THE ESTIMATION OF MEAN MONTHLY RIVER FLOWS USING LIMITED METEOROLOGICAL DATA AND CATCHMENT CHARACTERISTICS

BY

P.F.CLULEE

THESIS SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF ASTON IN BIRMINGHAM

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SYNOPSIS

This project aims to estimate mean monthly flows at any given point on a river in a region of sparce hydrometric data. A conceptual model of the rainfall/run-off process has been developed which utilises available mean monthly meteorological data and catchment characteristics. The essential characteristics of the hydrological stores and processes and their relationship with catchment morphology are identified. The physical characteristics are defined in quantitative terms, and the meteorological characteristics and hydrological stores and processes are examined. The development and calibration of a rainfall/run-off model, based upon a monthly time step and incorporating the hydrological components and catchment characteristics is described.

Two principal modifications were made to the model, firstly to the overland flow/interflow algorithm and secondly to the natural recharge/interflow algorithm. The validity of the model and its modified versions were tested using data from areas of the U.K. lying outside the original study area. The predicted mean monthly flows compared very favourably with the historic flows and thereby demonstrated the value of catchment characteristics for model calibration in areas of limited hydrometric data. Comparisons are made with the results obtained using a method based upon linear regression equations derived in a previous project using data from the same study area. The results show that the new models are far superior to the regression method when applied to areas outside the area used for calibration.

The development and testing of the models and their calibration procedures form the bulk of the project, and the use of catchment characteristics for the calibration of the model is a novel feature of the study.

RAINFALL, RUN-OFF, MODEL, CATCHMENT, CHARACTERISTICS

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THE ESTIMATION OF MEAN MONTHLY RIVER FLOWS USING LIMITED METEOROLOGICAL DATA AND CATCHMENT CHARACTERISTICS

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Investment in the development of water resources throughout the world is playing an increasingly major role in economic development. However, engineers and planners working on the development of projects, and relying to a large degree upon the reliability of hydrological data, are finding that available data is limited and of poor quality. Where data is available it often relates to sites many miles from the area of interest, and despite improvement to hydrological networks throughout the world, the quantity and quality of hydrological data continues to be poor.

The problem, therefore, is how to make the most effective use of the data which is available. This data can basically be categorised as historical hydrometeorological data and topographic data. Historical hydrometeorological data cannot be reproduced by experiment or survey, and such data of good quality is extremely valuable, yet is often scarce, unlike catchment characteristics including topographic, geologic and geomorphic characteristics which can be identified by survey and quantified. It is therefore beneficial to develop techniques which enable the maximum amount of information to be extracted or extrapolated from both these data sources.

1.2 Former Projects

This project is an extension of an earlier project (El Gusbi 1979) the object of which was to develop a method of estimating monthly flow data for ungauged catchments using rainfall and flow data from neighbouring catchments. In any given area there are hydrometeorological data available at given points. If flow characteristics are required at an ungauged point it should be possible to pool the data from all other points in the region to enable reliable estimates to be gained of the flow regime at the ungauged point. El Gusbi developed such a method, which is basically a set of regression lines relating flow statistics for the region to areal rainfall. His project demonstrated how this can be done for any region provided hydrometeorological data are available at sites other than the site of interest. The method was shown to be reliable within the region and provides the necessary data for the calibration of simple stochastic models of river flow (i.e. mean, st. dev., skewness, serial correlation, etc.). However, regression equations are very much specific to the area for which they were developed, and this restricts their application.

If only limited hydrometeorological data are available, especially flow data, El Gusbi's method cannot be applied. Under these circumstances catchment characteristics must be utilised by the hydrologist to develop other methods. Unlike hydrometeorological data, catchment characteristics have the advantage that data can be collected and evaluated at any time. They are a relatively poor substitute for hydrometeorological data but nevertheless if a reliable method of flow prediction can be developed which makes use of them it could prove most valuable.

In the United Kingdom both Flood Studies (1975) and Low Flow (1978) reports provide methods of estimating high and low flow characteristics of ungauged catchments using basic meteorological data and indices of the geomorphic character of the catchment. Flood flow characteristics are important in the planning and design of flood protection works, river bridges, spillways and other hydraulic structures and low flow characteristics are essential to studies of pollution control and the reliability of water supply schemes. However, the river flow regime, as represented by the seasonal variation of mean flow is also important in the design of water storage and supply facilities. However, very little work has been done on mean flow characteristics and it is the aim of this project to fill this gap.

Another project being carried out in the Department of Civil Engineering is closely related to the same aim, but tackles the problem from a different starting point. In this case remote sensing techniques are being used to derive quantifiable catchment characteristics for use in prediction equations, algorithms or models. However, the technique does not appear, at the present time, to be capable of deriving all the necessary indices to permit the formulation of reliable prediction techniques. It is for these reasons that this project concentrates on the development of methods for the prediction of mean river flow characteristics and their seasonal variations on the assumption that the catchment characteristics can be obtained from existing maps or by ground survey.

The aim of this project has been twofold:

i) to test El Gusbi's method on catchments lying outside the region used to develop and calibrate the method

ii) to develop and test a method of predicting monthly flow data for regions in which only rainfall and evaporation data are available

Such a method, if proved reliable, could be of immense value to engineers and hydrologists planning water projects in areas of sparse data.

This project is based solely on U.K. data, although it is hoped that the technique thus developed may be further developed for use in other countries. The intention is to produce a conceptual rainfall/run-off model designed to predict annual flow patterns for ungauged catchments. This is based upon an investigation of the spatial variability of the parameters most commonly used in model calibration. The model has been designed to use readily available data such as that provided by the Meteorological Office and Soil Survey, and parameters rapidly measureable from Ordnance Survey maps, such as drainage density and slope. The general nature of the method should permit its application to other areas, but this needs to be demonstrated.

Outline of the Thesis

Before commencing on the development of the rainfall/run-off model it was felt necessary to identify the essential characteristics of the hydrological stores and processes and their relationship with catchment morphology.

Chapter 2 discusses and evaluates those physical characteristics of a river catchment considered to be most important in shaping the rainfall/ run-off response. These include relief, drainage density, solid geology, soil type and vegetative cover. As these catchment characteristics were used as a means of calibrating conceptual rainfall/run-off models, they were defined in quantitative terms so that their influence upon the various hydrological stores and processes could be analysed and expressed in mathematical terms. The chapter concludes with a brief summary of each characteristic, its influence on the hydrological cycle and the method adopted for its quantification.

Chapter 3 discusses the meteorological characteristics and hydrological stores and processes acting upon and within the physical characteristics discussed in the previous chapter. The chapter identifies the principal components to be modelled and the ways in which they are related to catchment characteristics.

Having identified the essential hydrological and catchment characteristics, Chapter 4 outlines the development of a rainfall/run-off model based upon a monthly time step and incorporating the hydrological components and catchment characteristics. The calibration of the model using two different data sets drawn from catchments in the Mid-Wales/Welsh Borders region is described. The two sets comprise 16 year monthly flow records and their corresponding seasonal distributions of monthly flow averaged over the length of the record. Comparisons are made between the results obtained from the two sets and possible ways of improving the models performance are considered.

Chapter 5 describes two substantial modifications to the basic model which were implemented as a result of insights gained from Chapter 4. These modifications were:

i) modification of the overland flow/interflow algorithm

ii) modification of the natural recharge/interflow algorithm

Calibration of these new models were achieved by repeated simulation using the same two data sets as before and the results of these tests are described together with derived methods of calibration based upon catchment coefficients.

Chapter 6 examines the validity of the model and the derived calibration relationships for areas of the U.K. lying outside the original study area. Six new catchments, each providing reasonably reliable data were used to test the efficiency of each of the models. The results were then compared with predictions derived using El Gusbi's regression equations determined from an investigation of rainfall/streamflow relationships in the Mid-Wales, Welsh border region. The chapter concludes with a discussion of the precision of the various methods of prediction.

CHAPTER 2

CATCHMENT CHARACTERISTICS

2.1 INTRODUCTION

The physical characteristics of a river catchment provide the framework within which the hydrological processes operate. This chapter discusses and evaluates those characteristics considered to be most important in shaping the rainfall/run-off response. These include relief, slope, drainage density, solid geology, soil type and vegetative cover. The high degree of interdependence between these characteristics is similarly reflected in the hydrological stores and processes. For example, solid geology is a principal factor governing relief, slope, drainage density amd soil type, whilst infiltration is closely dependent upon slope and soil type and to a lesser degree upon the other characteristics.

If catchment characteristics are to be used as a means of calibrating conceptual rainfall/run-off models, they must first be defined in quantitative terms so that their influence upon the various hydrological stores and processes can be analysed and thereby expressed in mathematical terms. Studies of this type have been done for the extreme flow conditions of floods and droughts (N.E.R.C. Flood Studies 1975, Low Flow Studies 1978) but little research of this kind has been done on normal flow conditions. The following subsections examine each of the principal catchment characteristics in terms of their general effect upon hydrological stores and processes, and reviews proposed methods of quantification. They conclude by defining and describing the method used to quantify catchment characteristics relevant to this study.

2.2 RELIEF

2.2.1 General Hydrological Aspects

River basins with high relief possess more available potential energy than the more lowland basins, relief is therefore a drainage basin characteristic which exercises influence over both the rainfall/run-off process and sediment production. Thus relief affects the hydrological processes occuring within a catchment and is also a major factor governing the meteorological characteristics.

Precipitation in the form of rainfall is the major input into the hydrological system. Catchment relief greatly influences this input since it governs the production of orographic rainfall and may influence the production of convective rainfall. Orographic rainfall only occurs in the proximity of high ground and its magnitude depends upon the alignment with respect to prevailing air movements, and the size of the barrier. The presence of the barrier may either

1) Trigger conditional convective instability by giving an initial upward motion or by differential heating of mountain slopes.

2) Increase cyclonic precipitation by retarding the rate of movement of a depression and its associated fronts.

3) Cause convergence and uplift through the funnelling effect of valleys on airstreams.

Rain tends to be more intense on the windward rather than the leeward slopes of a barrier, consequently a rain shadow effect is created on the latter. Orographic precipitation lessons across a mountain barrier because the initial precipitation reduces the amount of precipitable moisture remaining in the atmosphere (see Fig. 2.1). In the lower Dee valley the leeward slopes receive less than 750 mm per year compared with over 2500 mm in Snowdonia.

In Great Britain orographic rainfall dominates spatial distribution, and increases the amount of rain in upland regions associated with frontal depressions and unstable airstreams. Even quite low hills such as the Chiltons and South Downs cause a rise in rainfall receiving 120 - 130 mm per year more than in the surrounding lowlands. Around the coast of Britain rainfall is approximately 700 mm and increases to over 2500 mm in the mountainous regions, but superimposed on this is a tendency for it to be greater in the West than in the East due to the rainshadow effect upon the prevailing S.W. winds caused by the Welsh mountains, Pennines and Western Highlands.

In the winter months, the areal distribution of snow also tends to reflect the pattern of relief. This is due to the fact that air temperature falls with altitude and, therefore, makes snowfall more likely on hills and mountains than in lowland regions. The vertical decrease in temperature on average equals 0.6°C per 100 m and this enables the snow to remain longer on hillsides, particularly where accumulations occur due to drifting. Manley (1952) found an almost linear relationship between altitude and snowmelt. Latitudinal effects across a land mass affect both temperature and atmospheric humidity and consequently influences the spatial and temporal distribution of snowfall and snowmelt.

Near sealevel there are approximately 5 days per year with

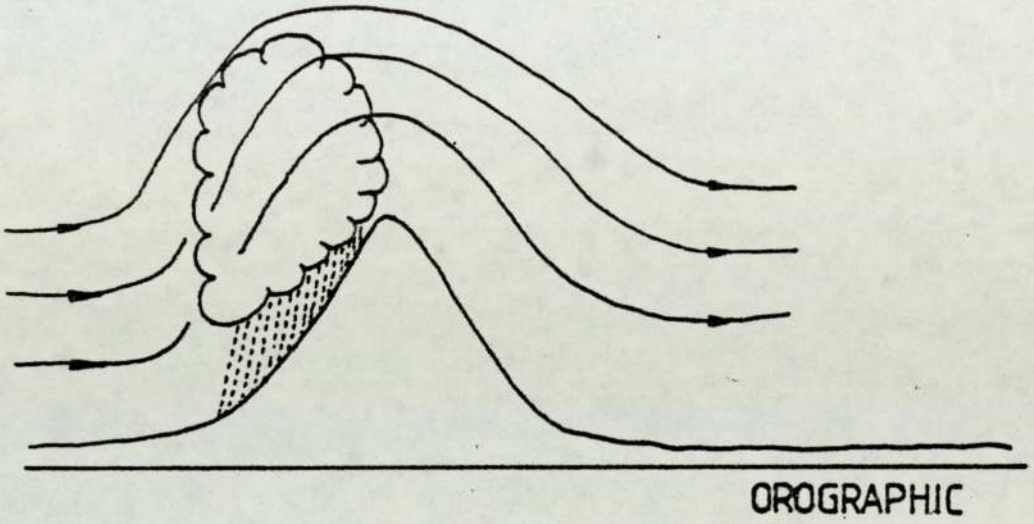


FIGURE 2.1 Orographic Precipitation

Simplistic?

snow in S.W. England. This increases to 15 in the South East and 35 in Scotland. Between the 60 - 300 m contours the frequency of snowfall increases by about 1 day per 15 m elevation and more rapidly on higher ground. In Northern Britain there are approximately 60 days with snow lying at 600 m and 90 days at 900 m.

2.2.2 Definition of Catchment Relief

Maximum basin relief (Nash and Shaw 1966) is the most frequently used descriptor of relief as a catchment characteristic. It measures the difference in height between basin mouth and the highest point in the basin perimeter. A second method utilises the hypsometric curve. This is constructed by planimetering the area between contours on a topographic map and plotting the cumulative area above and below a range of elevations. This curve is often expressed in terms of the percentage of area instead of actual area.

A similar method utilises the maximum and minimum altitudes of a sample of grid squares on a map. These figures then provide a series of average altitudes for the squares, which can be plotted against the percentage of total drainage basin area with squares above given heights.

2.2.3 Method Adopted

Relief was quantified by the method of grid square sampling mentioned above. This was incorporated with a procedure devised for the quantification of catchment slope, full details of which are given in section 2.3. In addition the maximum and minimum altitudes of the grid square samples taken from each catchment were determined, these figures were averaged and ordered in terms of magnitude. Hypsometric curves were then used to provide an indication of the general topographic character of the catchment from which each catchment could be viewed as three separate zones, an upland, mid-land and lowland zone, a concept which will be expanded in later sections.

2.3 SLOPE

2.3.1 General Hydrological Aspects

Several components of the hydrological cycle are strongly affected by slope. In steeply sloping areas the predominant movement of water is laterally by means of interflow and overland flow. In flatter areas these processes are less dominant giving way to vertical movement of water by means of infiltration and percolation. Hillslopes are normally convex-concave in profile, the top upper convex section and the base of the lower concave slopes are less steep than other areas of the hillside.

Rain arriving at the soil surface may either infiltrate the surface, pond on the surface or flow over it. Ponded water eventually evaporates or infiltrates the surface. The division between infiltration and overland flow is a complex one involving many factors including surface slope. Infiltration is the process by which water enters the soil surface, and tends to decrease as surface slope increases. In regions where gentler gradients predominate, soils tend to be thicker, so increasing their water storage capacity. In steeply sloping areas topographic factors, interacting with soil factors are related to produce complex areal patterns of subsurface and overland flow. Whipkey and Kirkby (1978) produced a simple two layered sloping soil plot, subjected to a period of steady rainfall. This illustrates initially rapid percolation at the upper end of the plot, continuing until entry into a less permeable lower layer is restricted causing saturation in the upper layers and the onset of overland flow. This model shows how overland flow results from saturation of soil surface layers. Similarly, on a concave slope saturation conditions reach the surface as a result of the slowing of saturated subsurface flow which causes a thickening of the saturated layer. In both cases interflow is the factor encouraging downslope saturation. Despite the slow movement of interflow, Hewlett and Hibbert (1967) found that interflow could react rapidly to storm events, because of the displacement of moisture downslope. Further upslope translatory flow serves to produce a pulse in soil moisture which forms a part of natural recharge.

Slope also affects the nature, thickness and distribution of soils since water induced erosion is particularly important for the movement of slope material and encourages a variation in soil thickness which is related to gradient. Erosion occurs when water moves over or through slope material, or when the slope material itself moves. In most cases moisture is predominant in determining slope stability.

2.3.2 Definition of Slope

Many methods of drainage basin slope measurement are available. They fall into three categories, channel slope, valley slope and overall drainage basin slope.

Strahler (1950) developed an index of valleyside slope which measures average slope steepness of the catchment. It is measured at intervals along valley sides and between divides and adjacent stream channels. Strahler also showed that there is a quantitative relationship between valley slopes and the slope of adjacent stream channels over a wide range of geographical conditions.

Standard methods of determining stream channel slope include the average slope of individual channel segments, the figure determined by dividing the difference between the height at the source and mouth of the channel by the channel length. The slope of the channel network is determined by the average gradient of all channels draining at least 10% of the total drainage area.

Linsley, Kohler and Paulus (1975) determined the distribution of land surface slope from a regular grid, or alternatively randomly located points placed over a map of the watershed. At each grid intersection or random point the slope of a short section of line normal to the contours is determined. The mean, median and variance of the resulting distribution can then be calculated. However, the accuracy of these indices depends upon the precision of the map which is used. The most frequently used method employs a topographical map divided into similar areas according to contour spacing, together with the application of a system of slope categories (Raisz & Henry 1937).

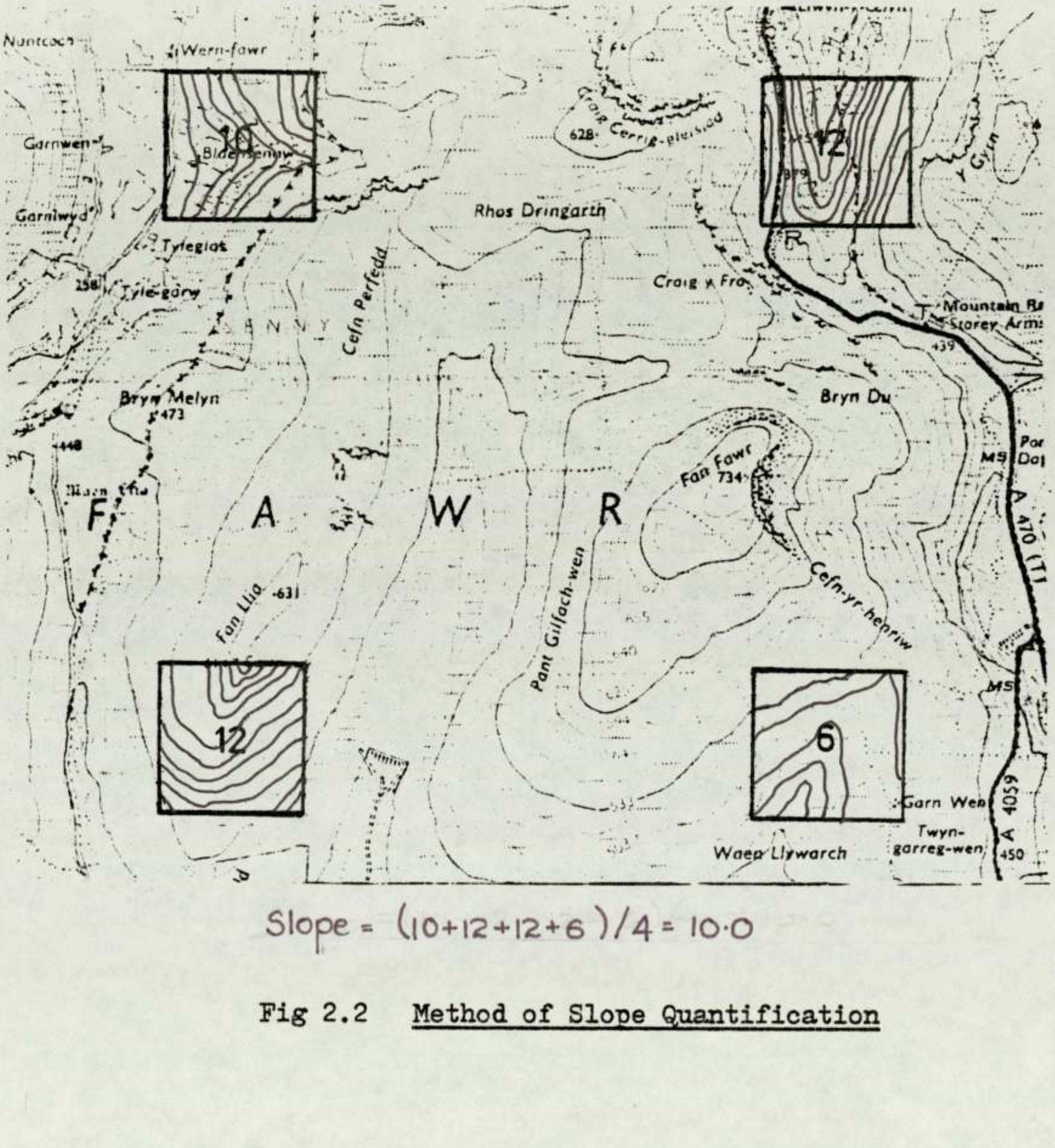
The N.E.R.C. Flood Studies Report (1975) used a measure of stream channel slopes which provided a more precise measure. They employed the Taylor/Schwarz (1952) indices of mainstream slope based on the square root of gradients. The velocity in each reach of a subdivided mainstream is related in the Manning equation to the square root of slope. The index is equivalent to the slope of a uniform channel having the same length as the longest watercourse and an equal time of travel.

2.3.3 The Method Adopted

The method of slope measurement chosen for this study was based upon the 1:50,000 O.S. relief maps. Previously, field and map based methods have been considered time consuming and have had the disadvantage that no single quantitative index could be easily determined. Consequently the method adopted was designed to provide a single index of catchment slope and to be:

1) accurate within definable limits
2) relatively quick and easy to apply
3) capable of meeting requirements (1) and (2) regardless of catchment size

An overlay marking the position of a catchment was placed over the appropriate map. A 1 km x 1 km grid square was then chosen and used to provide the starting point of a regular grid of sample grid squares. These sample squares were separated by several kilometers both vertically and horizontally (see Fig 2.2). The method was tested on four Welsh subcatchments where three regular sample grids were marked out, one ninth, one twenty-fifth and one fiftieth, sample sets. The choice of sample size was arbitary but three variations were chosen in order to establish the sample size necessary to provide a representative index regardless of catchment size. Within each square of a sample set the number of different contour lines contained within the square were counted (Fig 2.2) and noted. The sample mean of the number of contour lines per 1 km x 1 km square was then determined and used as the index of slope. By this method the slope index not only takes account of upland or lowland slopes but also of undulations in the landscape.



Slope = (10+12+12+6)/4 = 10·0

Fig 2.2 Method of Slope Quantification

2.4 SOIL

2.4.1 General Hydrological Aspects

Soil is composed of air, water, mineral and organic matter. The organic portion is derived from decaying matter, and the air and water are contained within the spaces between the particles. The mineral portion of the soil is derived from the parent material by weathering. This component of the soil is known as fine earth and it is upon this that soil texture is determined by the size of particles and the size of parts they form.

Soil texture is influenced by particle sizes which vary from small clay particles of less than 0.002 mm in diameter to sand size particles of up to 2 mm diameter (Bridges 1970) Both the size and shape of particles influences the storage of water, the larger and more angular a structural unit becomes the less water they retain

Pore sizes vary from larger than 0.075 mm which are soils free draining by gravity, to 0.1 - 0.55 mm which are free draining pores, channels and fissures. Capillary pores under 0.075 mm produce the suction pressures by which water is retained in the soil. Suction pressures cover pore ranges down to molecular dimensions. Salter and Williams (1965) related texture to available moisture where particle size is known (Fig 2.3) This provides a graphical method for determining available water capacity, based on laboratory tests in the range 60 mm/m depth of sand to about 200 mm/m depth of silt. However this method produces an underestimate for soils with a high organic content. Soil Survey have also produced a diagram of air capacity and water retention for certain particle size

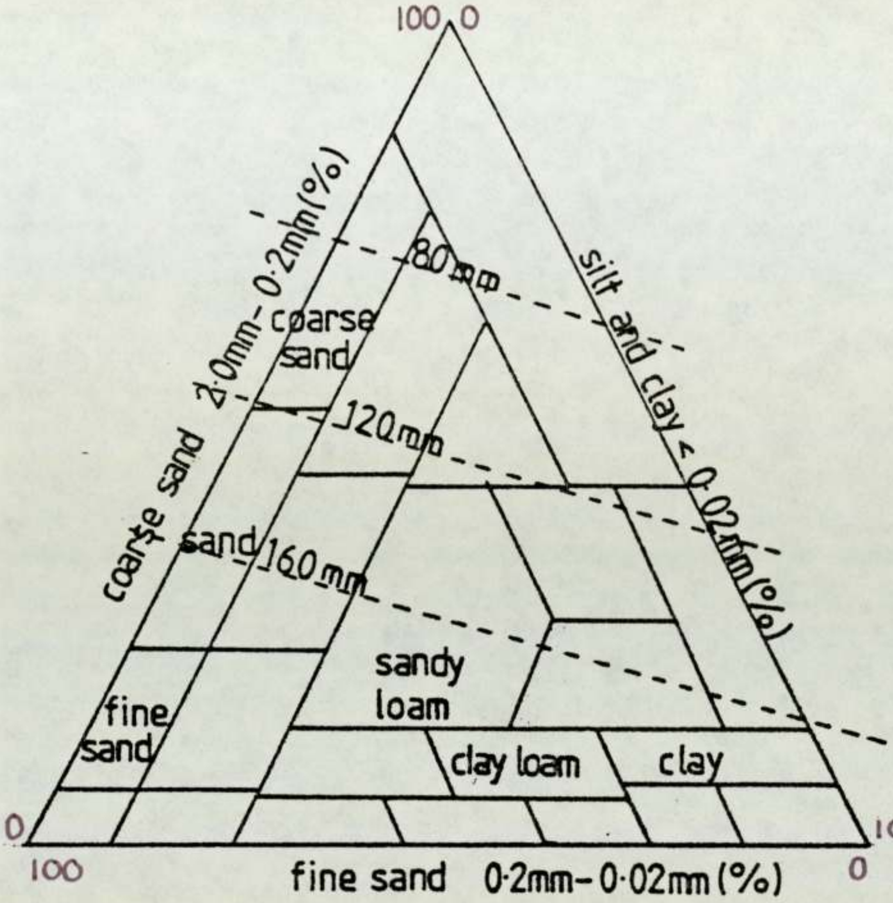


Fig 2.3 Relationship between Texture and Available Moisture (Salter & Williams)

classes in both topsoils and subsoils (Fig 2.4).

Soil structure is determined by the arrangement of particles, caused by physical forces induced by moisture changes, freezing and thawing, the effects of root growth and the activity of earthworms. These agencies form soil particles into distinct units, the size and shape depending largely on soil type. In soils with a medium to high clay content the strains caused by swelling and shrinkage are major factors in the production of structural units. Frost effects are largely confined to topsoils but are nonetheless vital, particularly on heavy soils. The fine and granular structures in the root zone owe their fineness and porosity to the development of fibrous roots. These particular agents of structure are more important in clays than sands.

Different structures visible in the soil profile include single grain simple structures which are loosely arranged, whilst massive aggregates are in a uniform mass, common in a soil with small amounts of clay and organic matter, such as sandy loams, loamy sands and silt. Puddled structures are aggregates deformed by treading or working when wet. Compound structures include rounded aggregates which are granules or porous crumbs, the product of root action and the decomposition of organic matter. Also blocky and peaty structures where the movement of water is via channels and fissures. Soil compaction and surface instability are also factors of soil structure which have a marked effect upon catchment hydrology, particularly in areas where intensive cropping is prevalent. When a soil is at field capacity topsoils are susceptible to damage, compaction can occur and puddling takes place. In

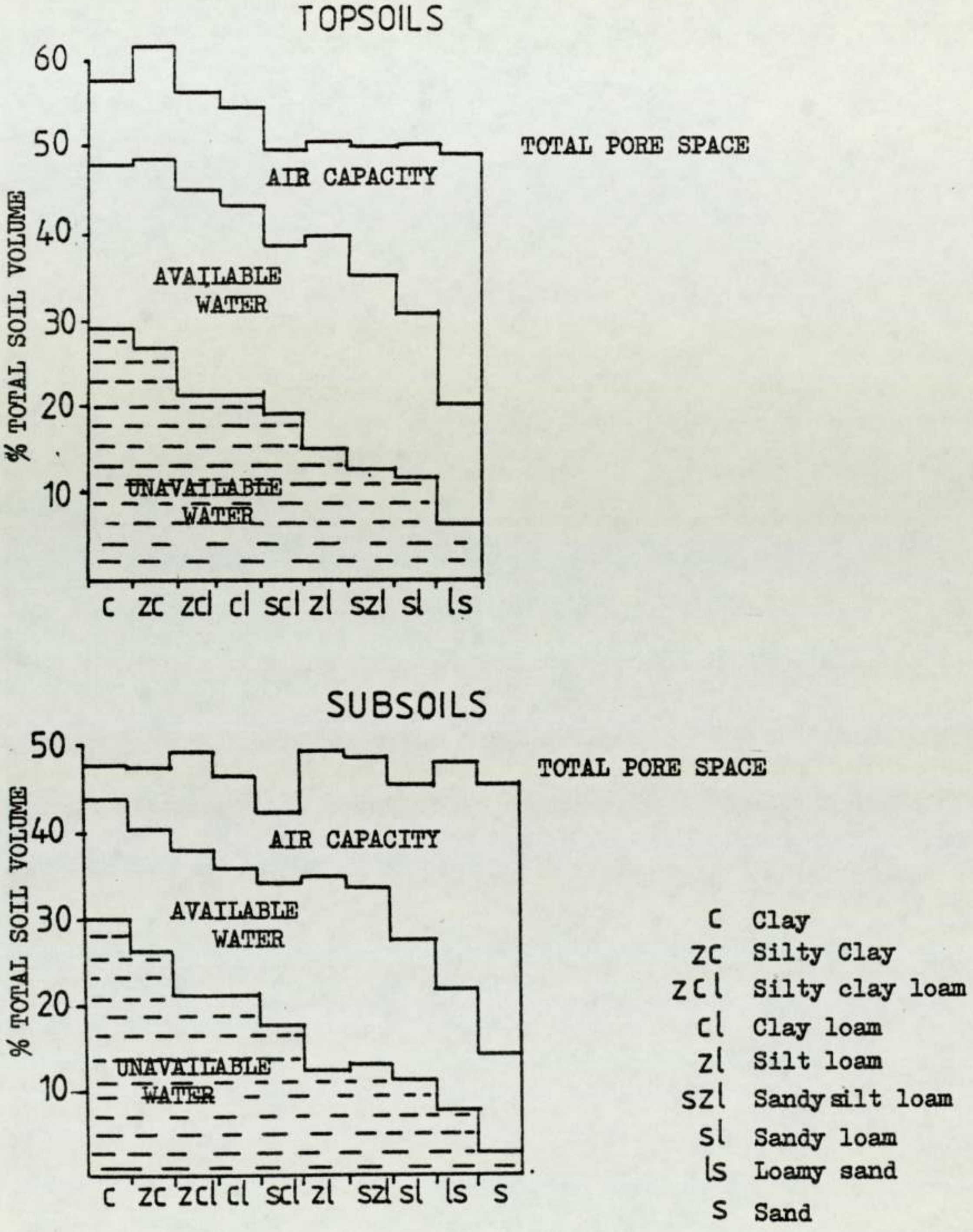


Fig 2.4 Air Capacity and Water Retention for Certain Particle-size Classes
(Soil Survey)

ack.

particular, well drained soils are susceptible to weak structure especially when worked in too moist a condition.

Evaporation occurs externally from the soil mantle. However it does affect the movement of soil moisture beneath the soil surface. It takes place from the soils after the cessation of rainfall and it results in a drying out of the surface. A suction gradient is created, and as it becomes greater than the opposing gravitational gradient it encourages an upward movement of moisture. Transpiration provides the transport system for the plant, and roots can extend several metres into the soil and abstract moisture and essential nutrients. Processes occuring upon and within the soil which include infiltration, overland flow, interflow and natural recharge are discussed at length in later sections.

2.4.2 Definitions and Method Adopted

It was necessary to develop an indicator of the moisture acceptance potential of the soil throughout the seasons, in order to provide a measure of the quantity of water expected to be retained as storage, or released as rapid response run-off or delayed run-off.

The first method which was considered relied upon a soil infiltration classification. Such a classification was first developed in the U.S.A. by G.W. Musgrave (1957) and has since been extended and now provides the U.S. Conservation Service with a detailed classification of soil infiltration capacities for named soil types. These are divided into four major soil groups, each classified on the basis of their intake of water during long duration storms, occuring after prior wetting and opportunity for swelling and without the protective effects of vegetation.

In 1971 R.B. Painter published a technical note which attempted to relate the classification system of Musgrave to British soil types. The result was a system containing eight groups formed by splitting each of Musgrave's groupings into two, each with their appropriate infiltration rates (Table 2.1).

For the purpose of this project the 1:1,000,000 soil map produced by Soil Survey and the Painter classification were used to determine the weighted mean infiltration capacities for each sub-catchment. The main disadvantage of this method is its reliance upon a classification of only eight groups when the area in question may contain 60 - 70 varied soil types. Consequently the choice of infiltration group for a particular soil type becomes, to some extent, an arbitrary decision. In addition, the groupings took no account of external characteristics such as slope, vegetation or depth to an impermeable horizon.

The N.E.R.C. Flood Studies Report (1975) rejected the Painter/Musgrave classification in favour of a more complex soil indicator based on the now more widely accepted contributing area model of catchment hydrology (Hewlett 1967). Consequently, Soil Survey were asked to construct an ordinal classification of run-off potential, using not more than five classes and based upon readily observable soil properties (Soil Survey 1978).

The Winter Rain Acceptance Potential (WRAP) was thus developed, the term winter being used to exclude periods when a soil moisture deficit is observable. It is assumed that the

Table 2.11. Painter's Infiltration Classification

Group A

Low run-off potential, high infiltration rates even when thoroughly wetted. Deep and well to excessively drained sands or gravels.

A1 9.6 mm/h minimum infiltration

A2 7.9 - 9.6 mm/h

Group B

Moderate infiltration rates when thoroughly wetted, moderately deep, moderately well to well drained sandy loams to sandy clay loams.

B1 5.8 - 7.8 mm/h

B2 4.1 - 5.7 mm/h

Group C

Slow infiltration rates when thoroughly wetted, either layer impedes downward movement or are clay loams to silty clay loams.

C1 2.8 - 4.0 mm/h

C2 1.5 - 2.7 mm/h

Group D

High run-off potential, low infiltration rate when thoroughly wetted. Clay soils, high swelling potential.

D1 0.8 - 1.4 mm/h

D2 0.0 - 0.7 mm/h

soil is already at field capacity and that any additional water is disposed of either vertically or laterally. Five soil classifications were distinguished each relating to four principal soil and site properties.

1) Soil water regime (drainage class in N.E.R.C. 1975)
2) Depth to an impermeable horizon
3) Permeability above an impermable horizon
4) Slope

The relative magnitutude of each of the above parameters remained a matter of judgement and as this system was designed to be used in a uniform manner, Table 2.2 was constructed to overcome this problem.

From the winter rain acceptance potential a numerical soil index was developed. This was achieved by multiple regression analysis of catchment characteristics, including the five soil types against mean annual floods. This produced a progression of exponents for the five variables consistent with constants derived in a regression of percentage run-off against the proportion of individual soils within the catchment. The five soil classifications ranged from WRAP 1, free draining sands, to WRAP 5, peats, stagnopodzols and stagnogley soils. Consequently a weighted mean of the soil classifications was adopted as the soil index where S_1 to S_5 are the areas of soil types 1 - 5 within the catchment.

$$\text{Soil} = \frac{(0.15S_1 + 0.35S_2 + 0.40S_3 + 0.45S_4 + 0.5S_5)}{(S_1 + S_2 + S_3 + S_4 + S_5)}$$

The soil index was subsequently determined for 150 British catchments, including those being used in this study. The index

Table 2.2 Winter Rain Acceptance Indices

Drainage class	Depth to impermeable layer (cm)	Slope classes								
		0 - 2^o			2 - 8^o			8^o		
		Permeability rates above impermeable layers								
		Rapid	Medium	Slow	Rapid	Medium	Slow	Rapid	Medium	Slow
1	> 80	1	1	2	1	2	2	1	2	3
	40 - 80	1	1	2	2	2	3	3	3	4
	< 40	---	---	---	---	---	---	---	---	---
2	> 80	2	2	3	3	3	4	---	4	5
	40 - 80	2	3	3	3	4	4	4	4	5
	< 40	3	4	4	4	4	4	4	5	5
3	> 80	4	4	5	5	5	5	---	5	5
	40 - 80	4	5	5	5	5	5	---	5	5
	< 40	5	5	5	5	5	5	5	5	5

1	very high	3	moderate	5	very low
2	high	4	low		

assumed that unclassified and classified soils were similarly distributed within the catchment. In a small number of cases where information was limited and a large proportion of the catchment was unclassified soils, the index was individually assessed

Regression analysis of percentage baseflow against the five soil classifications confirmed suspicions held by Soil Survey that WRAP classes 4 and 5 should be reversed for low flow purposes, since the upland peaty soils of class 5 can sustain low flows better than the clay soils of class 4. Thus for low flows the soil index is modified to:

$$\text{Soil} = \frac{(0.15S_1 + 0.3S_2 + 0.4S_3 + 0.5S_4 + 0.45S_5)}{(S_1 + S_2 + S_3 + S_4 + S_5)}$$

In developing a catchment model for this study use was made of minimum infiltration capacities, and both variations of the WRAP soil index. Details of these investigations are given in Chapter 3.

2.5 DRAINAGE DENSITY

2.5.1 General Hydrological Aspects

Drainage density is not only a physical characteristic of the catchment but also a quantifiable description of drainage networks. The extent of the drainage network reflects topographical, lithological, pedological and vegetational controls. It is related to precipitation, the character of the run-off response, and the topographic characteristics of the catchment. The water and sediment response to rainfall in a catchment is influenced by the length of water courses per unit area. Also in catchments where all other conditions are identical it characterises the infiltration capacity of soils forming the basin surface. For example in adjoining catchments of similar geological formation, infiltration capacities can be markedly dissimilar due to variations in the surface soil structure resulting possibly from drift deposits in one catchment not appearing in neighbouring catchments. These differences may well be reflected in the drainage densities of the two catchments, a high density being found in the catchment with the lowest infiltration capacity.

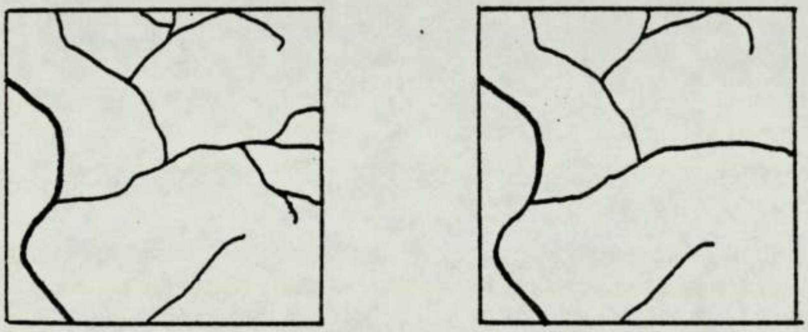
The measurement of drainage density provides a quantifiable description of a catchment characteristic and is defined as the length of streams per unit of drainage area. Strahler (1957) defined four main density values (km/km^2) related to different drainage networks (Fig 2.5).

Less than 5.0 - coarse network
5.0 - 13.7 - medium network
13.7 - 155.3 - fine network
Greater than 155.3 - ultra fine network

Coarse networks are common in Great Britain and are prevalent in areas of permeable rocks and/or low rainfall intensities. Medium networks have been measured in humid areas of Eastern U.S.A. and New Zealand, and fine densities have been recorded in the Badlands of South Dakota and on weak clays in New Jersey. Horton (1932) originally provided a range of densities from 1.5 miles per sq. mile (0.93 km per km^2) to 2.00 (1.24) for steep impervious areas in regions of high precipitation, and nearly 0.0 in permeable basins with high infiltration rates.

Ultra Fine Network

Fine Network



Medium Network

Coarse Network

Fig 2.5 <u>Four Principal Drainage Density Classes</u>

ack. /

2.5.2 Definitions of Drainage Density

The principal method of drainage density measurement is by measurement of the blue lines on a map which represent drainage channels. In the U.S.A. Morisawa (1957) compared results using the blue line method with a method which measures the line length, plus drainage channels assumed from contour crenulations. Morisawa found that although the method incorporating contour crenulations and field survey methods were not significantly different, they both differed markedly from results using the blue line method. She therefore concluded that the blue line method should not be used in the U.S.A. for basins of less than 7 km^2. These methods were also tested in South East Devon in the Otter Basin (Gregory 1966). In this instance the field mapped density measurement compared most closely with the blue line method. This method appears particularly appropriate in Britain where maps of many scales are available, thus removing the necessity of measuring contour crenulations, and estimating the position of drainage channels.

Did you consider?

The Flood Studies team used stream frequency as a description of channel network due to its high correlation with drainage density. Stream frequency was measured by counting junctions on a 1:25,000 map and dividing by basin area.

2.5.3 Method Adopted

The method of drainage density measurement adopted was that defined by Horton (1945) which reflects the closeness of channels. It was expressed as the length of drainage channels per unit area.

$$D = \Sigma L/A$$

D - Drainage Density

ΣL - Sum of the length of drainage channels

A - Area

The disadvantage of the blue line method is its reliance upon map scale, for whilst it can take account of all three stream categories (perennial, ephemeral, intermittent) it may ignore the existence of one or more. However, provided the same map scale is used throughout this effect is minimized. The 1:50,000 Ordnance Survey maps were used in the project as they provided sufficient accuracy for a project covering large catchment areas. It was felt that the accuracy of drainage density taken from a 1:25,000 map was not warranted as it would have been far too time consuming.

2.6 SOLID GEOLOGY

2.6.1 General Hydrological Aspects

The significance of solid geology to hydrological processes within the catchment is reflected in the natural recharge, baseflow processes and the size of the active groundwater store.

Of secondary significance is its interdependence with catchment characteristics. For example, the solid geology of a catchment dictates its relief, and that affects not only hydrological processes but also meteorological characteristics as mentioned earlier. In addition, geology is reflected in the soil type which subsequently influences infiltration, interflow and natural recharge. However the effect of solid geology upon hydrological processes withinthe catchment ultimately depends upon the nature of the deposit. Geologic groupings are normally classified as sedimentary, metamorphic and igneous. However for catchment studies unconsolidated and indurated categories provide more useful classificiations.

The grain size distribution and nature of the matrix are the principal factors controlling porosity and permeability in sedimentary rocks, which are the principal water bearing rocks. Porosity controls the volume of water held within the body of the deposit and is defined as the volume of voids, expressed as the percentage of total volume.

$$\text{Porosity} = \frac{\text{Vol. of voids in a deposit}}{\text{Bulk volume of the deposit}}$$

In the case of granular sediments porosity is not directly affected by the size of the grains, but is affected by the uniformity of size, shape and packing characteristrics of the grains. Permeability is a measure of the ease with which water moves through the ground and is affected by the size, shape and packing of grains and the degree of cementing between them.

Unconsolidated materials do not contain cementing materials in their pore spaces. They are characterised by relatively high porosities of 25 - 65%. In coarse poorly sorted muds the porosities are as low as 20%, and yet in soft muds and organic materials the porosities can be as high as 90% (Gregory and Walling 1973). Included in this category are alluvial, aeolian, colluvial and glacially transported materials. In aeolian materials there is a uniformity of grains in the silt and sand size range, whereas in contrast, glacial moraines are often poorly sorted. Permeability in unconsolidated materials varies greatly. The highest permeabilities can be as much as 10^{0}

greater than for the lowest (Gregory and Walling 1973).

Igneous and metamorphic rocks have low permeabilities and small porosities. In these rocks fractures provide the major means of water movement. Indurated rocks are the less permeable igneous and metamorphic formations where the interlocking nature of the crystalline structure leaves few, if any, voids.

Sedimentary rocks can also be indurated through cementation of the grains by chemical precipitates of iron oxides, calcium carbonates or some form of silica. One exception is limestone in which fractures are widened due to solution by groundwater, so making the rocks highly permeable.

2.6.2 Definitions and Method Adopted for Solid Geology

Solid geology is difficult to define in quantitative terms, but for the purpose of this project it was necessary to produce some form of quantitative description. As a result of the interdependence of catchment characteristics, slope, drainage density and soil indices all reflect some aspect of solid geology.

The Low Flow Studies Report (1978) indexed solid geology by estimating the proportion of total flow which drains from a catchment as baseflow. This index was named the Baseflow Index (B.F.I.) and is calculated as a ratio of flow under a separated hydrograph to flow under the total hydrograph. In ungauged catchments BFI is determined by reference to typical BFI values for geologic types (Table 2.3) contained within the catchment. Annual values of BFI are stable, since even high run-off years do not produce significantly higher or lower

Table 2.3 <u>Typical BFI Values</u> (Low Flows)

Dominant Permeability Characteristics	Dominant Storage Characteristics	Example of rock type	Typical BFI range
Fissue permeability	Low storage	Carboniferous Limestone Millstone Grit	.25 - .65
	High storage	Chalk	.90 - .98
		Oolite Limestone	.84 - .94
Intergranular permeability	Low storage	Hastings Beds Coal Measures	.35 - .53
	High storage	Permo Triassic Sandstone	.72 - .78
Impermeable	Low storage at shallow depth	Lias	.40 - .70
		Old Red Sandstone	.46 - .54
		Silurian/Ordovician	.30 - .50
		Metamorphic-Igneous	.30 - .50
	No storage	Oxford Clay Weald Clay London Clay	.14 - .45

BFI values than average.

BFI values are similar to soil and drainage density values in that they reflect an aspect of solid geology. It was thought that solid geology could be used to calculate BFI using the method described in the Low Flow Studies Report (1978). However, it was discovered that both BFI and the baseflow parameters in the model could be better estimated using other catchment characteristics such as drainage density, soil etc. This was due to the strong interdependence which exists between geology and these other characteristics. The problems of quantifying solid geology were overcome by simply calculating the % of each geological formation present in each catchment

2.7 VEGETATION

2.7.1 General Hydrological Aspects

The importance of vegetation to catchment processes lies in interception of moisture by the vegetative canopy, the consequent reduction in overland flow and the abstraction of moisture by roots and subsequent transpiration through leaves. Horton (1919) produced the first definitive report on the effect of vegetation and consequent interception with a study of a New York hardwood forest. Research has tended to concentrate upon forest cover since this is the type of vegetation which affects interception losses and overland flow. Wilm (1956) wrote that forest cover had the most substantial effect upon net precipitation.

The most important factor controlling interception loss is total canopy storage. The extent of loss is dependent upon surface tension and configuration, leaf area, and storm size and intensity. Leaf surface configuration alters with type and condition of leaves in the canopy. This may change season to season with insect activity and growth factors. Surface tension increases with increased viscosity, viscosity increases with decreased temperature. A large heavily veined, rough textured leaf in still, cool air should have a large storage capacity. Winter interception losses are significantly greater in forests than in grassland where winter interception values are normally very low. In deciduous forests in winter, interception losses are reduced compared with coniferous forest due to the leafless condition of the trees.

