120	393488	398398	393505	398411
25448	1	384830	398142	384833	398175	386903	399959	386926	399996

25449	1	386926	399996	386975	400044	388305	409965	388304	409996
25450	1	388304	409996	388298	410045	394686	419042	394685	419061
25451	1	393505	398411	393511	398405	395796	390019	395827	390001
25452	1	395827	390001	395876	389978	399967	384595	400016	384572
25453	1	400016	384572	400050	384560	401333	382298	401331	382282
25454	1	393505	398411	393534	398423	397557	399990	397558	399990
25455	1	397558	399990	397556	400028	400000	406829	400015	406841
25456	1	400015	406841	400046	406866	400522	407797	400542	407809
25457	1	401331	382282	401320	382270	401201	381607	401205	381592
25458	1	401331	382282	401355	382280	402188	382054	402233	382042
25459	1	340505	377494	340507	377445	339987	366751	339996	366702
29995	1	339996	366702	339997	366700	345346	364387	345371	364367
25460	1	345371	364367	345420	364326	360006	357983	360009	357982
25461	1	360009	357982	360058	357941	361229	357088	361265	357056
25462	1	340505	377494	340514	377471	346362	377466	346403	377469
25463	1	361265	357056	361314	357022	362613	355354	362618	355342
25464	1	361265	357056	361314	357081	370561	365719	370567	365719
25465	1	362618	355342	362569	355321	360024	347908	360003	347921
25466	1	360003	347921	359974	347948	353273	344732	353262	344708
25467	1	362618	355342	362637	355293	366876	340045	366874	340010
25468	1	366874	340010	366873	339961	368083	335021	368095	335004
29999	2	343348	380001	343397	380035	346285	380172	346287	380171
30000	2	346287	380171	346322	380136	346516	379997	346517	379997
30001	2	352206	384092	352255	384098	355494	384785	355511	384831
30002	2	355511	384831	355526	384880	356543	386672	356565	386670
30003	2	360000	386489	360049	386506	360271	386598	360286	386614
30004	3	360286	386614	360300	386634	361771	388142	361781	388173
30005	2	357549	386967	357563	386972	358681	386692	358701	386692
30006	2	358701	386692	358711	386702	359984	386473	360000	386489
30007	2	361781	388173	361806	388152	363274	388209	363294	388220
30008	2	363294	388220	363319	388240	363734	388933	363752	388947
30009	2	364991	387894	365036	387884	367461	389125	367510	389130
30010	3	367510	389130	367516	389131	369638	390340	369648	390360
30011	2	348336	380000	348380	380049	348652	380617	348658	380666
30012	2	348658	380666	348662	380697	348779	381791	348783	381805
30013	2	360286	386614	360300	386634	361635	387635	361640	387650
30014	2	361640	387650	361640	387660	361771	388142	361781	388173
30015	2	367510	389130	367516	389131	368589	389035	368638	389059
30016	2	368638	389059	368687	389084	369638	390340	369648	390360
30017	2	346287	380171	346403	377469	346287	380171	346403	377469
30018	2	355511	384831	356542	384864	355511	384831	356542	384864
30019	2	360286	386614	360305	386134	360286	386614	360305	386134
30020	2	358701	386692	359297	385815	358701	386692	359297	385815
30021	2	363294	388220	364109	387466	363294	388220	364109	387466
30022	2	367510	389130	367633	388702	367510	389130	367633	388702
30023	2	361640	387650	361652	386576	361640	387650	361652	386576
30024	1	368638	389059	368245	388894	368638	389059	368245	388894
30025	2	348658	380666	350207	379963	348658	380666	350207	379963
30026	2	368638	389059	368245	388894	368638	389059	368245	388894
25469	1	328522	424645	328571	424658	336783	426266	336799	426265
25664	3	359995	416195	360012	416230	362153	414565	362176	414593
25698	3	361381	419104	361388	419106	364658	418784	364697	418789
25707	3	361557	416438	361546	416465	362224	419962	362222	420000
26001	1	330571	421352	330620	421398	337636	420690	337674	420685