Horizontal interception is principally found in forests as trees are able to extract moisture from the air which would not normally fall as precipitation. Delfs (1967) found that crowns of Norway Spruce are able to precipitate more moisture from deep clouds than the leafless crowns of beech. Direct condensation causes the formation of water droplets upon the vegetation particularly during fog conditions and when wind-speeds are high. The magnitude of fog drip is difficult to determine although Nagel (1956) for example has produced figures for Table Mountain. It will tend to occur on the windward edge of upstanding vegetation and in foggy conditions may exceed precipitation by a factor of two or three.

Plant debris and litter are known to be surface detention stores, yet whereas overland flow has traditionally been seen as the major contributor to run-off. Hewlett and Hibbert (1967) have shown this to be an over-simplification. A study of rainfall and runoff records from sloping forested catchments at Coweeta highlighted the importance of vegetation to hydrological processes. They showed that only exceptional storms could produce flows in excess of 25% of gross rainfall, and the greatest flows on record have rarely exceeded 50% of the rainfall that produced them. Most of the flow on forested catchments was shown to be subsurface, thus substantiating the theory that infiltration even on a sloping surface is increased with the existence of vegetation and plant litter.

The water balance at the ground/air interface is not only affected by water lost in transit between the vegetative canopy and the ground, but also between the vegetative canopy and the lower atmosphere. This loss is in the form of evapotranspiration and depends on the availability of water at the surface and the rate of diffusion of water vapour from the surface. Compared with short vegetation, a forest constitutes a rough aerodynamic surface and the resultant atmospheric turbulence provides an efficient mechanism for the transport of water vapour away from its surface. The Institute of Hydrology (1973) found that this effect was shown by data from their Thetford project which showed that the evaporation of intercepted rainfall frequently exceeds the net radiational energy.

2.7.2 Definition and Method Adopted for Vegetation

An index to express the coverage of woodland and grass/arable was developed from a forestry commission 1:625,000 map used by the N.E.R.C. Flood Studies report (1975) in their consideration of land use. N.E.R.C. Flood Studies used the percentage forest cover for each catchment experimentally in regressions with mean annual floods for North West England, but this did not prove useful. However, for this project, the map did provide a means of separating grass/arable landscape from a forest landscape. This offered an indication of the degree of interception which can be expected in a predominantly rural catchment, given that, as previously mentioned forest lands intercept significantly greater quantities of moisture than usually expected from grass/arable lands. Unfortunately, private woodland was not represented on the map but the Forestry Commission believed the acreage of this within the Welsh catchments to be small. The percentage woodland and grass/arable were calculated for each catchment and tabulated.

2.8 SUMMARY

This chapter has discussed and evaluated those characteristics considered to be most important in shaping the rainfall/run-off response, including relief, slope, drainage density, solid geology, soil and vegetation. In summarising each of these characteristics a number of important factors have been noted and those indices developed to quantify catchment characteristics have been tabulated.

2.8.1 Relief

i) Drainage basin characteristic exercising influence over both the rainfall/run-off process and sediment production.

ii) Influences precipitation by governing the production of orographic rainfall and possibly convective rainfall

iii) In winter months the areal distribution of snow reflects patterns of relief, since air temperature falls with altitude.

iv) Relief is defined by maximum basin relief (Nash and Shaw 1966) or hypsometric curves.

v) The method adopted utilises the maximum and minimum altitudes of a sample of grid squares on a map, from which average altitude can be determined and plotted against percentage of total basin area with squares above given heights. The average altitudes of each zone are shown in Chapter 4, Table 4.14.

2.8.2 Slope

i) In steeply sloping areas the predominant movement of water is laterally via interflow and overland flow. In flatter areas water tends to move vertically by means of infiltration and percolation.

ii) Infiltration tends to decrease as surface slope increases, where gentler gradients predominate soils are thicker and their water storage capacity is increased.

iii) Degree and shape of slope, concave or convex, affects the degree of saturation which is reflected not only in infiltration but also interflow and translatory flow (Hewlett and Hibbert 1967).

iv) Slope affects the nature and thickness of soils since water induced erosion is particularly important for the movement of slope material and encourages a variation in soil thickness related to gradient.

v) Slope can be defined by indices of valleyside slope

(Strahler 1950), stream channel slope (N.E.R.C. Flood Studies Report 1975), or land surface slope (Linsley, Kohler and Paulus 1949).

vi) The method adopted was based upon the 1:50,000 O.S. relief maps and provided a single index of catchment slope based on a regular grid of sample grid squares. The slope indices are shown in Table 2.4

2.8.3. Soil

i) Soil is composed of air, water, mineral and organic matter. The organic portion is derived from decaying matter, and the air and water are contained within spaces between the particles, and the mineral portion is derived from weathering.

ii) Soil texture is influenced by particle size and shape which influences the storage of water.

iii) Soil structure is determined by the arrangement of particles, and includes single grain structures, massive aggregates, compound structures and puddled structures.

iv) Soil can be defined in terms of soil infiltration classifications (Musgrave 1957, Painter 1971), or a more complex indicator based on an ordinal classification of run-off potential based upon observable soil properties.

v) The method adopted used the winter rain acceptance potential (WRAP) indices from which a numerical soil index was developed. The soil indices as determined by Soil Survey can be seen for each of the catchments in Table 2.4

Table 2.4 Quantified Catchment Characteristics

	Area	Drainage Density	% Woodland	Slope	Density of Points	Mean Infiltration Capacity	S_1	S_2	S_3	S_4	S_5	Soil A	Soil B	BFI
Caban Coch	184.0	1.42	2.67	7.9	1/9	2.8						0.46		—
Vyrnwy	94.3	1.4	6.65	11.9	1/9	3.5	-	0.17	-	-	0.83	0.465	0.425	—
Rhayader	166.8	1.45	15.8	11.53 11.6	1/9 1/25	4.36	-	0.45	-	-	0.55	0.410	0.383	0·379
Abernant	72.8	1.15	59.4	9.69 9.63	1/9 1/25	3.61	-	0.05	-	-	0.95	0.489	0.443	0·373
Upper Wye	858.5	1.36	8.13	9.5	1/25	4.35	-	0.65	-	0.003	0.32	0.357	0.366	0·414
Upper Severn	1930.7	0.99	10.29	9.9	1/25	4.45	0.29	0.31	-	0.33	0.2	0.386	0.398	0·464
Mid Wye	613.9	1.05	6.16	5.81	1/25	5.41	-	0.82	-	0.06	0.13	0.329	0.316	0·559
Mid Severn	2300.0	0.66	6.69	3.3	1/25	5.62	0.37	0.2	-	0.44	0.01	0.318	0.331	0·576
Teme	1135.0	0.55	11.04	5.65 5.26	1/9 1/25	5.42	-	0.79	-	0.19	0.02	0.333	0.341	0·58
Lower Wye	2144.1	0.5	5.0	4.96 4.88	1/25 1/50	6.05	-	0.9	-	0.009	0.05	0.296	0.294	0.63

2.8.4 Drainage Density

i) Drainage density is a physical characteristic of the catchment and a quantifiable descriptor of drainage networks.

ii) The extent of the drainage network reflects topographical, lithological, pedological and vegetational controls, and is related to precipitation, run-off response and topographic characteristics of the catchment.

iii) Measurement of drainage density is defined as the length of streams per unit of drainage area.

iv) Drainage density is usually measured using the blue drainage channels on a map, and this method was adopted for this study. The measured drainage density values are shown in Table 2.4

2.8.5 Solid Geology

i) The effect of solid geology within a catchment is reflected in natural recharge, baseflow processes, and the size of the active groundwater store.

ii) The effect of solid geology upon hydrological processes within the catchment ultimately depends upon the nature of the deposit, and for catchment studies these are normally classified as unconsolidated or indurated.

iii) Geologic groupings are normally classified as sedimentary, metamorphic and igneous.

iv) Porosity controls the volume of water held in the body of a deposit, whilst permeability is a measure of the ease with which water moves through the ground.

v) Solid geology was indexed by Lowflow Studies Report

(1978) by estimating the baseflow index (BFI) calculated as a ratio of flow under a separated hydrograph to flow under the total hydrograph.

iv) Solid geology was quantified by calculating the percentage of each geological formation present in each catchment as shown in Table 2.5.

2.8.6 Vegetation

i) The importance of vegetation to catchment processes lies in the interception of moisture by the vegetative canopy, the consequent reduction in overland flow, and the abstraction of moisture by roots and subsequent transpiration through leaves.

ii) The most important factor controlling interception is total canopy storage.

iii) Horizontal interception is principally found in forests as trees are able to extract moisture from the air which would not normally fall as precipitation.

iv) Plant debris and litter are known to be surface detention stores and it has been shown that the existence of vegetation and plant litter increases infiltration even on a sloping surface and most of the flow in forested catchments is subsurface.

v) Water is not only lost in transit between the vegetative canopy and the ground but also between the vegetative canopy and the lower atmosphere in the form of evapotranspiration.

vi) The method adopted to quantify vegetation was based upon the percentage woodland and grass/arable for each catchment, as shown in Table 2. 4

Table 2.5 Solid Geology

Catchments	Devonian			Silurian			Ordovician		New Red Sandstone	Triassic	Carboniferous	
	Upper Old Red Sandstone	Middle Devonian and Brecon Bitton Series	Downtown Series and Lower Devonian	Ludlow	Wenlock	Tarannon and Llandovery	Ashgill and Caradoc	Ashgill and Caradoc - Llandeilo - Arenig	Keuper Marl	Bunter Sandstones - Pebble Beds	Barren Upper Coal Measures	Small Deposits making up an Area
Caban Coch						93.4	6.6					
Vyrnwy					5.2	73.4	21.4					
Rhayader						86.1	13.9					
Abernant						63.0	37.0					
Upper Wye				21.4	32.1	10.0	26.5					
Upper Severn					43.8	22.5	30.6	5.0				
Mid Wye		15.2	63.0	21.8								
Mid Severn									15.1	43.2	21.3	20.4
Usk	33.4		65.6									
Teme		13.1	41.2	38.6	7.1							
Lower Wye		32.9	43.1	12.4	3.6							

CHAPTER 3

METEOROLOGICAL CHARACTERISTICS AND HYDROLOGICAL STORES AND PROCESSES

3.1 INTRODUCTION

The previous chapter reviewed those physical characteristics important to catchment hydrology. This chapter discusses the meteorological characteristics and hydrological stores and processes acting upon and within those physical characteristics. The aim is to identify the principal components to be modelled and the ways in which they are related to catchment characteristics.

The spatial and temporal variation of precipitation and evaporation, the two primary meteorological processes, to a large extent govern the spatial and temporal variation of the hydrological stores and processes ultimately reflected in streamflow. The temporal variation of precipitation and evapotranspiration is quite different, but contains similar elements since both exhibit periodic and random variation. Annual and diurnal variations exist in both processes, but these are generally less apparent in precipitation than evapotranspiration. On the other hand, the random nature of precipitation is far more significant than that of evapotranspiration. Precipitation is more spatially varied than potential evapotranspiration, because in most regions rainfall is closely related to topographical relief and this is in general more spatially variable than the factors governing evapotranspiration. Temperature is also a factor which can significantly affect the spatial and temporal distribution of streamflow because in regions where snow cover commonly persists for several weeks or months it is the principal factor governing the accumulation and melting of the snowpack.

The variability of precipitation input into the system is reflected in the state of the hydrological stores which govern moisture movements via the hydrological processes. Two principal stores exist which retain water for substantial periods of time. They are the soil moisture and groundwater stores, but other stores like the interception and snowpack stores, although small and intermittent have a significant role to play. The soil moisture store in particular is seen as a key controller within the hydrological cycle since its status governs the behaviour of several primary processes. Fig 3.1 shows a schematic representation of the hydrological cycle in which the system is clearly divided into the principal stores and processes. The snowpack store and snowmelt processes are somewhat unusual since they, unlike other stores and processes, are highly temperature dependent.

The input of precipitation is significantly redistributed in both time and space as it progresses through the system. Nevertheless, these input characteristics together with the equivalent characteristics of the potential evapotranspiration output, provide the essential raw data from which it should be possible to evaluate the streamflow characteristics. The rate at which the system reacts to these primary processes can vary from the rapid response of infiltration and overland flow, to the relatively stable cycle of baseflow which tends to maintain a more regular response to catchment conditions.

In the following sections the main points raised here will be discussed in greater detail. Each section deals with one of

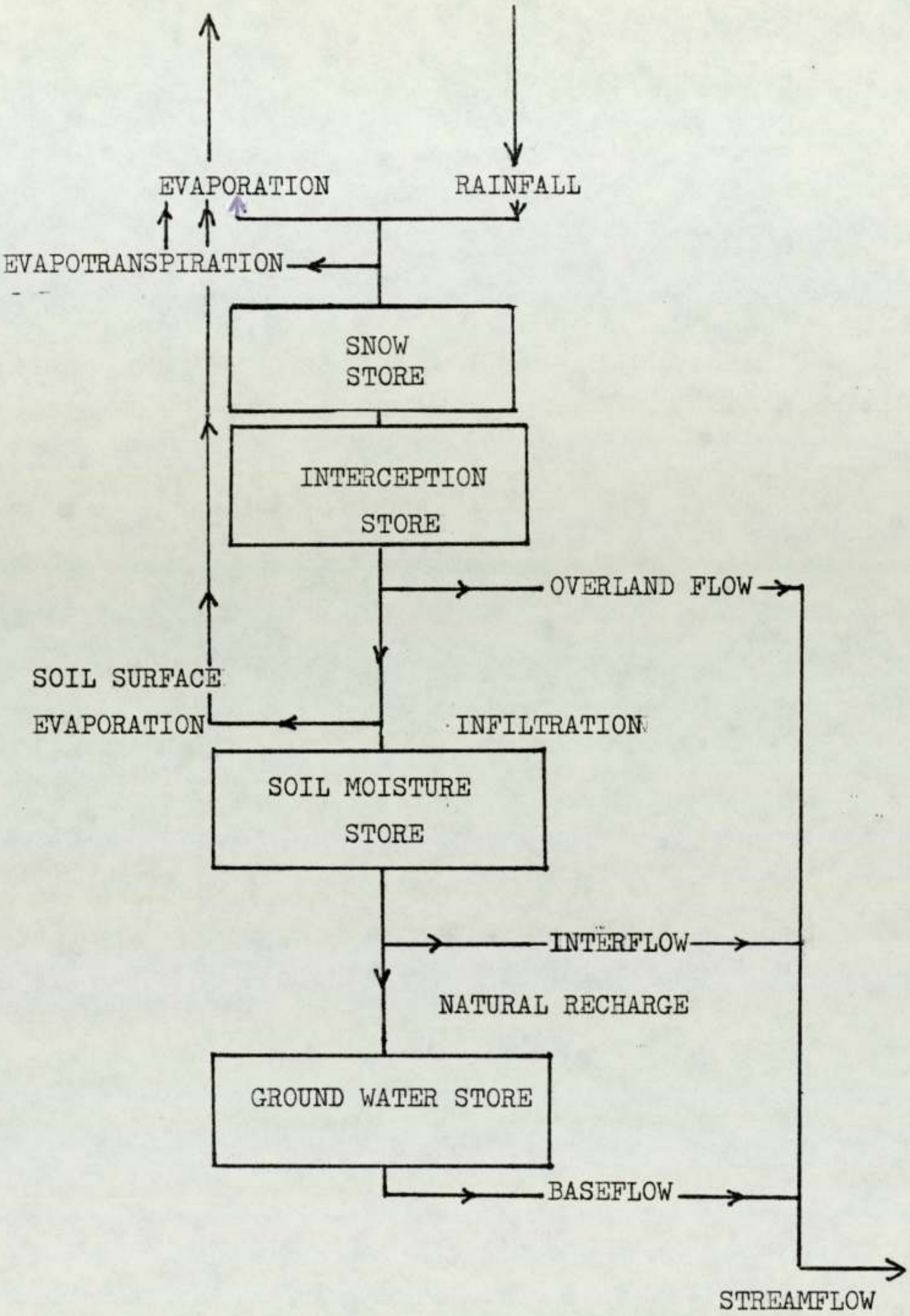


Fig 3.1 Schematic representation of the Hydrological Cycle

the hydro-meteorological stores or processes and examines its relationship to the catchment characteristics defined in Chapter 2, its interaction with other stores and processes and the nature and causes of its spatial and temporal variability.

3.2 Precipitation

The term precipitation refers to all forms of deposition of water on the earth's surface, both liquid and solid. The liquid forms include rain, drizzle, dew and fog drip which enter the hydrological cycle immediately. In contrast precipitation in the solid form occurs as snow, hail and hoar frost in which there can be a long time lapse before these melt and continue their passage through the hydrological cycle. By far the most significant forms of precipitation are rainfall (including drizzle) and snowfall.

3.2.1 Rainfall

For rainfall to occur warm moist air must be lifted through the atmosphere. This lifting causes cooling which, in turn, causes condensation of vapour into minute droplets of liquid water, thus forming clouds. Provided these droplets remain of microscopic size, no precipitation occurs. However, in thick turbulent cloud or freezing temperatures droplets can grow in size and gain sufficient mass to fall. The rate of lifting is an important factor governing the rate of formation and ultimate size of the droplets. For rainfall to occur there must be a lifting mechanism, and it is therefore convenient to classify rainfall in terms of the lifting mechanism causing its formation. On this basis there are three forms, cyclonic, orographic and convective. Each of these forms has its own characteristics in terms of intensity, duration and spatial distribution.

Cyclonic precipitation is caused by the horizontal convergence of cold airstreams in an area of low pressure which results in warm moist air being forced to rise above the cold air, as illustrated in Fig 3.2. The gradient of the frontal surface influences the nature of the precipitation produced. The shallow warm front gradients tend to produce widespread moderate rains of low intensity due to gradual lifting and cooling. The steeper cold front gradients produce more rapid uplift and cooling over shorter horizontal distances giving rise to more intense rainfall of shorter duration. Cyclonic precipitation characteristically lasts between 6 - 12 hrs. at an average rate of about 2.5 mm/hr. (Barry R.G. and Chorley R.J. 1976).

Orographic precipitation occurs as a result of an air mass being forced to rise over a physical barrier and tends to increase both the frequency and intensity of rainfall, especially in mid-latitudes, and generally derives from warm, particularly cumulus congestus clouds. The intensity of orographic precipitation varies with the depth of the uplifted layer of moist air, deep layers producing heavier rainfall than a shallow layer, and with the humidity of the rising air. Two primary sources of orographic precipitation are firstly, the influence of surface friction assisting the formation of stratus or stratocumulus layers causing light precipitation, and secondly, frictional slowing of an airstream moving inland over the coast (Fig 3.3). Orographic precipitation rarely occurs independently but more usually reinforces convective or cyclonic situations.

Convective precipitation derives from three sources and is the least important form of precipitation in terms of total

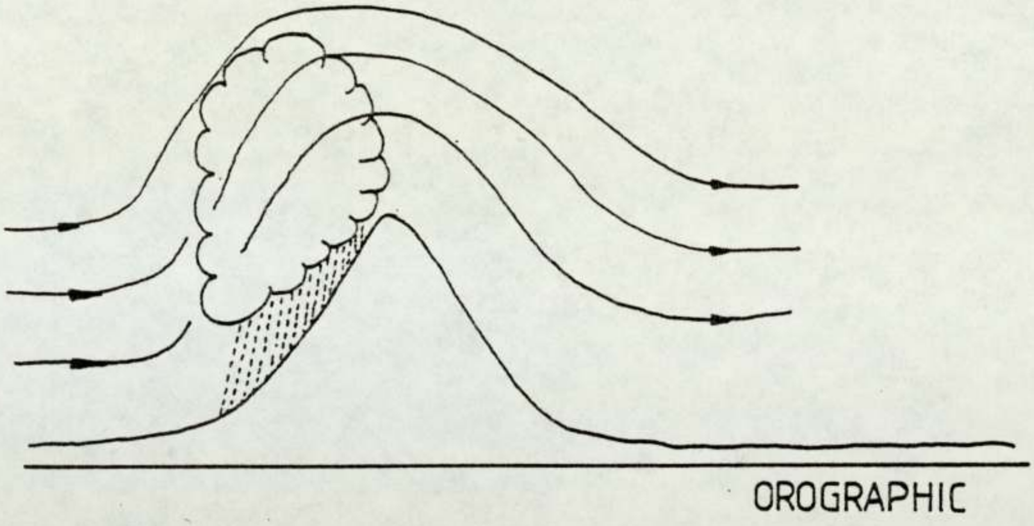


Fig 3.3

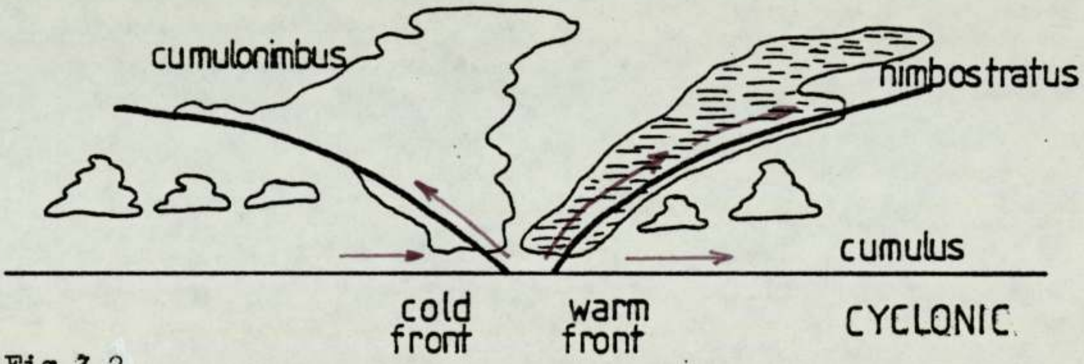


Fig 3.2

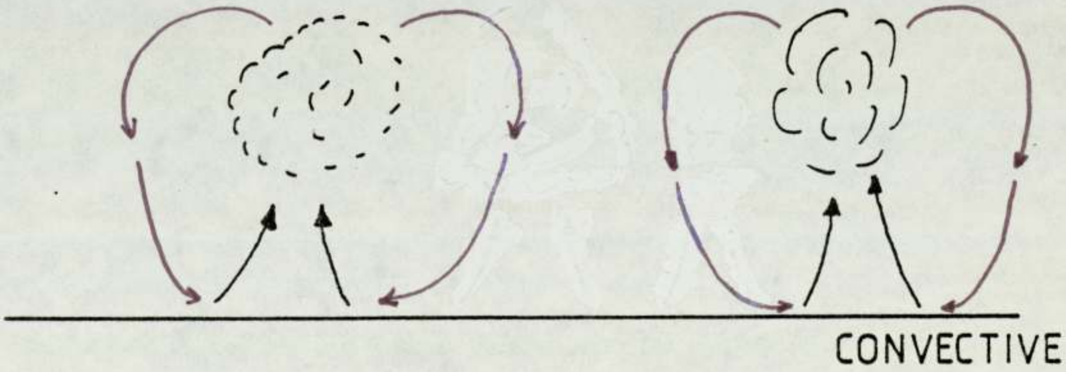


Fig 3.4

Orographic, Cyclonic and Convective Precipitation volume in the British Isles. Scattered convective cells develop from strong heating of the land surface in summer, and in moist unstable air passing over a warmer surface, also tropical cyclones produce cumulonimbus clouds particularly noticeable in the decaying stages of cyclones (Fig 3.4). Convective precipitation produces a rate of downfall which is greater than 4 mm/hr. (Barry R.G. and Chorley R.J. 1976) in the form of showers and downpours which are generally brief and localised.

In mountainous regions the interception of mist can provide a significant part of total precipitation. Nagel (1956) found that conditions on Table Mt., studies of which can provide the foremost indicator of the effect of fog, are such that clouds drift over so rapidly that the intensity of fog precipitation measured and evaluated is twice that of mean rainfall. This intensity is a function of the liquid water content of the cloud and the speed with which it moves. However due to the difficulty of measurement, the importance of fog precipitation has merely been noted in the event of discrepancies arising between catchment input and output which could realistically be due to fog precipitation.

3.2.2 Snow

The hydrological importance of snowfall derives from the timelag between the occurence of precipitation in the form of snow and its active participation in the run-off process. The occurence of snow in the United Kingdom although seasonal is irregular and unpredictable and forms a very small proportion of total precipitation, except in the Eastern Highlands of Scotland.

Wide variations in the frequency of snowfall and the duration of snow cover exist due to differences in mean monthly temperatures. Between elevations 60 - 3000 m the frequency of snowfall (days/years) increases by about one day per 15 metres elevation. The average figures range from 5 days per year in S.England and Ireland to between 30 to 50 days in the Pennines, plus an additional 10 days in the Grampians and Cairngorms. On Ben Nevis there are several semi-permanent snowbeds at about 1160 m., and it is estimated that the theoretical climatic snowline, above which there is a net accumulation of snow, is approximately 1620 m over Scotland (Barry R.G. and Chorley R.J. 1976 ed.).

Increase in snowfall with altitude is due to the ambient lapse rate or vertical temperature gradient. This is the rate of fall of temperature with height in the free atmosphere. Opinion differs as to the mean lapse rate, from 0.6°C per 100 m (Linsley, Kohler & Paulus 1949) to 0.7°C per 100 m (Cole 1975). The greatest variations in lapse rate are found in the layer of air just above the land surface because of the diurnal cycle of heating and cooling of that surface.

Snowmelt is important to the hydrologist primarily because of the time lapse between snowfall and snowmelt. Snowmelt occurs unpredictably, possibly within hours, weeks or months of snow falling. In the U.K. snowpacks are generally shallow and many catchments relatively small with limited elevation range, melt commonly occurs simultaneously over entire catchments and is often rapid and complete. Consequently on occasions snowmelt assumes a significant role in a major river flood. For example, the River Severn experienced an extreme snowmelt river flood in 1947, the highest peak discharge on record. In the more mountainous regions (e.g. the Cairngorms) large differences in surface temperatures exist within short distances because of topographical variations. Consequently, both snow accumulation and snowmelt are spatially highly variable. This results in snowmelt run-off being spread over several weeks or even months.

3.3 Evapotranspiration

Evapotranspiration is the process by which liquid water at the earth/atmosphere boundary is converted to vapour and mixed with the atmosphere. The term has two components, evaporation and transpiration. Evaporation occurs from free water surfaces such as rivers, streams, lakes, ponds and puddles, and from soil moisture and intercepted water. Transpiration is the process by which water vapour escapes from living plants, principally the leaves, and enters the atmosphere.

Evaporation from free water surfaces and evapotranspiration are both governed by micro-meteorological conditions such as radiation, temperature, humidity and wind speed. The rate of evaporation is directly proportional to the difference between saturation vapour pressure at the water surface and the vapour pressure of the air at given temperatures. Wind velocity is a factor since wind provides the mechanism for the importation of fresh unsaturated air which will absorb available moisture.

Transpiration occurs when the vapour pressure in leaf cells is greater than the atmospheric vapour pressure. It is controlled by plant and soil factors as well as atmospheric conditions. Plant factors comprise the stage of growth, rooting depth, density, spacing, height and orientation, whilst soil factors comprise the surface and root zone moisture contents, slope, aspect, colour and surface roughness. Transpiration occurs when plant stomata are open in order to reduce the temperature of plant leaves and follows the diurnal variation of temperature and intensity of solar radiation.

On bare soil surfaces the finer the soil texture and the smoother the surface, the closer evaporation will approximate the potential rate, decreasing rapidly below this as the surface moisture content falls. However, on a vegetated soil surface evapotranspiration will take place at a potential rate provided the root system of the vegetative cover is not short of water. Opinions differ as to the point at which soil moisture depletion causes evapotranspiration to fall below the potential rate. Veihmeyer and Hendrikson (1955) and Gardner and Ehlig (1963) found that between field capacity and wilting point evapotranspiration takes place at the potential rate. However, Kramer (1952) and Thornthwaite (1954) found that although evapotranspiration began at the potential rate, as soil moisture content reduced so did the rate of evapotranspiration.

Penman (1949) observed that deeper rooted plants can go on transpiring longer at or near the potential rate than shallow rooted plants. He assumed that moisture is readily extracted by different root systems up to a specified limit or 'root constant'. The 'root constant' is defined as the maximum soil moisture deficit that can build up without checking transpiration.

Penman suggested that because moisture tends to move relatively slowly through the soil body, the available moisture is restricted to the water in the immediate proximity of the rooting system, which will be partly limited by the depth of soil and partly by soil type. Grass generally has a root constant of about 75 mm, and this would mean that 75 mm of moisture can be removed by grass before transpiration falls below the potential, after which transpiration falls to between .1 - .08 of the potential. Other general root constant estimates are cereals 140 mm and trees 200 mm upwards. Walley and Hussein (1982) developed a soil-moisture-plant model in which, when the soil moisture is relatively high, the estimated potential suction in the leaf is low. Therefore, actual suction is close to the potential value and transpiration proceeds at close to potential. When the soil moisture is relatively low, potential suction is high, but actual suction is reduced and actual transpiration falls below potential.

The temporal variation of evapotranspiration is seasonal, being greatest in summer months, and smallest in winter months, whilst the spatial variation relates primarily to altitude, being less at high altitude than at low altitude. El Gusbi (1979) used the MAFF Bulletin No. 34 which contained mean monthly potential evapotranspiration and altitude data for the Welsh catchments, to produce a linear regression equation between monthly mean evapotranspiration and altitude for each month of the year. This equation was initially only related to an altitude range of 100 - 350 mm and subsequently extended to cover high altitude regions. This was done by using high altitude evapotranspiration data published by the

Meteorological Office together with the aforementioned data to derive the monthly evapotranspiration/altitudinal relationship. A linear regression equation was determined which can be used to estimate monthly evapotranspiration in the Welsh catchments for any altitude in the range 0 - 1400 m. Although due to the shortage of high altitude data this method is only considered to be reliable in the 0 - 400 m range, the figures calculated by El Gusbi for the rate of change of evapotranspiration with altitude (Table 4.1) were subsequently used in the estimation of catchment evapotranspiration in this study.

3.4 Interception

The water lost in transit between the lower atmosphere, just above the vegetative canopy, and the ground surface represents the interception loss. Interception is essentially of two types - vertical and horizontal. Vertical interception is by far the most significant and represents a reduction in precipitation input, whereas horizontal interception can result in a gain in moisture input to the hydrological system.

Vertical interception refers to that amount of precipitation, normally rainfall or drizzle, which is intercepted in its downward journey by vegetation and subsequently either evaporates (interception loss), drips to the ground (drip) or runs down the stem of the plant (stemflow). Interception loss is that part of total interception which evaporates from the vegetative canopy and is thereby lost to the hydrological system. The amount of water, expressed in terms of equivalent rainfall, which can at any time be held in storage within the vegetative canopy is called the interception store. It is from the interception store that the hydrological processes of interception loss, drip and stemflow operate. Normally the interception store is empty, but during rainfall it accumulates water and may become full and even overflow by means of the drip and stemflow processes. These processes cease soon after the rainfall ceases and the interception store slowly empties by means of evaporation, thus producing the interception loss. Meanwhile, transpiration reduces to a low level while the evaporative power of the atmosphere is utilised to remove the intercepted water. Once this is removed transpiration returns to its normal level.

Horizontal interception refers to water which accumulates on the vegetative canopy as a result of the interception of drifting fog or mist. When this accumulation is so great as to cause stemflow and drip it thereby results in a gain of moisture to the hydrological system, since the drifting fog and mist would not otherwise result in precipitation.

The significance of interception loss to the catchment water balance is that firstly, interception losses are essentially evaporative. Interception loss is closely related to evapotranspiration loss since evaporation provides the mechanism by which the loss occurs. Although no different to the evaporation of rainfall from the ground surface, it can, especially in forests, result in a moisture loss over and above the calculated potential evapotranspiration. This is because the trees in effect 'hang their leaves out to dry' and thereby present a larger and better ventilated drying surface than can be presented by the ground surface. Secondly the water balance is affected by the loss of intercepted precipitation otherwise available for direct evaporation, infiltration or overland flow.

Thirdly the interaction of water loss and gain in vertical and horizontal interception may result in a net gain of water in the catchment area. This is most likely to be true in forested areas of high relief where fogs or low cloud are prevalent.

On a local scale interception affects catchment hydrology via the areal distribution of precipitation actually reaching the ground. Thus throughfall and meltwater are concentrated on the edges of the crowns whilst stemflow and concentrated drip close to the trunk often results in striking differences in soil moisture content over very small distances.

The effects of afforestation have highlighted the significance of interception loss. On an area of 0.111 acres at Stocks Reservoir, Slaidburn, a loss of one million gallons per day resulted for every 1,500 acres afforested (Law 1956). The total estimated throughfall on the Sitka Spruce plantation showed 38% interception, yet the amount of interception was not a constant ratio with rainfall, being greater with light rains of short duration than with heavy or prolonged rains. Therefore the interception store will form a small proportion of a heavy rainfall event, but a larger proportion of a light fall. Heather communities also have large interception losses due to the thickness of the vegetative canopy, and interception values of 35% - 66% of total precipitation penetrate the canopy indicating values similar to pine stands. In Leyton's (1967) study of heather communities it was found, as might be expected, that interception loss was governed by the number of wetting and drying cycles in the vegetation, and these in turn generally relate to the number, size and distribution of rain showers.

Snow interception does not rely upon the intensity and duration of precipitation but on snow accumulation or the vegetative surfaces. This is prone to large scale mass release by rainwash and sliding resulting from its own weight, and is frequently aided by wind induced movement of the vegetation and the smaller scale release of snow particles and meltwater drip.

Careful consideration must therefore be given to the effect which interception, particularly in forested areas, has upon the real system before deciding how, if at all, it should be represented when modelling.

3.5 Infiltration

Infiltration is the term used to describe the process by which surface water enters the soil moisture store. The proportion of total rainfall infiltrating the soil surface is spatially varied depending upon the distribution of rainfall, soil type distribution, soil moisture conditions and topography of the catchment. The infiltration capacity at any point in time or space represents the ability of the soil to admit water if supplied to its surface, and is dependent upon three principal factors.

(a) The physical nature of the soil i.e. porosity, pore size, distribution, structure, proportion of colloids.
(b) Soil moisture content.
(c) Surface slope.

Water will only enter the soil body when a water film exists at the void entrances. Consequently, if the soil surface dries out due to evaporation it requires wetting before infiltration begins, except where water is entering macrovoids which allow easy entry. Infiltration is also slowed where clay mineral swelling has reduced pore size, particularly near the surface, and where inwashing of fine materials into soil surface openings impedes entry.

The infiltration of water into the soil has two components. The transmission component represents a steady flow through the soil in a continuous network of large pores. The diffusion component represents flow in discrete steps from one small pore space to the next in an haphazard fashion. When a soil moisture deficit exists flow into the soil body just replenishes the deficit and then creates a surplus. The flow is initially rapid and then gradually slackens as air in the voids is displaced and replaced by water. Thus the capacity of the soil to infiltrate water decreases as the moisture content of the soil increases, given that water continues to be applied to the surface at a rate greater than or equal to the current infiltration capacity. The minimum infiltration rate is reached when the infiltration capacity has declined until a steady state level is attained. Its value depends upon the rate at which the surplus water within the soil can continue draining either vertically as deep percolation, laterally as interflow or through land drainage systems. Following the cessation of rainfall, wind action and differential temperature close to the soil surface aids the reopening of soil pores, shrinkage of colloids takes place and the infiltration capacity of the soil slowly returns to a higher value. Minimum infiltration rates vary with soil grain size and ranges from 0 - 4 mm/hr. for clays to 12 mm/hr. or more for sands. The effects of soil and slope upon infiltration capacity are discussed more fully in sections

2·3 and 2·4

The effect of vegetation cover can produce long term changes in the base status of soils, affecting the stability of aggregates and altering soil pH which consequently affects the micro-organic population causing structural breakdown and decreasing infiltration. The surface detention store created by plant debris on forest floors provides for constant infiltration during rainfall events, whilst the removal of vegetation cover followed by heavy rain can reduce infiltration by causing a surface pan to form as fine particles are displaced from peds by impact and washed into the voids.

3.6 Soil Moisture

The soil moisture store is a key controller within the hydrological cycle, and within the vertical and lateral movement of water with the soil mantle. The main factors affecting the retention of water within the soil are the soil texture and structure. Texture may be defined by the grain size distribution and this, together with bulk density, governs the pore size distribution which in turn determines the capillary characteristics of the soil. It is the system of capillary channels formed by the interconnection of the pore spaces between the soil grains which is principally responsible for the soils ability to retain water against gravitational and other forces. This retaining force is called the soil moisture suction or tension.

Soil structure is defined by the size and shape of natural blocks or peds consisting of a conglomeration of grains. The peds are separated by a system of cracks which are somewhat wider than the pore spaces between grains. When the soil is very wet these cracks provide important drainage channels which supplement the system of capillary channels and enable the soil to drain down to the moisture content known as field capacity. At field capacity moisture is retained naturally against gravitational forces, but in excess of field capacity the surplus moisture cannot be held in the soil and therefore drains away, some through the peds and some along the cracks. The division between the two depends upon the nature of the soil and the degree and type of structuring. Drainage along cracks, for example, being more predominant in clayey soils than sandy soils. At moisture contents below field capacity the cracks tend to become filled with air and cease to be of significance to water movement. Under these conditions the movement of moisture towards root hairs within peds predominates. A comprehensive soil-moisture plant model which incorporates unsaturated flow and root abstraction algorithms has been presented by Walley and Hussein (1982).

The two principal retention forces which exist are adsorption and capillary. The adsorption of liquid soil water or vapour upon the surface of soil particles is of an electrostatic nature, where polar water molecules attach to the charged face of solids. It produces only a thin film, yet where the total surface area of the particles is large, as is the case with clays, the amount held overall can be quite significant. Capillary forces occur in unsaturated granular soils at the interface between soil-air and soil-water. The removal of water from the unsaturated zone by roots or surface evaporation induces an upward movement of water from the water table which is powered

by capillary forces. In clays this upward movement is restricted by the low hydraulic conductivity due to fine pores.
Capillary rise may also become restricted in granular soils if the moisture content drops to a level where the unsaturated hydraulic conductivity is very small.

Water enters the soil body as infiltration and the initial downward movement is generally quite rapid since surface porosity is often relatively high and during periods of moisture deficit the suction gradient near the surface is large. As the moisture content throughout the soil profile increases, the suction gradient decreases towards the unit gravitational gradient and the rate of downward movement tends to decline. When the supply of water at the surface ceases, the movement of moisture within the soil decreases further and the water content of the upper zone stabilises within a few days at the field capacity value, field capacity is the amount of water held in the soil after excess water has drained away and the rate of downward movement has effectively ceased. It corresponds to a soil moisture suction (tension) of about 0.05 to 0.2 bars. Fig 3.5 shows a typical field capacity profile for a loamy sand overlying clay.

Other standard soil descriptions include wilting point which may be defined as that moisture content at which permanent wilting of plants occurs, and which corresponds to a suction of about 15 bars, and saturation which corresponds to a suction of 0 bars. The wilting point and field capacity moisture contents define the approximate limits to the amount of water available for plant use, commonly referred to as 'available moisture'. In reality the limits to 'available moisture' are not precise constants because the real soil-moisture-plant system is far more

Typical Water Retention Characteristics of Soil Profiles

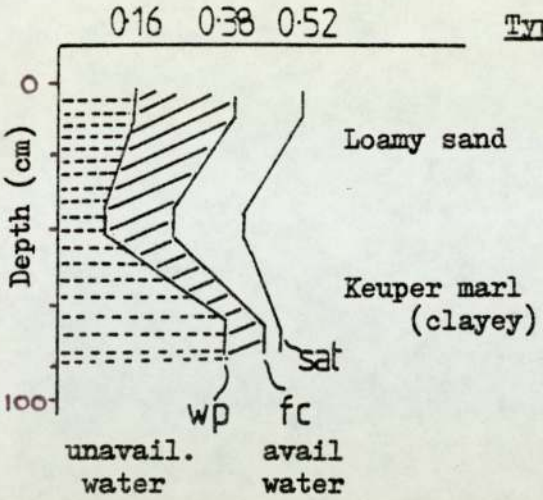


Fig 3.5

Depth - rooting depth or soil thickness whichever is the lesser

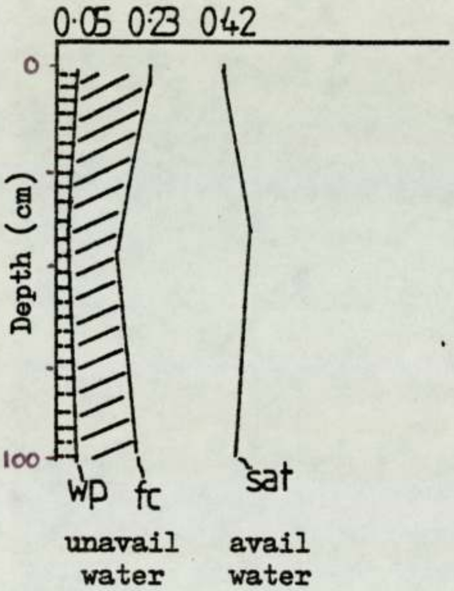


Fig 3.6.2

Loamy sand over sand, with a large quantity of fine sand in all horizons

WP - corresponds to suction of about 15 bars
FC - " " " 0.1-0.2bars
SAT - " " " 0 bars

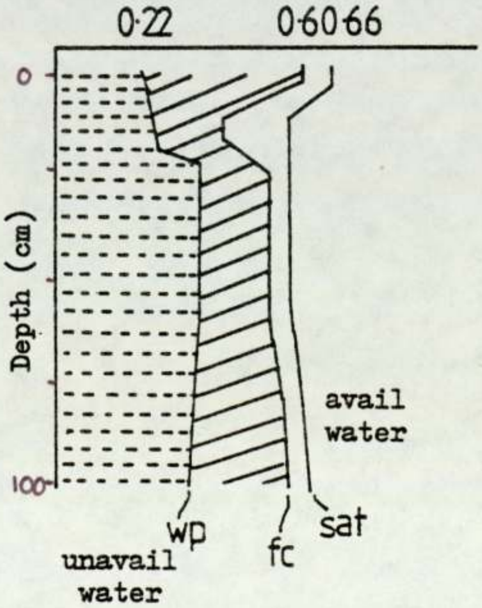


Fig 3.6.3

Clay loam to clay boundary at A horizon

complicated than this simple theory assumes. Nevertheless, the concepts of field capacity, wilting point and available moisture are sufficiently close to reality to provide a sound basis for a working model. Figs 3.5, 3.6.1 and 3.6.2 show retention characteristics of three soil profiles, Fig 3.5 is a loamy sand overlying clayey keuper marl. The large volume of unavailable water reflects the high clay content in the lowest horizon. The fall in available water with depth is a common feature of soil profiles, and in this instance is accentuated by a relatively dense clay subsoil. Fig 3.6.1 is a loamy sand over sand with a large amount of fine sand in all horizons. The negligible unavailable water is typical of sandy soils, and evaluation of the field capacity for such soils can be difficult as the water content can alter markedly between 1 - 5 days after saturation. Fig 3.6.2 is a clay loam soil with a clay boundary at the 'A' horizon. The large volume of available water at the surface is due to the organic matter content. In deeper horizons there is a typically large volume of unavailable water.

In the case of Fig 3.7 which shows the redistribution of moisture following the cessation of infiltration downward percolation is limited and lateral movement depends on local relief, hydraulic conditions and efficient drainage measures. Drainage as natural recharge only occurs in significant amounts when the soil moisture content exceeds field capacity. Divergence between the water content at 0.05 bar, a commonly used upper limit of available water, and field capacity at 48 hours after saturation is likely to be greatest in peaty soils and in coarse textured soils with shallow water tables. Elsewhere the difference is likely to be small and most likely within the

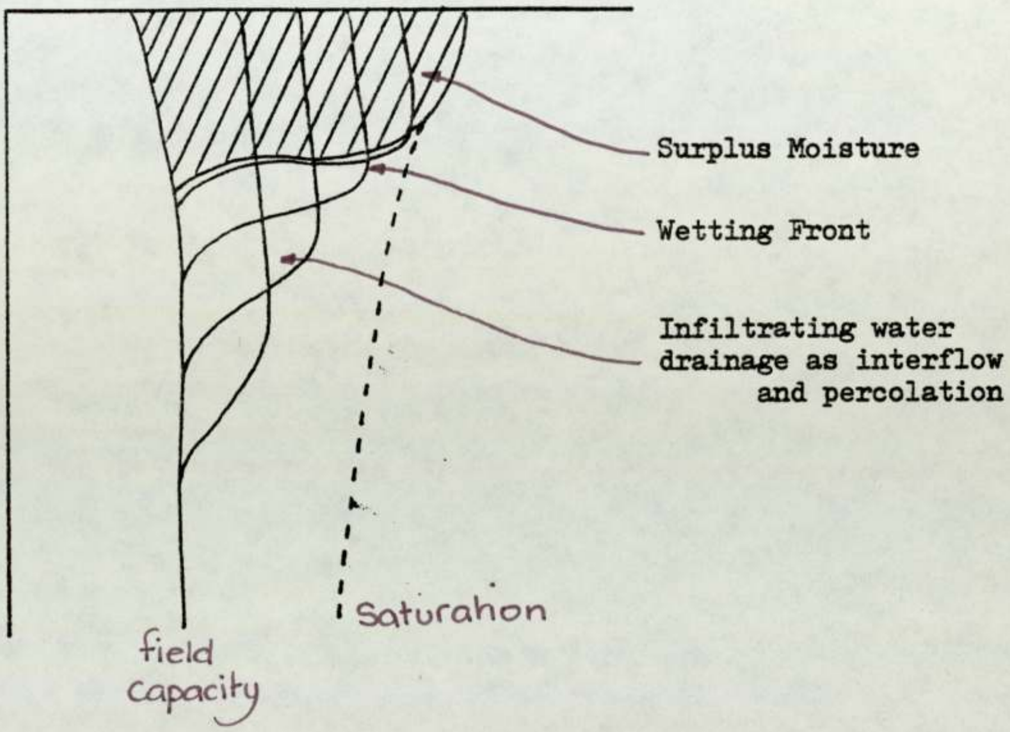


Fig 3.7 Redistribution of Moisture following the cessation of infiltration

random error inherent in the physical measurements. In general terms Linsley (1975) found that the total amount of stored available soil moisture varied with soil type, ranging from about 4 cm per 100 cm depth in sand, to 17 cm or more for each 100 cm depth in clay loam.

The total amount of water available for transpiration therefore depends upon the soil type and the effective depth of the soil. The effective depth being the rooting depth of the vegetation or the soil thickness, whichever is the lesser. At some point between field capacity and wilting point the decreasing moisture content reaches a level at which the roots cannot maintain abstraction at the potential transpiration rate. Root abstraction ceases altogether at wilting point. Milthorpe (1960) in summarising evidence from a number of studies concluded that the weight of evidence was for a progressive decline in the rate of transpiration as the soil water deficit increased. Opinions differ on the point when potential and actual transpiration rates depart from one another and by how much. Penman (1963) found that transpiration from a crop proceeds at the potential rate until the root reservoir is depleted, beyond this point, which is known as the root constant, transpiration drops below the potential rate. The root constant is principally a plant characteristic dependent upon the depth of rooting, and has been described as the maximum soil moisture deficit that can be built up without checking transpiration. For the purposes of this project as the deficit proceeds below the root constant actual transpiration declines linearly until wilting point is reached. This problem is further discussed in Chapter 4 and illustrated in Fig 4.2

3.7 Overland Flow

Overland flow occurs when rainfall intensity is so great that all the water can not infiltrate and consequently flows across the surface. It moves over the ground surface as a thin sheet of water or as flow anastomosing in small trickles or minor rivulets. Overland flow is intermittent and spatially highly varied, supplied by rain and depleted by infiltration, neither of which are constant in time or location.

The temporal distribution of overland flow is related to seasonal changes in soil moisture content. Overland flow being greatest in winter when soils are wetter, evaporation low and rainfall high. The spatial distribution of overland flow tends to be related to rainfall distribution and is often common in what? areas with no vegetation and a thin soil cover, such as in steep mountainous areas where rainfall is greatest. Many storms produce overland flow from limited contributing areas at much lower rainfall intensities than are required to exceed the infiltration capacity over the whole basin. The concept of variable source areas (Hewlett and Hibbert, 1967) attempts to reconcile the absence of widespread overland flow with the rapid response of most streams to precipitation by postulating that over the surface movement of water is restricted to limited areas of the drainage basin. Areas contributing to overland flow include the zones at the slope base marginal to the stream channels, where despite usually thicker soils lateral soil drainage commonly produces high antecedent moisture conditions in the upper layers (Kirkby and Chorley 1967). As the storm continues the zone of saturation extends upslope to an extent determined by storm intensity and the character of the soil profile. Dunne and Black (1971) applied the variable source area concept to snowmelt produced where frost and subsnow pack saturated soils may provide the mechanism for the generation of overland flow from a continuously varying area.

The direction of overland flow is along the line of steepest descent. The rate of flow being governed by the physical character of the catchment, particularly the capability of the soil to allow re-entry via infiltration, and the topographic form of the ground surface.

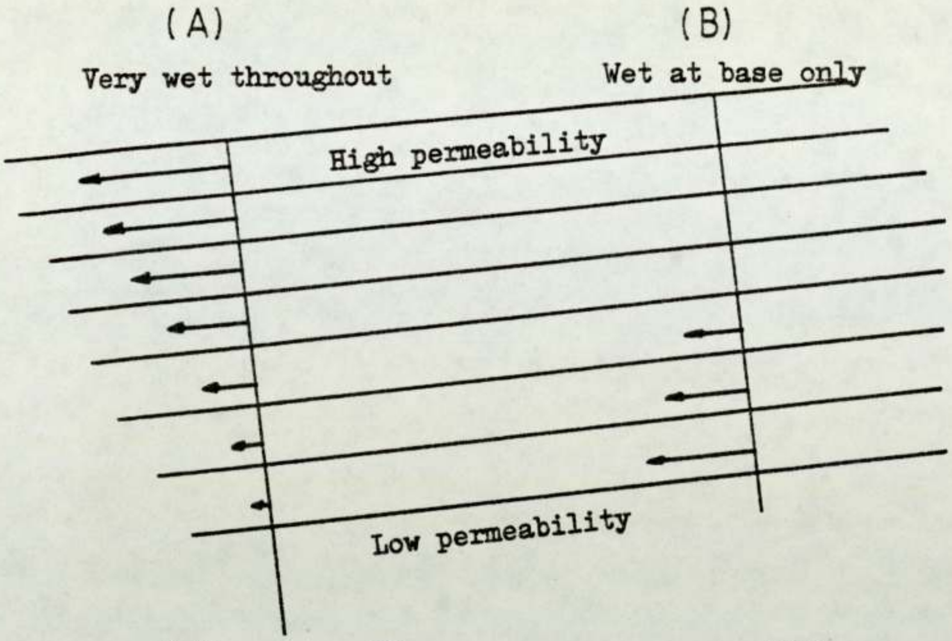
3.8 Interflow

Interflow is that water which moves transversely through the soil zone without penetrating to the underlying zone of saturation. As such it embraces all water discharged from the unsaturated zone including that from perched water tables. The conditions favouring interflow are those in which lateral hydraulic conductivity in the surface horizons of the soil is substantially greater than the overall vertical hydraulic conductivity through the soil profile. During prolonged or heavy rainfall water will enter the upper part of the profile more rapidly than it can pass vertically through the lower part, thus forming a perched saturated layer from which water will escape laterally, i.e. direction of greater hydraulic conductivity. Hydraulic conductivity is greater in the surface layers than deeper down the profile. There may be several levels of interflow below the surface corresponding to textural changes between horizons and the junction between the weathered mantle and bedrock.

At the onset of rainfall some water enters the soil and percolates downwards, raising the soil moisture content as it goes. Hewlett and Hibbert (1967) found that translatory flow, which is flow produced by the displacement of water stored in the soil mantle, enables rainfall events at times when the soil is at or above field capacity to produce a rapid interflow response. This form of flow is most noticeable on mid or lower slopes and explains the rapid response of streamflow to rainfall events in areas where overland flow is not discernible.

Weyman (1970) in his studies of East Twin Brook found maximum interflow to be in the 'B' horizon, but concluded that all soil layers must be saturated before interflow could begin to contribute to channels. In the conditions illustrated in Fig 3.8.1 the soil profile is completely saturated and lateral flow is occuring rapidly, particularly in the highly permeable surface layers. Flow continues in the less permeable layers of the profile but is more restricted. A zone of potential lateral flow in all soils is at the base of the 'C' horizon where it meets the bedrock. Fig 3.8. 2 illustrates a soil profile where saturation conditions exist in the lower less permeable areas of the profile, and even though the entire profile is not saturated interflow is still occuring.

The conifer and grass covered headwaters of the Severn and Wye at Plynlimon show the existence of 'pipes' to be the principal factor to interflow (Inst. of Hydro. 1971). The hillside peat soils transmit water through a natural network of pipes, commonly ephemeral and occuring at depths of less than 300 mm with diameters of 20 - 40 mm. They usually run normal to the contours of the hillslope and have been traced for several hundred metres. The location of pipes may be governed by an



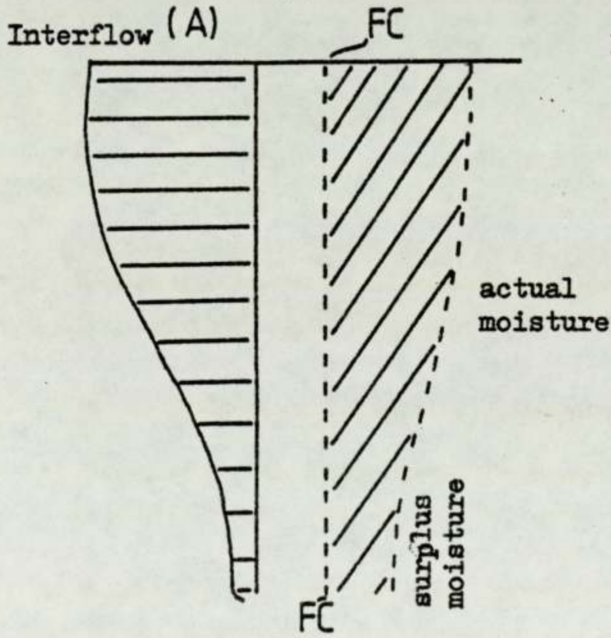


Fig 3.8.1

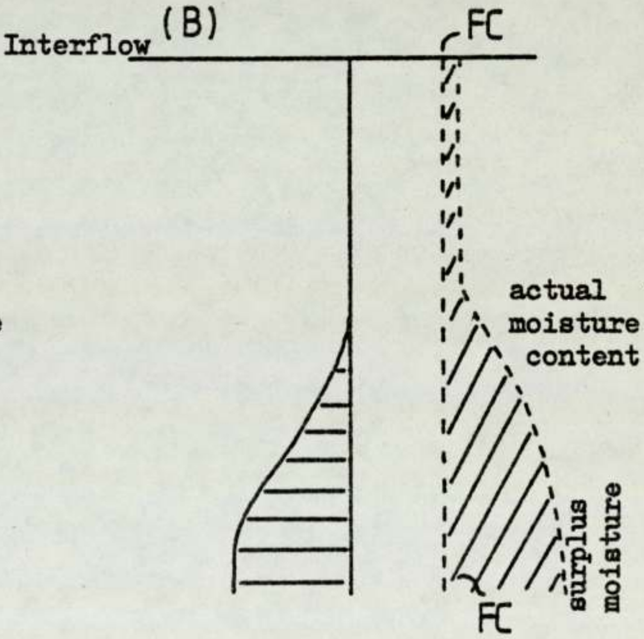


Fig 3.8.2

Diagrammatic Representation

Fig 3.8 Effect of Soil Moisture Profiles upon Lateral Flow horizon of low stability but animal and rodent burrows may also initiate piping. Piping tends to occur in soils with a high silt content and high percentage of swelling clays, and in areas with periodic high intensity rainfall and a record of devegetation.

Interflow emanates from the soil moisture store, the rate of movement being principally determined by the quantity of precipitation infiltrating the soil, and the antecedent moisture condition of the soil body. Its significance for the hydrological system relies increasingly upon the view that interflow is a rapid contributor to stormflow.

3.9 Natural Recharge/Deep Percolation

The term natural recharge as used in this study is defined as that water which percolates through the soil body to supplement the groundwater. Recharge occurs as a result of infiltration at the ground surface and as groundwater leakage from adjoining catchments. In arid or semi-arid areas it can also result from influent seepage from surface water bodies such as lakes and streams into the groundwater.

Recharge usually results from the surplus soil moisture conditions caused by winter rainfall following the soils return to field capacity. Hewlett and Hibbert (1967) suggest that translatory flow, which is flow produced by a process of displacement, occurs upslope and can be regarded as a pulse in soil moisture which migrates both downwards as natural recharge and transversely as interflow. One result of translatory flow is that even deep water table levels may respond rapidly to precipitation, even though the rates of downward percolation are very low. Natural recharge of a river basin system by means of groundwater leakage is due to the fact that surface water and groundwater catchments are rarely coincident, thus some groundwater will cross the boundary of the surface water system and vica versa. For example, the groundwater catchment of the River Itchen to Allbrook is 35% larger than the surface water catchment. Also in the London Basin a proportion of the rain infiltrating into the surface catchment of the River Lee discharges into the Great Ouse Basin.

In areas having highly permeable deposits such as sands, gravels and limestones occuring above the water table, the annual natural recharge is the difference between rainfall and actual evaporation. Although recharge usually occurs when a soil moisture surplus exists it can also be found when soil moisture deficits occur. This is because the base of the soil profile may still have a moisture surplus while the surface layers are in substantial deficit. In cases where a marked increase of permeability exists between the lower parts of the weathered soil mantle and the weathered bedrock a more complex situation exists in which perched water tables occur.

3.10 Groundwater Storage

Groundwater storage is provided by the voids and fractures within a geological formation. All rocks contain and transmit water, properties which are expressed in terms of porosity and permeability. As discussed in section 3.6, porosity controls the volume of water held with the ground and is defined as the volume of voids per unit volume of materials whilst permeability is a measure of the ease with which water moves through the ground.

The principal factors affecting porosity are shape, arrangement and degree of sorting of the constituent particles. All interstices contribute to porosity, and total interstitial volume includes pores, vertical and horizontal joints and factures. In highly porous formations large volumes of water are contained, whilst the reverse is generally true in low porous formations except where extensive fissures contain water. Permeability is affected by the size, shape and packing of grains, and the degree of cementation between grains.

As the texture of a material becomes coarser, and the number of large interstices increases, the porosity and specific retention decreases. Specific retention is the volume of water which a rock will retain against the force of gravity. There is no fixed moisture content at which gravity drainage ceases as drainage is initially rapid and then slows over a long period of time. The water which does drain under the influence of gravity represents the specific yield when expressed as the percentage volume of the drained material. This water is readily available to drain and supply wells and streamflow, whilst the retained water is not available and moves more slowly. Porous but impermeable rocks tend to have a low specific yield, whilst porous and permeable rocks have a high specific yield, and are known as aquifers.

An aquifer is defined as a geological formation, which can over long periods, yield significant quantities of water. These are generally sedimentary deposits having interconnected voids between their grains, but a rock which itself is impermeable and not porous can still be a good aquifer due to its well developed jointing. Aquifers facilitate groundwater storage, but in contrast aquicludes are impermeable formations which although containing water, are not capable of transmitting significant quantities of it.

Groundwater levels rise in response to natural recharge and fall as baseflow drains from storage. Groundwater storage is considered to be in two parts, active storage which is capable of draining into local rivers and streams and is dependent upon replenishment via infiltration, and the inactive or 'dead' store which lies beneath the level of natural outlets and is not depleted during drought (see Fig 3.9). The potential size of the active groundwater store is dependent upon topography, in terms of hillyness, and bulk porosity, which includes fissures. The degree to which this potential source is filled at any given time will depend upon several factors including the rate of natural recharge and the rate of discharge, which will be determined by the permeability and hydraulic gradient, and the density of the drainage system.

The size of the active store differs markedly between upland (i.e. mountainous) and lowland terrains. In upland terrains low porosity, but a large overall active store is found in areas which have characteristically high rainfall, low soil moisture deficit and small but prolonged natural recharge due to high runoff and interflow. Although permeability is low in these regions a large hydraulic gradient normally exists and there is therefore a significant baseflow component. In contrast lowland terrains exhibiting low rainfall, high soil moisture deficits and high natural recharge, with a consequent lack of overland flow and interflow, tend towards higher porosity with a relatively small overall storage. Permeability is often

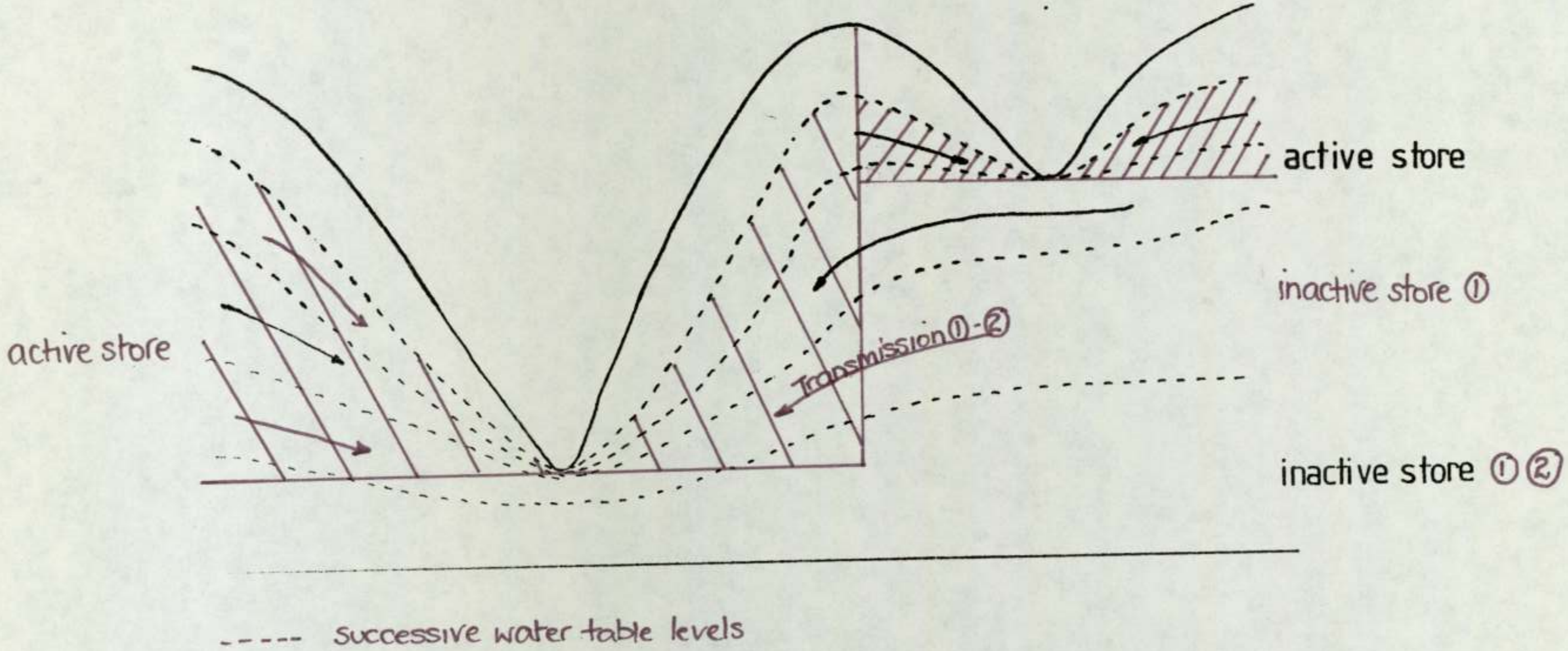


Fig 3.9 Active and Inactive (dead) Groundwater Storage

higher but the hydraulic gradient is small which means that the baseflow component may be less than in mountainous regions. Institute of Hydrology baseflow indices (BFI) (Low Flow Studies 1978) for low storage impermeable geological formations indicate that upland regions can have large active groundwater stores (Table 2.3). El Gusbi substantiated this view when he investigated the seasonal variations shown in a number of Welsh catchments. He found that in upland regions large seasonal variations occured in total catchment storage, and more particularly in groundwater storage.

3.11 Baseflow

Baseflow has been variously defined (Langbein and Iseri 1960, Tischendorf 1969, Butler 1957) but for the purpose of this study it is defined as the component of stream discharge provided by the saturation zone via spring and seepages directly into the river and its tributaries. It is derived from groundwater recharged by water infiltrating the soil and proceeding to the zone of saturation. The rate of water outflow being governed by the capability of rocks to absorb and retain water.

Baseflow is discharged directly from the groundwater store, and the rate of flow is related to rock type, groundwater levels, and the magnitude of the hydraulic gradient, which is usually low in flat lowland areas and often greater in hilly or mountainous areas.

An indication of baseflow discharge is particularly important for summer low flows when discharge can exist almost exclusively of baseflow. The Low Flow Studies team (1978) developed a baseflow index (BFI) which measures the proportion of river run-off that derives from stored sources. They found that annual BFI values are generally stable, high runoff years not experiencing higher or lower BFI values than average years. They listed BFI values for geological classes based upon their storage characteristics (Table 2.3). Geological formations having low storage were classified by BFI values in the range .3 - .05, which supports the conclusion drawn by El Gusbi that seemingly impermeable rocks can still yield significant quantities of baseflow.

One means of comparing the groundwater discharge from drainage basins, according to rock type, utilises the baseflow recession curve. Wright (1970) plotted recession curves, calculated a geological index appropriate to the geological formations beneath the catchments studied, and then developed an equation relating mean lowest annual daily mean flow, mean catchment slope, mean annual runoff and catchment area. Baseflow duration curves describe discharge characteristics of a basin, using a technique similar to that of the flow duration curve, but showing the percentage time in which daily baseflow is equalled or exceeded. In 1962, Kunkle used this method to study six locations on the Huran River, above Ann Arbor, Michigan. Using the curve to represent discharge from bank and basin storage he found that the curve assumed a particular form according to the deposits drained.

Conclusion

This chapter has discussed the meteorological characteristics and hydrological stores and processes acting upon and within those physical characteristics discussed in the previous chapter. The aim has been to identify the principal components and highlight the relationships between them, in order that a semi-empirical model can be developed. The model will, therefore, be designed to reflect relationships between principal components given the means to quantify catchment characteristics in order to provide a measure of water movement through a catchment.

CHAPTER 4

DEVELOPMENT OF A BASIC RAINFALL/RUN-OFF MODEL

4.1 INTRODUCTION

This chapter outlines the development of a rainfall/run-off model, from its original inception as a soil moisture simulation model, to a rainfall/run-off model incorporating the catchment characteristics and hydrological stores and processes outlined in the previous chapters. The calibration and testing of the model is described and the results presented. The chapter concludes with a discussion of the results and the subsequent alterations to the model.

The rationale behind the model is based upon the need for a simple conceptual model which can be easily calibrated using quantifiable indices of the physical characteristics of any given catchment. Throughout the development it was necessary to weigh the relative merits of simplicity and sophistication, so that the basic aim for a relatively simple but sufficiently accurate model could be achieved. Sophistication may lead to a greater precision but can result in a model being considered too complex and time consuming for general use.

In attempting to reproduce the dynamic spatial variation within catchments it was necessary to compromise between the use of large numbers of variables requiring time consuming measurement, and a limited number of variables which although rapidly measured will tend to reduce the accuracy of the model. The time step of the model was chosen to be one month, for three reasons -

i) One month was sufficiently short to enable simulation of seasonal variables in the hydrological stores and processes.

ii) Reliable monthly rainfalland streamflow data over 15 or more years were readily available for a number of catchments.

iii) A one month time step kept the magnitude of the task (i.e. calibration, analysis and computer time) within an acceptable limit.

It was felt that once this exercise had been satisfactorily completed it may be possible to reduce the time step, if necessary, to one week or less.

Two computer models were developed. one which uses mean monthly rainfall data as input (MODELMEAN), and a second (MODELBASIC) which uses a sequence of several years of monthly rainfall data. When using the former it was necessary to repeat the same annual cycle three times in order to provide a two year 'warm up' period. The model "MODELMEAN" was developed first and then extended to the second form following the optimisation of interflow and natural recharge coefficients (Section 4.5.4) During all subsequent developments and tests emphasis was placed on the latter design since the monthly rainfall input included extremes within the seasonal patterns, as well as the general trends expressed by data averaged over a long time period. The models were programmed using Fortran IV and listings appear in Appendix No. 1

4.2 Restructuring the Soil Moisture Simulation Model

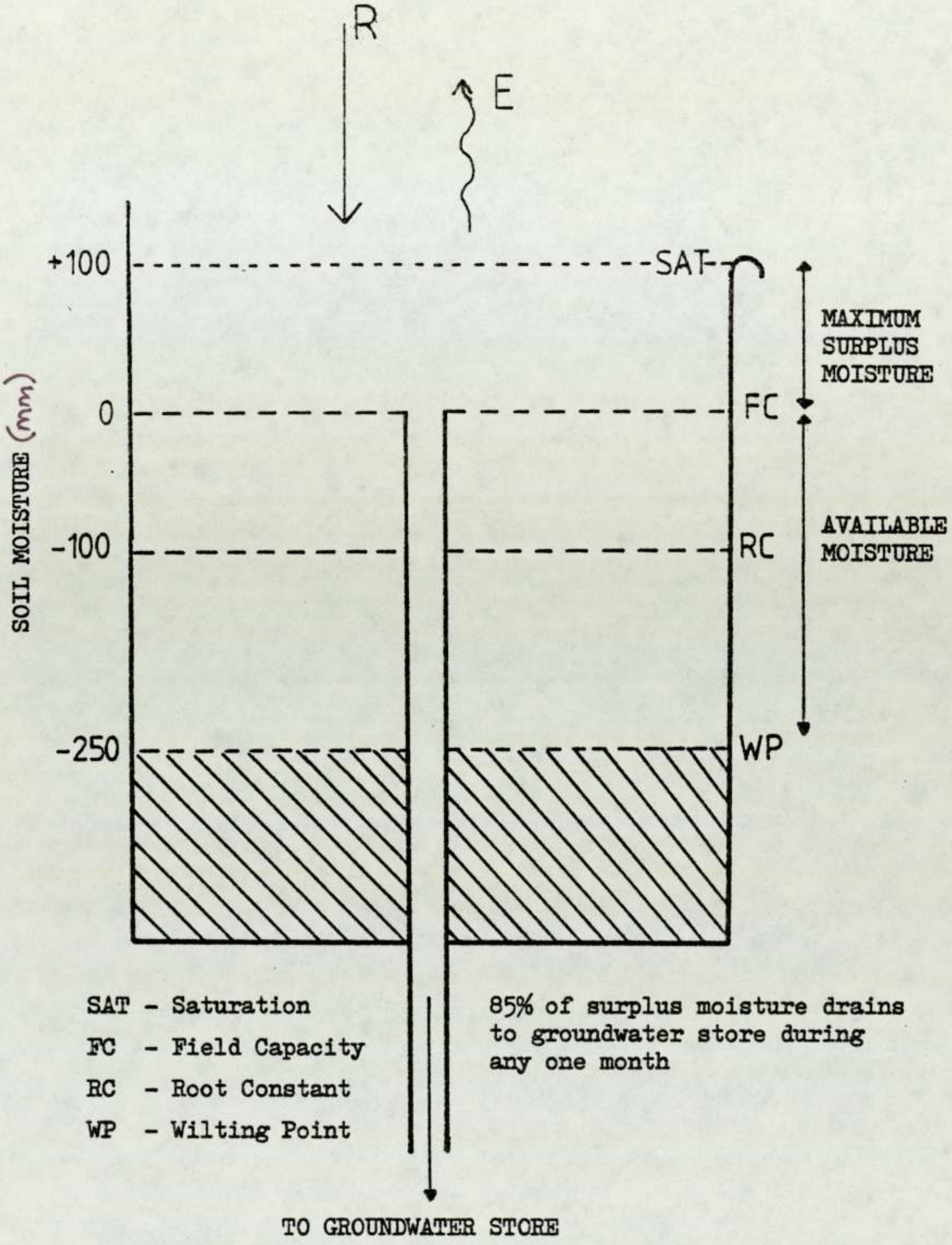
The original soil moisture simulation model was a deterministic parametric monthly model conceived by El Gusbi (1979), which was subsequently adapted to provide the basic soil moisture store routine for the rainfall/run-off model presented here. El Gusbi's model was designed to run with two concurrent streams of climatic input data, mean monthly rainfall and potential evapotranspiration (Fig 4.1). It produced end of month soil moisture figures evaluated on the assumption that 85% of the soil moisture in excess of field capacity drained to the groundwater store during the month, thus allowing the accumulation of a soil moisture surplus during winter months. El Gusbi derived the figure of 85%, and a figure of 100 mm, maximum moisture surplus, later amended to 75 mm, by comparing his simulated surpluses with those recorded in the field by his colleague Hussein (1980).

In summer months when potential evapotranspiration exceeds rainfall the model allows a soil moisture deficit (S.M.D.) to accumulate until a deficit of 100 mm is reached. Between this point and a deficit of 250 mm the actual evapotranspiration (Ea) is reduced below the potential value (Ep) as follows:

$$Ea = \left(\frac{250 - SMD}{150}\right) Ep$$

This is equivalent to a linear reduction in Ea from Ep at a deficit of 100 mm (i.e. root constant) to zero at a wilting point of 250 mm (Fig 4.2). El Gusbi found that the values of 250 and 150 in the above equation produced mean monthly actual evaporation for lowland catchments consistent with river authority figures, and in addition they compared favourably with the results obtained by Hussein (1980).

The value of the soil moisture simulation model was demonstrated by El Gusbi in a comparison of his simulated SMD's for high, medium and low rainfall catchments with Meteorological Office end of month soil moisture deficit figures. Simulated soil deficits for high rainfall (i.e. mountainous) catchments



SAT - Saturation
FC - Field Capacity
RC - Root Constant
WP - Wilting Point

85% of surplus moisture drains to groundwater store during any one month

Fig 4.1 Soil Moisture Simulation Model

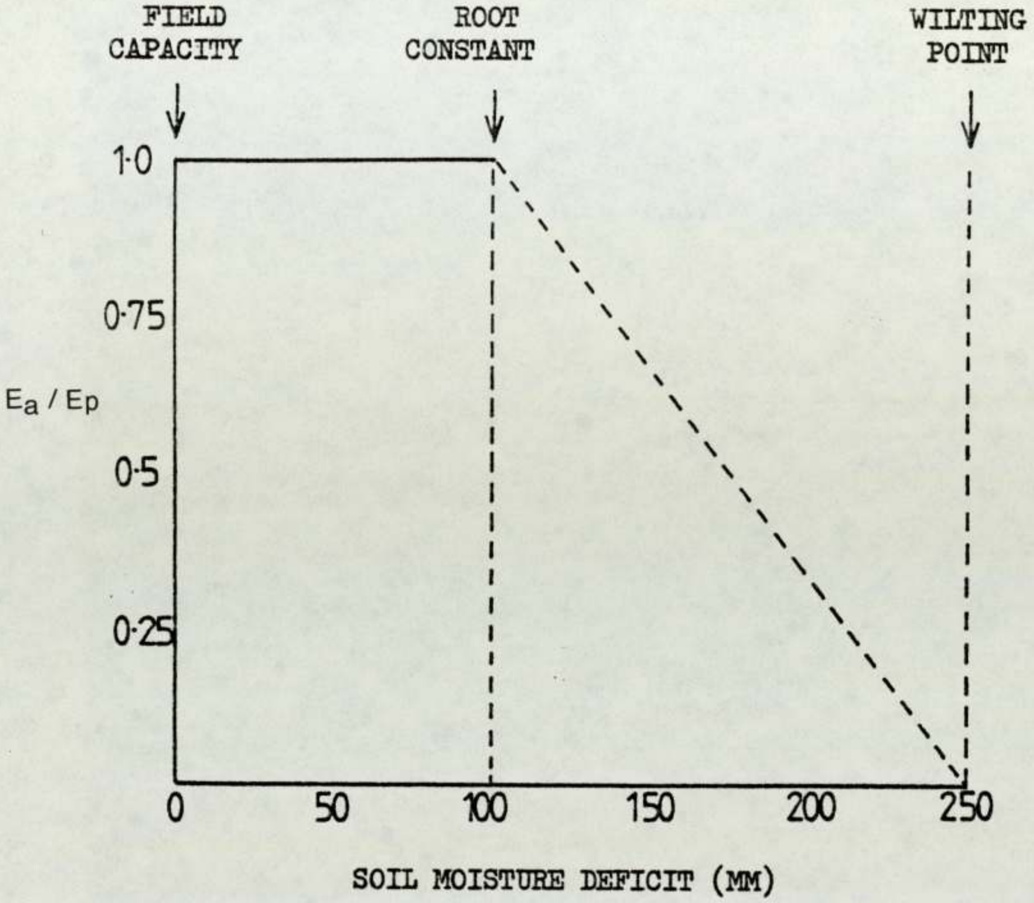
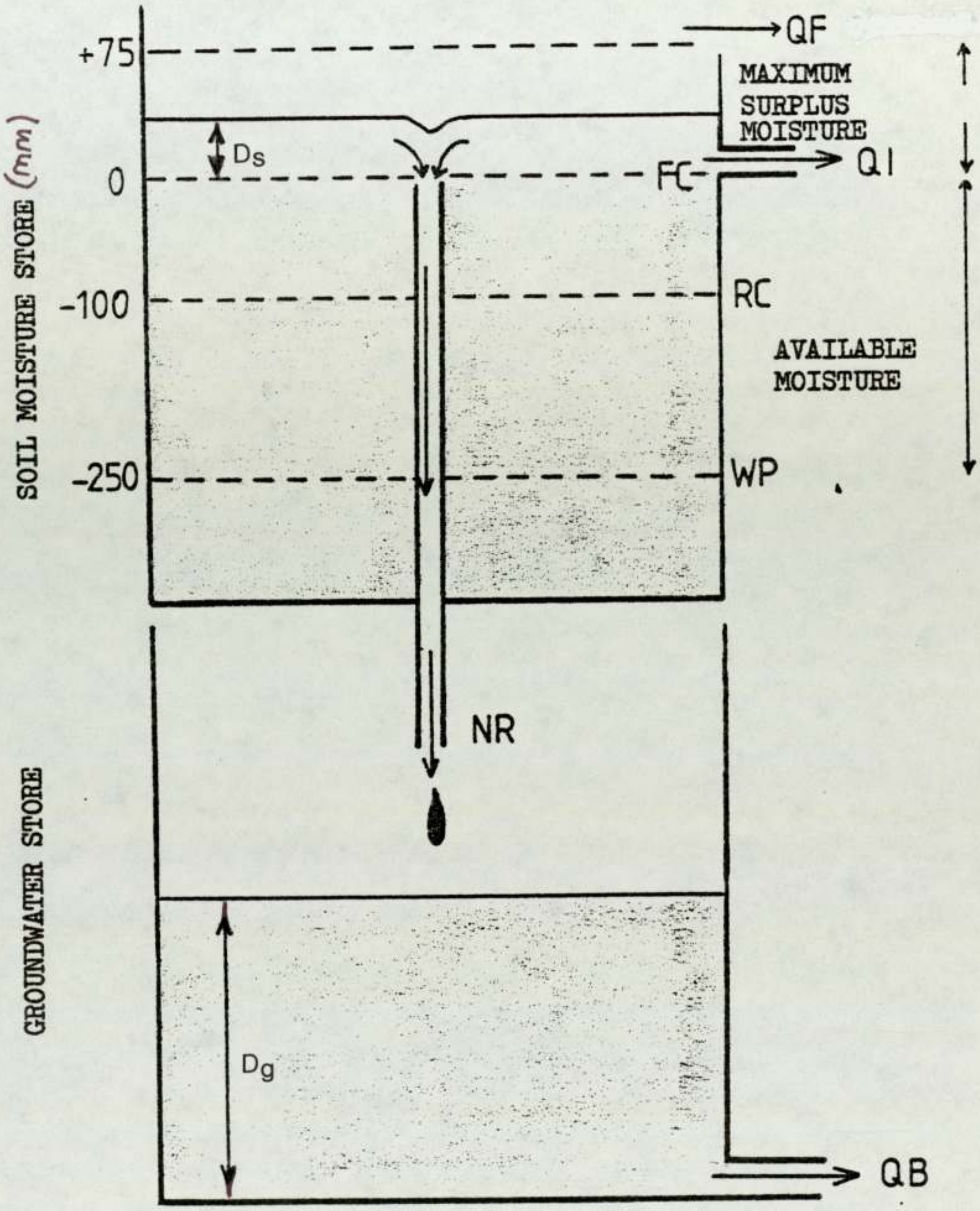


Fig 4.2 <u>Variation of Ea/Ep Ratio with Soil Moisture Deficit</u>

recorded lower deficits than those predicted by the Meteorological Office. This was because Meteorological Office figures rely upon stations situated at low altitudinal levels where predictions relate to valley bottoms and side slopes, whilst simulated deficits related to mean altitudinal levels which are therefore more representative. As expected medium and low subcatchment simulated deficits were found to be of a similar order to Meteorological Office figures. The soil moisture simulation model was therefore felt to provide an adequate foundation on which to develop a rainfall/run-off model.

During the first stages of development the soil moisture simulation model was extended to include a groundwater store (Fig 4.3). The soil moisture store retained its basic form, climatic data continued to be input in a similar form to previously and the calculation of actual and potential evaporation remained the same.

Precipitation was input into the soil moisture store which had an initial value of 0.0, this represented the value for field capacity, and reflected soil moisture conditions at the onset of the year. It also allowed for the easy calculation of seasonal deficits and surpluses. Moisture continued to be output as evaporation or natural recharge into the groundwater store, but overland flow and interflow became additional factors. Overland flow was calculated as that moisture in excess of saturation, saturation having retained the amended value of 75 mm surplus moisture above field capacity. Natural recharge (NR) and interflow (QI) were calculated on the assumption that the surplus moisture store behaved as a linear reservoir. Thus



QF - Overland Flow
QI - Interflow
QB - Baseflow
NR - Nat. Recharge
FC - Field Capacity
RC - Root Constant
WP - Wilting Point

Fig 4.3 Restructured Soil Simulation Model

$$NR = A_1 D_s$$

$$QI = A_2 D_s$$

where A_1 and A_2 are arbitrarily chosen discharge coefficients and D_s is the amount of surplus moisture (mm).

The active groundwater store was also designated an initial value of 0.0 (i.e. empty) since it was difficult to estimate a more realistic value. In order to enable this to achieve a realistic value all simulations were preceded by a two year 'warm up' period. The quantity of baseflow (QB) was calculated by treating the groundwater store as a linear reservoir with an arbitrarily chosen discharge coefficient, thus

$$QB = A_3 D_g$$

During calibration of the model the discharge coefficients A_1, A_2 and A_3 were optimised so that the discharges from the stores were consistent with reality.

Changes to the soil moisture simulation model therefore provided the basis from which a catchment storage model could be developed. It was then necessary to incorporate into the model the remaining hydrological stores and processes of any significance and the effect of catchment characteristics and their spatial distribution.

4.3 BASIC STORAGE MODEL

4.3.1 INTRODUCTION

At this stage in the development of the model, fundamental changes were made to its design. The original model was a simple two-tiered lumped model comprising a soil moisture and groundwater store with no possibility of incorporating the spatial variability of the various stores and processes. The design was therefore altered to a three zone distributed model to allow those variations in catchment characteristics which affect the magnitude of stores and processes to be incorporated into the model. The modification to a three zone model was based upon altitude with each catchment considered as having an upland, mid-land and lowland zone, each having its own snow, soil and groundwater stores (Fig 4.4). Altitude was chosen as the basis for the division of zones since spatial variation of stores and processes is closely related to the catchment characteristics which in turn are generally related to altitude. Some aspects of spatial variability are well known, for example rainfall where recorded data is available, but others such as the interflow/natural recharge relationship are not and require investigation during calibration of the model.

The three zones therefore represent not only variations in altitude and processes such as rainfall, evaporation, snowfall and snowmelt which are related to it, but also variations in other factors such as available moisture, the interflow/natural recharge relationship and the infiltration/overland flow relationship. These latter factors being related to variations in other catchment characteristics such as slope, stream density and soil etc. The development of **a** distributed model was therefore considered crucial to the development of a model based upon catchment characteristics, and it was hoped that calibration would provide an insight into the relationship between hydrological processes and catchment characteristics.

4.3.2 Outline of the Basic Storage Model

The basic storage model is illustrated in Fig 4.4 and a flow diagram is shown in Fig 4.5.

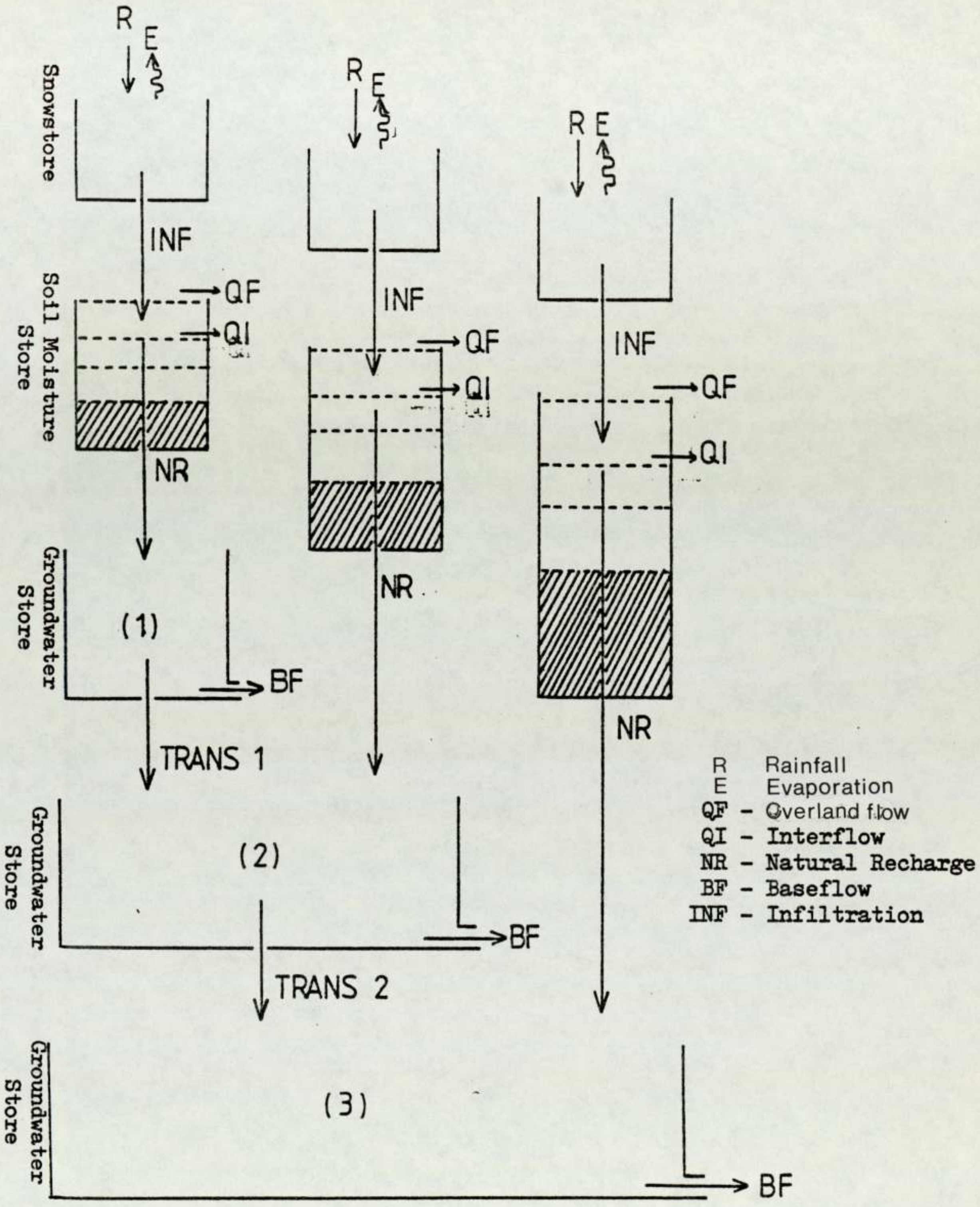


Fig 4.4 Basic Storage Model

As is normal the procedure begins with the input of data. The meteorological data in the form of precipitation, evaporation and temperature is input together with the model parameters.

The monthly meteorological data is adjusted for the mean altitude of each zone, which aids the calculation of zonal surface stores and processes. First, the precipitation and temperature data are used to determine the amount of snowfall, if any. If snowfall occurs it passes into the snowstore where it is added to the water equivalent of the snowpack. The zonal temperature is then used to estimate the monthly snowmelt which is deducted from water equivalent of the snowpack and added to the amount of rainfall, entering the soil moisture store. If the amount of moisture in this store exceeds the field capacity value, some of the surplus moisture is allowed to drain vertically as percolation and laterally as interflow. Evaporation at the potential rate is then removed from the volume of moisture in the soil moisture store. Any moisture remaining in the soil moisture store which is surplus to the overall moisture holding capacity of the soil (i.e. saturation) is treated as if it never actually entered the soil and allowed to drain as overland flow. That is, overland flow is treated as overflow from the soil moisture store after percolation and interflow has taken place.

If, however, the amount of moisture in the soil moisture store after the addition of rainfall plus snowmelt, is less than field capacity, then no moisture is allowed to drain from the soil as percolation or interflow. The calculation of the evaporation loss from the soil moisture store is then based upon the magnitude of the soil moisture deficit (SMD). If the deficit is less than the root constant then evaporation is put equal to the potential value, but if the deficit lies between the root constant and wilting point values, then it is derived by linear interpolation between the potential value (Ep) at an SMD equal to the root constant and zero at an SMD equal to the wilting point value.