26044	1	346108	420015	346123	419980	345138	411553	345116	411514
26046	1	345116	411514	345102	411544	337653	410275	337626	410227
26047	1	337625	410227	337604	410178	339234	399393	339254	399353
26048	1	339254	399353	339274	399328	334304	392199	334274	392172
26049	1	345116	411514	345118	411514	355383	407288	355414	407299
26050	1	355414	407299	355458	407314	358343	404957	358384	404920
26052	1	358384	404920	358374	404907	357959	404584	357924	404538
26053	1	358384	404920	358409	404923	359980	406015	360014	406042
26054	1	360014	406042	360047	406091	360027	407331	360008	407358
26055	1	360008	407358	359975	407395	359142	419994	359121	420018
26056	1	359121	420018	359087	420066	359096	420648	359085	420694
26057	1	359085	420694	359085	420733	359984	421561	360010	421539
26058	1	360012	421538	360061	421571	364800	424735	364801	424736
26059	1	364801	424736	364821	424781	373403	428441	373428	428416
26060	1	373428	428416	373463	428381	382182	432612	382227	432602
26061	1	382227	432602	382257	432597	385646	438132	385656	438157
26062	1	385656	438157	385656	438162	388727	448174	388742	448189
26063	1	359085	420694	359045	420723	358878	420937	358872	420957
26064	1	334274	392172	334225	392175	333865	392162	333863	392162
26065	1	334274	392172	334244	392154	334142	391191	334143	391190
26066	1	382492	457216	382453	457255	382492	457216	382453	457255
26067	1	382492	457216	382453	457255	382492	457216	382453	457255
27071	1	361381	419104	361388	419106	361983	418983	361998	418983
26072	1	361996	418981	362016	418975	364658	418784	364697	418789
26069	2	361381	419104	361388	419106	361983	418983	361998	418983
26070	2	361996	418981	362016	418975	364658	418784	364697	418789
26071	2	361557	416438	361546	416465	362006	418968	362006	418998
26072	2	362006	418998	362021	419028	362224	419962	362222	420000
26074	2	359995	416195	360012	416230	362153	414565	362174	414591
26075	2	362298	414298	362176	414593	362298	414298	362176	414593
26066	1	329008	450572	329057	450604	334359	447570	334358	447523
26067	1	328017	451980	328066	452022	336155	453979	336187	453979
26804	1	344294	456629	344308	456603	348157	454511	348164	454515
26806	1	348164	454515	348166	454466	349971	444790	349986	444800
26807	1	349986	444800	350001	444815	346425	433089	346427	433074
26808	1	346427	433074	346430	433079	352673	430226	352708	430216
26809	1	348164	454515	348167	454537	347047	459983	347035	460014
26810	1	347035	460014	347043	460039	346940	464298	346920	464302
26811	1	346920	464302	346945	464283	351323	470887	351328	470897
26812	1	351328	470897	351342	470908	352058	485433	352026	485441
26813	1	327007	453506	327012	453516	336391	459992	336435	460006
26815	1	326017	454788	326012	454792	329473	459990	329513	460015
27495	1	322195	460000	322244	460035	321459	465557	321413	465589
27496	1	316132	473605	316181	473634	318394	473738	318424	473714
27497	1	314792	476303	314841	476324	316484	476830	316512	476839
27498	1	307437	488198	307486	488208	309411	486876	309424	486877
27499	1	306330	493912	306379	493943	308131	496113	308149	496114
27500	1	301868	502515	301850	502543	302227	502693	302261	502714
27501	1	298938	506779	298955	506811	298776	511169	298760	511206
27502	1	296616	510487	296643	510536	298291	513728	298337	513757
27503	1	295767	511537	295792	511586	296399	513129	296425	513156
27504	1	296786	518662	296821	518659	297741	516637	297757	516599
27505	1	297594	521056	297643	521064	298313	521217	298326	521221
27506	1	298524	525296	298573	525312	299269	525510	299270	525551

27897	1	298260	529797	298309	529762	299061	529264	299089	529244
27898	1	301079	533354	301128	533315	303194	532557	303209	532567
27899	1	301956	534575	302005	534549	304444	533487	304462	533488
27900	1	302189	534970	302238	534954	305464	534582	305494	534587
27901	1	302816	536968	302865	536955	306977	537179	307002	537164
27902	1	304704	539017	304753	538971	307629	539358	307653	539374
27903	1	306831	541089	306867	541095	307506	540012	307508	539998
27905	1	307465	543658	307491	543673	309336	542470	309349	542461
27906	1	307170	544913	307211	544935	308003	544981	308016	544976
27907	1	313351	557673	313386	557642	314639	557095	314676	557074
27908	1	313920	558683	313969	558670	322754	557530	322760	557543
28409	1	312985	561207	313034	561251	332958	561981	332966	561961
29142	1	328310	562928	328306	562938	332365	566129	332385	566120

Appendix 2 Development of a modal flow index

INTRODUCTION

The intuitive value of a modal flow index in water resource studies derives from the expression of the most frequently recurring discharge. In an ecological context, it is speculated that aquatic life may develop in association with the modal flow. Departures from the modal flow may prove detrimental to the "modus operandi" of species or else may stimulate reaction, for example migration.