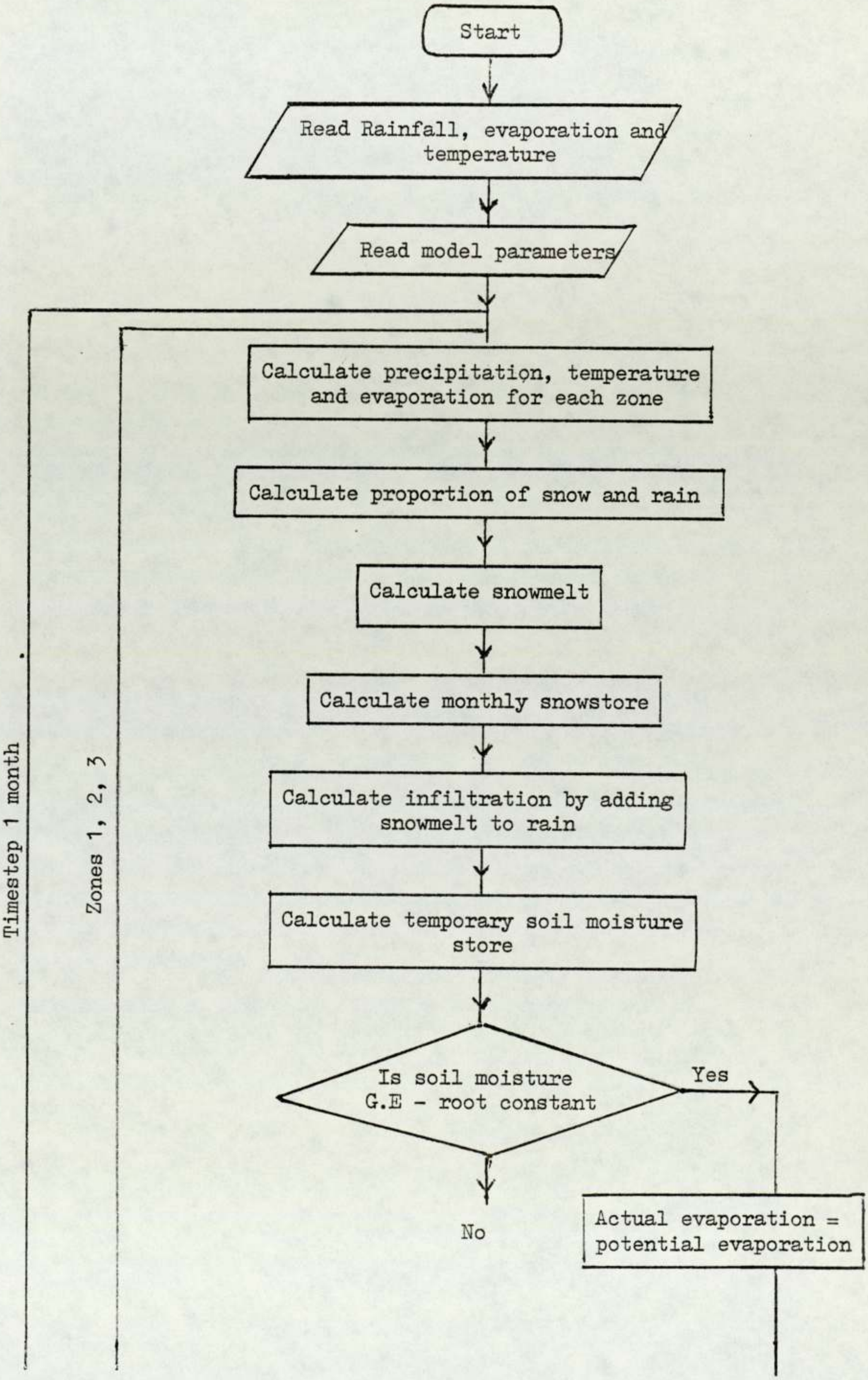
Having calculated the overland flow, interflow and natural recharge for each of the three zones, the model then allows the percolation from each zone to recharge its corresponding groundwater store (i.e. the percolation becomes natural recharge). Discharges from the groundwater stores, which are treated as linear reservoirs, take two forms:

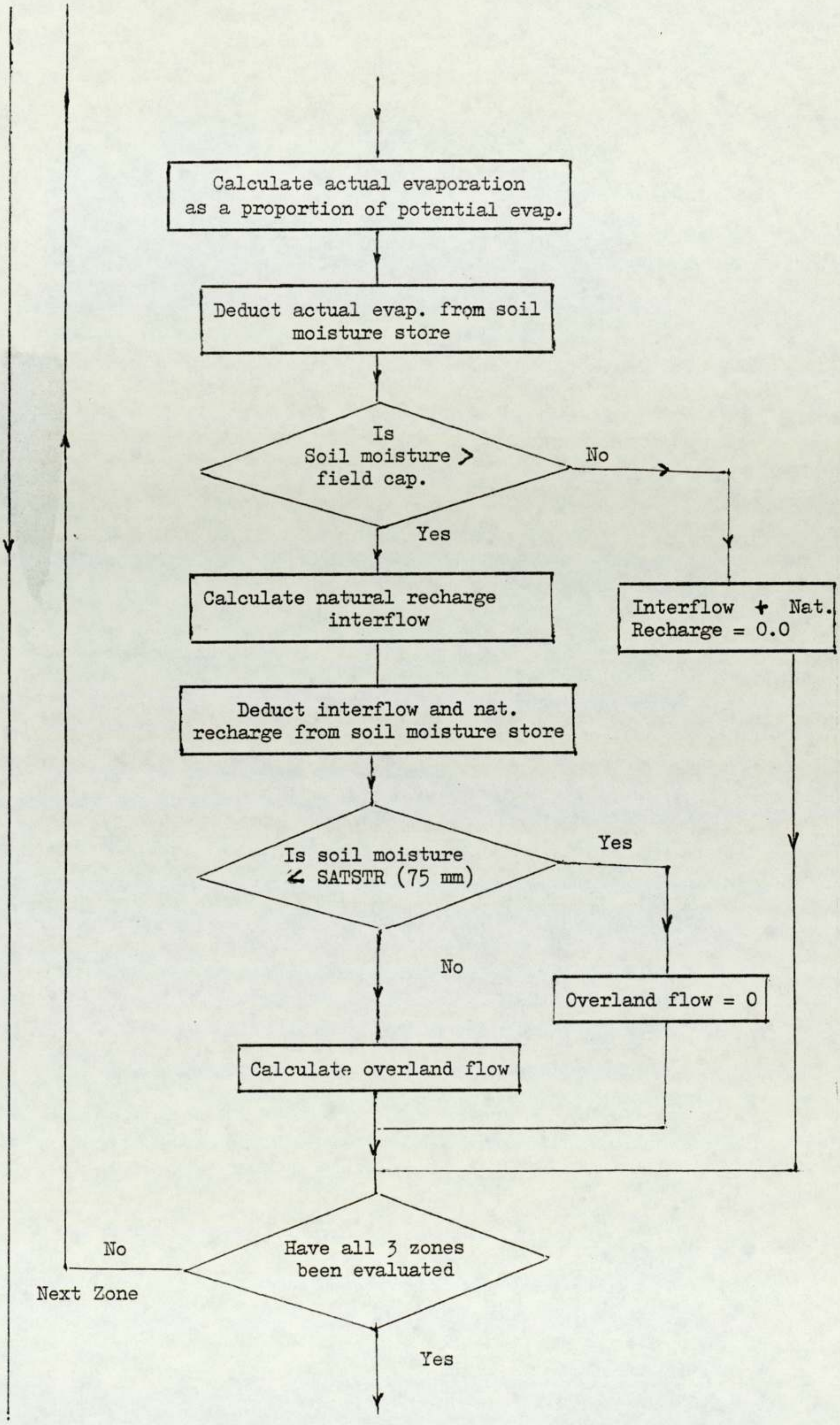
i) baseflow which combines with the zonal overland flow and interflow to form the total zonal streamflow for the month;

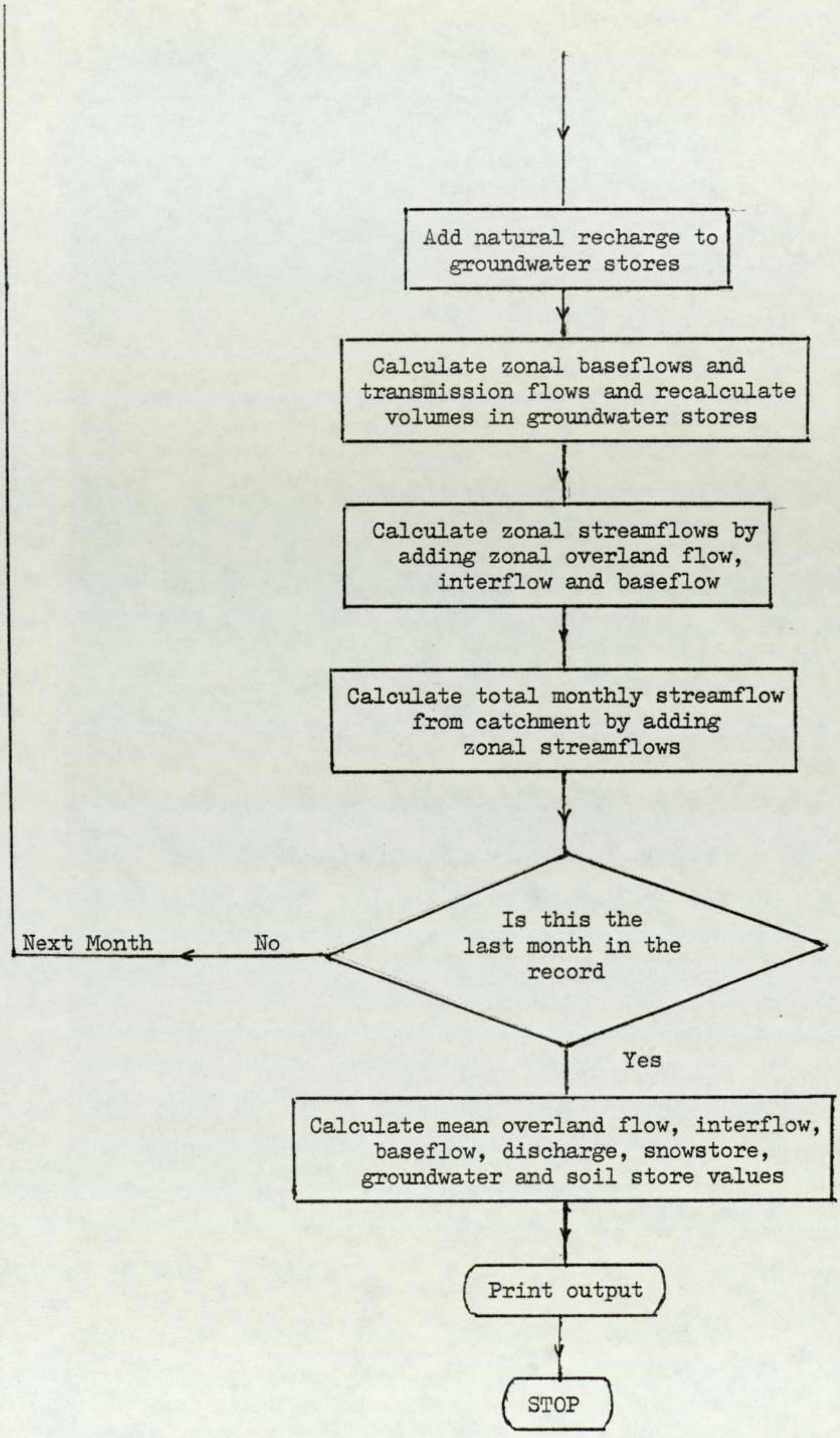
ii) transmission flow which allows a higher groundwater store to discharge into a lower one.

Finally the three zonal streamflows are combined to form the total monthly streamflow from the basin (catchment). The model then repeats the whole process for the following month using the next set of meteorological data and the new storage volumes in the soil moisture and groundwater stores.

Fig 4.5 SIMPLIFIED FLOW DIAGRAM OF THE BASIC STORAGE MODEL




Calculate actual evaporation as a proportion of potential evap.
Deduct actual evap. from soil moisture store
Is Soil moisture > field cap.
No
Yes
Calculate natural recharge interflow
Interflow + Nat. Recharge = 0.0
Deduct interflow and nat. recharge from soil moisture store
Is soil moisture < SATSTR (75 mm)
Yes
No
Overland flow = 0
Calculate overland flow
No
Have all 3 zones been evaluated
Next Zone
Yes


Add natural recharge to groundwater stores
Calculate zonal baseflows and transmission flows and recalculate volumes in groundwater stores
Calculate zonal streamflows by adding zonal overland flow, interflow and baseflow
Calculate total monthly streamflow from catchment by adding zonal streamflows
Is this the last month in the record
No
Next Month
Yes
Calculate mean overland flow, interflow, baseflow, discharge, snowstore, groundwater and soil store values
Print output
STOP

4.4 SPATIAL VARIATION OF THE STORES AND PROCESSES

4.4.1 Rainfall

The spatial variation of the meteorological characteristics of the catchment is ultimately reflected in the spatial and temporal variation in the hydrological stores and processes. Precipitation is particularly spatially varied since it tends to follow patterns of relief, consequently it was necessary to consider the rainfall/altitude relationship when the model was restructured to include three zones. Three methods designed to proportion monthly areal rainfall figures between the three zones were explored.

i) By evaluation of topographic maps and the rainfall/altitude relationship.

ii) The use of Meteorological Office published rainfall maps.

iii) The use of simple coefficients to apportion rainfall.

Evaluation of topographical maps and the rainfall/altitude relationship was considered, and in particular the linear arithmetic relationship between annual rainfall and altitude designed by the Institute of Hydrology (Newson 1976) for the Plynlimon experimental catchment. The relationship took the form

$$P = 1.71h + 1530$$

where P - annual catch (mm)

and h - altitude (m)

However when $h = 0$, $P = 1530$ and this is twice the annual rainfall for the Mid Severn. When applied to the average altitudes of a number of Welsh catchment zones the total annual rainfall exceeded the measured value, and consequently the relationship was not used in the model.

The use of Meteorological Office maps provided a good indicator of the annual rainfall/altitude relationship, however they do, understandably, tend towards a bias from low altitude gauges. They were nonetheless useful in developing a rainfall/altitude relationship based upon the use of simple coefficients to apportion zonal rainfall. The coefficients for zones 1, 2 and 3 were 1.2, 1.0 and 0.8 respectively. They were determined from a zonal breakdown of catchment annual rainfall distribution, which showed that overall the estimated rainfall from Meteorological maps for each catchment zone could roughly be calculated by the above coefficients. For example, Mid Severn which has an average rainfall of 718 mm, was estimated to have zonal rainfall values of 850, 700 and 600 mm, whilst the use of coefficients gave their respective rainfall values as 859, 716 and 572 mm. Although the use of coefficients ignored peculiarities in catchment meteorological characteristics, it did provide a simple indicator of zonal rainfall distribution which proved to be adequate on a monthly time scale.

4.4.2 Evaporation

The spatial variation of evaporation principally relies upon the evaporation/altitude relationship since evaporation decreases as altitude increases. El Gusbi (1979) produced a linear regression equation which can be used to estimate monthly evapotranspiration in the Welsh catchments for any altitude in the range 0 to 1400m. The figures calculated by El Gusbi for the rate of change of evapotranspiration with altitude are tabulated in Table 4.1.

TABLE 4.1 COEFFICIENT OF CHANGE IN EVAPORATION PER METRE RISE IN ALTITUDE (mm)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
- 0.01	-0.016	-0.024	-0.034	-0.042	-0.046	-0.044	-0.036	-0.025	-0.014	-0.008	-0.007

4.4.3 Snowfall and Snowmelt

As discussed in Chapter 3 the spatial variability of snowfall tends to follow the general pattern of relief, this is principally due to the temperature/altitude relationship and orographic enhancement of precipitation. The vertical decrease in temperature per 100 m of altitudinal rise increases the possibility of snowfall in upland regions. The use of altitude to separate the zones is particularly useful in this context since it facilitates the inclusion of temperature variations. This is necessary as it significantly affects the spatial and temporal distribution of streamflow and in snowcover governs the accumulation and melting of snow.

The operational design of each of the three zonal catchment stores used in the model is identical. At each time step the temperature ($T^{o}C$) for each zone is estimated from

$$T = T_s - 0.006 (Z - Z_s)$$

where T_s is the recorded monthly mean temperature at a nearly meteorological station

Z_s = altitude of the meteorological station

Z - mean altitude of zone

0.6 - ambient lapse rate (°C/100m)

When T falls below T2 (the maximum temperature at which snow is likely to occur) the proportion of the monthly precipitation falling as snow is estimated from

$$SNS = RL \ ((T2 - T) / (T2 - T1))$$

where SNS - snowfall (mm equivalent rainfall)

RL - monthly precipitation (mm)

T1 - minimum temperature (°C) (i.e. temp (°C) below which all precipitation is likely to be snow)

T, T2 - as defined above

when $T \leq T1$ $SNS = RL$

$T \geq T2$ $SNS = 0.0$

That proportion of precipitation which has fallen as snow is then added to the temporary snowmelt store (SNMS) thus -

$SNMS = SN + SNS$

where SN - water equivalent of the snowpack at the beginning of the month (mm)

The amount of snowmelt over the month is then estimated from

$RSNM = A1 + A2 \times T$

where RSNM - snowmelt over the month (mm equivalent rainfall)

A1 + A2 - constants

The water equivalent of the snowpack at the end of the month (i.e. beginning of next month) is then estimated by deducting the snowmelt and evaporation losses, thus -

$SN = SNMS - RSNM - ES$

where ES = evaporation from snowpack (mm)

If the snowmelt (RSNM) plus evaporation (ES) jointly exceed the current snowstore (SNMS) then they are reduced in the same proportion until they are equal to it. The end of month snowstore (SN) is then put equal to zero. Total evaporation for the month is then returned to the potential value by removing the appropriate amount from the soil moisture store.

Calibration of the parameters T1, T2, A1 and A2 is described and discussed in section 4.5.

4.4.4 Soil Moisture Store and Processes

The development of the soil moisture store has retained much of the simplicity inherent in the original model. The most marked change was the separation of the catchment into three zones.

The soil moisture routine was designed to evaluate outputs from the temporary soil store (SOILM) in the form of quickflow (QF), interflow (QI) and natural recharge (NR) following the input due to the infiltration of rainfall and loss due to evaporation. Initially, all water supplied to the surface is assumed to infiltrate the soil surface, thus monthly infiltration (INF) is equal to the precipitation falling as rain plus the snowmelt. Hence -

$$\mathrm{INF} = \mathrm{RL} - \mathrm{SNS} + \mathrm{RSNM}$$

The amount of surplus moisture in the temporary soil moisture store (SOILM) is then evaluated as follows

$$\mathrm{SOILM} = \mathrm{SM} + \mathrm{INF} - \mathrm{EL}$$

where SM - soil moisture surplus at the beginning of the month (mm)

EL - potential evapotranspiration for the month (mm)

It should be noted that soil moisture is measured relative to field capacity, hence moisture in excess of field capacity is surplus moisture (+VE) whereas soil moisture deficits are negative values.

If $\mathrm{RL} \leq \mathrm{EL}$ and the soil has a moisture deficit in excess of the root constant (RTC) then actual evapotranspiration (EA) is assumed to be less than the potential value (EL). In these circumstances the actual amount is estimated from

$$\mathrm{EA} = \mathrm{RL} + \mathrm{PHI}\,(\mathrm{EL} - \mathrm{RL})$$

where $\mathrm{PHI} = (\mathrm{AVMT} + \mathrm{SOILM}) \,/\, (\mathrm{AVMT} - \mathrm{RTC})$

AVMT - available soil moisture (mm)

RTC - root constant (mm)

Under these circumstances SOILM is in deficit and therefore negative in value.

It is then necessary to correct the SOILM value calculated in previous equations to allow for the fact that $EA < EL$ thus

$$SOILM = SOILM + (EL - EA)$$

The drainage of surplus soil moisture (i.e. when $SOILM > 0$) may be as interflow (QI) or natural recharge (NR) to the groundwater store. For the purpose of calculating these flows the soil moisture store was assumed to behave as a linear reservoir. Thus -

$$QI = QICOEF \times SOILM$$

$$NR = NRCOEF \times SOILM$$

where QICOEF and NRCOEF are discharge coefficients

The amount of moisture in the soil moisture store at the end of the month (i.e. beginning of the next month) is thus given by

$$SM = SOILM - QI - NR$$

In the exceptional circumstances of SM exceeding the surplus moisture capacity of the soil SATSTR (i.e. the storage between field capacity and saturation) the excess moisture is assumed to drain as overland flow (QF). That is, it drained away before entering the soil store. Hence -

$$QF = SOILM - SATSTR$$

$$\text{and } SM = SOILM - QF$$

The calibration of the parameters SATSTR, QICOEF and NRCOEF is described in section 4.5.

4.4.5 Groundwater Store and Baseflow

The groundwater store was altered to accommodate three groundwater/transmission stores. The effect of transmission flow is to allow for the delayed movement of moisture through the catchment from one zone to another. Schematic representation of the groundwater (GW 1, 2, 3) and transmission (Trans 1, 2, 3) flows is shown in Fig 4.4.

In the Upland zone 1 the groundwater store is recharged by natural recharge (NR1) from the overlying soil body such that

$$GW1 = GW1 + NR1$$

Baseflow and transmission flow is then calculated and removed to give the end of month groundwater store value for zone 1 thus -

$$QB1 = BFCOEF \times GW1$$

$$TRANS1 = TRCOEF \times GW1$$

$$GW1 = GW1 - QB1 - TRANS1$$

where GW1 - groundwater store for zone 1 (mm equivalent rainfall)

TRANS1 - transmission flow (mm)

BFCOEF - baseflow discharge coefficient

TRCOEF - transmission flow coefficient

QB1 - baseflow for zone 1 (mm)

Baseflow (QB1) subsequently becomes a part of the total catchment discharge, whilst transmission flow from GW1 enters GW2 together with natural recharge from zone 2, the mid-land zone such that

$$GW2 = GW2 + TRANS1 + NR$$

Both baseflow and transmission flow are calculated as before, and whilst baseflow becomes a part of total discharge, the transmission flow moves to GW3 together with the natural recharge from zone 3, the lowland zone -

$$GW3 = GW3 + TRANS2 + NR3$$

Following the use of various transmission coefficients the value of 0.05 was retained for use throughout, since the limits within which it functioned satisfactorily were quite broad. This basically says that 5% of the Upland groundwater transfers to the Mid-land groundwater in one month and similarly for Mid-land to Lowland. This is clearly possible for small catchments, however, the % transfer will probably reduce as the catchment size increases. The calibration of BFCOEF is described in section 4.5.4.

Total stream discharge subsequently comprised the following -

QFL = QF1 + QF2 + QF3 - Total overland flowfor zones 1 - 3 (mm)

QBF = QB1 + QB2 + QB3 - Total baseflow for zones 1 - 3 (mm)

QIN = QI1 + QI2 + QI3 - Total interflow for zones 1 - 3 (mm)

and Q = QFL + QIN + QBF - Total flow (mm)

4.5 CALIBRATION AND TESTING OF THE BASIC MODEL

4.5.1 INTRODUCTION

Calibration and testing of the basic model considers those values incorporated in snowfall and snowmelt equations. It also determines values for the discharge coefficients and subsequent linear regression equations. This process therefore validates those values which are ultimately used in the "model".

4.5.2 Snowfall

It was initially accepted that snow can fall at temperatures of 0°C and above, and that rain can fall at temperatures below 0°C and in the absence ofany conclusive data it was assumed that:

i) at temperatures less than -2°C (T1) all precipitation is snow

ii) at temperatures greater than 2°C (T2) all precipitation is rain

iii) at temperatures (T) between 2°C and -2°C the proportion of precipitation (P%) events occuring as snow was

$$P = \left(\frac{T2 - T}{T2 - T1}\right) \times 100\% = \left(\frac{2 - T}{4}\right) \times 100\%$$

These temperatures were later adjusted following analysis of daily precipitation and temperature data obtained from Edgbaston Observatory, Birmingham, used to derive a temperature/ snowfall relationship. The data which was used covered the period 1971 to 1978. It recorded average daily temperature, the total number of hours in which precipitation occurred, and whether the precipitation could be categorised as rain, sleet or snow. By treating sleet as half snow and half rain it was possible to determine the percentage of precipitation events at any given temperature which occurred as snow. The results of this analysis are shown plotted on Fig 4.6. T2 and T1 were consequently taken as $5^\circ C$ and $-2^\circ C$ respectively. However, it should be noted that this relationship is based upon daily precipitation and temperature data, whereas it has been applied to monthly data. This may not be strictly valid, but it seems a reasonable assumption and time did not permit a more detailed analysis of this phenomena.

4.5.3 Snowmelt

Snowmelt depends upon many factors including temperature, windspeed, relative humidity, sunshine hours, etc. However, in a model of this type it is not practical to input all these factors and so a simpler approach had to be adopted. This took the form of a linear mathematical equation for the rate of snowmelt

Rate of snowmelt (mm/month) = $A1 + A2 \times T$

where T - monthly mean zonal temperature ($^\circ C$)

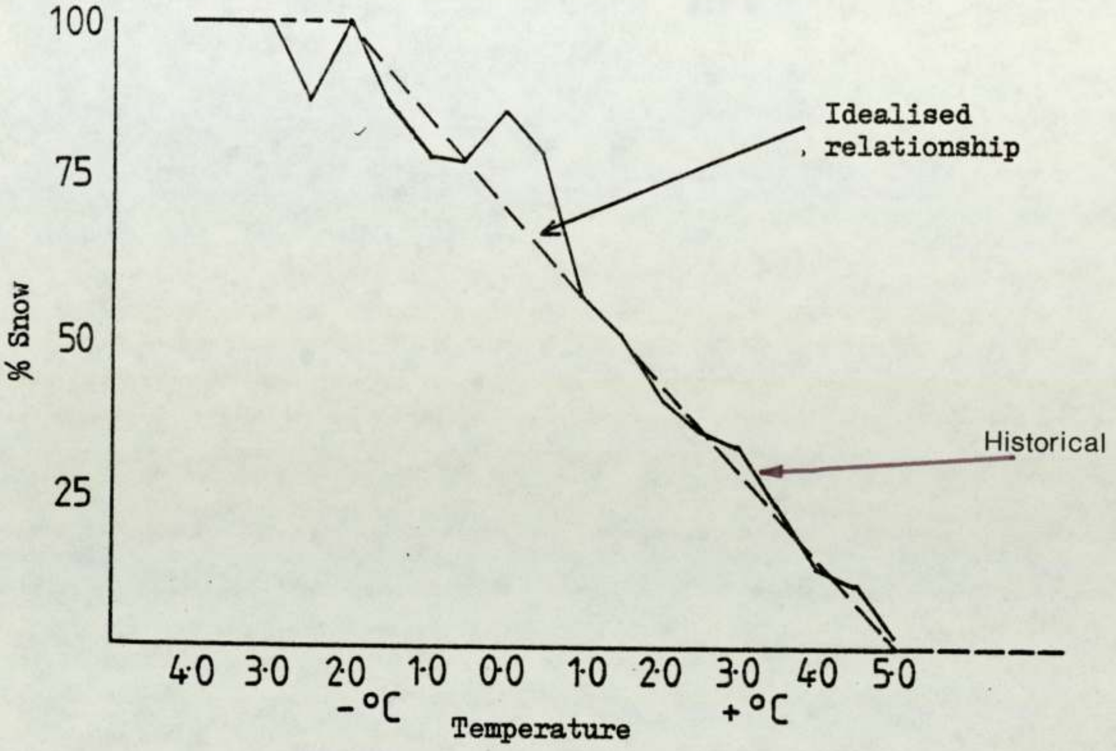


Fig 4.6 <u>Snowfall/temperature Relationship</u>

A1 and A2 are constants and were initially given the values 60 mm /month and 120 mm/°C/month, following calibration using data from Rhayader catchment. Negative rates of snowmelt (i.e. when $T < -\frac{A1}{A2}$) were set equal to zero. Rhayader is an upland catchment with fairly reliable data that could be used to test a range of values for A1 and A2 (Table 4.2). The results, however, were not very sensitive across the range of values of A1 and A2 which were tested. The values of A1 and A2 were also compared with the values derived from the work of the US Corps of Engineers (1956). Bruce and Clark (1966) describe the effect of six factors upon total melt computations which were combined in the Snow Hydrology (U.S. Corps of Engineers 1956) studies to form semi-empirical equations which give basin-wide melt estimates. For example, they gave melt (M) during rain in fairly open drainage areas as -

$$M = (0.029 + 0.0084\, KV_w + 0.007\, P_r)(T_a - 32) + 0.09$$

By substituting typical British values into this equation it was possible to reduce it to:

$$\text{Rate of snowmelt} = 90 + 155T$$

However it must be remembered that their equation was derived for Canadian catchments, not British catchments. Nevertheless it confirms that the initial values used for A1 and A2 were in the right order of magnitude.

4.5.4 Calibration of the Natural Recharge, Interflow and Baseflow Values

Since 0.85 had been shown by El Gusbi (1979) to be a realistic discharge coefficient for combined interflow and natural recharge it was decided to set the discharge coefficients for interflow and natural recharge such that their sum equalled 0.85. The optimum values of these and the baseflow discharge

TABLE 4.2 CALIBRATION OF SNOWMELT FACTORS FOR RHAYADER CATCHMENT

Snowmelt factors		Sum of Deviations
A1	A2	
60	200	68.3
60	150	68.45
60	120	68.11
90	120	68.84
120	120	68.12

coefficient were determined by repeated simulations using the Welsh catchments and intermediate subcatchments. Consequently the program 'MODELMEAN' was run using averaged catchment and subcatchment data to produce the 'best-fit' predicted discharges. This was achieved using the sum of the differences between historical and predicted discharges as the objective function to be minimised. The response surface was then illustrated graphically to discern general trends and patterns, examples of this process can be seen in Figs 4.7.1/3. When all the results had been evaluated it was possible to see a pattern emerging whereby the interflow and natural recharge coefficients tended to lie within distinct ranges depending upon the nature of the catchment (see Fig 4.8) These ranges are summarized in Table 4.3.

Having determined guidelines for the calibration of these parameters using averaged data, the exercise was repeated using 16 year sequences of rainfall and streamflow data, but this time using the guidelines outlined above to provide the starting point for the simulations. The final results differed little from those previously obtained, despite the fact that the 16 year sequences contained far more random variability (i.e. noise) than the averaged data. It was therefore concluded that the looped sequences of average monthly rainfall and streamflow provided a satisfactory means of calibrating the discharge coefficients for interflow and natural recharge, and that the guidelines given above provided a sound basis for model calibration. In order to test the validity of the assumption that QICOEF plus NRCOEF should equal 0.85, three catchments were optimised using 0.8, 0.9 and 0.95, instead of 0.85. The three catchments were Rhayader, Tenbury and Lower Wye, and covered the

Calibration of QI, NR and BF coefficients

TENBURY

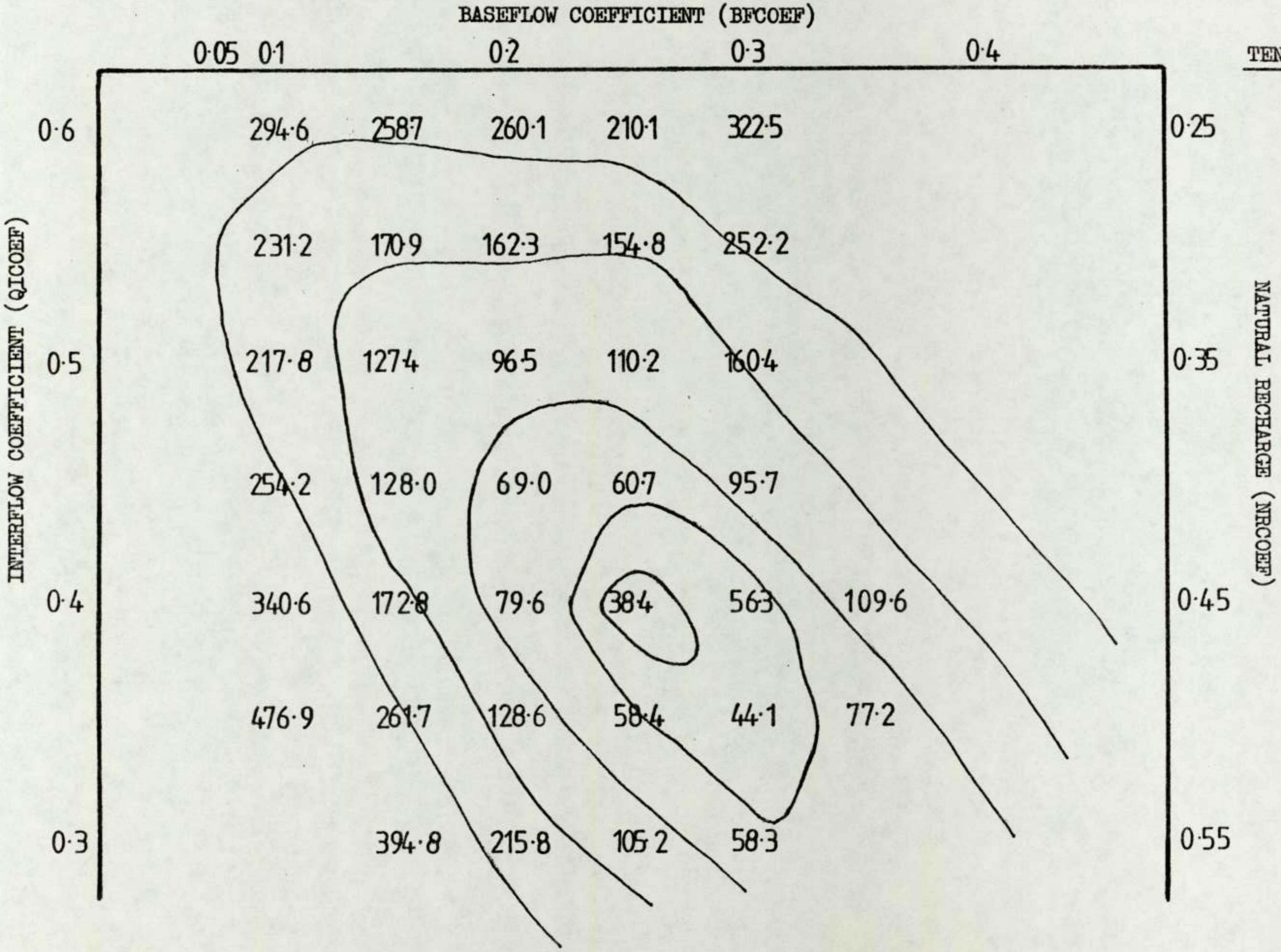


Fig 4.7.1

LOWER WYE

Calibration of QI, NR and BF coefficients

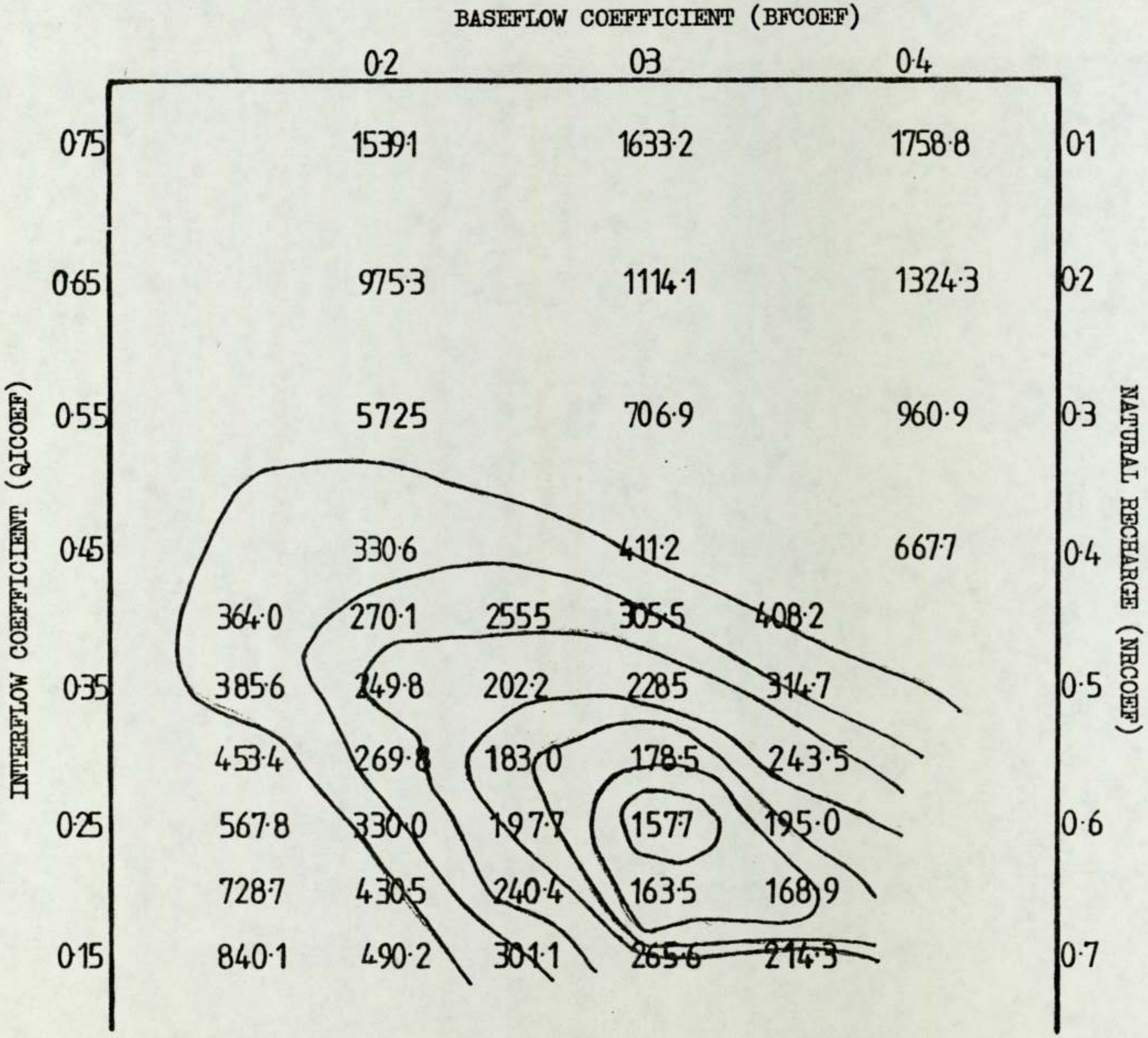


Fig 4.7/2

Calibration of QI, NR and BF coefficients

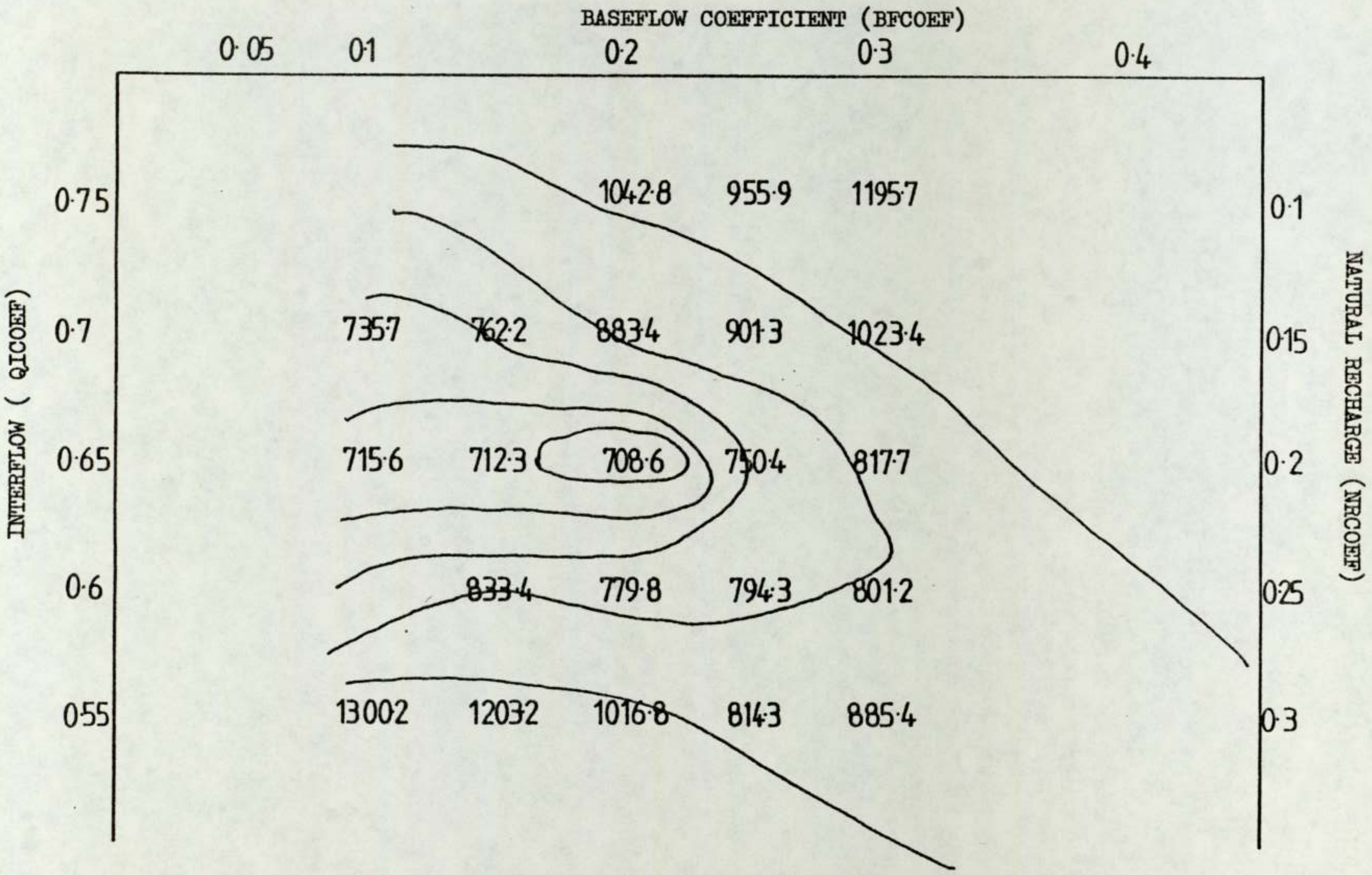
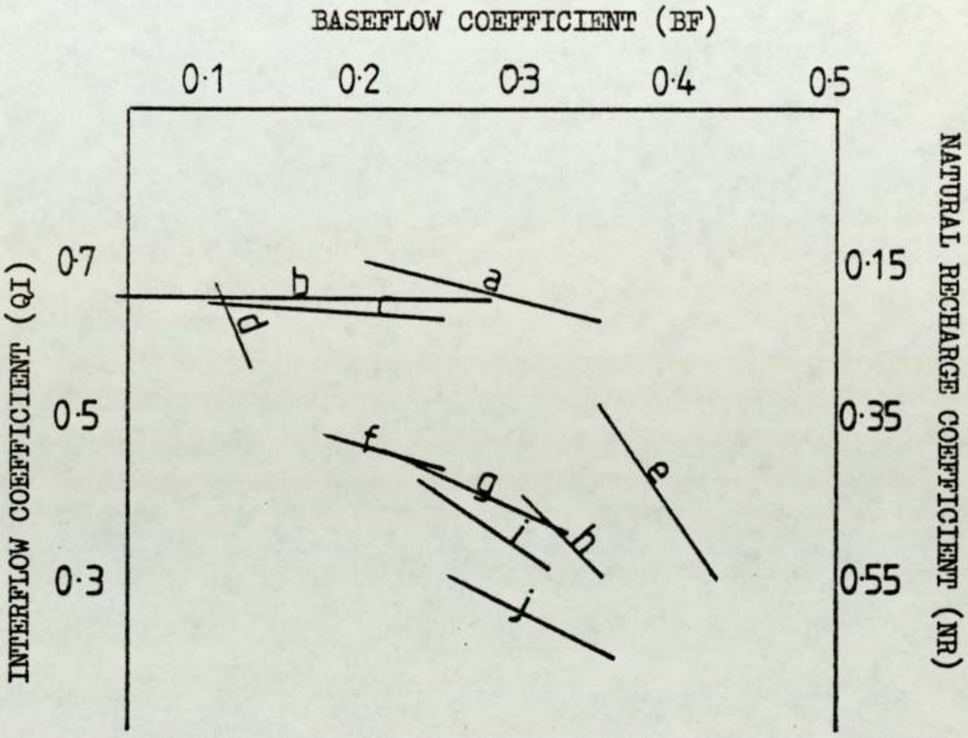


Fig 4.7.3 **Rhayader**



a	Abernant	f	Mid Wye
b	Caban Coch	g	Upper Severn
c	Rhayader	h	Mid Severn
d	Vyrnwy	i	Tenbury
e	Upper Wye	j	Lower Wye

Fig 4.8 <u>Range of Calibrated QI, NR and BF Coefficients for each Catchment</u>

TABLE 4.3 INTERFLOW AND NATURAL RECHARGE COEFFICIENTS FOR LOW, MID AND UPLAND CATCHMENTS

Catchment Type	Interflow Coeff. (QTCOEF)	Natural Recharge Coeff. (NRCOEF)
Upland catchments	0.6 - 0.7	0.15 - 0.25
Mid-land catchments	0.4 - 0.5	0.25 - 0.35
Lowland catchments	0.2 - 0.4	0.45 - 0.65

TABLE 4.4 CALIBRATED INTERFLOW, NATURAL RECHARGE AND BASEFLOW COEFFICIENTS

Catchment	Interflow Coef. (QI)	Natural Recharge Coef. (NR)	Baseflow Coef. (BF)
Caban Coch	0.7	0.15	0.05
Vyrnwy	0.65	0.2	0.1
Rhayader	0.65	0.2	0.2
Abernant	0.65	0.2	0.28
Upper Wye	0.4	0.45	0.4
Upper Severn	0.45	0.4	0.25
Mid Wye	0.45	0.4	0.2
Mid Severn	0.35	0.5	0.32
Usk	0.45	0.4	0.4
Tenbury	0.4	0.45	0.25
Lower Wye	0.25	0.6	0.3

spectrum of upland, mid-land and lowland catchments. The results however did not provide an improvement on those previously obtained and so it was decided to retain 0.85 as the best value for total drainage coefficient (NRCOEF + QICOEF) (Table 4.4).

4.5.5 Determination of Linear Regression Equations for Interflow, Natural Recharge and Baseflow Coefficients

Natural recharge and interflow are water losses from the soil body and as such should bear some relationship to the known catchment characteristics, particularly 'SOIL' as indexed by Soil Survey (1978), slope and drainage density as quantified in sections 2.3 and 2.5, and winter rainfall. Winter rainfall for the period October - March is particularly important as the soil is rarely in deficit during winter and interflow and natural recharge are most prevalent when the soil contains large amounts of surplus moisture.

The individual catchment characteristics and a range of combinations of characteristics were plotted against the interflow coefficients (Fig 4.9.1-8). Linear regression equations and their cross correlation coefficients were then determined. As can be seen from Table 4.5 the regression line between the interflow coefficients and Winter Rainfall x Soil x Drainage Density gave the best absolute value of correlation. This regression equation

$$QICOEF = 0.2977 + 0.00054 (WR \times SOIL \times DD)$$

was then used for the calibration of QICOEF and NRCOEF (i.e. NRCOEF = 0.85 - QICOEF) in all subsequent models.

In contrast the baseflow coefficients seem to bear little relationship to catchment characteristics, particularly SOIL (Figs 4.10.1/8) unlike interflow and natural recharge values which correlate well with all topographic features. The

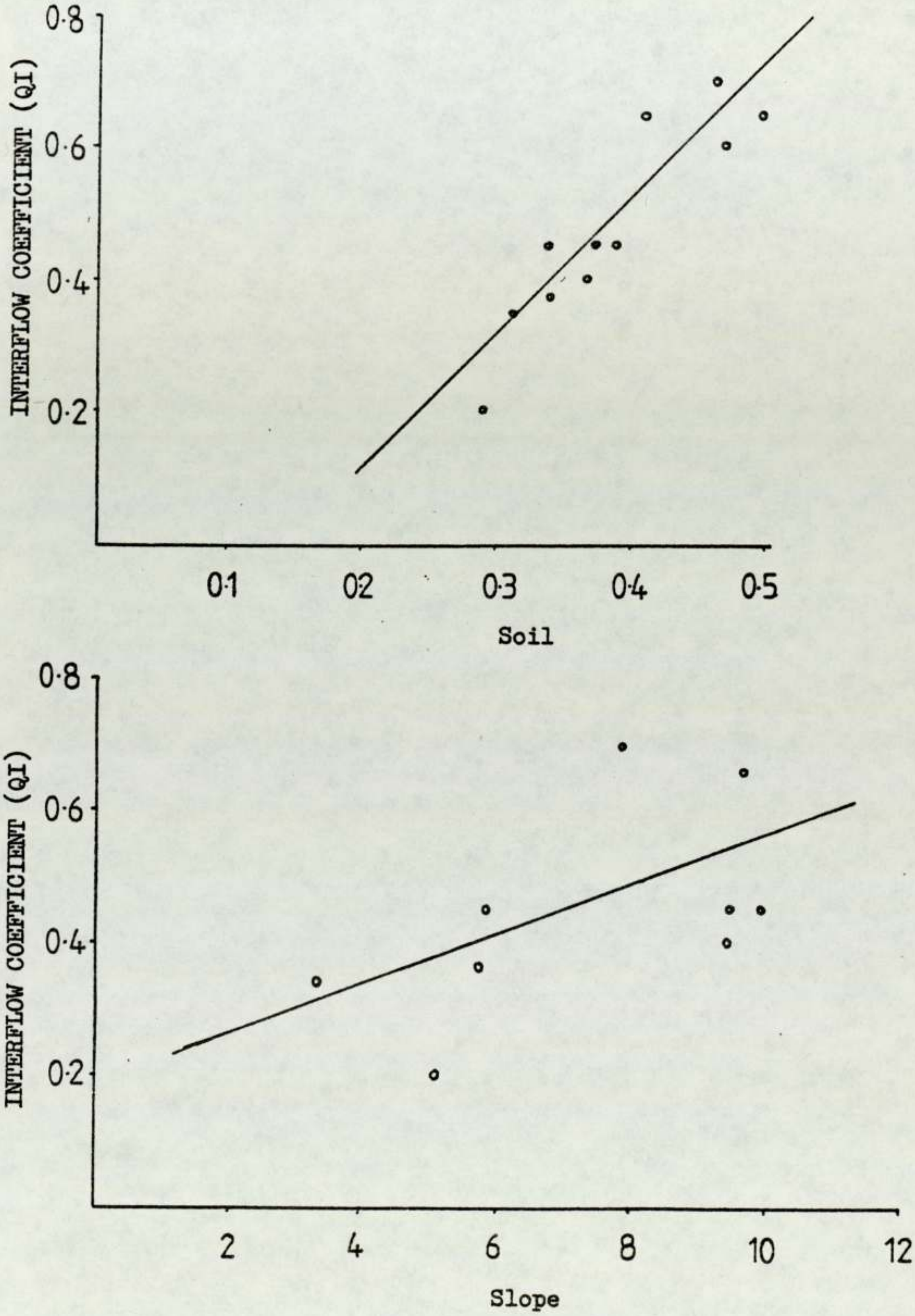


Fig 4.9.1

Linear Regression Analysis of Interflow / Catchment Characteristics

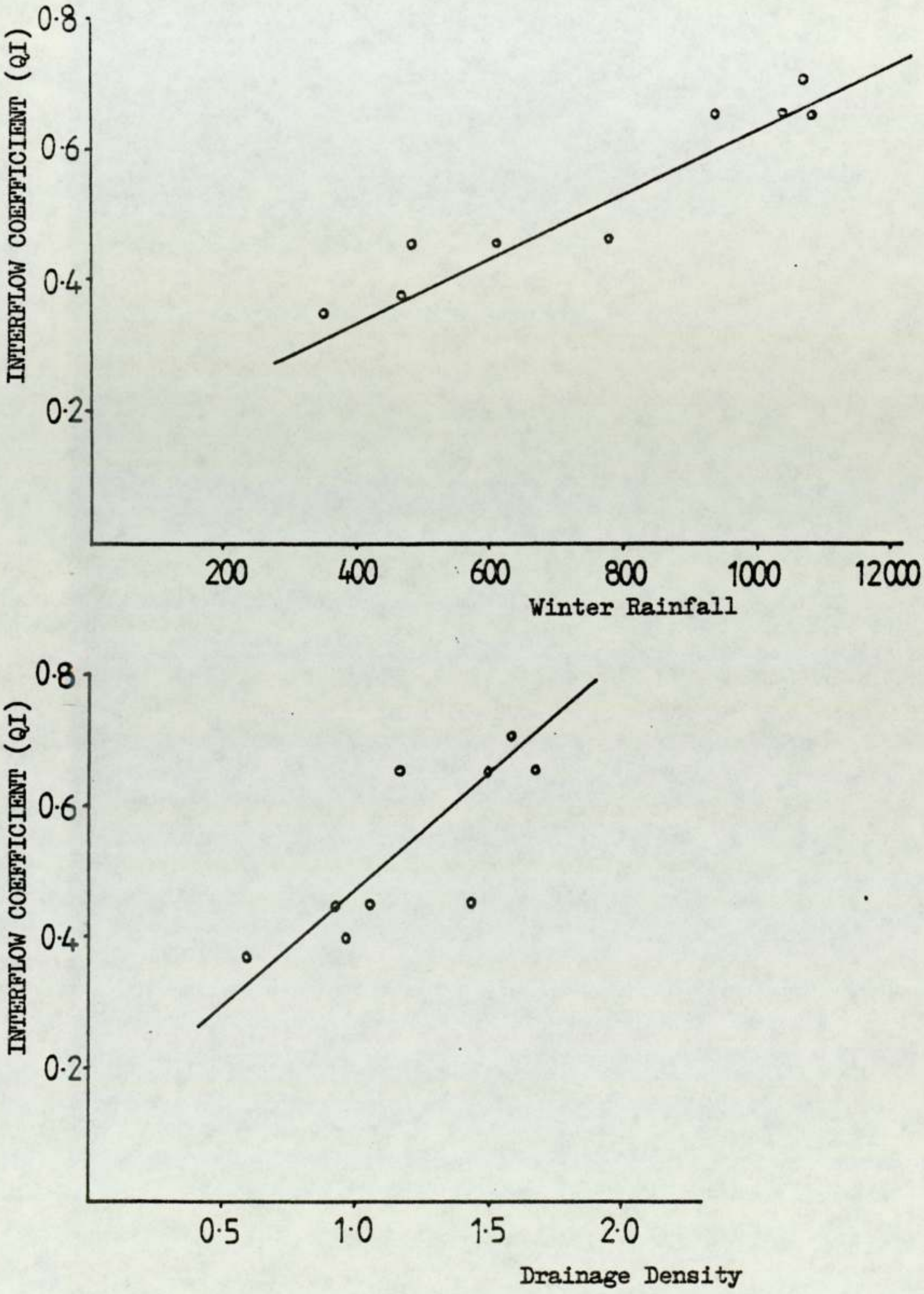


Fig 4.9.2

Linear Regression Analysis of Interflow /

Catchment Characteristics

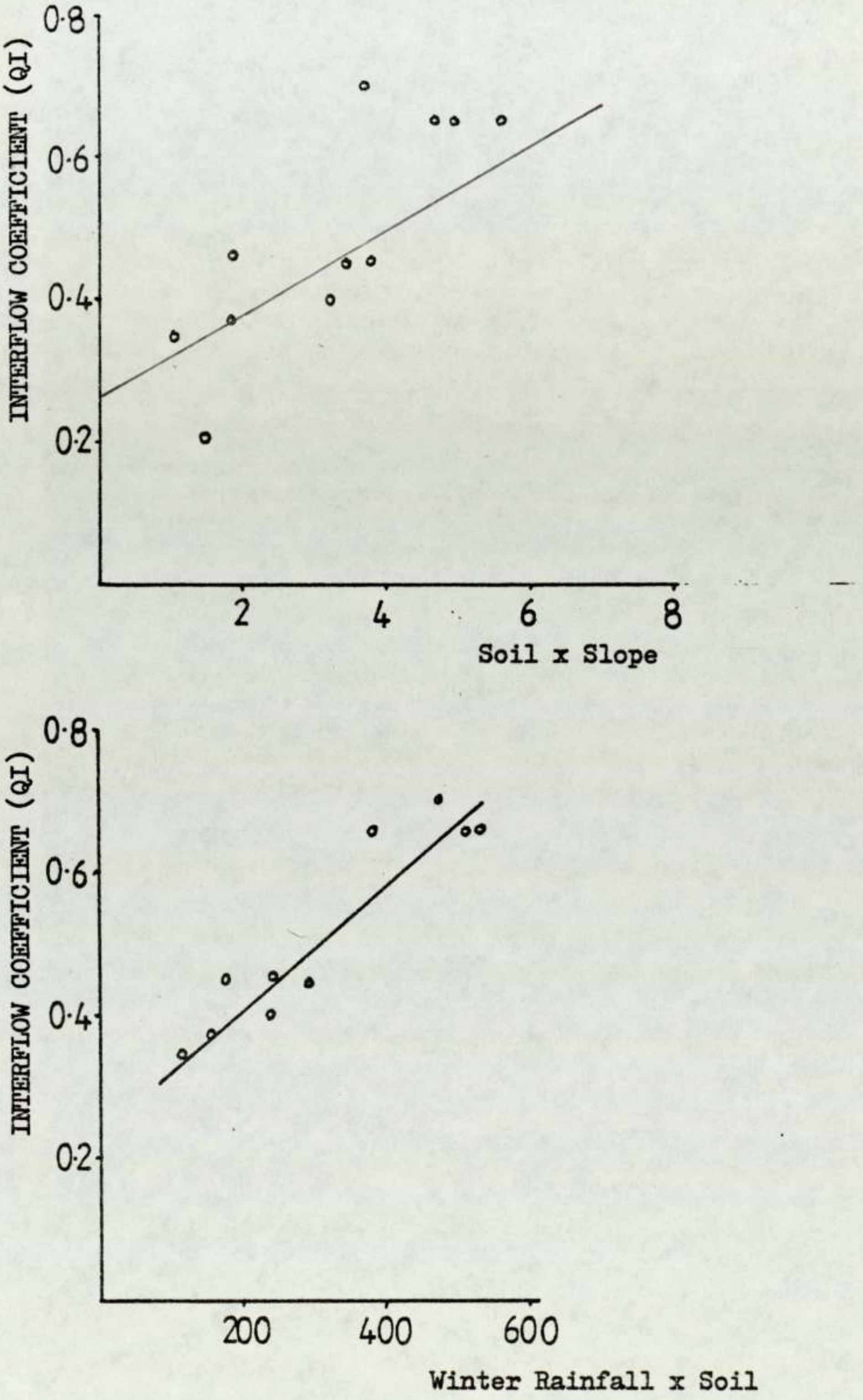


Fig 4.9.3

Linear Regression Analysis of Interflow/ Catchment Characteristics

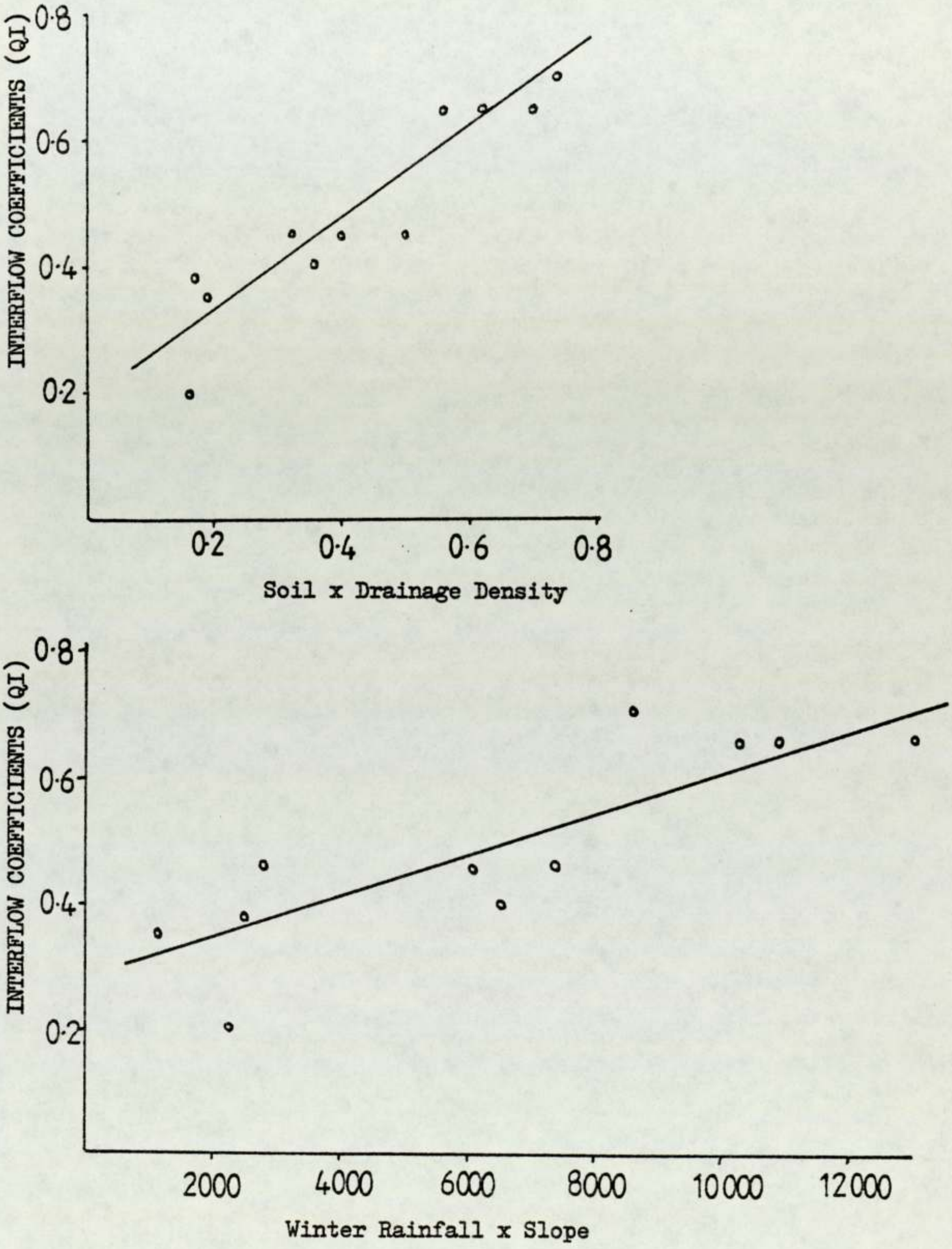
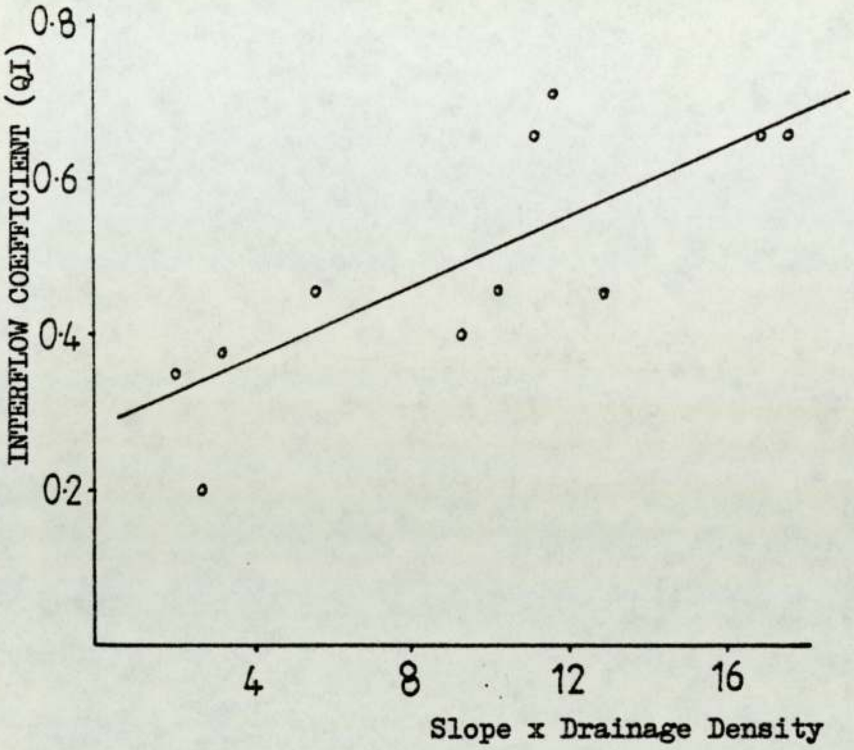


Fig 4.9.4

Linear Regression Analysis of Interflow/

Catchment Characteristics



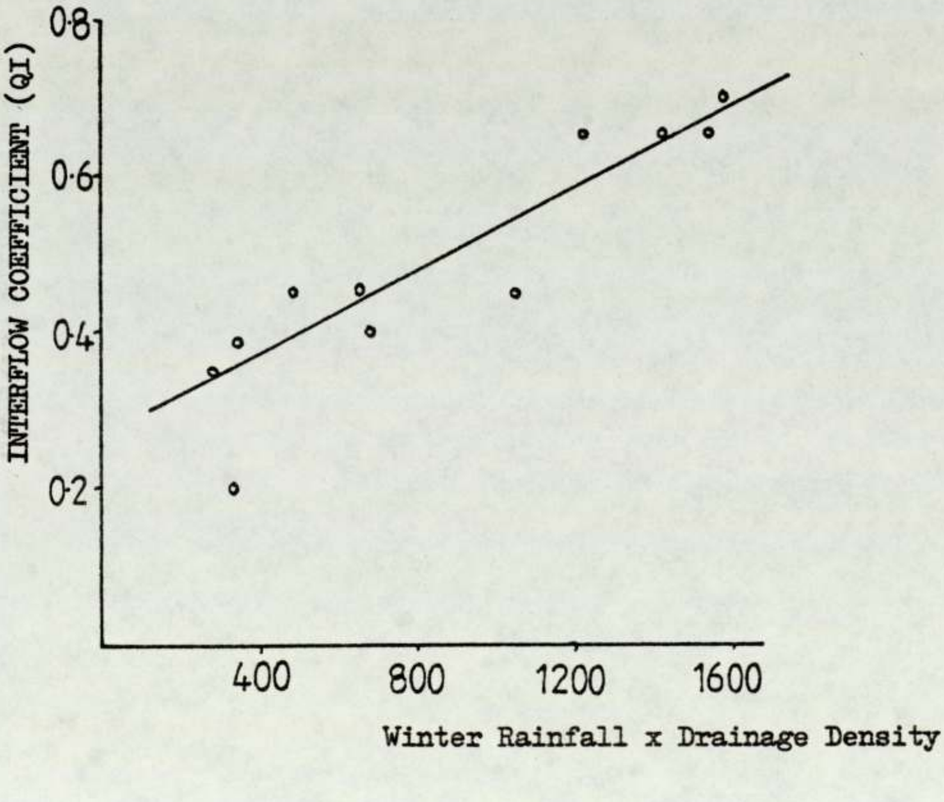


Fig 4.9.5

Linear Regression Analysis of Interflow/ catchment characteristics

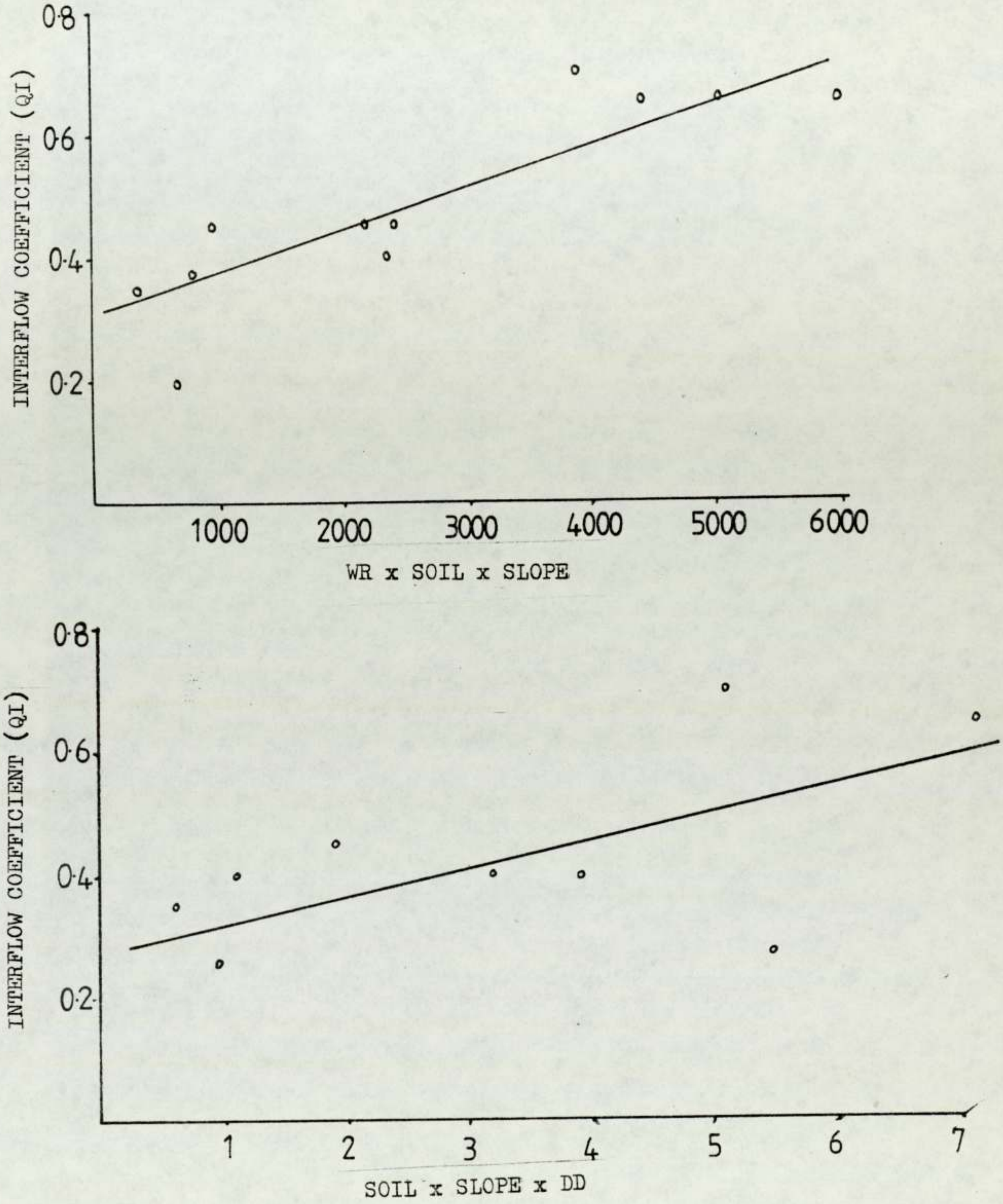


Fig 4.9.6

Linear Regression Analysis of Interflow/ Catchment Characteristics

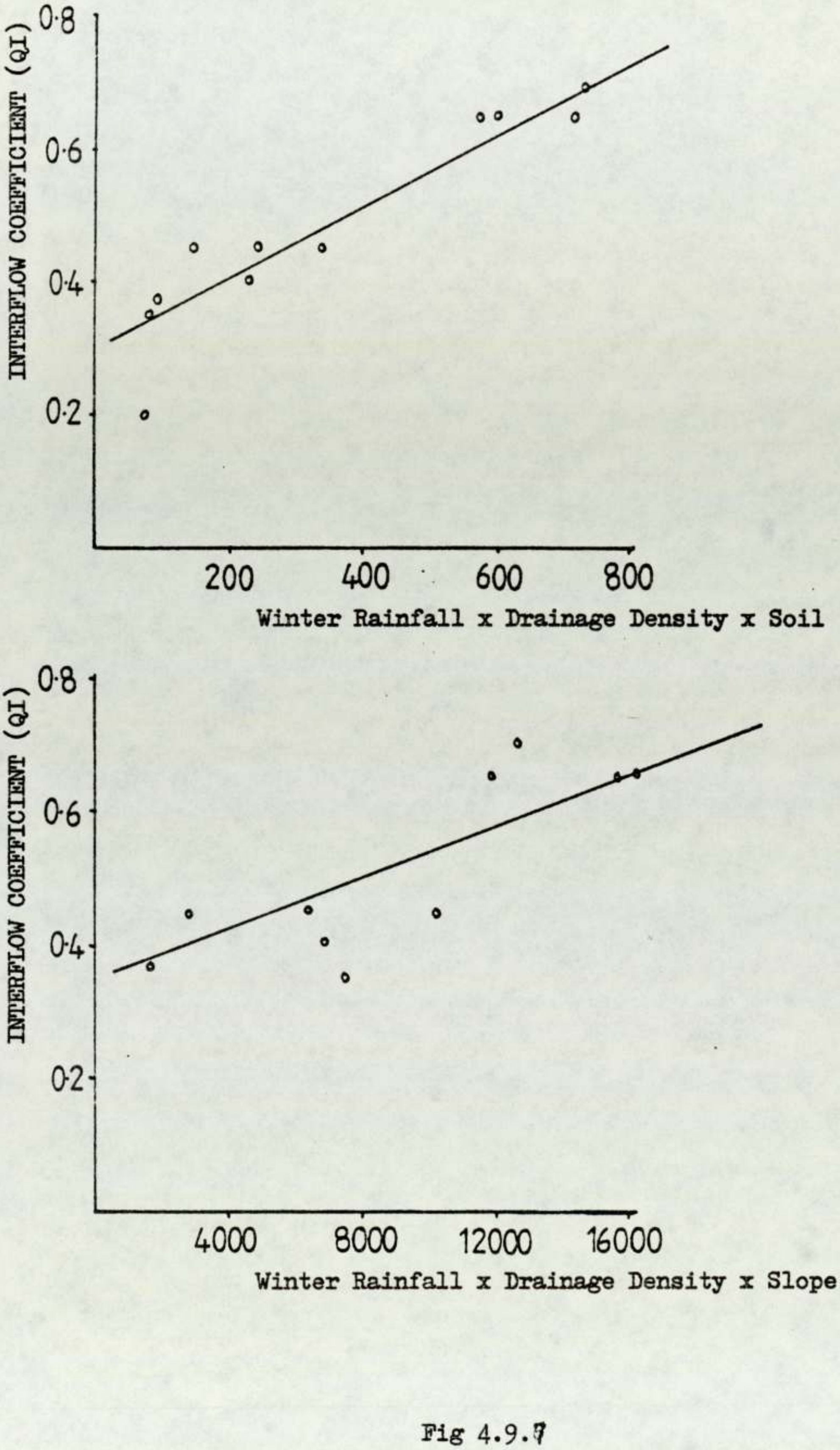


Fig 4.9.7

Linear Regression Analysis of Interflow / Catchment Characteristics

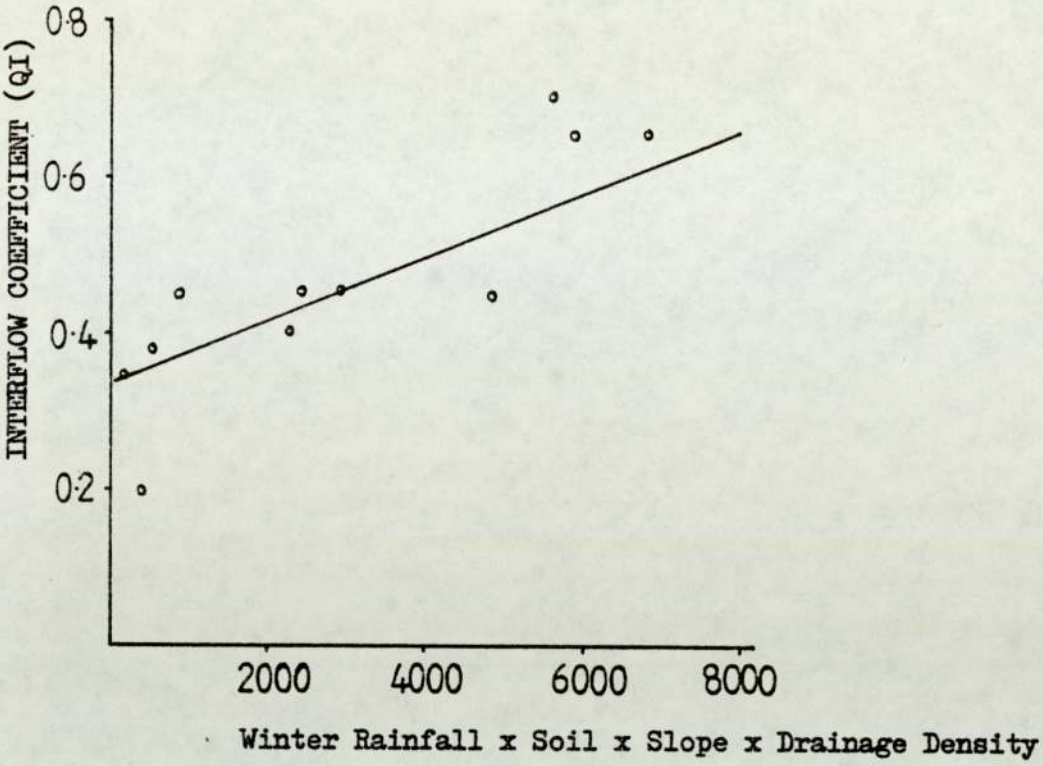


Fig 4.9.B

Linear Regression Analysis of Interflow / Catchment Characteristics

Table 4.5 Linear Regression Analysis of QI/Catchment Characteristics

QI	Slope (m)	Intercept (y)	Corr. Coeff (r)
Soil	2.053	- 0.293	0.93
Slope	0.0361	0.194	0.68
Winter rainfall	0.00049	0.134	0.92
Drainage Density	0.355	0.117	0.87
Soil x Slope	0.06	0.27	0.54
WR x Soil	0.00087	0.232	0.93
Soil x DD	0.733	0.183	0.94
WR x Slope	0.000032	0.2769	0.86
Slope x DD	0.022	0.28	0.80
WR x DD	0.00026	0.268	0.93
WR x Soil x Slope	0.000068	0.3079	0.89
Soil x Slope x DD	0.042	0.29	0.68
WR x DD x Soil	0.00054	0.2977	0.95
WR x DD x Slope	0.000019	0.351	0.89
WR x Soil x Slope x DD	0.00004	0.334	0.91

WR - Winter Rainfall (Nov - Apr)

DD - Drainage density

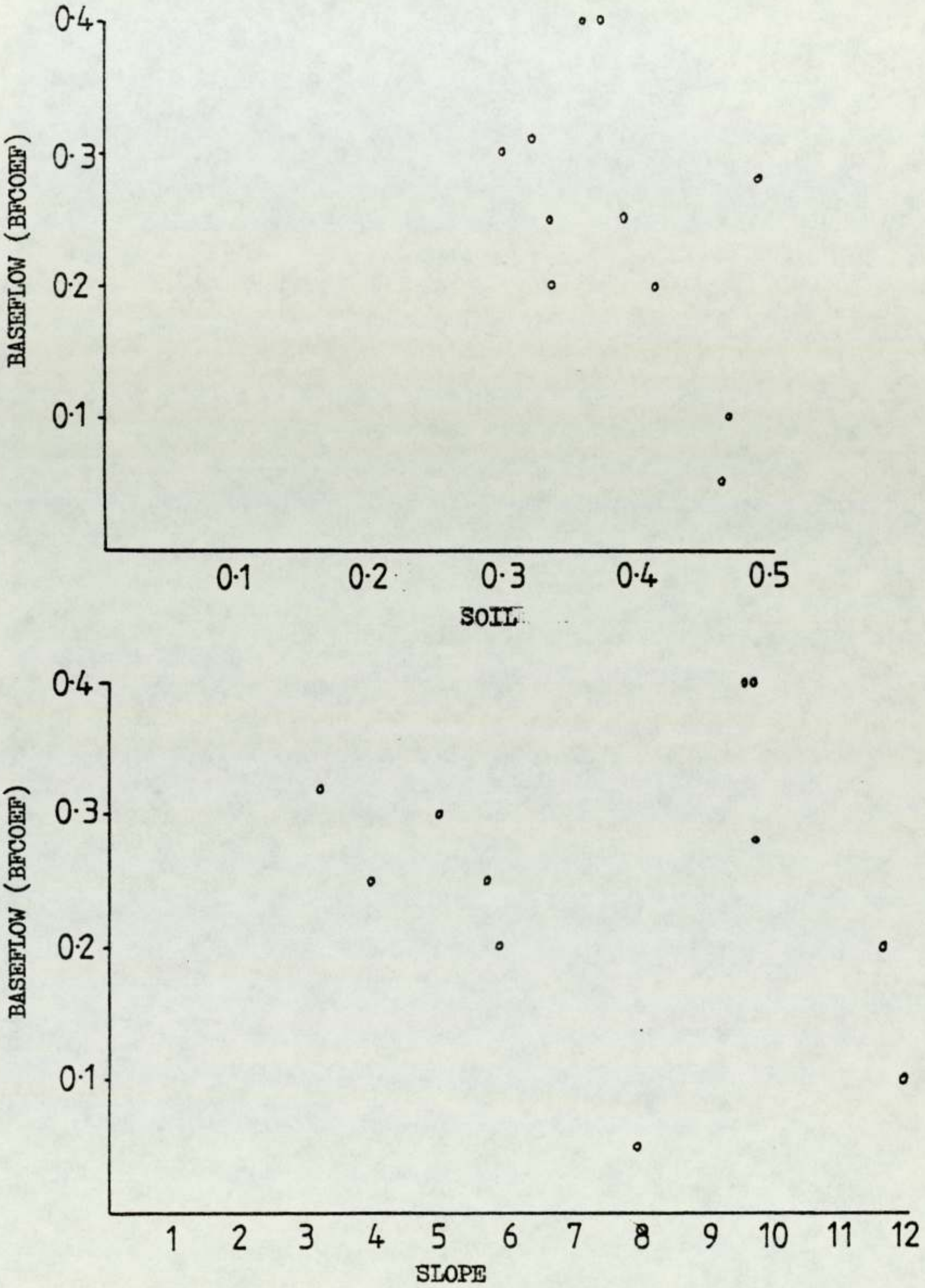


Fig 4.10.1 Linear Regression Analysis of Baseflow/ Catchment Characteristics

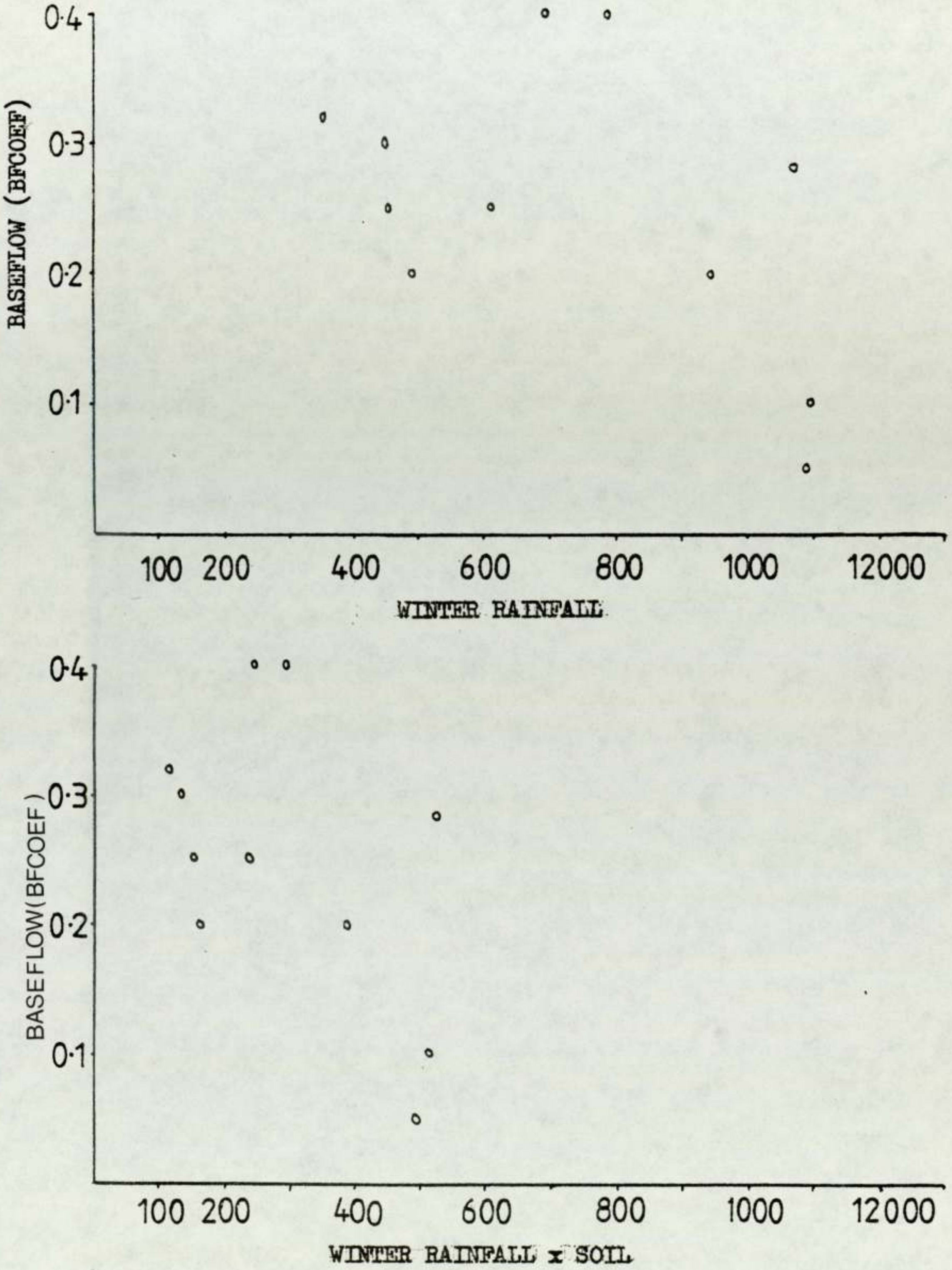
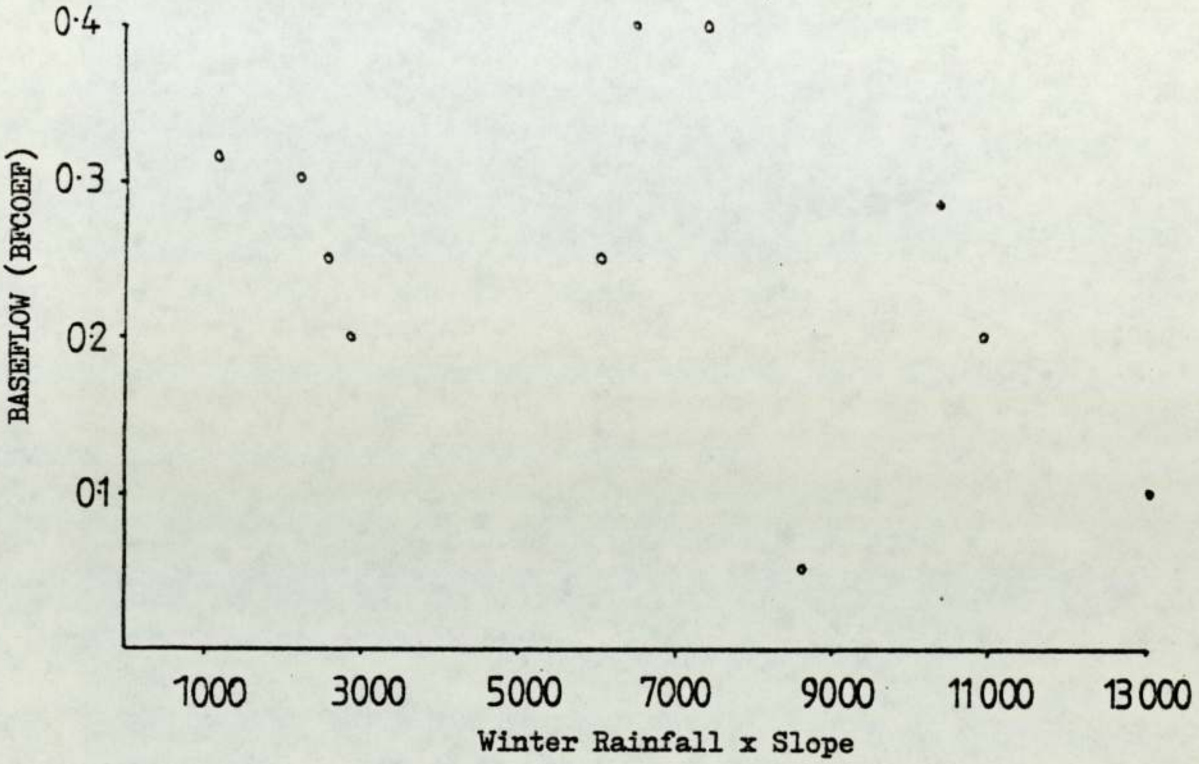