In water quality studies, the selection of a suitable flow index is primarily dependent upon the purpose of the consent. Water quality flow indices are typically directed towards high effluent concentrations associated with low river flows. In such cases, a Minimum Acceptable Flow criterion is adopted which may, for example, be defined as the 95 percentile exceedance flow. However, as Ellis (1986) points out, "if the stated endeavours are largely directed towards maintaining an acceptable *average* quality of effluent, then a mean-type consent would be a sensible choice". In the context of an average quality of effluent, the modal flow could prove more valuable than a mean-type consent by expressing the most frequently recurring flow and by considering a range of flows within the modal class.

An early reference to the mode as a flow statistic (Bransby-Williams 1953) notes the tendency of the modal flow to be associated with the "lower rates of discharge". No strict definition of the mode is offered, but presented histograms reveal the class interval is fixed at 1/35 of the range of mean daily flows.

Reference has been made to the Mode/Mean ratio by the Mersey and Weaver River Authority (1963). In this case, the modal definition, as determined from the presented data, equals the mid-point of the modal class of daily flows. The class interval boundaries for the 11 presented histograms are fixed to 10, 20, 50 or 200 Ml/D depending upon the range of recorded discharge. High Mode/Mean ratios and high Median/Mean ratios, reflecting a tendency for stable regimes and relatively higher low flows, indicate a greater "attractiveness for potential development for abstraction".

The following Mode/Mean ratios were presented for 11 catchments in the Mersey and Weaver area;

Gauging station	Mode/Mean ratio
R. Alt at Sefton	0.58
R. Bollin at Dunham Massey	0.45
Glaze Brook at Little Woolden Hall	0.41
R. Irk at Scotland Weir	0.39
R. Mersey at Irlam Weir	0.40
R. Irwell at Adelphi Weir	0.38
R. Weaver at Ashbrook	0.35
R. Dane at Rudheath	0.33
R. Dane at Hulme Walfield	0.33
R. Gowy at Picton	0.29
R. Weaver at Audlem	0.23

Source: First Periodical Survey, Mersey and Weaver River Authority 1963.

Development of a modal flow index

A formal definition of the mode is "the value of the class within a statistical group in which there are most incidences". Difficulty may arise in defining the mode because;

- the distribution of values in a series may not be unimodal ie the series may contain two or more modal groups of roughly equal importance.

- the selection of class limits will determine the final mode and as such the modal value for an individual series may vary depending upon class boundary selection.

- the convenience of a single-value modal expression restricts the analytical usefulness of modal class limits and mid-point expressions in combination.

- unlike the mean expression, it is not possible to express a single effective deviation value expressing sample scatter about the mode.

These general difficulties of modal definition present specific difficulties in the context of hydrological data;

- the modal flow may be biassed by hydrometric anomalies, particularly in cases where stage data were recorded or processed on an interval rather than a ratio scale. This problem was prevalent amongst early data within hydrometric zone 68.

- the selected class width must be greater than 0.001 cumecs to ensure that certain classes are not totally excluded from containing flow data, which is stored to three decimal places.

- regional estimation procedures based on multiple regression of single value low flow statistics against catchment characteristics will have difficulty in accomodating a flow statistic represented by three numerical values - the mid-point of the modal class and the upper and lower class limits.

Five approaches to modal flow definition were investigated to assess the relative merits of each. The five procedures are each briefly described and the associated advantages and drawbacks tabulated.

Discussions with North West Water revealed a concern only for a single-value modal index, which largely overcomes the problem of modal definition by both the mid-point and the modal class range. Consequently, Method 5 was considered to be the more appropriate procedure for calculation of the mode. Class limits were set arbitrarily to 1%, 10%, 20% and 30% of time in the flow record and the modal values, termed MODE(1), MODE(10), MODE(20) and MODE(30) respectively, calculated for each of the 114 catchments employed in the study. Relationships with the Base Flow Index revealed that none of the indices showed a notably stronger relationship with catchment soil type, and in each case the relationship was generally poor. In the absence of strong relationships between modal indices and BFI, MODE(30) was identified as the most suitable index because by describing the flow which occurs 30% of the time it better represents the value of a modal index in describing average conditions than say the most frequently recurring daily mean discharge.