Fig 4.10.2

Linear Regression Analysis of Interflow/
Catchment Characteristics



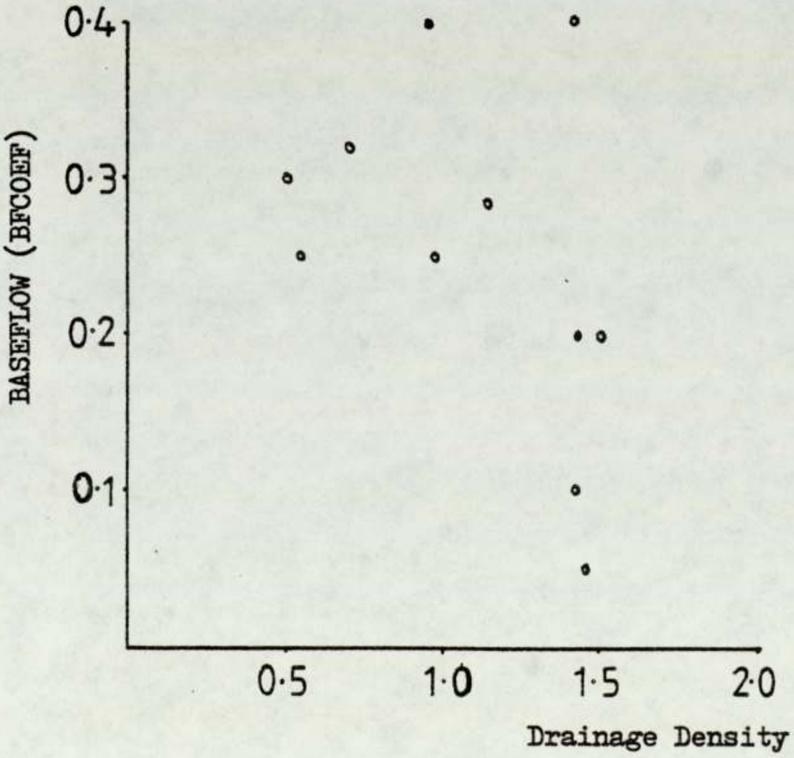


Fig 4.10.3

Linear Regression Analysis of Interflow / Catchment Characteristics

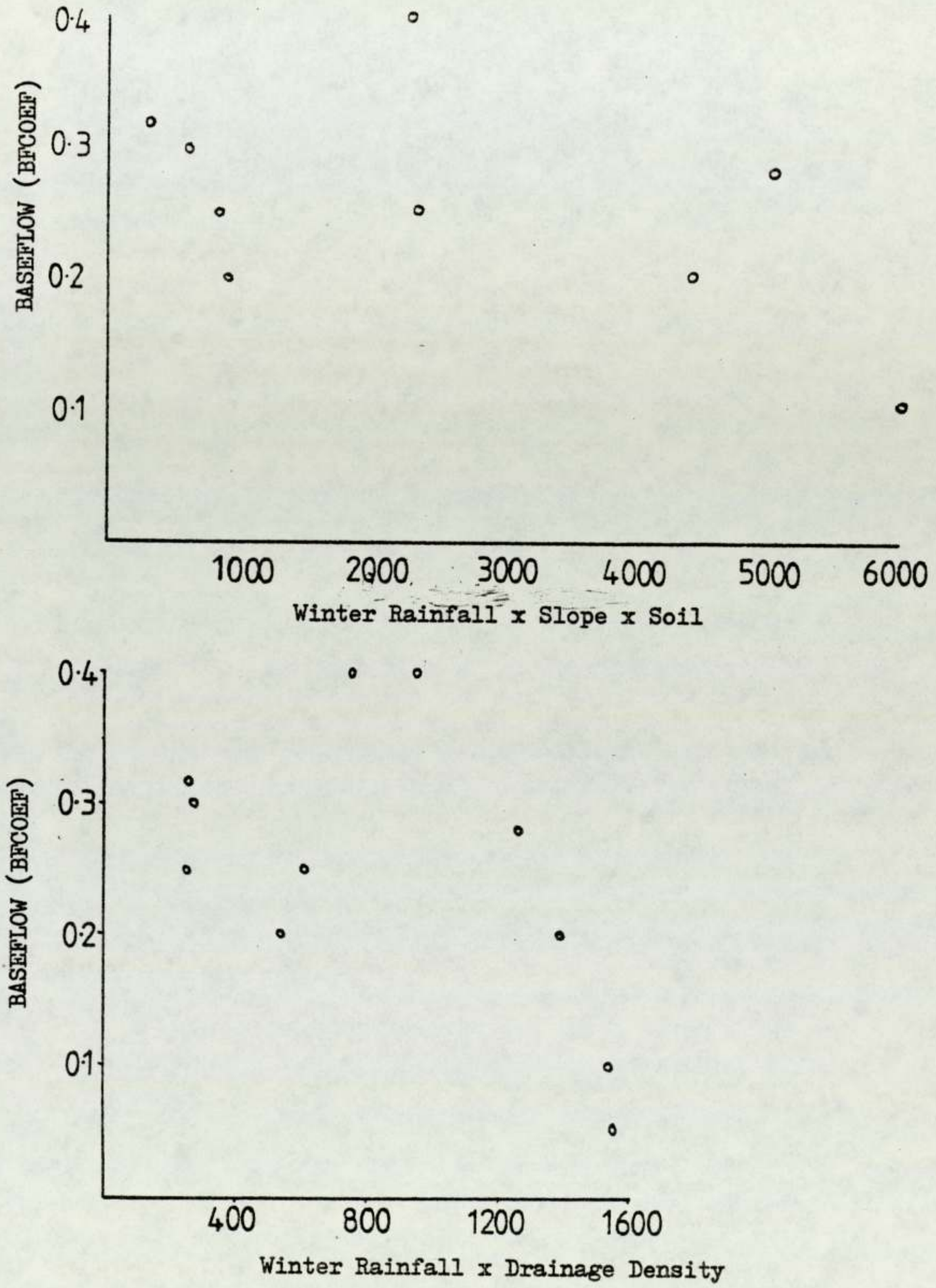


Fig 4.10.4

Linear Regression Analysis of Interflow / Catchment Characteristics

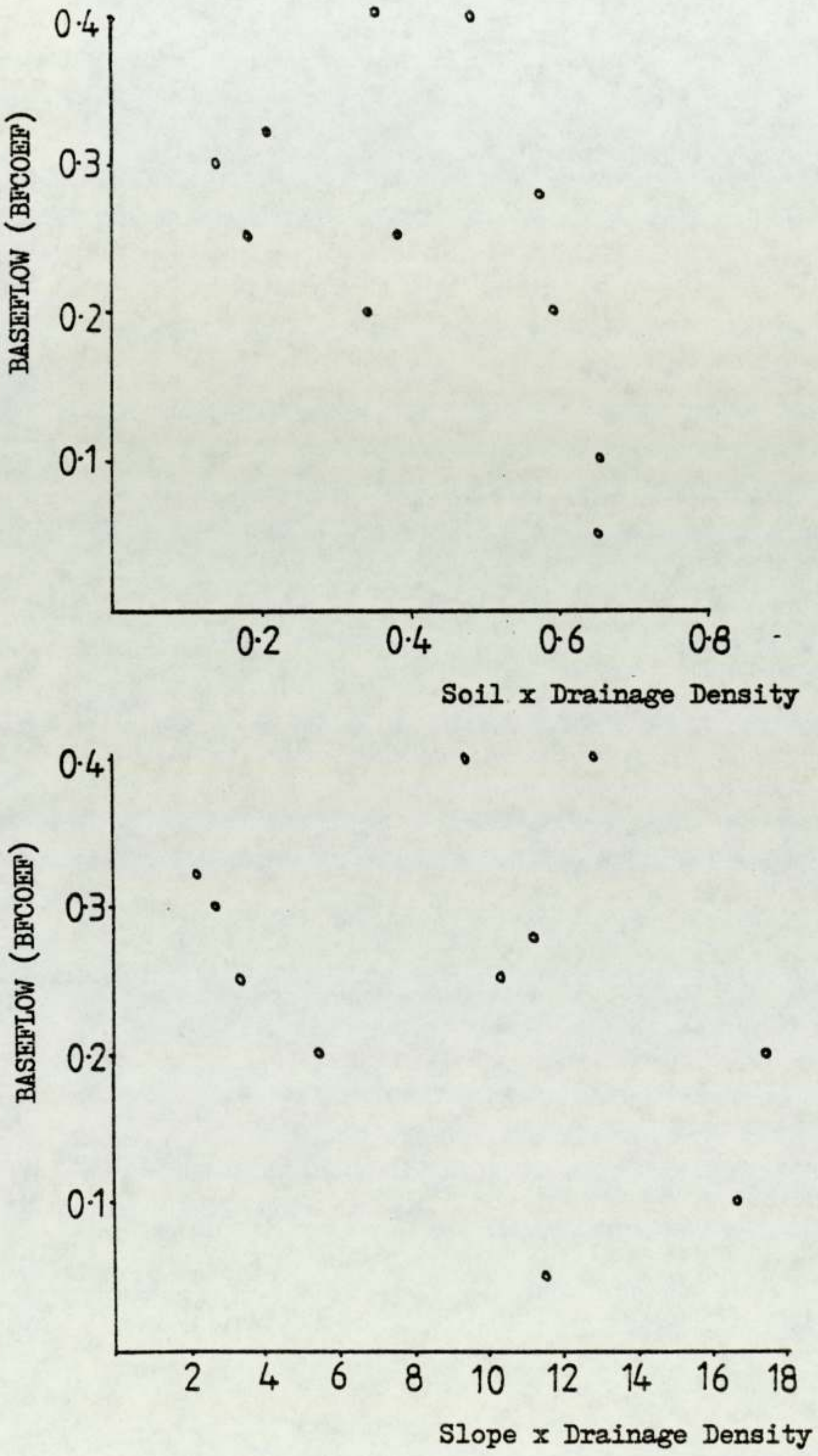


Fig 4.10.5

Linear Regression Analysis of Interflow / Catchment Characteristics

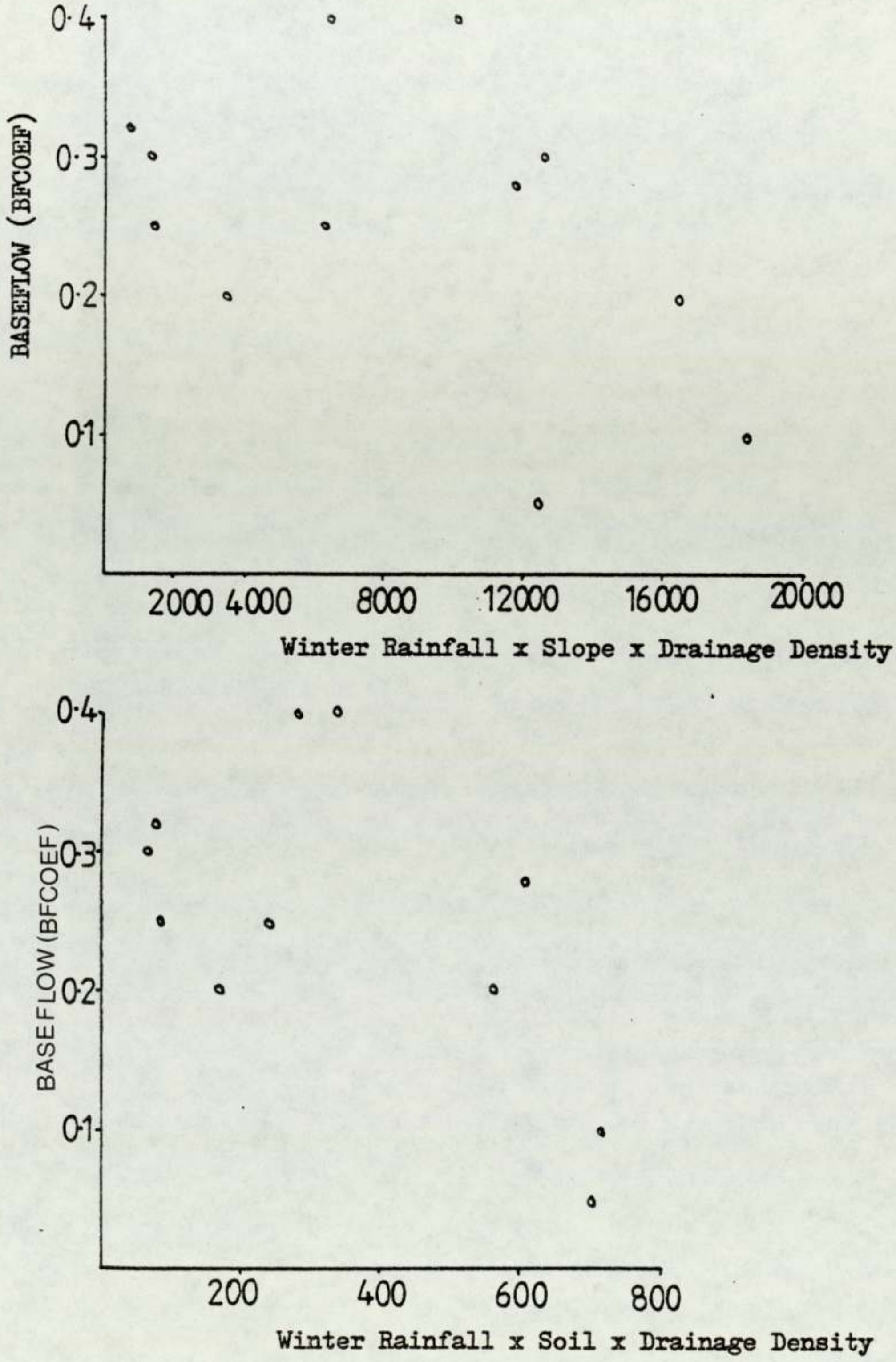


Fig 4.10.6

Linear Regression Analysis of Interflow /

Catchment Characteristics

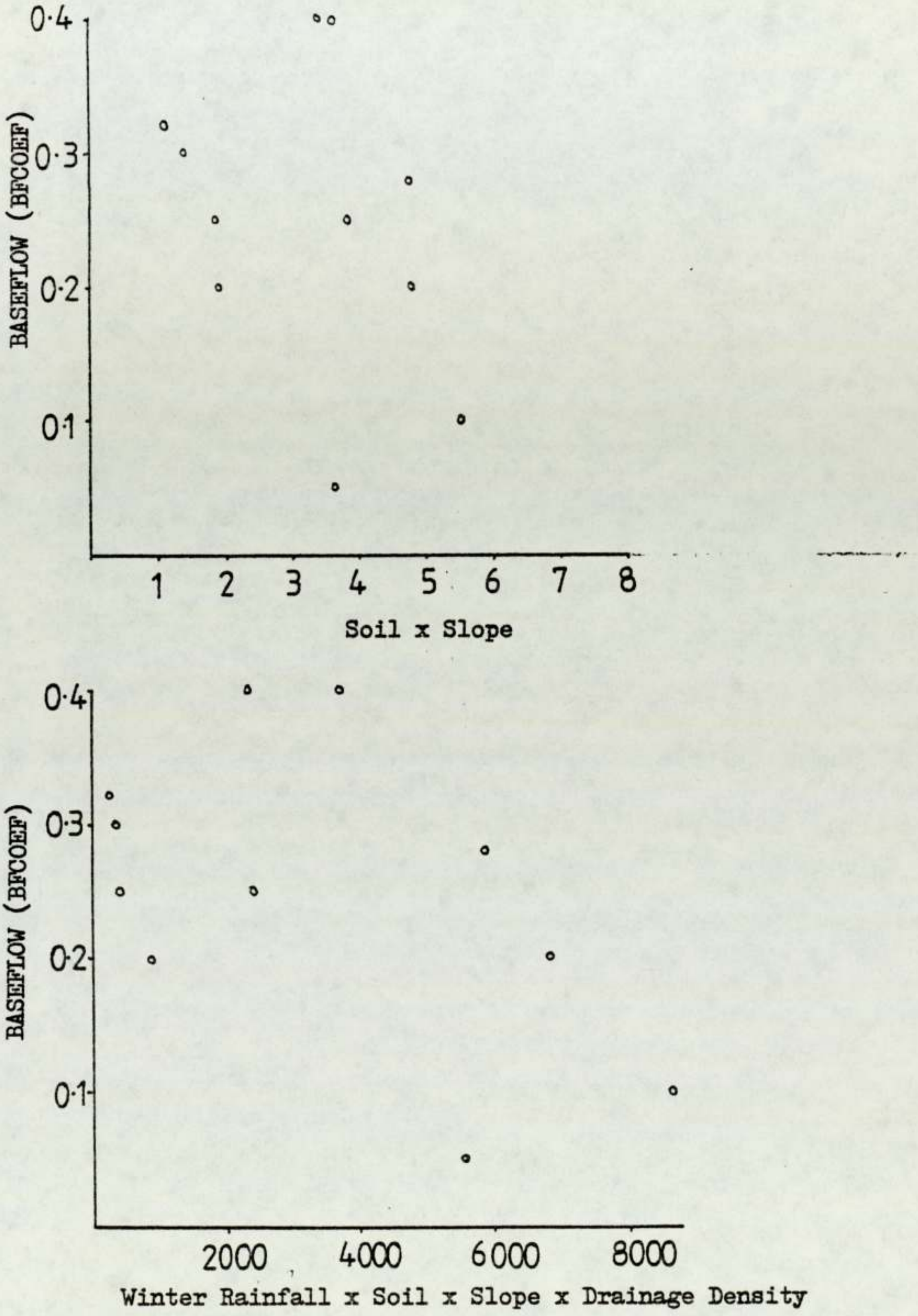


Fig 4.10.7

Linear Regression Analysis of Interflow / Catchment Characteristics

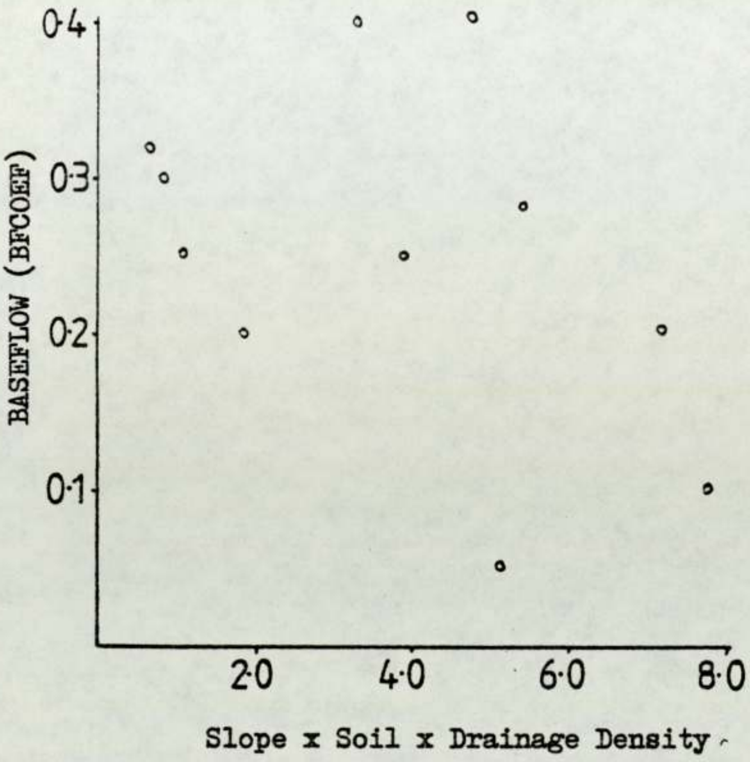


Fig 4.10.8

Linear Regression Analysis of Interflow / Catchment Characteristics

difference between baseflow and the other parameters is that the baseflow coefficient is the result of groundwater flow for which many other factors are important, but principally the amount and seasonal distribution of recharge (hence rainfall) and the transmissibility (hence geology) of the ground. For this reason it seemed pertinent to consider the relationship between the baseflow coefficient and ERMAX (defined as rainfall minus evaporation for Nov - Apr) ERMIN (rainfall minus evaporation for months May - Oct), the natural recharge coefficient (as previously defined) and the average amplitude of the annual groundwater storage cycle (El Gusbi 1979) (Fig 4.11).

Amplitude denotes the annual change in groundwater storage which varies as a result of seasonal maximum and minimum rainfall minus evaporation periods, so creating two alternating levels of inflow. When viewed as a linear reservoir the alternating input of R - E during the annual wet and dry seasons can be shown as in Fig 4.12 where H can be seen to vary seasonally. Consequently, it is fair to assume that:

$$\text{Amplitude} = f\left[(\text{NRMAX} - \text{NRMIN})\,K\right]$$

$$K = f\left(\frac{\text{NRMAX} - \text{NRMIN}}{\text{Amplitude}}\right)$$

NRMAX/MIN - maximum and minimum natural recharge

Since the values of NRMAX and NRMIN are not known it seems reasonable to assume that (NRMAX - NRMIN) is proportional to

$$(\text{RMAX} - \text{RMIN}) \times \text{NRCOEF}$$

where RMAX/MIN - Maximum and minimum rainfall

thus $$K = f\ \frac{(\text{RMAX} - \text{RMIN}) \times \text{NRCOEF}}{\text{Amplitude}}$$

Amplitude for the Welsh catchments has been calculated by El Gusbi (1979). However, it is not possible to evaluate

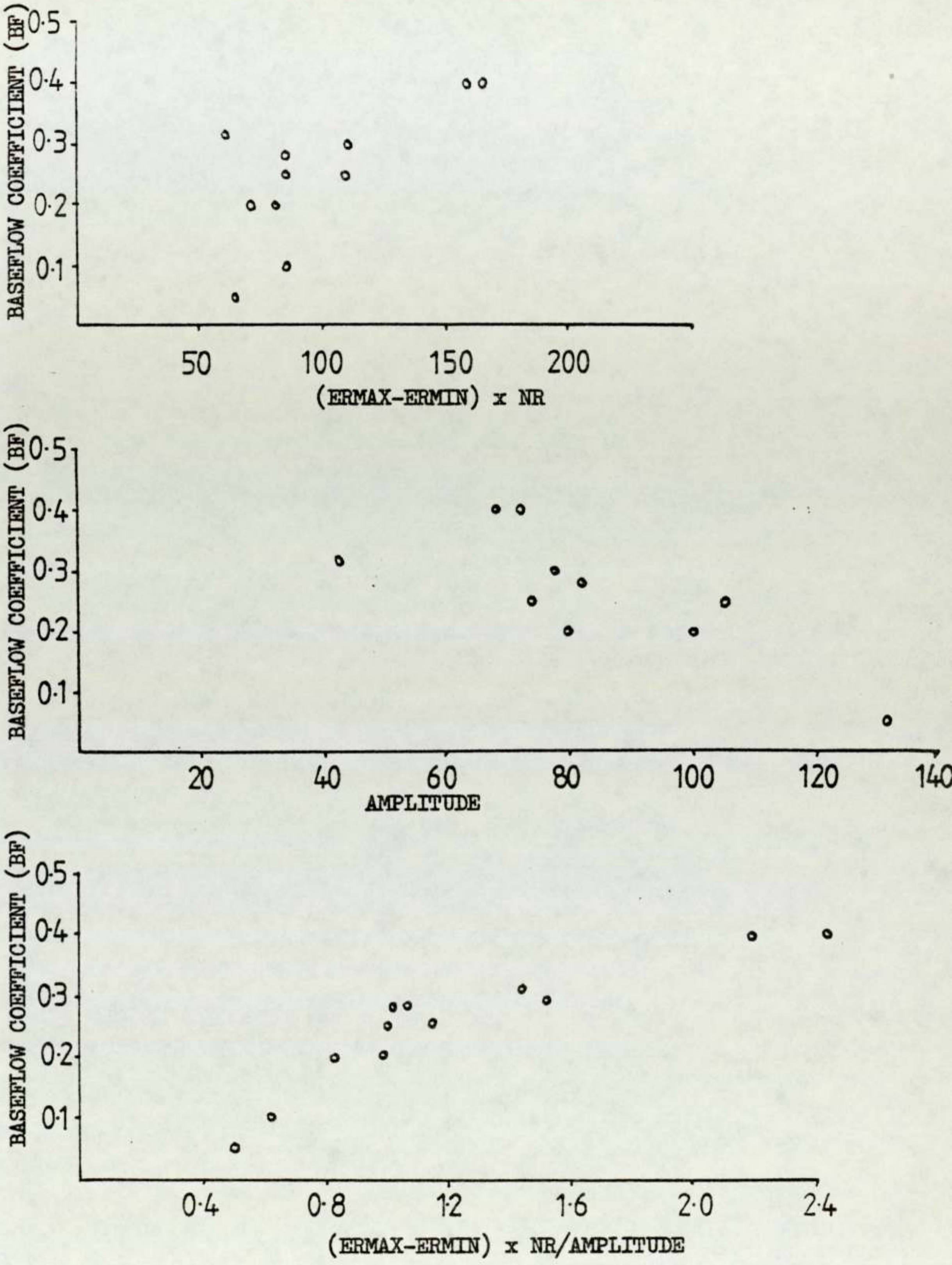
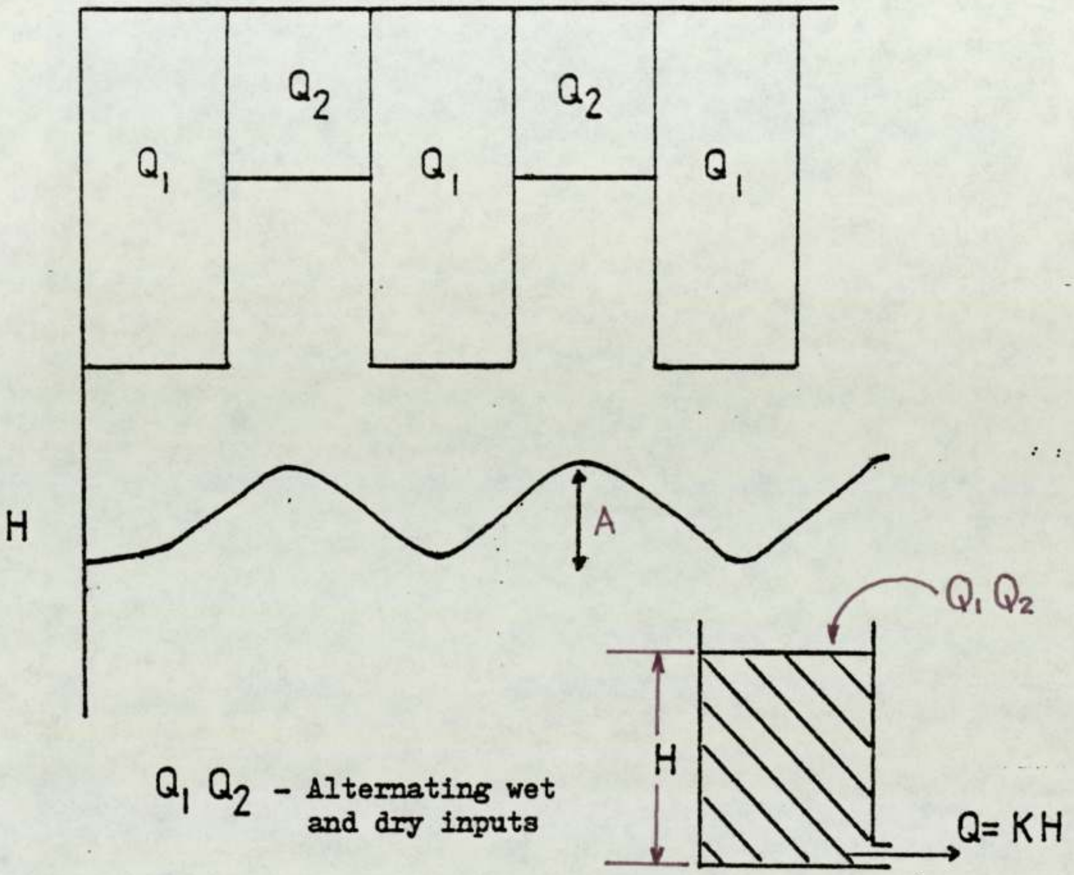

BASEFLOW COEFFICIENT (BF)
0·5
0·4
0·3
0·2
0·1
50
100
150
200
(ERMAX-ERMIN) x NR
BASEFLOW COEFFICIENT (BF)
0·5
0·4
0·3
0·2
0·1
20
40
60
80
100
120
140
AMPLITUDE
BASEFLOW COEFFICIENT (BF)
0·5
0·4
0·3
0·2
0·1
0·4
0·8
1·2
1·6
2·0
2·4
(ERMAX-ERMIN) x NR/AMPLITUDE

Fig 4.11



Q_1 Q_2 - Alternating wet and dry inputs

A - Amplitude

K - BFCOEF

Fig 4.12 <u>Linear Reservoir with Alternating Input of R - E</u>

'Amplitude' for ungauged catchments, therefore it must be estimated from nearby gauged streams if it is to be used for the calibration of K (i.e. BFCOEF in the model). The method of evaluating amplitude was fully described by El Gusbi, but basically involves the sequential summation of (R - E - Q) on a monthly timestep, where R = monthly rainfall, E is monthly evaporation and Q is monthly stream discharge expressed in mm over the catchment.

Linear regression analysis was carried out between the baseflow coefficient (BFCOEF) and (ERMAX - ERMIN) NRCOEF, (ERMAX - ERMIN) NRCOEF/Amplitude, and Amplitude. The results show that it is unnecessary to determine amplitude since the basic rainfall and NRCOEF values produce the best correlation with BFCOEF. Consequently it was possible to determine the baseflow coefficient simply and efficiently using readily available data.(Table 4.6).

4.5.6. The Relationship Between Baseflow Index (BFI) and Catchment Characteristics

The relationship between the baseflow index (BFI) as defined by the Institute of Hydrology Low Flow Studies (1978), and the various combinations of catchment characteristics including soil, slope, drainage density and winter rainfall were considered at the same time as those for baseflow discharge coefficient (BFCOEF). Simple regression and correlation analyses were subsequently carried out (Figs 4.13.1-8) (Table 4.7.1). the results of which showed a strong correlation of 0.97 between the BFI and Soil x Drainage Density. This strong correlation exists for both the value of SOIL as originally conceived by the Soil Survey, and also for the value of SOIL where coefficients

TABLE 4.6 <u>LINEAR REGRESSION ANALYSIS OF BFCOEF/CATCHMENT CHARACTERISTICS</u>

BFCOEF	Slope (m)	Intercept (y)	Correlation Coefficient (r)
(ERMAX - ERMIN) x NRCOEF	.002	.075	.85
(ERMAX - ERMIN) x NRCOEF/ AMPLITUDE	.07	- .046	.71
AMPLITUDE	- .003	.54	- .73

NRCOEF - Natural recharge coefficient
ERMAX - Mean monthly rainfall (minus evaporation Nov-Apr.)
ERMIN - " " " (" " May-Oct.)

TABLE 4.7.1 LINEAR REGRESSION ANALYSIS OF BASEFLOW INDEX (BFI)/CATCHMENT CHARACTERISTICS

BFI/	Slope (m)	Intercept (y)	Correlation Coefficient (r)
Soil	- 1.409	1.0148	.86
Slope	- .0289	.72	- .86
WR	- .00034	.7197	.87
DD	- .2505	.7409	.89
Soil x Slope	- .0625	.684	.92
Soil x WR	- .000607	.6507	- .89
Soil x DD	- .568	.7057	.97
Slope x WR	- .000024	.6335	.91
Slope x DD	- .0149	.623	.82
WR x DD	- .00021	.6419	.94
Soil x Slope x WR	- .000051	.612	.9
Soil x Slope x DD	- .036	.6155	.87
Soil x WR x DD	- .00044	.6177	.94
Slope x WR x DD	- .000015	.593	.85
WR x Soil x Slope x DD	- .000034	.586	.86

WR - Winter rainfall (Nov - Apr)
DD - Drainage Density

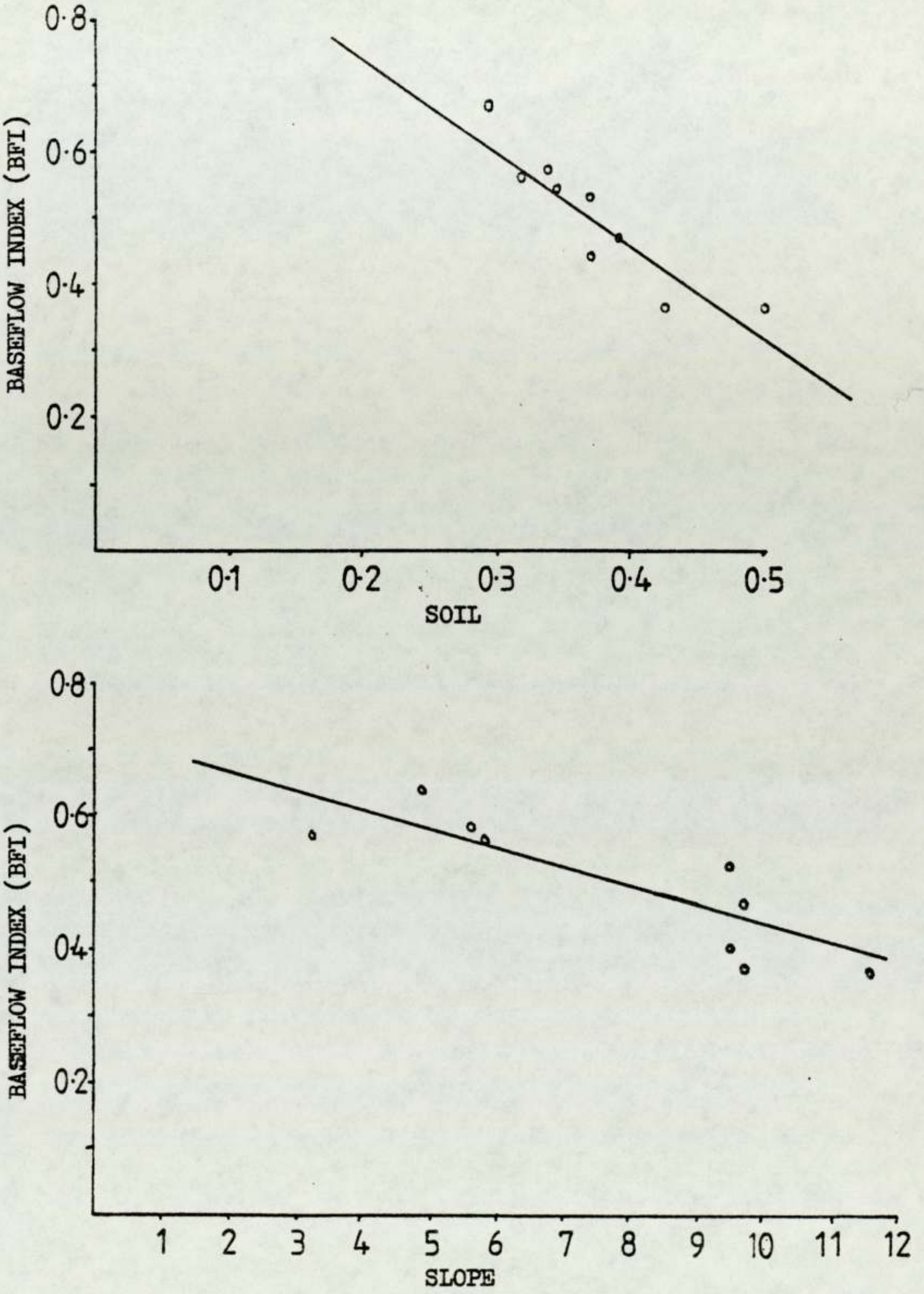
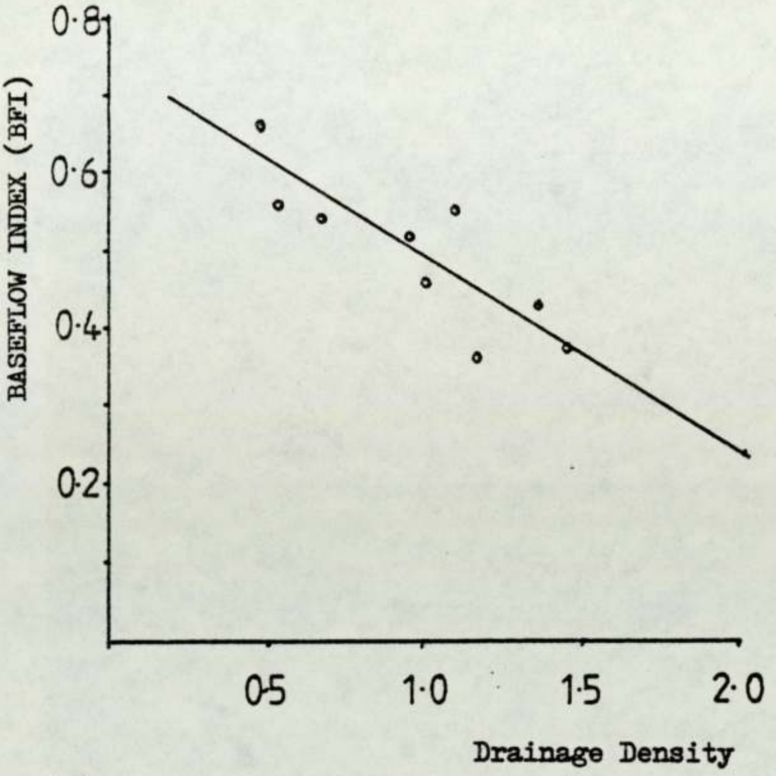


Fig 4.13.1 Linear Regression Analysis of BFI/Catchment Characteristics



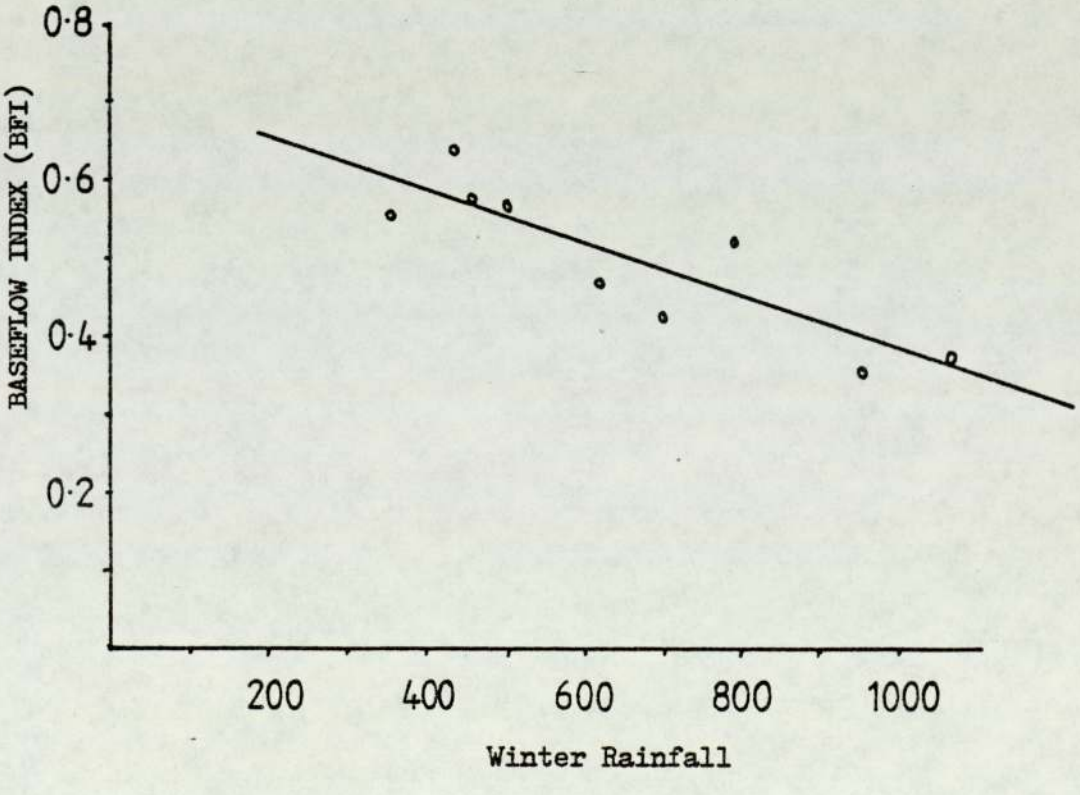


Fig 4.13.2

Linear Regression Analysis of BFI/Catchment Characteristics

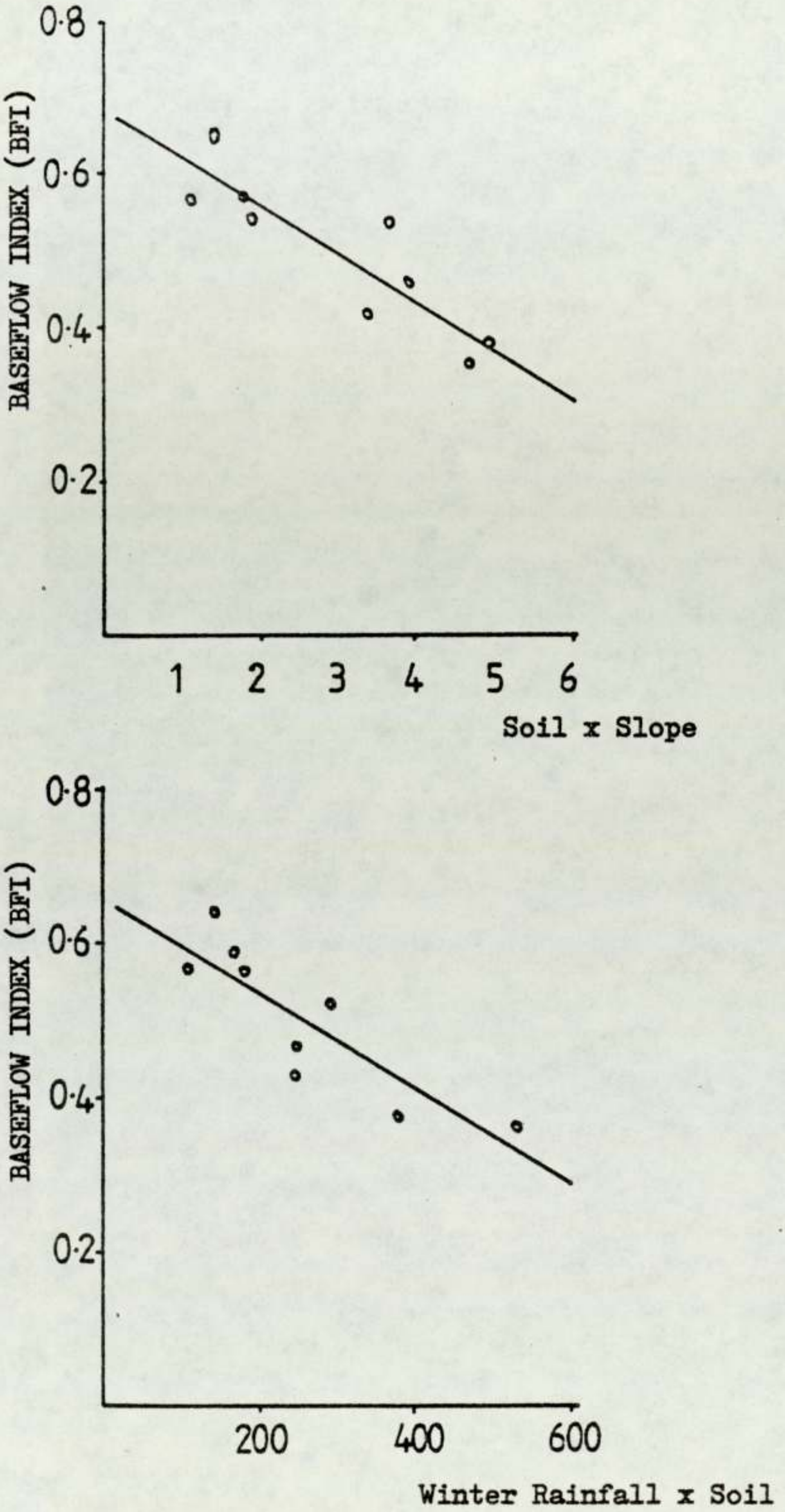


Fig 4.13.3

Linear Regression Analysis of BFI/Catchment Characteristics

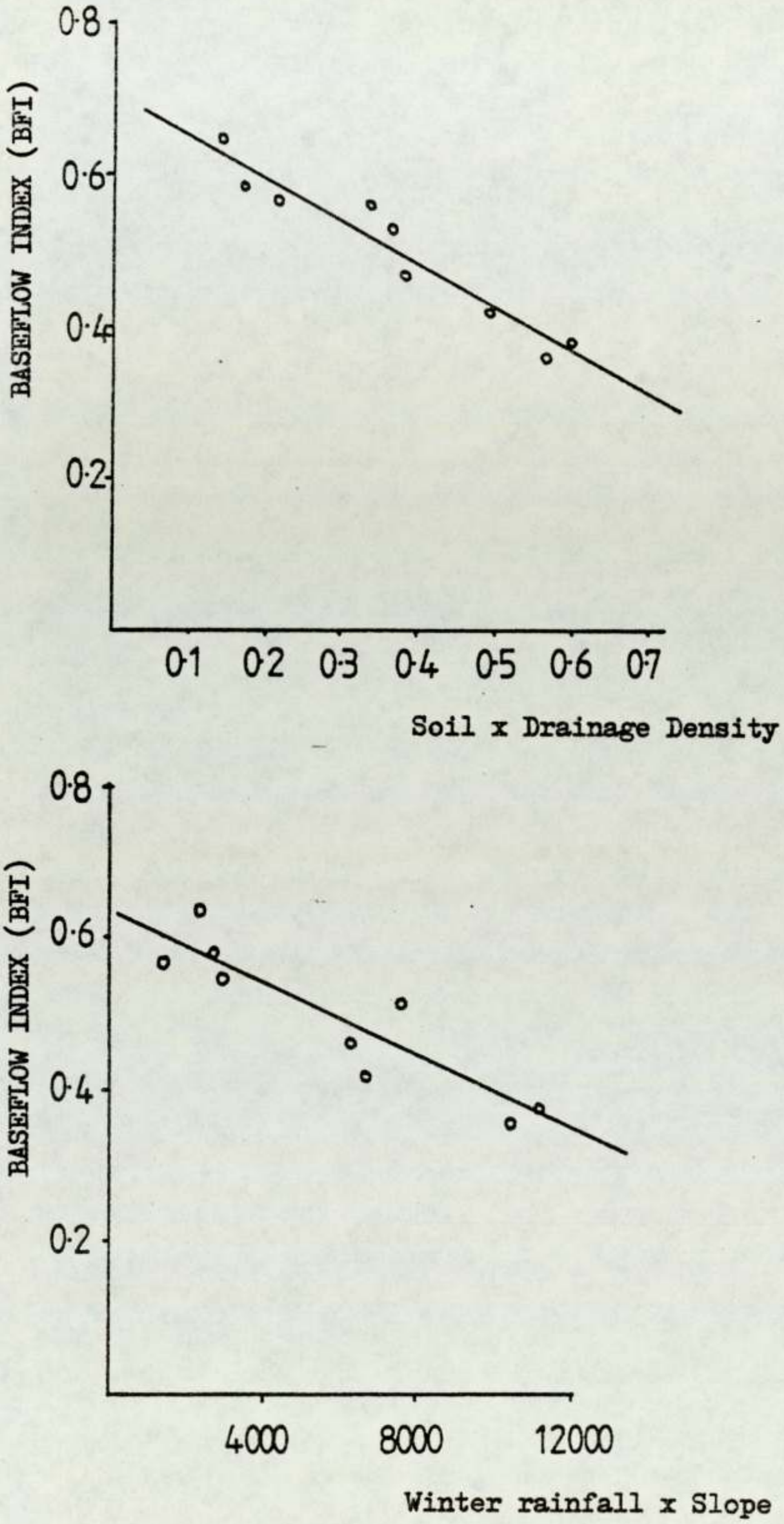


Fig 4.13.4

Linear Regression Analysis of BFI/catchment Characteristics

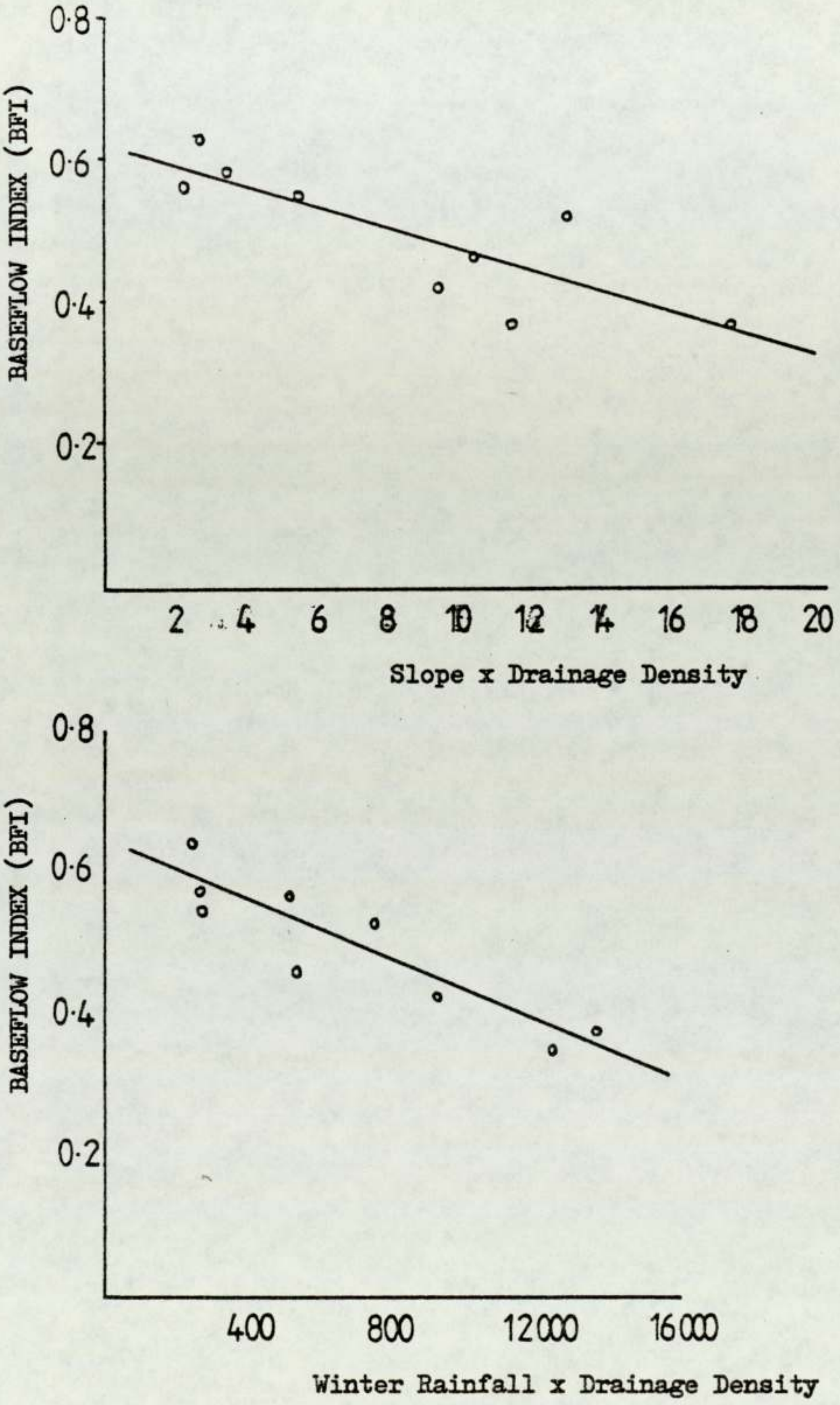


Fig 4.13.5

Linear Regression Analysis of BFI / Catchment characteristics

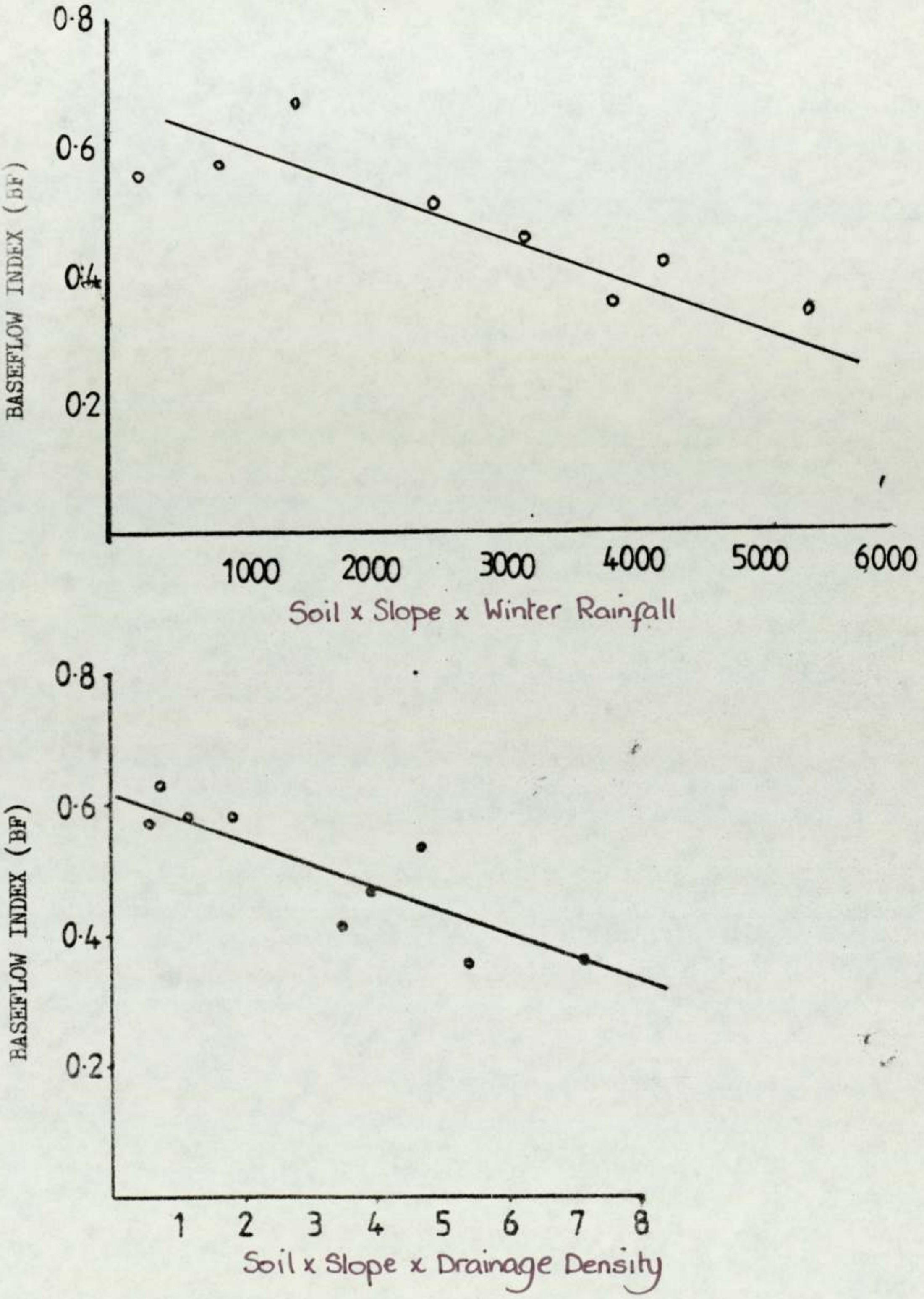


Fig 4.13.6

Linear Regression Analysis of BFI/ Catchment Characteristics

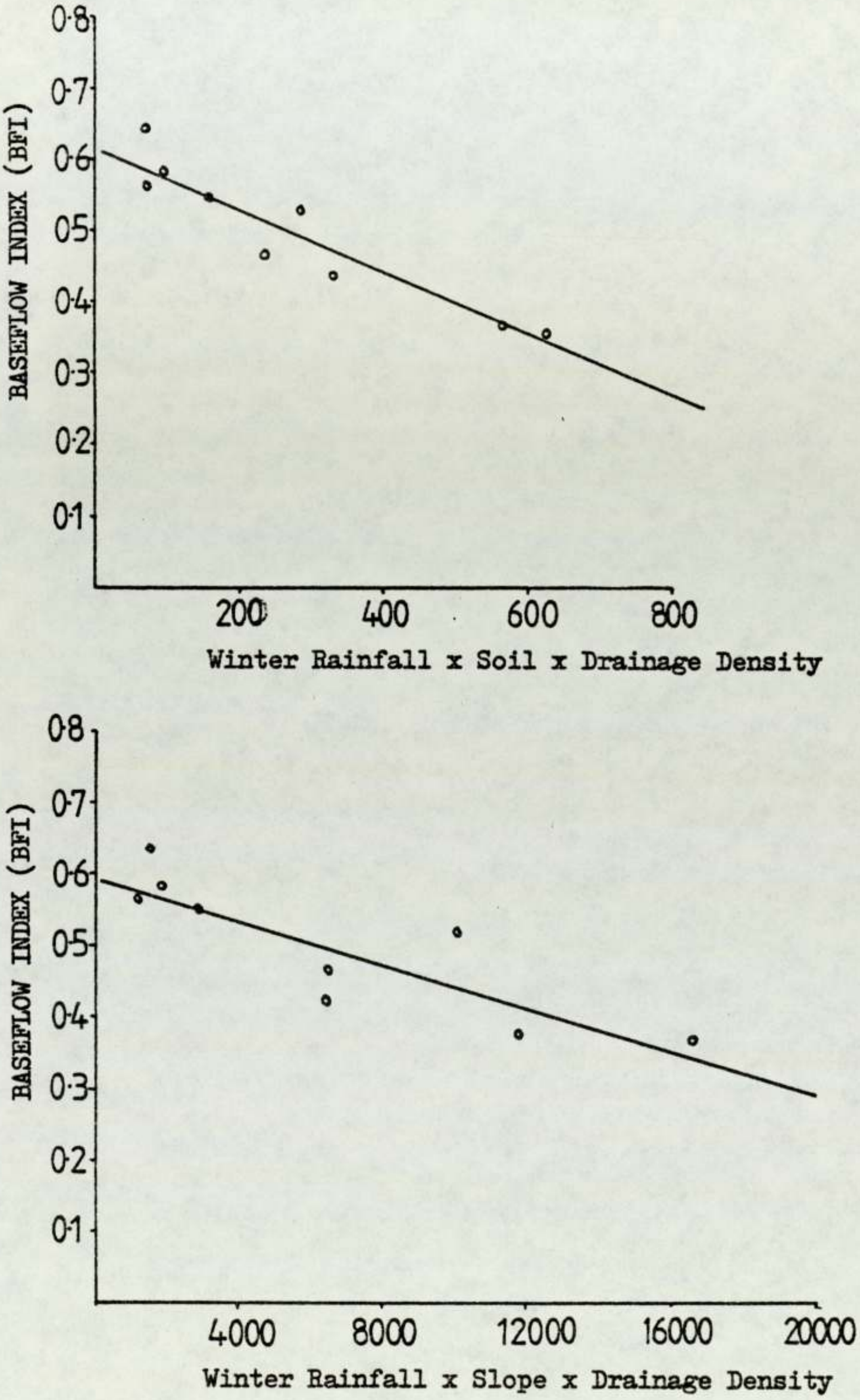


Fig 4.13.7

Linear Regression Analysis of BFI/catchment Characteristics

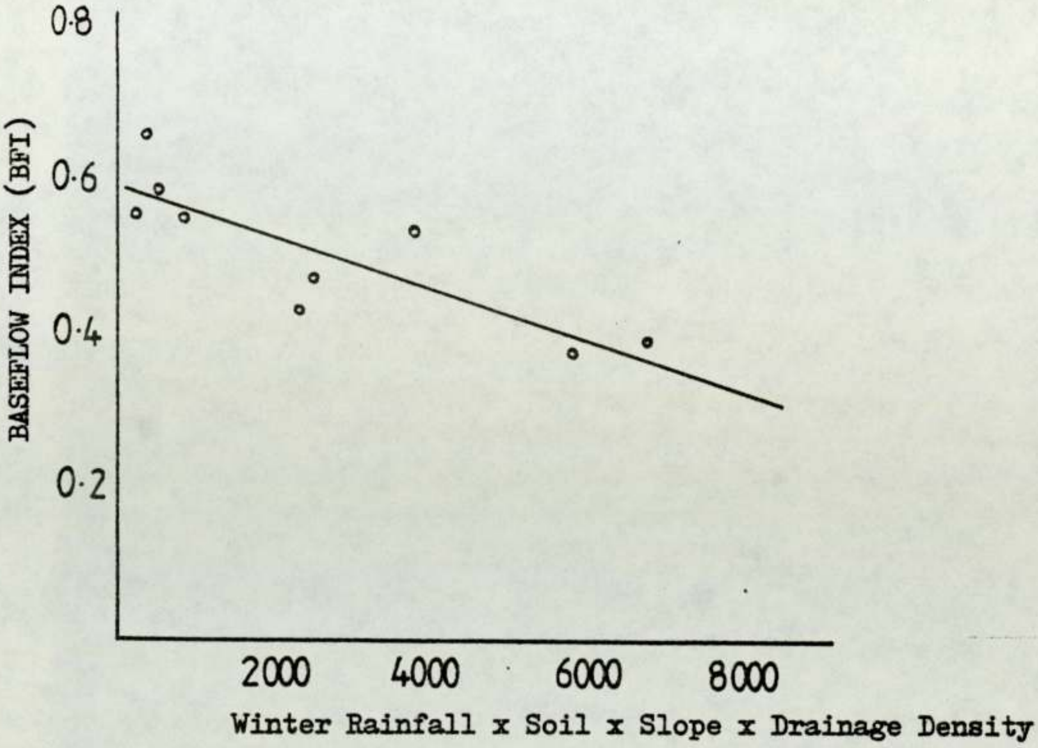


Fig 4.13.8

Linear Regression Analysis of BFI / Catchment Characteristics

TABLE 4.7.2 LINEAR REGRESSION ANALYSIS FOR BASEFLOW INDEX (BFI)/CATCHMENT CHARACTERISTICS WHERE THE SOIL EQUATION IS ALTERED AS FOR LOW FLOWS (see Chpt. 3)

Catchment Characteristics	Slope (m)	Intercept (y)	Correlation Coefficient (r)
BFI/ Soil	- 1.844	1.16	- .88
Slope	- .0289	.72	- .86
WR	- .00034	.7197	.87
DD	- .2505	.7409	.89
Soil x Slope	- .068	.695	- .92
Soil x WR	- .00071	.671	- .89
Soil x DD	- .623	.719	- .97
Slope x WR	- .000024	.6335	.91
Slope x DD	- .0149	.623	.82
WR x DD	- .00021	.6419	.94
Soil x Slope x WR	- .000057	.62	- .92
Soil x Slope x DD	- .044	.635	- .96
Soil x WR x DD	- .000496	.627	- .95
Slope x WR x DD	- .000015	.593	.85
WR x Soil x Slope x DD	- .000042	.5995	- .95

WR - Winter rainfall (Nov - Apr)
DD - Drainage density

4 and 5 were reversed to make the value more relevant for periods of low flows. The results generally show a distinct relationship between the BFI and several catchment characteristics, and certainly suggest that it is possible to obtain a good estimate of BFI values without access to a long period of gauged data. The best equation for this purpose was found to be -

$$\mathrm{BFI} = .7057 - .568\,(\mathrm{Soil} \times \mathrm{D.D.})$$

where DD = Drainage Density

While this equation was found to be of noreal value in the calibration of the model, it did come to light during this part of the study, and has been mentioned here because its use could significantly enhance the method of estimating low flow characteristics as described in the Low Flow Studies Report (1978).

4.6 THE FINAL SIMULATIONS

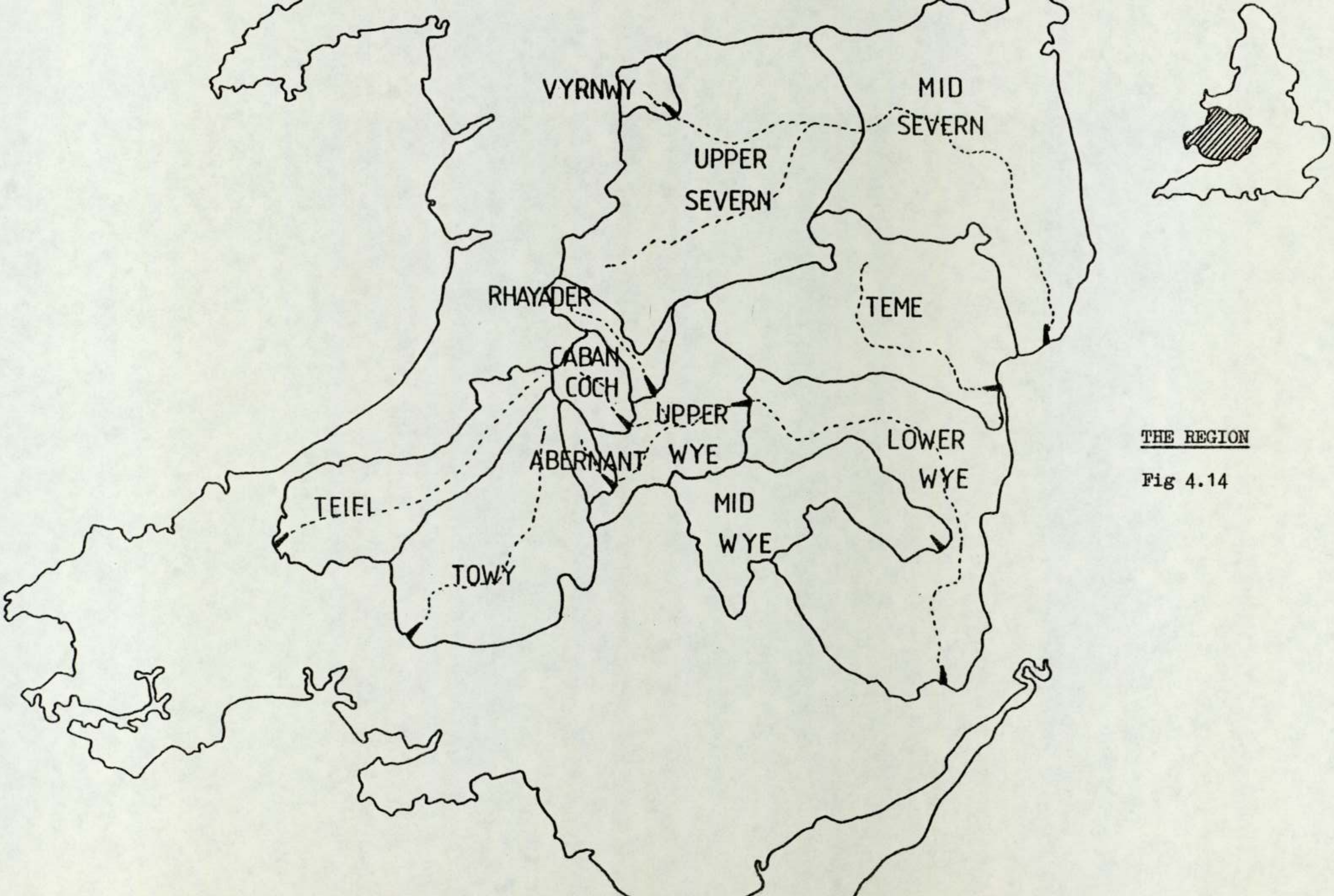
4.6.1 The Catchments

The catchments used in this part of the study covered a general area comprising Mid and South Wales and the Welsh borderlands (Fig 4.14). Two types of catchment were used -

i) 'full' or whole catchments upstream of a gauging point

ii) 'intermediate' subcatchments consisting of only that part of the catchment contributing to the river reach contained between two gauging stations, the flow being evaluated by subtracting the upstream record from the downstream record.

The advantage of using intermediate subcatchments in this study was that they enabled the effects of relief to be studied more effectively. That is, intermediate subcatchments can be chosen to be essentially lowland or upland thereby separating



THE REGION

Fig 4.14

the essential characteristics of these regions.

The following table (4.8) gives basic details of the catchments used and Fig 4.14 shows their location.

4.6.2 Meteorological Data and Systems Parameters

The mean monthly rainfall and evaporation data (1960-75) used as input to MODELMEAN are given in Tables 4.9 and 4.10. The sixteen year evaporation records (1960-75) used as input into MODELBASIC are given in Table 4.11 and Appendix 2
Temperature data for Edgbaston Observatory, Birmingham was used with MODELMEAN and is shown in Table 4.12. The temperature data for the sixteen year period is from Ross-on-Wye and is listed in Table 4.13.

The system parameters (ZONAL ALT, AVMT, RTC, QICOEF, NRCOEF and BFCOEF) used in the final simulation are given in Table 4.14.

4.7 RESULTS

Tables 4.15.1/10compare the predicted monthly flows for each of the catchments and intermediate subcatchments using both MODELMEAN (averaged input) and MODELBASIC (16 year rainfall record input) with the average monthly flows obtained from the historical flow data. These results are also shown graphically on Fig4.15/1.5

4.7.1 Discussion of Results for 'MODELMEAN'

When the model variables had been calibrated comparisons could be made between the predicted and historical mean monthly flows. Taken overall these showed a good fit between the predicted and historical sets (mean deviation being ± 8·3 %). However, certain characteristics were discernible between catchments.

TABLE 4.8 "FULL" AND "INTERMEDIATE" SUBCATCHMENT DETAILS

Catchment	Area	Type	Gauging Stations
Wye	4040.1	FC	Cadora
Lower Wye	2144.1	ISC	Cadora - Belmont
Mid Wye	613.9	ISC	Belmont - Erwood
Upper Wye	858.5	ISC	Erwood - Rhayader
Rhayader	166.8	FC	Rhayader
Abernant	72.8	FC	Abernant
Caban Coch	184.0	FC	Caban
Severn	4325.0	FC	Bewdley
Mid-Severn	2300.0	ISC	Bewdley - Montford
Upper Severn	1930.7	ISC	Montford - Vyrnwy
Vyrnwy	94.3	FC	Vyrnwy
Tenbury	1135·0	FC	Tenbury

TABLE 4.9 MEAN MONTHLY CATCHMENT RAINFALL (1960-75)

Catchment	MEAN MONTHLY RAINFALL (1960-75) (mm)												Annual
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Lower Wye	93.4	61.1	59.4	61.9	67.0	50.4	63.2	66.2	76.3	71.4	86.0	76.9	833.2
Mid Wye	101.6	69.4	65.4	65.5	77.7	64.3	65.1	71.0	77.7	80.0	90.7	82.1	810.5
Upper Wye	135.5	94.1	77.7	88.6	88.3	67.9	83.1	91.9	110.1	107.8	135.8	137.7	1118.71
Rhayader	181.9	130.4	107.0	122.0	111.7	86.7	103.9	125.7	137.9	139.3	184.4	199.9	1630.8
Abernant	220.9	148.6	118.9	137.1	121.7	100.3	119.4	139.3	163.1	168.5	209.2	203.1	1850.1
Caban Coch	218.4	153.1	125.3	137.2	115.4	91.3	109.5	133.3	152.6	155.1	206.1	224.1	1821.9
Mid Severn	65.6	45.7	48.1	54.4	64.6	49.3	65.0	68.0	65.9	57.7	71.9	62.4	718.6
Upper Severn	114.7	82.6	72.5	81.1	85.5	66.9	84.1	94.6	103.1	95.8	125.2	121.8	1127.9
Vyrnwy	203.9	150.9	124.5	134.5	125.3	95.6	119.8	138.7	166.9	169.9	220.6	228.0	1695.6
Tenbury	89.5	62.4	61.4	64.5	69.9	51.3	62.6	74.2	75.4	70.5	88.5	79.1	849.3

TABLE 4.10 <u>MEAN MONTHLY POTENTIAL EVAPORATION (1960-75)</u>

Catchment	MEAN MONTHLY POTENTIAL EVAPORATION (1960-75) (mm)												Annual
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Lower Wye	7	13	27	50	74	87	88	72	41	23	13	8	503
Mid Wye	7	12	25	47	70	82	83	68	39	22	12	8	475
Upper Wye	6	11	24	45	67	78	79	65	37	21	11	7	451
Rhayader	6	11	23	42	63	74	74	61	34	20	11	7	426
Abernant	6	10	21	40	59	69	70	58	32	18	10	6	399
Caban Coch	6	10	21	40	59	69	70	58	32	18	10	6	399
Mid Severn	8	13	28	53	53	92	93	76	43	24	13	9	522
Upper Severn	7	11	25	48	71	83	84	69	39	22	11	8	478
Vyrnwy	6	10	21	40	59	69	70	58	32	18	10	6	399
Tenbury	7	12	26	49	49	85	86	71	40	23	12	8	484

TABLE 4.11 <u>VALUES OF MEAN MONTHLY EVAPORATION AT BEWDLEY</u> (mm)

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1960	4.3	8.2	29.3	55.8	76.5	110.1	72.1	55.3	39.0	18.8	9.1	1.9
1961	6.7	11.5	31.3	37.0	83.7	93.3	89.0	77.4	42.3	21.6	5.3	2.0
1962	5.8	23.6	27.9	50.5	68.3	94.8	77.9	66.9	40.9	20.2	4.8	0.5
1963	1.4	8.2	25.0	39.9	75.0	89.4	74.6	58.2	43.8	19.7	8.7	3.4
1964	2.9	12.0	21.2	51.0	86.6	75.0	85.1	72.0	49.5	16.8	7.7	1.4
1965	8.2	12.5	32.2	48.1	73.6	85.6	66.4	71.7	35.6	17.8	5.8	1.0
1966	8.2	12.8	34.2	40.4	83.7	80.3	80.8	66.4	42.3	19.2	9.6	4.8
1967	5.3	20.7	48.1	53.4	61.1	91.4	96.2	67.8	45.2	34.2	5.8	5.3
1968	18.3	10.1	40.9	52.4	59.6	87.5	77.0	67.8	47.6	23.6	11.1	7.7
1969	7.2	5.8	23.6	57.2	59.6	96.2	99.1	67.3	36.6	21.6	11.1	5.3
1970	4.3	19.7	28.4	43.3	81.8	108.7	86.6	66.9	47.6	17.8	11.1	6.3
1971	6.3	12.5	26.4	42.8	84.7	66.9	94.8	66.4	40.9	26.5	8.7	7.2
1972	7.2	11.5	28.9	49.5	62.5	68.8	76.5	64.0	38.0	20.7	2.4	8.2
1973	8.2	8.7	30.3	54.4	75.5	88.5	82.7	68.3	41.8	15.9	5.8	1.9
1974*	6.7	12.7	30.6	48.3	73.7	88.3	82.8	66.9	42.2	21.0	7.6	4.1
1975*	6.7	12.7	30.6	48.3	73.7	88.3	82.8	66.9	42.2	21.0	7.6	4.1

* Based on average figures for the previous 14 years

TABLE 4.12 MEAN MONTHLY TEMPERATURE FOR EDGBASTON OBSERVATORY

MEAN MONTHLY TEMPERATURE (^{o}C)											
JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
4.2	4.2	5.4	7.3	9.7	13.8	15.8	16.6	13.1	10.9	7.2	4.7

TABLE 4.13 VALUES OF MEAN MONTHLY TEMP. °C. AT ROSS-ON-WYE

Year	Temperature (°C)											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1960	4.6	4.7	6.7	9.4	13.2	16.5	15.4	15.3	15.3	13.1	7.5	4.6
1961	4.5	7.9	8.5	10.5	11.3	14.5	15,6	16.1	15.1	11.0	6.1	2.5
1962	4.9	5.3	3.0	8.1	10.5	14.3	15.3	14.7	12.9	10.6	5.7	2.3
1963	-3.1	-0.7	6.4	9.0	10.8	15.1	15.5	14.5	13.3	11.4	8.7	2.2
1964	3.5	4.9	4.9	8.9	13.1	14.1	16.1	15.7	14.5	8.9	8.2	3.7
1965	4.2	3.3	5.7	8.6	11.9	14.5	14.3	15.5	12.3	10.9	5.1	5.5
1966	3.3	6.5	6.9	7.5	11.5	15.7	15.5	15.3	13.9	10.5	5.5	6.9
1967	5.1	5.9	7.6	8.5	10.8	14.8	17.2	16.0	14.1	11.3	5.9	4.9
1968	5.3	2.0	6.8	8.2	10.1	15.3	15.5	15.9	14.0	13.1	6.9	3.5
1969	6.1	1.5	4.1	8.3	11.5	14.3	17.1	16.7	13.7	13.1	6.2	3.8
1970	4.6	3.7	4.3	7.2	13.3	16.2	15.6	15.9	14.8	10.9	8.7	4.3
1971	0.8	5.0	5.7	8.1	12.0	12.9	17.4	16.2	14.7	11.7	6.7	6.9
1972	4.3	5.1	7.1	8.9	10.7	11.9	16.0	15.7	11.7	10.5	6.9	6.3
1973	5.3	5.1	6.4	7.8	11.7	15.1	16.1	16.9	14.6	9.7	6.9	5.9
1974	6.7	6.1	5.9	8.4	11.2	14.0	15.4	15.1	11.9	8.1	7.2	9.5
1975	7.3	4.5	5.2	9.0	10.7	15.4	18.0	18.8	13.9	10.6	7.4	5.8

TABLE 4.14 SYSTEMS PARAMETERS

Catchment	Altitude (m.)			Available Moisture			Root Constant			Discharge Coefficient		
	1	2	3	1	2	3	1	2	3	QI	NR	BF
Upper Wye	443	354	237	100	125	150	50	65	75	0.04	0.45	0.4
Mid Wye	310	205	97	100	150	200	50	75	100	0.45	0.4	0.2
Lower Wye	300	175	63	150	200	250	75	100	125	0.25	0.6	0.3
Abernant	487	395	302	75	100	125	36	50	75	0.65	0.2	0.28
Caban Coch	504	426	298	75	100	125	36	50	75	0.7	0.15	0.05
Rhayader	452	341	228	100	125	150	50	65	75	0.65	0.2	0.2
Vyrnwy	527	447	328	75	100	125	36	50	75	0.65	0.2	0.1
Upper Severn	450	350	250	100	125	150	75.0	85	100	0.45	0.4	0.25
Mid Severn	296	121	55	150	200	250	75	100	125	0.35	0.5	0.32
Tenbury	337	208	115	100	150	200	50	75	100	0.4	0.45	0.25

Table 4.15.1 <u>Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Caban Coch</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	183.3	123.2	101.3	99.0	72.5	44.5	45.9	68.9	95.2	119.5	165.2	203.1	1321.6
	Predicted Streamflow (mm)	185.2	134.6	103.1	82.4	62.8	45.6	58.9	78.5	105.3	126.1	165.0	182.3	1329.8
	E	- 1.9	- 11.4	- 2.8	16.6	9.7	-1.1	-13	- 9.6	-10.1	- 6.6	.2	20.8	-8.2
MODELBASIC	Historical Streamflow (mm)	183.3	123.2	101.3	99.0	72.5	44.5	45.9	68.9	95.2	119.5	165.2	203.1	1321.6
	Predicted Streamflow (mm)	172.0	137.4	126.5	104.3	78.6	51.9	51.5	77.5	108.4	125.3	170.5	193.2	1397.1
	E	11.3	-14.2	-25.2	-5.3	-6.1	- 7.4	-5.6	-8.6	-13.2	-5.8	-5.3	9.9	-75.5
	Stan. Dev. - Historical (mm)	83.2	62.5	54.1	46.6	33.4	32.8	43.1	32.2	61.5	63.7	59.2	103.8	
	Stan. Dev. - Predicted (mm)	84.6	67.3	59.8	36.7	30.4	18.5	17.5	16.6	49.8	60.1	55.2	94.7	

TABLE 4.15.2 **Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Vyrnwy**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	176.1	125.8	113.9	107.5	87.5	45.9	55.7	81.2	112.7	134.3	179.8	205.3	1425.7
	Predicted Streamflow (mm)	183.2	150.5	112.7	92.4	71.6	55.2	64.4	85.9	108.5	145.9	168.3	178.5	1417.1
	E	- 7.1	24·9	1.2	15.1	15.9	- 9.3	- 8.7	- 4.7	4.2	-11.6	11.5	26.8	8·6
MODELBASIC	Historical Streamflow (mm)	176.1	125.8	113.9	107.5	87.5	45.9	55.7	81.2	112.7	134.3	179.8	205.3	1425.7
	Predicted Streamflow (mm)	168.4	140.2	132.6	113.4	89.8	61.2	64.5	81.8	112.4	133.6	172.1	192.0	1462
	E	7.7	-14.4	-18.7	-5.9	-2.3	-15.3	- 8.8	- .6	.3	.7	7.7	13.3	36·3
	Stan. Dev. - Historical (mm)	78.4	65.6	62.1	51.4	46.3	30.0	27.5	41.6	69.3	90.5	79.8	100.9	
	Stan. Dev. - Predicted (mm)	90.1	74.8	60.5	36.2	38.8	21.3	20.1	26.2	65.1	95.8	83.6	114.2	

Table 4.15.3 **Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Rhayader**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	161.5	117.2	87.6	93.7	64.3	37.2	41.5	59.2	76.2	104.6	147.7	183.6	1174.3
	Predicted Streamflow (mm)	167.2	130.9	98.8	76.1	56.9	36.9	48.8	67.8	97.6	117.4	154.9	166.8	1220.1
	E	5.7	13.7	11.2	17.6	7.4	0.3	7.3	8.6	21.4	12.8	7.2	16.8	45·8
MODELBASIC	Historical Streamflow (mm)	161.5	117.2	87.6	93.7	64.3	37.2	41.5	59.2	76.2	104.6	147.7	183.6	1174.3
	Predicted Streamflow (mm)	160.3	116.2	89.5	93.8	64.2	35.8	40.9	58.5	78.3	104.8	144.6	180.9	1167.8
	E	1.2	1.0	1.9	.1	.1	1.4	.6	.7	2.1	.2	3.1	2.7	6·5
	Stan. Dev. - Historical (mm)	75.4	60.3	42.6	48.5	33.7	23.4	22.1	26.8	46.5	60.7	63.2	91.1	
	Stan. Dev. - Predicted (mm)	75.6	58.2	35.9	33.2	29.7	15.7	14.3	13.2	47.9	64.3	66.2	100.5	

Table 4.15.4 <u>Historical and Predicted Flow Values for MODELMEAN - Abernant</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	198.3	139.1	108.9	104.3	85.4	57.3	55.9	82.8	99.3	134.3	171.6	216.7	1453.9
	Predicted Streamflow (mm)	203.2	151.0	112.4	110.3	76.6	49.2	54.3	80.7	115.9	136.2	175.1	185.8	1450.7
	E	- 4.9	-11.9	- 3.5	- 6	8.8	8.1	1.6	2.1	-16.6	- 1.9	- 3.5	30.9	3·2

Table 4.15.5 **<u>Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Upper Wye</u>**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	127.7	92.9	68.3	58.8	46.1	22.4	17.1	23.1	39.4	63.0	98.4	125.9	783.1
	Predicted Streamflow (mm)	120.1	98.4	72.3	58.6	38.1	18.5	15.2	21.8	44.3	67.5	98.9	112.4	766.1
	E	7.6	5.5	4.0	.2	8.0	3.9	1.9	1.3	4.9	4.5	.5	13.5	17·0
MODELBASIC	Historical Streamflow (mm)	127.7	92.9	68.3	58.8	46.1	22.4	17.1	23.1	39.4	63.0	98.4	125.9	783.1
	Predicted Streamflow (mm)	120.6	98.2	73.6	59.1	40.2	22.4	17.0	18.3	42.7	61.7	95.0	113.6	762.4
	E	7.1	5.3	5.3	.3	5.9	-	.1	4.8	3.3	1.3	3.4	12.3	20·7
	Stan. Dev. - Historical (mm)	57.3	50.2	33.8	32.6	26.1	24.5	23.5	22.8	34.1	53.8	52.6	60.1	
	Stan. Dev. - Predicted (mm)	38.4	32.6	20.1	18.7	20.4	9.9	7.5	8.6	32.5	50.9	45.6	53.0	

Table 4.15.6 Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Upper Severn

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	94.3	70.4	57.2	47.6	37.7	17.8	16.8	22.2	30.2	48.3	76.5	102.6	621.6
	Predicted Streamflow (mm)	98.2	68.4	61.0	50.4	33.5	26.7	22.8	25.6	38.7	54.9	84.3	92.9	657.4
	E	- 3.9	2	- 3.8	- 2.8	4.2	- 8.9	- 6	- 3.4	- 8.5	- 6.6	- 7.8	9.7	-35.8
MODELBASIC	Historical Streamflow (mm)	94.3	70.4	57.2	47.6	37.7	17.8	16.8	22.2	30.2	48.3	76.5	102.6	621.6
	Predicted Streamflow (mm)	84.0	71.5	66.3	54.2	40.8	24.5	20.4	22.0	35.3	51.0	80.8	98.7	649.5
	E	10.3	- 1.1	- 9.1	-6.6	- 3.1	- 6.7	- 3.6	.2	- 5.1	- 2.7	- 4.3	3.9	27.9
	Stan. Dev. - Historical (mm)	45.2	34.8	24.6	24.8	22.1	6.5	11.2	6.8	10.5	16.3	18.4	27.9	
	Stan. Dev. - Predicted (mm)	36.4	38.2	27.1	17.4	21.5	19.8	19.2	21.7	24.3	33.9	29.4	38.5	

Table 4.15.7 **Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Mid Wye**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	77.2	62.6	50.9	35.4	33.8	23.9	20.1	13.7	11.9	28.8	39.3	61.9	459.5
	Predicted Streamflow (mm)	68.3	52.3	41.5	25.8	20.5	12.6	10.0	13.5	19.1	32.3	50.3	58.7	404.9
	E	8.9	10.3	9.4	9.6	13.3	11.3	10.1	.2	-7.2	-3.5	-11.0	3.2	54·6
MODELBASIC	Historical Streamflow (mm)	77.2	62.6	50.9	35.4	33.8	23.9	20.1	13.7	11.9	28.8	39.3	61.9	459.5
	Predicted Streamflow (mm)	75.2	62.4	53.0	40.4	32.1	21.8	18.1	15.7	25.1	38.4	53.1	59.7	495
	E	2.0	0.2	-2.1	-5.0	1.7	2.1	2.0	-2.0	-13.2	-9.6	-13.8	2.2	35·5
	Stan. Dev. - Historical (mm)	27.6	31.5	24.0	16.3	22.4	15.1	17.6	14.2	13.1	30.5	32.6	41.3	
	Stan. Dev. - Predicted (mm)	27.8	27.5	19.3	16.2	17.1	9.4	15.3	7.4	16.5	40.3	36.2	31.1	

Table 4.15.8 <u>Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Mid Severn</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	46.7	36.9	34.0	24.8	22.6	12.8	12.1	11.1	13.6	17.9	27.8	40.4	300.7
	Predicted Streamflow (mm)	48.3	40.1	28.7	17.2	10.6	6.7	4.4	4.2	9.3	13.7	32.0	36.4	251.6
	E	-1.6	-3.2	5.3	7.6	12.0	6.1	8.3	6.9	4.3	4.2	-4.2	4.0	52.9
MODELBASIC	Historical Streamflow (mm)	46.7	36.9	34.0	24.8	22.6	12.8	12.1	11.1	13.6	17.9	27.8	40.4	300.7
	Predicted Streamflow (mm)	41.8	35.3	26.1	18.3	14.3	7.5	6.1	4.7	8.3	13.0	24.0	33.5	232.9
	E	4.9	1.6	8.1	6.5	8.3	5.3	6.0	6.4	5.3	4.9	3.8	6.9	63.8
	Stan. Dev. - Historical (mm)	21.4	16.3	10.2	8.5	14.6	6.8	11.4	6.5	10.3	16.6	18.2	27.5	
	Stan. Dev. - Predicted (mm)	20.5	14.7	5.3	4.8	12.3	2.4	1.5	2.3	5.0	9.4	13.6	20.8	

Table 4.15.9 **<u>Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Tenbury</u>**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	67.2	50.3	47.1	30.6	28.7	13.7	11.5	9.4	12.5	24.1	39.7	52.8	387.6
	Predicted Streamflow (mm)	67.9	56.2	42.6	28.6	16.7	11.8	8.7	8.8	14.6	23.1	42.0	55.4	376.4
	E	- 0.7	-5.9	4.5	2.0	12.0	1.9	2.8	0.6	- 2.05	1.0	-2.3	2.6	11·25
MODELBASIC	Historical Streamflow (mm)	67.2	50.3	47.1	30.6	28.7	13.7	11.5	9.4	12.5	24.1	39.7	52.8	387.6
	Predicted Streamflow (mm)	63.5	54.2	46.1	35.8	28.5	16.2	13.5	11.2	17.9	27.6	47.3	57.7	419.5
	E	-3.7	-3.9	1.0	-5.2	.2	-2.5	-2.0	-1.8	-5.4	-3.5	-7.6	-4.9	31·9
	Stan. Dev. - Historical (mm)	28.3	25.4	21.6	13.8	17.4	6.5	11.8	4.2	8.9	26.5	39.2	52.9	
	Stan. Dev. - Predicted (mm)	28.9	23.1	11.6	7.5	15.3	4.6	4.8	3.4	12.2	25.1	27.9	27.8	

Table 4.15.10 <u>Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Lower Wye</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	63.9	54.7	51.3	32.8	26.7	15.9	12.7	9.8	10.7	21.8	36.6	45.9	382.8
	Predicted Streamflow (mm)	60.8	52.6	44.1	30.7	21.1	12.8	9.2	5.6	10.3	17.3	35.7	42.0	342.2
	E	3.1	2.1	7.2	2.1	5.6	3.1	3.5	4.2	.4	4.5	.9	3.9	40.6
MODELBASIC	Historical Streamflow (mm)	63.9	54.7	51.3	32.8	26.7	15.9	12.7	9.8	10.7	21.8	36.6	45.9	382.8
	Predicted Streamflow (mm)	56.7	51.2	42.3	32.4	24.0	18.0	16.0	14.5	16.8	22.5	32.3	40.5	367.2
	E	7.2	3.5	9	.4	2.7	2.1	3.3	4.7	6.1	.7	4.3	5.3	15·6
	Stan. Dev. - Historical (mm)	28.5	27.0	22.1	13.5	11.4	8.2	14.7	5.3	6.2	27.8	34.4	28.9	
	Stan. Dev. - Predicted (mm)	25.2	23.5	12.4	11.3	10.8	4.6	3.2	2.9	4.5	18.1	25.8	22.4	

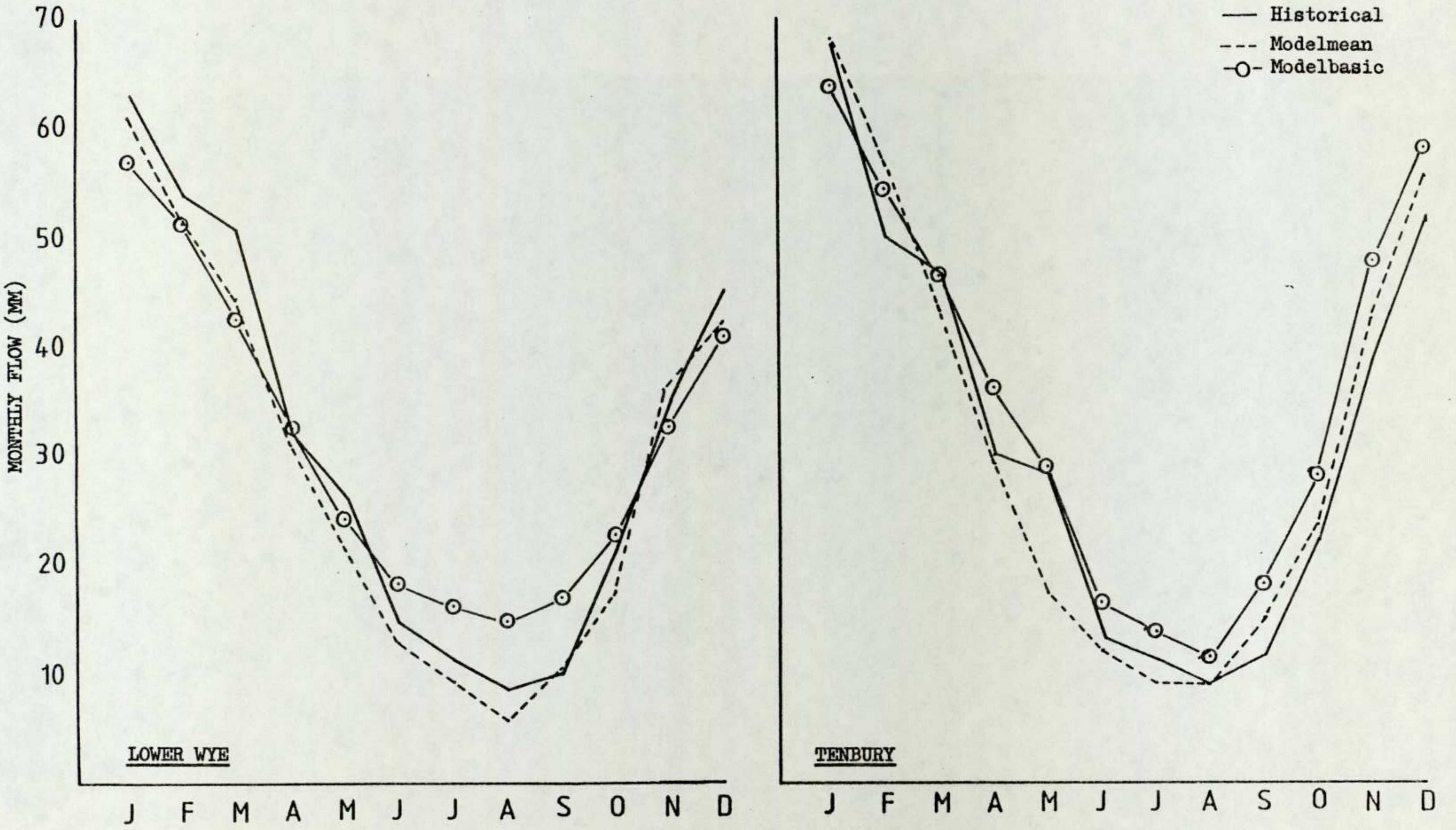
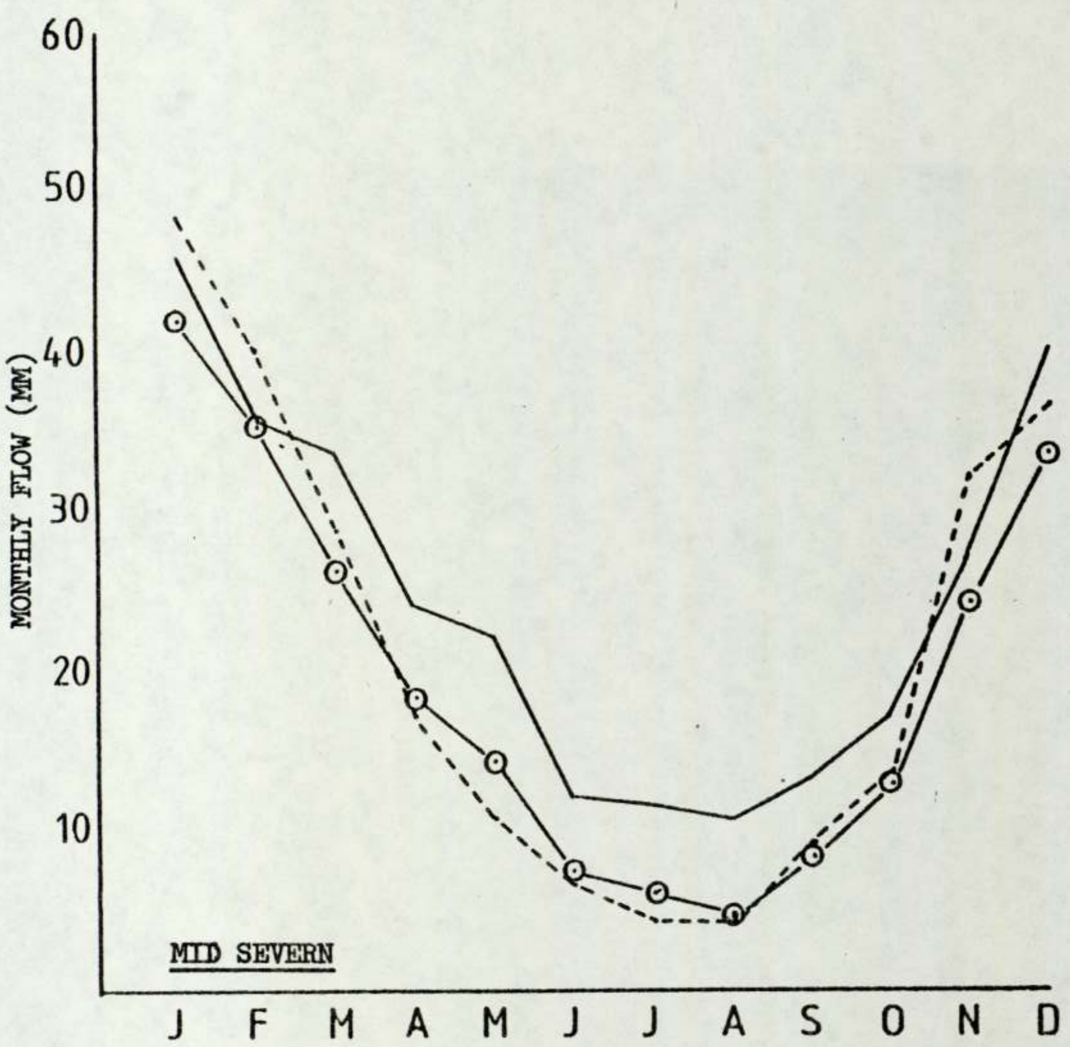