METHOD 1: **Modal daily mean flow**

Procedure - calculation of the most frequently occurring daily mean flow (to three significant figures).

ADVANTAGES	- Rigid class interval definition
	- Indexed by a single discharge value
	- Easily calculated from available data
DISADVANTAGES	- Prone to hydrometric anomalies due to crude stage-discharge relationships, substitution of constant values for up to one month, and storage of data in rounded units of discharge.
	Prone to short records; fewer available data increases the probability of either a poorly defined mode or a multimodal distribution.
	Prone to variations in catchment area; large catchments with a greater range of flow values have a reduced probability of a clearly defined modal value. Similarly, small basins may exhibit a very low range of data, with an increased probability of a multimodel distribution.

METHOD 2: **Generalised relationship between the averages**

Procedure - a generalised relationship exists between the three average measures of a sample, such that for a positively skewed sample:

Mode = Mean - 3(Mean - Median)

ADVANTAGES	- No problem of class definition
	- Mode represented by a single numerical index
	- Easily calculated from available data
DISADVANTAGES	- The approximation of the mode depends upon the degree of skew present in the flow data. Because of the highly skewed nature of daily flow data, the difference between the mean and the median may be sufficiently large to generate negative modal flow values

METHOD 3 **Fitting of an appropriate probability distribution to the histrogram of daily mean flows**

Procedure - three extreme value probability distributions (EV1, EV2, log-Normal) were each fitted to the daily discharge data. In each case, the modal value was estimated from the parameters of the distribution. Goodness-of-fit tests were considered to lack dicriminatory value *in selecting* the most appropriate distribution, although log-Normal appeared to present the most appropriate fit to the raw data.

ADVANTAGES

- Avoids class interval definition
- Mode represented by a single numerical index

DISADVANTAGES

- Application of an extreme value distribution is invalid as a "distribution *fitting" procedure in this case because the* daily flow data are not independent
- Selection of most appropriate distribution is hindered by lack of discrimination amongst statistical goodness-of-fit tests

METHOD 4 **Class interval set to 1% of ADF**

Procedure - the modal class limits are fixed to 1% of the average daily flow. Mid-point of the modal class is calculated using the following equation;

$$\text{Mid point} = L + \left[\frac{Fm - Fb}{(fm - Fb) + (Fm - Fa)} \cdot C \right]$$

ADVANTAGES	- Rigid class interval definition
	- Less subject to hydrometric errors than methods based on original data alone
DISADVANTAGES	- Small class interval is prone to hydrometric anomalies
	- Expression of the mode by mid-point and upper and lower class boundaries
	- Prone to range of catchment area; in small catchments, a particular problem arises if 1% of ADF is less than 0.001 cumecs because classes are defined into which no data can be assigned

METHOD 5: **Class interval set to contain a fixed proportion of the total number of recorded days within the modal class**

Procedure - unlike method 4 in which the class interval is fixed by units of discharge, this method fixes the modal class limits around a selected proportion of the total flow record - proportions of 1%, 10%, 20% and 30% were studied. The weighted mid-point of the narrowest flow range to contain the required percentage of days gives the modal flow index. The index was calculated for each series of gauging station data as follows

- a histogram of the flows with a bin-width of ADF/500 was created

- starting at the lowest bin, the contents of adjacent bins were added together until the required percentage of flow days was exceeded. The procedure was repeated starting from the next-lowest bin, and so on through the range of bins. The narrowest bin to just exceed the required number of number of days was the "modal bin".

- a histogram of flows with the bin-width equal to the modal bin was then produced and the modal flow index, Mode(x%), was then calculated as the weighted mid-point employing the equation presented in Method 4.

ADVANTAGES

- Largely overcomes problems of hydrometric anomalies

- Largely overcomes problems introduced by range of catchment area

- Conceptually most appropriate in defining average conditions because a greater range of data is included in the modal class

DISADVANTAGES

- Arbitrary class limit definition

- Expression of the mode by mid-point and upper and lower class boundaries

Appendix 3 Directory of low flow estimates by river stretch

See accompanying volume