Fig 4.15.1 Historical and Predicted Flow Values for MODELMEAN and MODELBASIC



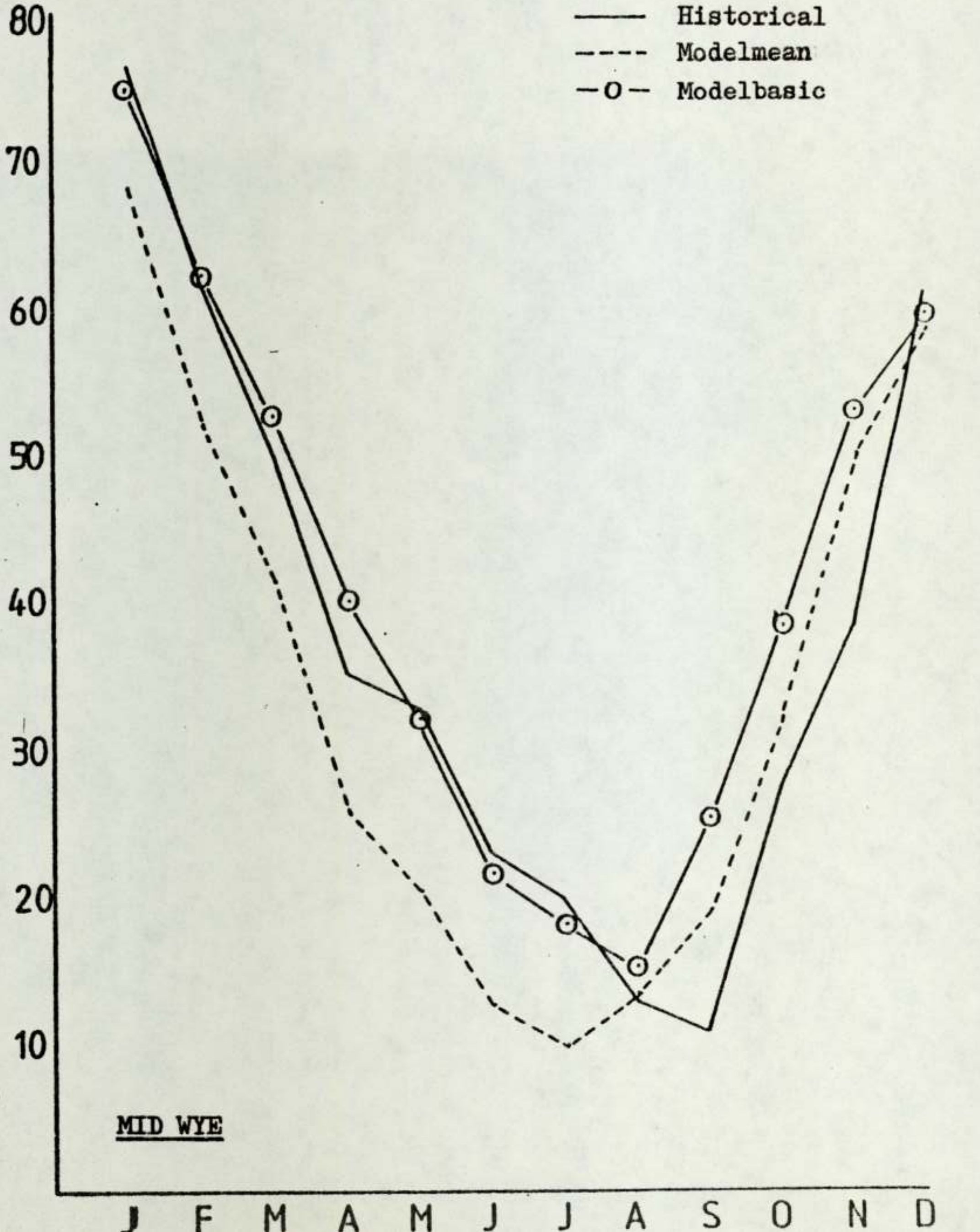


Fig 4.15.2 Historical and Predicted flow Values for MODELMEAN and MODELBASIC

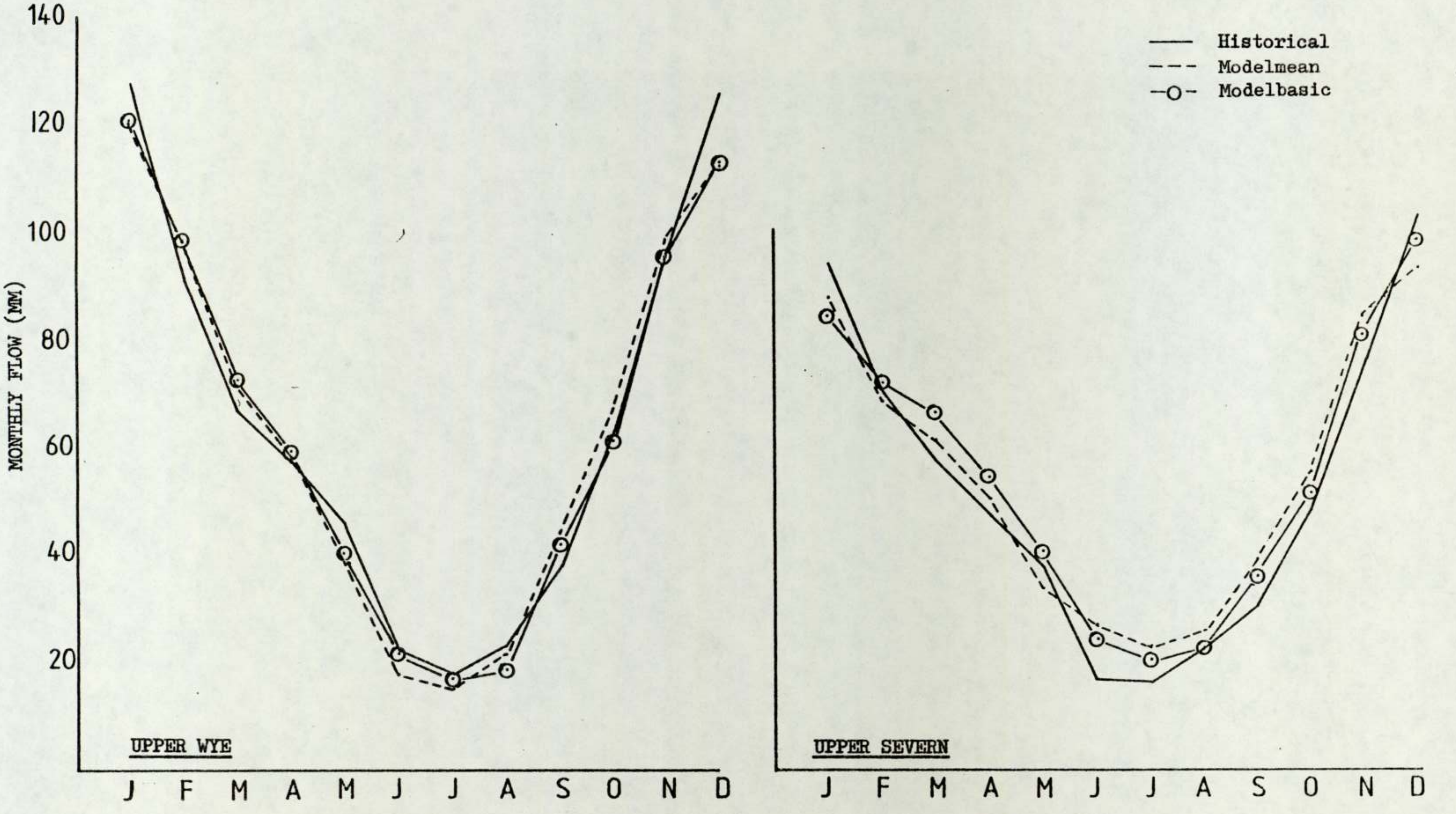


Fig 4.15/3 Historical and Predicted flow Values for MODELMEAN and MODELBASIC

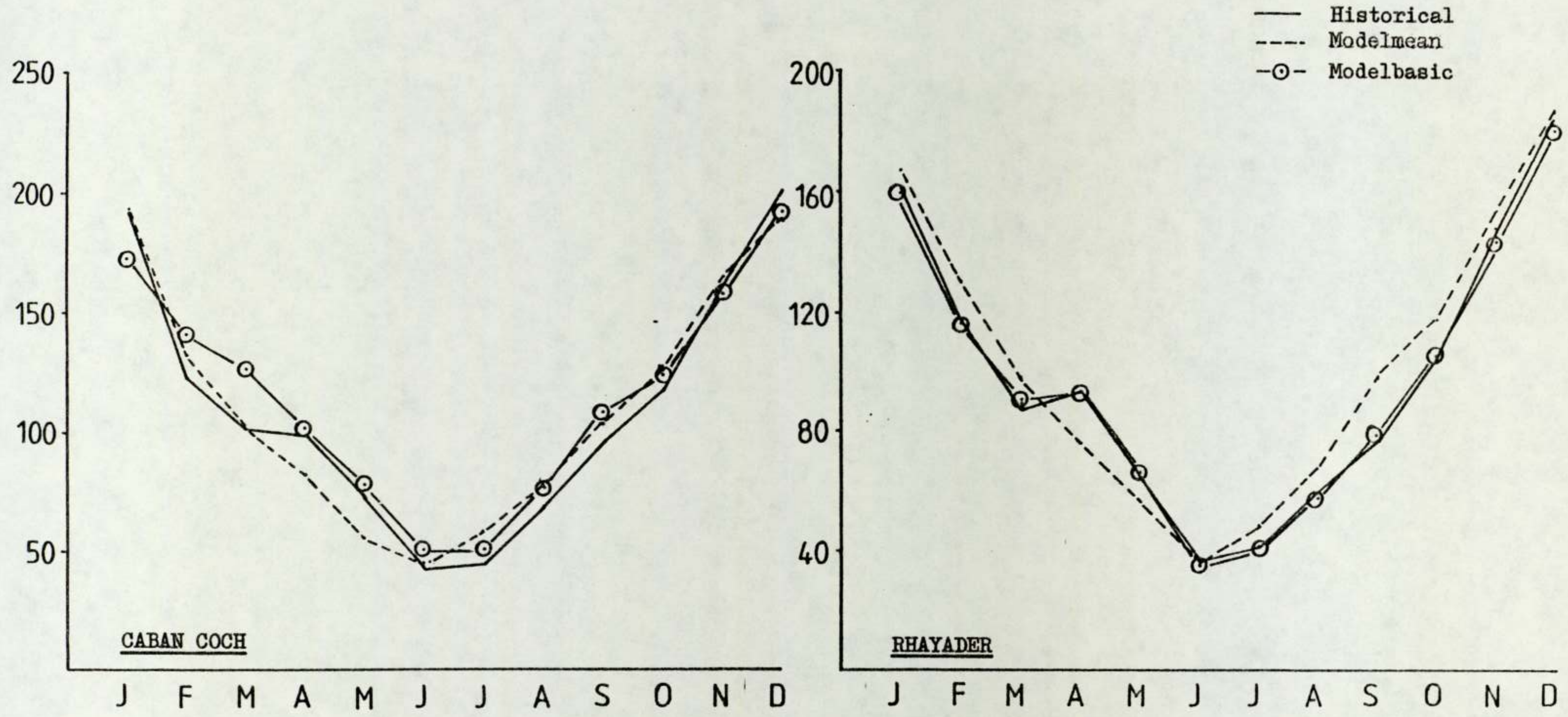


Fig 4.15.4 Historical and Predicted flow Values for MODELMEAN and MODELBASIC

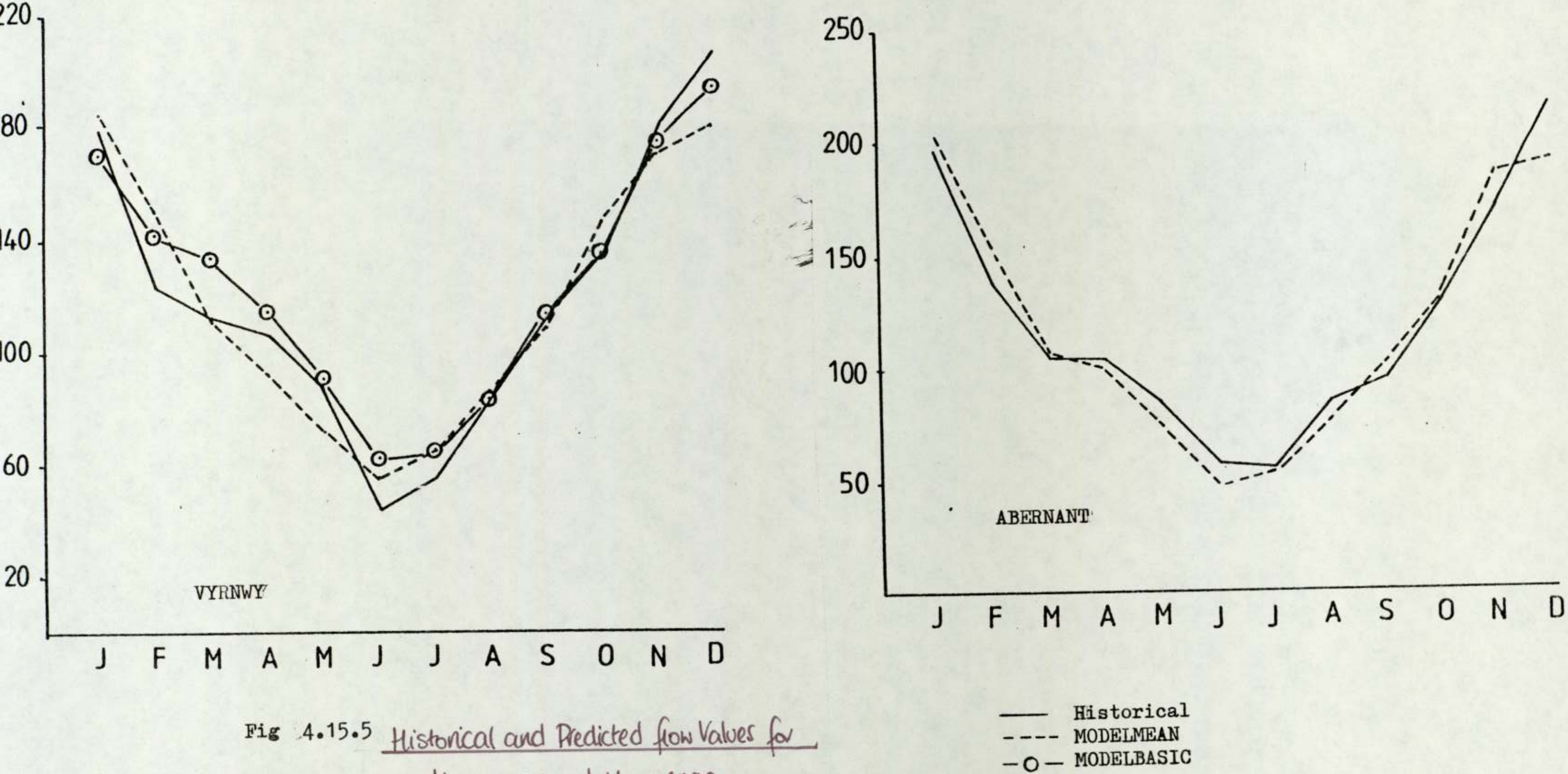


Fig 4.15.5 Historical and Predicted flow Values for MODELMEAN and MODELBASIC

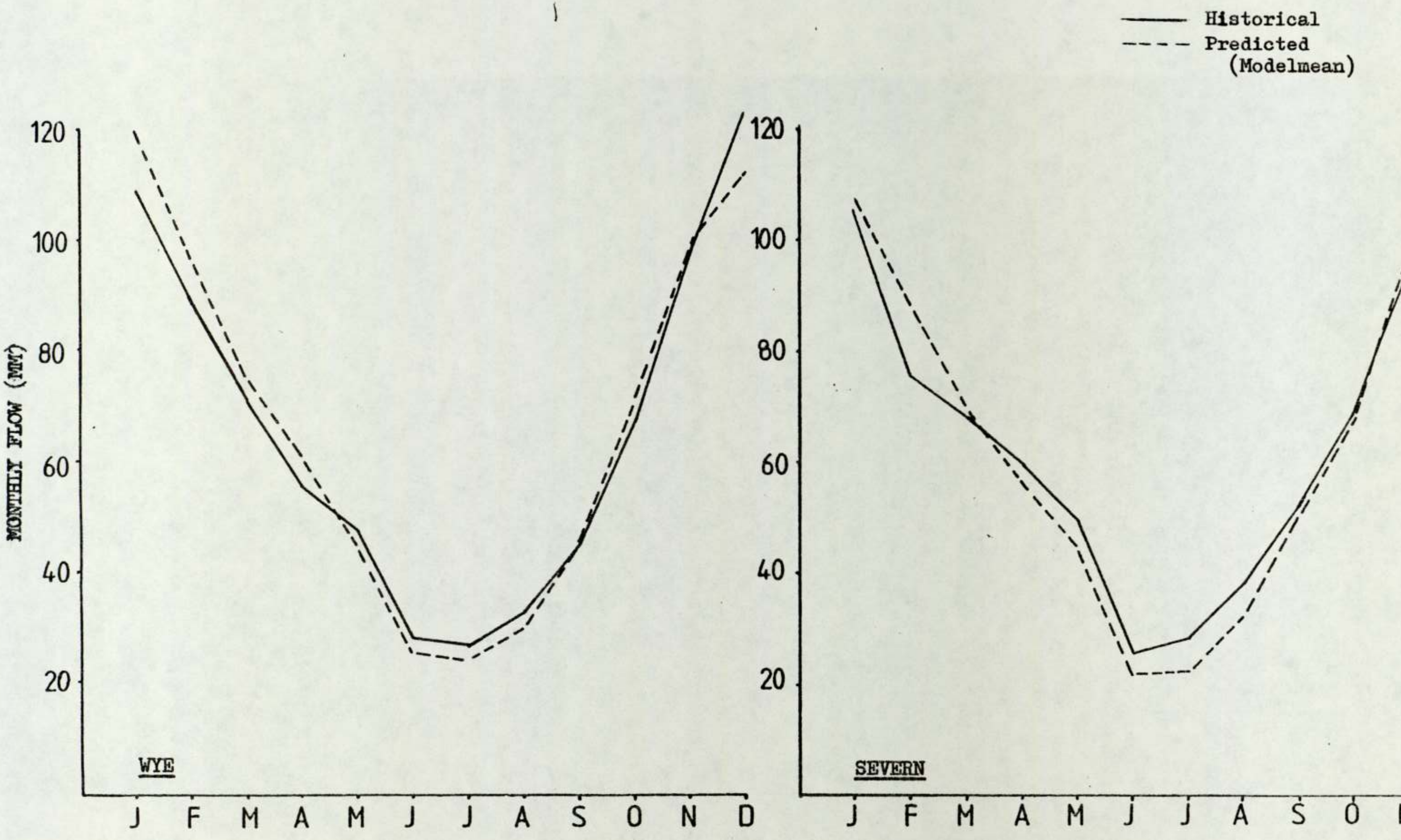


Fig 4.15.6 Historical and Predicted flow Values for MODELMEAN

E effect?

i) The upland catchments tended to exhibit results in which the predicted discharge consistently over-estimated historical discharges for the period September - March, whilst for the remainder of the year discharge values were underestimated. This was probably due to inadequate treatment of the infiltration/overland flow division and was noted as an area of potential improvement.

ii) for mid-land catchments, excluding Mid-Severn the model tended to underestimate historical discharges for the first six months of the year, and then over-estimate the remaining six months. This is possibly due to a soil moisture or baseflow lag problem which in the first half of the year could reduce the quantity of moisture available for baseflow so increasing groundwater storage, and consequently discharge in the later months.

iii) The Lower Wye and Mid-Severn subcatchment predicted discharge values which consistently underestimated the historical flow values. The variation between historical and predicted discharge data for the Lower Wye was quite small, but, for the Mid-Severn the variation was marked and this is discussed in detail later.

When using mean monthly data it was only possible to reproduce seasonal variations in mean monthly flow, however, certain weaknesses in the design of the model were nonetheless discernible. In the upland catchments comparison of the predicted and historical flows suggest further consideration is necessary of the overland flow process, which in periods of soil moisture surplus (during winter) should do more to increase the discharge values instead of adding to groundwater storage for discharge as baseflow in later months.

The predicted results for the Mid-Severn follow a curve of similar form to that of historical discharge but displaced from it. El Gusbi did, however, find that the discharge from the subcatchment exceeded the input of rainfall minus evaporation by an approximate annual average of 50 mm. It is possible therefore that the problem is due to a movement of water across the catchment groundwater boundary and that the surface and groundwater catchments are not coincident or alternatively slight gauging error in each gauge combining to produce a more significant error or possibly erroneous estimation of Ea

The systems parameters used for the catchments and intermediate subcatchments of the Severn and Wye were subsequently combined to attempt a prediction of flow values for the Severn above Bewdley, and the Wye above Cadora. The two catchments were separated into three zones which coincided roughly with the subcatchments of which they were composed.

The predicted and historical values for these two simulations are shown in Figs 4.15.6. The predicted values for the Severn and Wye produced a good fit,however the predicted discharges for the Severn are overestimated for December and underestimated the remaining time.This is most probably due to the problems inherent in a prediction of Mid-Severn flow values.

4.7.2 Discussion of the Results for 'MODELBASIC'

The basic model was also used to predict flow values for a sixteen year period (1960-75) and the results, as shown in Figs 4.15.1/5 and Tables 4.15.1/9, exhibited certain characteristics.

i) The upland catchments Rhayader, Caban Coch, Vyrnwy and also Tenbury exhibited flows which were a general overestimation of the historical values. The reason for this most probably results from gauging errors for rainfall, evaporation and discharge.

ii) The results for the Upper Wye and Upper Severn, though initially erratic produced a good fit in later months, as also did the predicted values for the Lower Wye which were a distinct improvement upon those previously obtained.

iii) The predicted flows for the Mid-Severn again underestimated the historical flow data, however, the difference between the predicted and historical values was not as marked as previously.

The standard deviations of flow are shown in Figs 5.8.1/4. A feature of the actual standard deviations is that the value of deviation in July in the lower lying catchments increases, a factor which is not expressed by the predicted deviations. However, generally the predicted deviations closely reflect the historical for all catchments.

4.8 CONCLUSION

The results were generally only a slight improvement upon those previously obtained, and it was found that for the model to reflect more than just seasonal trends, modifications would be necessary. In particular the effects of quickflow and soil moisture surplus during winter months were initially ignored and this was evident in the results for the upland catchments. At this point snow was not very important since the Welsh catchments rarely have snow which lies on the ground for a period in excess of one month. However, if extremes within the data were to be accounted for, these factors must be taken into consideration.

It was at this stage that the Abernant catchment was abandoned. When using mean monthly data no error was readily discernible, However, when using 16 years of data, gauged flows were consistently in excess of rainfall during the month of December. For this reason Abernant was not used since either the naturalised flow data or the rainfall data appears to be erroneous, and the problem of gauging errors is important since it can markedly affect the predicted discharges.

CHAPTER 5

DEVELOPMENT OF THE IMPROVED RAINFALL/RUN-OFF MODEL

5.1 INTRODUCTION

The aim of this chapter is to describe and discuss developments made to the basic model. The previous chapter outlined the basic model and analysed the predicted flow results obtained using MODELMEAN and MODELBASIC. Discussion of these results highlighted the alterations necessary to improve the reliability of the model. These alterations fell into two categories -

i) modification of the overland flow/interflow algorithm

ii) modification of the natural recharge/interflow algorithm

Both modifications to the model are discussed together with the use of catchment characteristics for calibration. A set of results using Welsh catchment data are presented and conclusions drawn. Copies of MODELQF, which includes modification (i) and MODELFAC which includes modifications (i) and (ii) are given in Appendix 1

5.2 MODIFICATION TO THE OVERLAND FLOW/INTERFLOW ALGORITHM

The modification to the overland flow/interflow algorithm utilises the generalised rainfall intensity/duration curve proposed by W.J. Walley (see Appendix 3). Since heavy rainfall is more likely to produce surface flow than is light rainfall, the intensity/duration curve offers some measure of the amount of rainfall during the month which is likely to have become overland flow. The generalised intensity/duration curve was calibrated for use in the model using field data from Plynlimon provided by the Institute of Hydrology.

5.2.1 Calibration of the rainfall intensity/duration curve using field data

The rainfall intensity/duration curve for a typical month may be approximately represented by a parabolic equation of the following form (see Fig 5.1)

$$(r + b)\ (t + a) \ = \ C^2$$

where a, b and c are constants

The calibration of the generalised rainfall intensity/duration curve using field data from Plynlimon followed six basic steps.

i) Field data was plotted and a smooth curve was drawn through the plotted points. The field data for Plynlimon was recorded hourly rainfall and therefore did not express instantaneous intensity.

ii) Derived r_m corresponding to $t = 0$, t_1 corresponding to $r = 1$, using the smoothed curve, and derived co-ordinates for an intermediate point using the smoothed curve (e.g. t_4 corresponding to $r = 4$ mm/hr).

iii) Co-ordinates $(0,\ r_m)$, $(t_4,\ 4)$ and $t_1,\ 1)$ were substituted into the above equation and hence derived the three unknowns a, b, c^2 for the curve passing through the three points.

This was repeated for several months data covering a range of monthly rainfalls (R_m). Calibration using field data obtained from the Institute of Hydrology for Plynlimon gave the results shown in Table 5.1.

iv) Use of linear regression analysis to derive general equations relating parameters a, b and c^2 to the monthly rainfall R_m.

Table 5.1 Estimation of a, b, C^2, for Recorded Monthly Rainfalls at Plynlimon

Month and Year	Recorded total rainfall (mm)	Results of Calibration a	b	C^2
Nov. '70	367.8	14.17	- 0.04	120.83
Oct. '70	346.7	13.67	- 0.02	114.75
Oct. '71	211.9	10.6	0.1	75.93
Sept. '70	198.8	10.3	0.11	72.15
Aug. '71	192.9	10.17	0.12	70.46
Aug. '70	164.1	9.51	0.14	62.96
July '70	163.2	9.49	0.14	61.9
June '71	159.5	9.4	0.15	60.83
June '70	99.2	8.02	0.2	43.47
July '71	76.7	7.51	0.22	36.99
Sept. '71	68.2	7.31	0.23	34.54
May '71	67.6	7.3	0.23	34.37

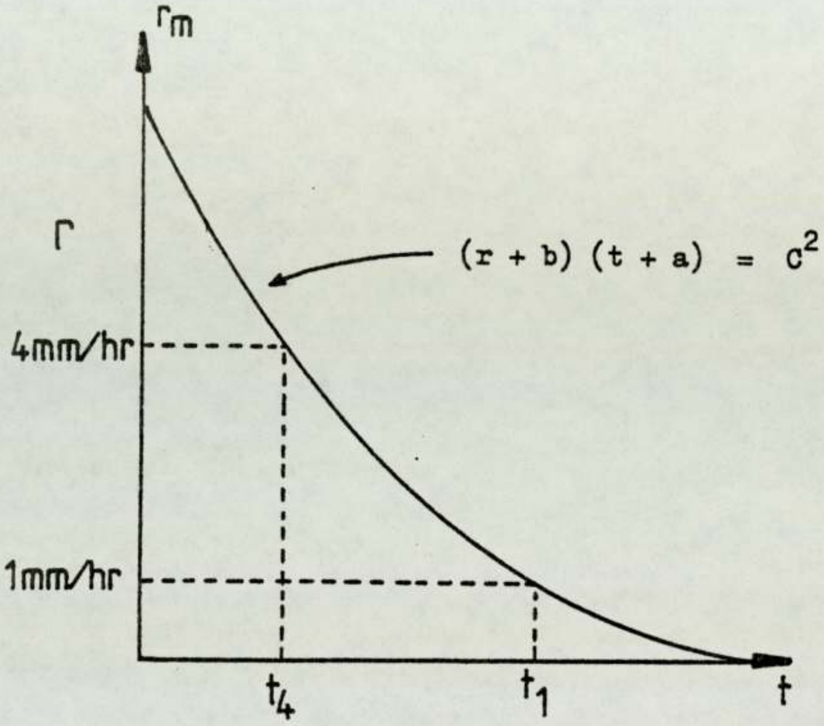


Fig 5.1 Calibration of the Rainfall Intensity/Duration Curve

The results of this analysis were as follows:

$$a = 5.75 + 0.0229\, R_m \quad (r^2 = 0.1345)$$

$$b = 0.286 - 0.000874\, R_m \quad (r^2 = 0.0959)$$

$$c^2 = 14.9 + 0.288\, R_m \quad (r^2 = 0.5607)$$

where R_m = monthly rainfall

Thus for any given monthly rainfall the values a, b, c^2 can be estimated for use in the general rainfall intensity/duration equation as:

$$r = \frac{c^2}{(t + a)} - b$$

However, when the calculated total monthly rainfall (Equation 7 see Appendix 3) was checked against the recorded rainfall it was found that at high values of R_m the theoretical equation overestimated the total rainfall. Further investigation of this problem revealed that the linear regression equation for "b" was far from adequate. Replacement of this equation by the following non-linear equation was sufficient to overcome the problem.

$$b = \left(\frac{9.88}{R_m + 4.0} \right) + 0.121$$

Thus the final equations for the estimation of the parameters a, b, c^2 for any given month were -

$$a = 5.75 + 0.0229\, R_m$$

$$b = \left(\frac{9.88}{R_m + 4.0} \right) + 0.121$$

$$c^2 = 14.9 + 0.288\, R_m$$

where R_m = the recorded monthly rainfall

5.2.2 Development of Model Incorporating the Overland Flow/ Quickflow Algorithm

The generalised rainfall intensity/duration curve was derived to facilitate the development of an overland flow/interflow algorithm. Having derived this curve it was necessary to incorporate into the model the ffect of catchment characteristics such as slope, vegetation, and the degree of soil saturation, since these factors ultimately effect infiltration and consequently the respective proportions of overland flow and interflow.

The procedure devised for the evaluation of monthly overland flow was based upon the assumption that all rainfall in excess of a critical intensity (RCRIT) would become overland flow and rainfall less than this intensity would infiltrate the ground surface. Thus RCRIT was a crude estimate of the mean infiltration rate during high intensity storms. For the purpose of this project RCRIT was defined as follows:

Horton's approach?

$$\text{RCRIT} = \alpha \beta f$$

where α = slope factor

β = vegetation factor

f = infiltration on a flat ground surface

The effect of slope was equated as below:

$$\alpha = ((15 - \text{SLOPE}) / 15)^{1.5} + 0.2$$

where 15 was the maximum expected slope value

This produced an exponential curve (Fig 5.2) showing the slope factor inversely related to the slope index, whereby a maximum slope index of 15 produces a slope factor of 0.2.

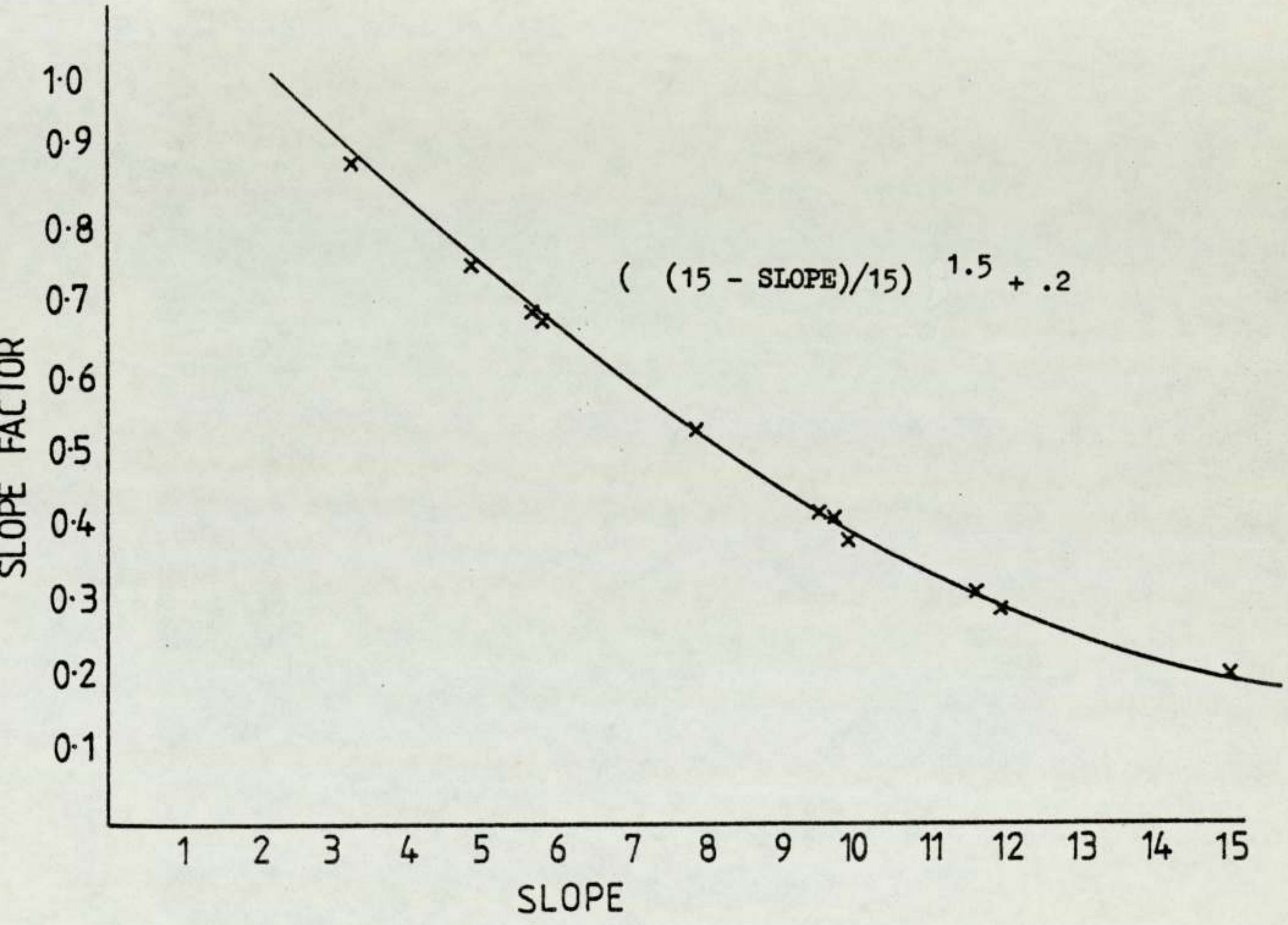


Fig 5.2 <u>Slope Factor</u>

The effect of forest vegetation was simply equated as

$$\beta = 1 + PF$$

where P is the proportion of forest in a catchment

The value of f was determined as shown in Chapter 2, and utilises minimum infiltration rate values determined using Soil Survey maps and the work of R.B. Painter (1971).

The effect of soil moisture upon infiltration was equated using two basic premises, that infiltration is theoretically at a maximum when soil is at wilting point, and at a minimum when soil is saturated (ss Fig 5.3). Between maximum (FMAX) and minimum (FMIN) infiltration is seen to reduce exponentially. Since overland flow is most important where soil moisture is in excess of field capacity, in the case of a soil moisture (SM) figure exceeding field capacity

$$f = \mathrm{FMIN} + C \left(\frac{\mathrm{SATSTR} - \mathrm{SM}}{\mathrm{SATATR}}\right)^2$$

where SATSTR - saturation to 75 mm in excess of field capacity

and when SM = wilting point

$$f = \mathrm{FMAX}$$

therefore $\mathrm{FMAX} = \mathrm{FMIN} + C \left(\frac{\mathrm{SATSTR} + \mathrm{AVMT}}{\mathrm{SATSTR}}\right)^2$

where AVMT - available moisture between wilting point and field capacity

therefore $(\mathrm{FMAX} - \mathrm{FMIN}) \;/\; \left(\left(\frac{\mathrm{SATSTR} - \mathrm{AVMT}}{\mathrm{SATSTR}}\right)^2\right) = C$

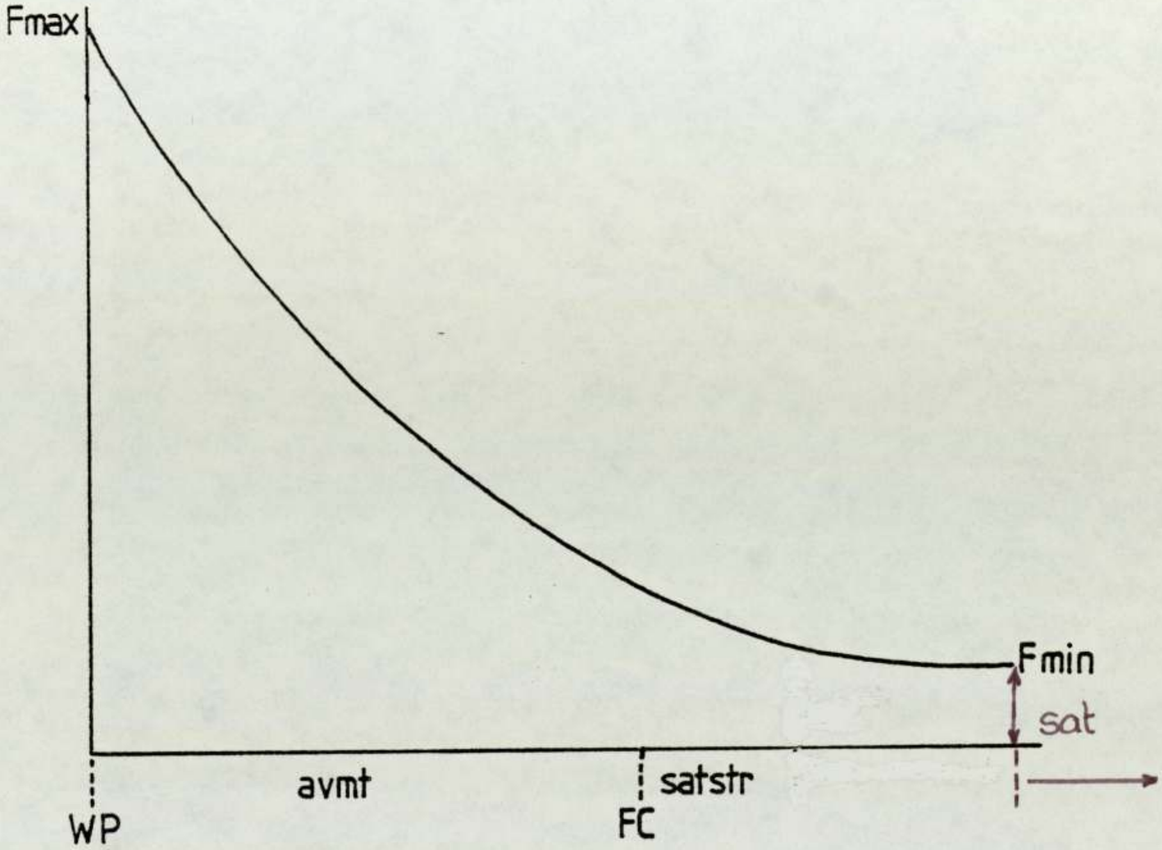
and

$$f = \mathrm{FMIN} + (\mathrm{FMAX} - \mathrm{FMIN}) \left(\frac{\mathrm{SATSTR} - \mathrm{SM}}{\mathrm{SATSTR} + \mathrm{AVNT}}\right)^2$$

and if FMAX = FMIN x 2

then $\mathrm{RCRIT} = \mathrm{FMIN}\left[1 + \left(\frac{\mathrm{SASTR} - \mathrm{SM}}{\mathrm{SATSTR} + \mathrm{AVMT}}\right)^2\right]$

RCRIT was incorporated into the model as above, and FMIN



WP - Wilting Point
FC - Field Capacity
avmt - Available Moisture
satstr - Saturation Store

Fig 5.3 Relationship between Soil Moisture and Infiltration was read into the program for each catchment. Overland flow was subsequently equated as

$$QF = C2\ (ALOG(C2/(a(RCRIT + b))) - 1.0) + A(RCRIT + b)$$

and $RMAX = C2/\ a - b$

therefore if $RCRIT \geq RMAX \quad QF = 0.0$

and $\text{Infiltration} = INF - QF$

where $INF = R - E + RSNM$

where $RSNM = \text{Snowmelt}$

RESULTS

Tables 5.2.1/ 9 compare the predicted monthly flows for each of the catchments and intermediate subcatchments using MODELQF (16 years rainfall input) with the average monthly flows obtained from the historical flow data. These results are shown graphically in figures 5.4.1/5

Discussion of Results Using MODELQF

The results of using MODELQF with the Welsh catchment data appear to show a general improvement from those obtained from MODELBASIC(see Table 5.3). Three principal factors are apparent from a review of the results.

i) The two lowland catchments, Lower Wye and Tenbury fit reasonably closely. However, in both cases, MODELQF tends to produce a fairly smooth curve which ignores eccentricities in the data visible around February - April. In the Lower Wye predicted flow values underestimated the actual value for March, whilst in Tenbury predicted values overestimated historical values for February and April.

ii) The predicted flow values of the upland catchments comprising Rhayader, Caban Coch, Vyrnwy, Upper Wye

Table 5.2.1 <u>Historical and Predicted Flow Values for MODELQF - Caban Coch</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	183.3	123.2	101.3	99.0	72.5	44.5	45.9	68.9	95.2	119.5	165.2	203.1	1321.6
	Predicted Streamflow (mm)	188.79	143.81	117.21	104.7	72.98	48.53	52.61	76.08	109.07	127.89	175.78	197.62	1415.07
	E	- 5.49	-20.61	-15.9	- 5.67	- .48	- 4.02	- 6.76	- 7.18	-13.87	- 8.39	-10.58	5.48	- 203.47
	Stan. Dev. - Historical (mm)	82.9	62.3	54.8	46.5	33.9	32.6	23.1	32.7	61.5	62.8	59.3	103.5	
	Stan. Dev. - Predicted (mm)	76.4	66.7	55.2	40.0	33.8	23.2	22.1	22.8	50.6	55.4	49.6	82.4	

Table 5.2.2 **Historical and Predicted Flow Values for MODELQF - Vyrnwy**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	176.1	125.8	113.9	107.5	87.5	45.9	55.7	81.2	112.7	134.3	179.8	205.3	1425.7
	Predicted Streamflow (mm)	180.6	144.89	117.97	106.59	85.22	56.25	63.53	80.90	118.89	137.92	186.38	201.65	1479.98
	E	- 4.5	-19.09	- 4.07	0.9	2.3	-10.35	- 7.83	0.3	- 6.19	- 3.52	- 6.58	3.65	-54.28
	Stan. Dev. - Historical (mm)	78.4	65.6	62.1	51.4	46.3	30.0	27.5	41.6	69.3	90.5	79.8	100.9	
	Stan. Dev. - Predicted (mm)	80.7	67.9	57.12	40.9	42.2	23.3	24.7	30.8	64.9	82.0	63.8	90.91	

Table 5.2.3 <u>Historical and Predicted Flow Values for MODELQF - Rhayader</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	161.5	117.2	87.6	93.7	64.3	37.2	41.5	59.2	76.2	104.6	147.7	183.6	1174.3
	Predicted Streamflow (mm)	164.06	122.8	93.01	84.54	59.12	35.31	36.0	48.12	81.88	103.09	152.4	175.85	1156.18
	E	- 2.55	- 5.58	- 5.44	9.21	5.19	1.94	5.54	11.06	- 5.67	1.48	- 4.64	7.19	17.73
	Stan. Dev. - Historical (mm)	75.4	60.3	42.6	48.5	33.7	23.4	22.1	26.8	46.5	60.7	63.2	91.1	
	Stan. Dev. - Predicted (mm)	67.5	57.5	38.2	37.2	35.2	27.1	48.2	15.7	51.8	58.4	55.4	83.1	

Table 5.2.4 <u>Historical and Predicted Flow Values for MODELQF - Upper Wye</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	127.7	92.9	68.3	58.8	46.1	22.4	17.1	23.1	39.4	63.0	98.4	125.9	783.1
	Predicted Streamflow (mm)	120.73	95.36	70.75	58.12	40.54	22.54	17.96	19.25	43.41	61.85	96.41	115.31	761.8
	E	6.07	- 2.46	- 2.45	0.68	5.56	- 0.14	- 0.86	3.85	4.01	1.15	1.99	10.59	21.3
	Stan. Dev. - Historical (mm)	57.1	50.4	33.2	32.8	26.2	14.9	13.6	13.1	34.3	54.8	52.1	60.2	
	Stan. Dev. - Predicted (mm)	35.2	36.8	21.5	20.1	19.9	10.2	8.9	10.5	32.4	46.1	39.8	46.7	

Table 5.2.5 <u>Historal and Predicted Flow Values for MODELQF - Upper Severn</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	94.3	70.4	57.2	47.6	37.7	17.8	16.8	22.2	30.2	48.3	76.5	102.6	621.6
	Predicted Streamflow (mm)	90.52	73.04	67.25	54.0	41.31	25.63	21.44	22.72	35.4	53.11	89.27	106.6	680.3
	E	3.78	- 2.64	-10.05	- 6.4	- 3.61	- 7.83	- 4.56	- .52	- 5.2	- 4.81	-12.77	- 4.0	58.7
	Stan. Dev. - Historical (mm)	44.9	34.2	24.8	24.0	21.3	10.1	13.5	11.4	18.6	36.6	41.2	58.3	
	Stan. Dev. - Predicted (mm)	37.51	37.0	23.9	16.6	26.2	9.7	11.9	12.9	27.1	36.4	36.2	43.1	

Table 5.2.6 <u>Historical and Predicted Flow Values for MODELQF - Mid Wye</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	77.2	62.6	50.9	35.4	33.8	23.9	20.1	13.7	11.9	28.8	39.3	61.9	459.5
	Predicted Streamflow (mm)	75.1	62.3	51.9	37.8	32.3	21.4	17.2	15.4	25.0	37.8	53.1	59.5	488.8
	E	2.1	0.3	- 1.08	- 2.4	1.5	2.5	2.9	- 1.7	-13.1	- 9.0	-13.8	2.4	-29.38
	Stan. Dev. - Historical (mm)	27.2	31.1	24.8	16.4	21.9	15.0	17.2	14.3	13.4	30.1	31.8	41.2	
	Stan. Dev. - Predicted (mm)	31.8	29.2	20.1	19.3	20.4	10.8	15.9	8.1	18.5	38.2	35.1	29.9	

Table 5.2.7 <u>Historical and Predicted Flow Values for MODELQF - Mid Severn</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	46.7	36.9	34.0	24.8	22.6	12.8	12.1	11.1	13.6	17.9	27.8	40.4	300.7
	Predicted Streamflow (mm)	41.8	35.34	26.14	18.25	14.3	7.54	6.05	4.72	8.31	12.98	24.0	33.51	232.9
	E	4.91	1.61	7.86	6.54	8.34	5.23	6.09	6.43	5.31	4.96	3.84	6.87	67.99
	Stan. Dev. - Historical (mm)	21.4	16.3	10.2	8.5	14.6	6.8	11.4	6.5	10.3	16.6	18.2	27.5	
	Stan. Dev. - Predicted (mm)	20.0	18.0	8.5	7.1	13.8	3.9	3.7	3.1	8.8	13.1	16.6	22.2	

Table 5.2.8 <u>Historical and Predicted Flow Values for MODELQF - Tenbury</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	67.2	50.3	47.1	30.6	28.7	13.7	11.5	9.4	12.5	24.1	39.7	52.8	387.6
	Predicted Streamflow (mm)	65.5	55.9	47.3	36.4	25.3	14.4	10.4	10.2	16.8	25.9	44.2	53.9	406.2
	E	1.7	- 5.6	- 0.2	- 5.8	3.4	- 0.7	1.1	- 0.8	- 4.3	- 1.8	- 4.5	- 1.1	-18.6
	Stan. Dev. - **Historical** (mm)	28.3	25.4	21.6	13.8	17.4	6.5	11.8	4.2	8.9	26.5	39.2	52.9	
	Stan. Dev.- Predicted (mm)	28.2	22.5	12.8	10.3	16.4	4.9	7.4	5.3	12.1	22.0	23.3	22.8	

Table 5.2.9 <u>Historical and Predicted Flow Values for MODELQF - Lower Wye</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	63.9	54.7	51.3	32.8	26.7	15.9	12.7	9.8	10.7	21.8	36.6	45.9	382.8
	Predicted Streamflow (mm)	60.49	52.7	43.31	32.33	22.87	13.77	10.08	7.4	10.87	17.83	31.94	42.9	346.49
	Σ E	3.41	2.0	8.0	0.47	3.83	2.13	2.62	2.4	- 0.17	3.97	4.66	3.0	36.31
	Stan. Dev. - Historical (mm)	28.5	27.0	22.1	13.5	11.4	8.2	14.7	5.3	6.2	27.8	34.4	28.9	
	Stan. Dev. - Predicted (mm)	21.3	21.8	12.1	12.4	8.1	3.95	2.6	1.7	4.4	12.6	18.8	20.2	

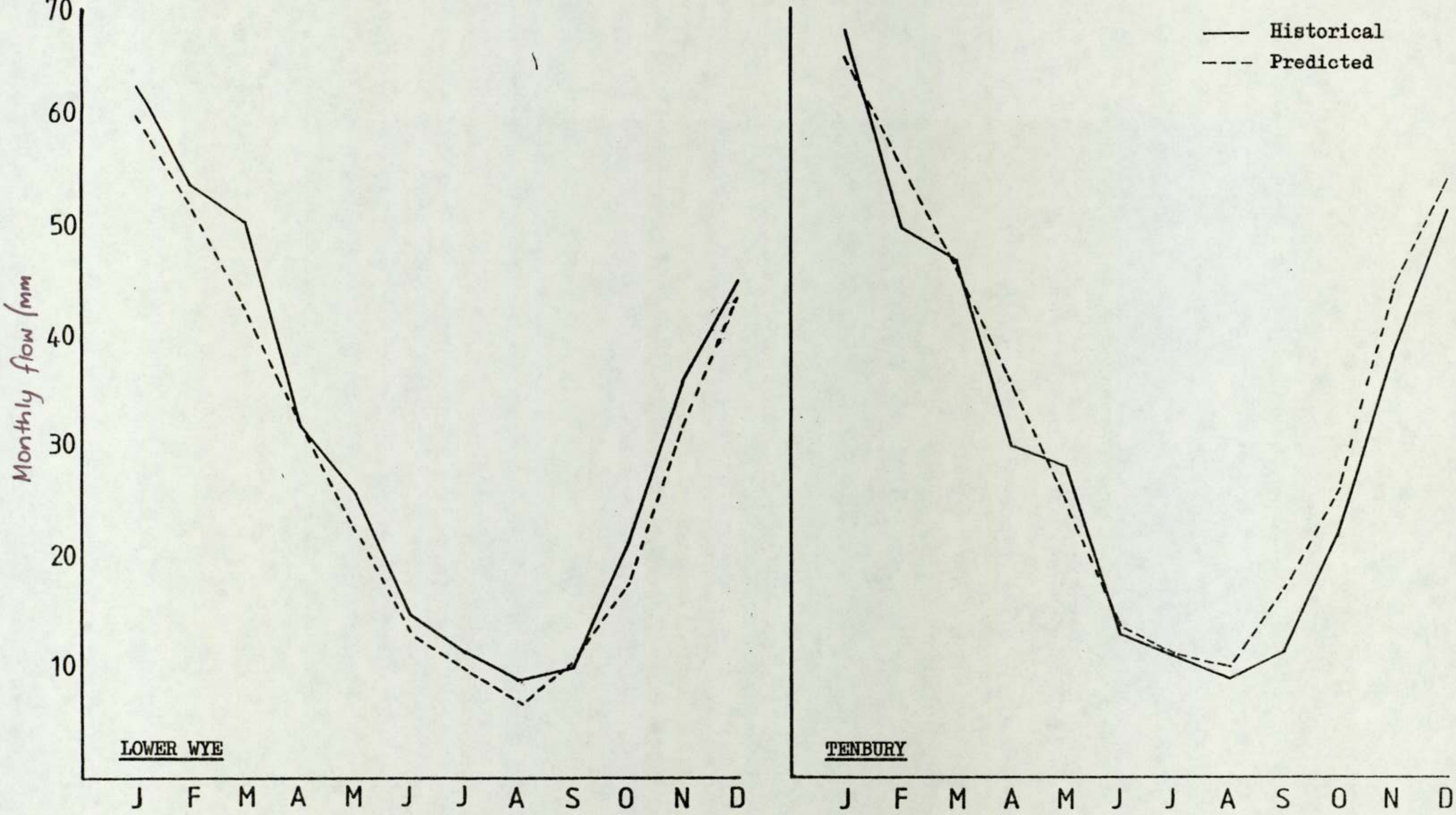


Fig 5.4.1 1960-75 - Monthly Mean Predicted Flow Values for 16 years using MODELQF

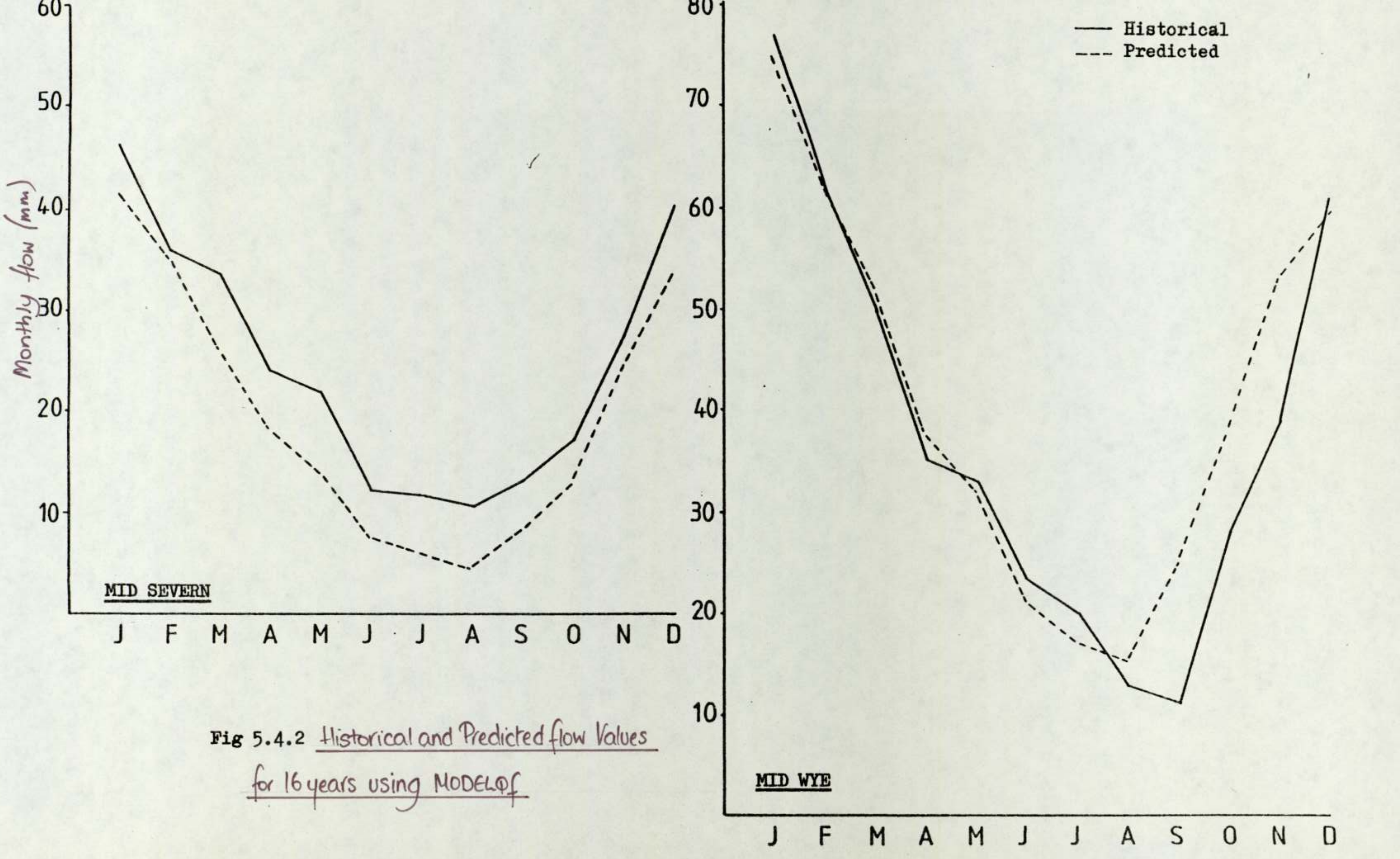


Fig 5.4.2 Historical and Predicted flow Values for 16 years using MODEL0f

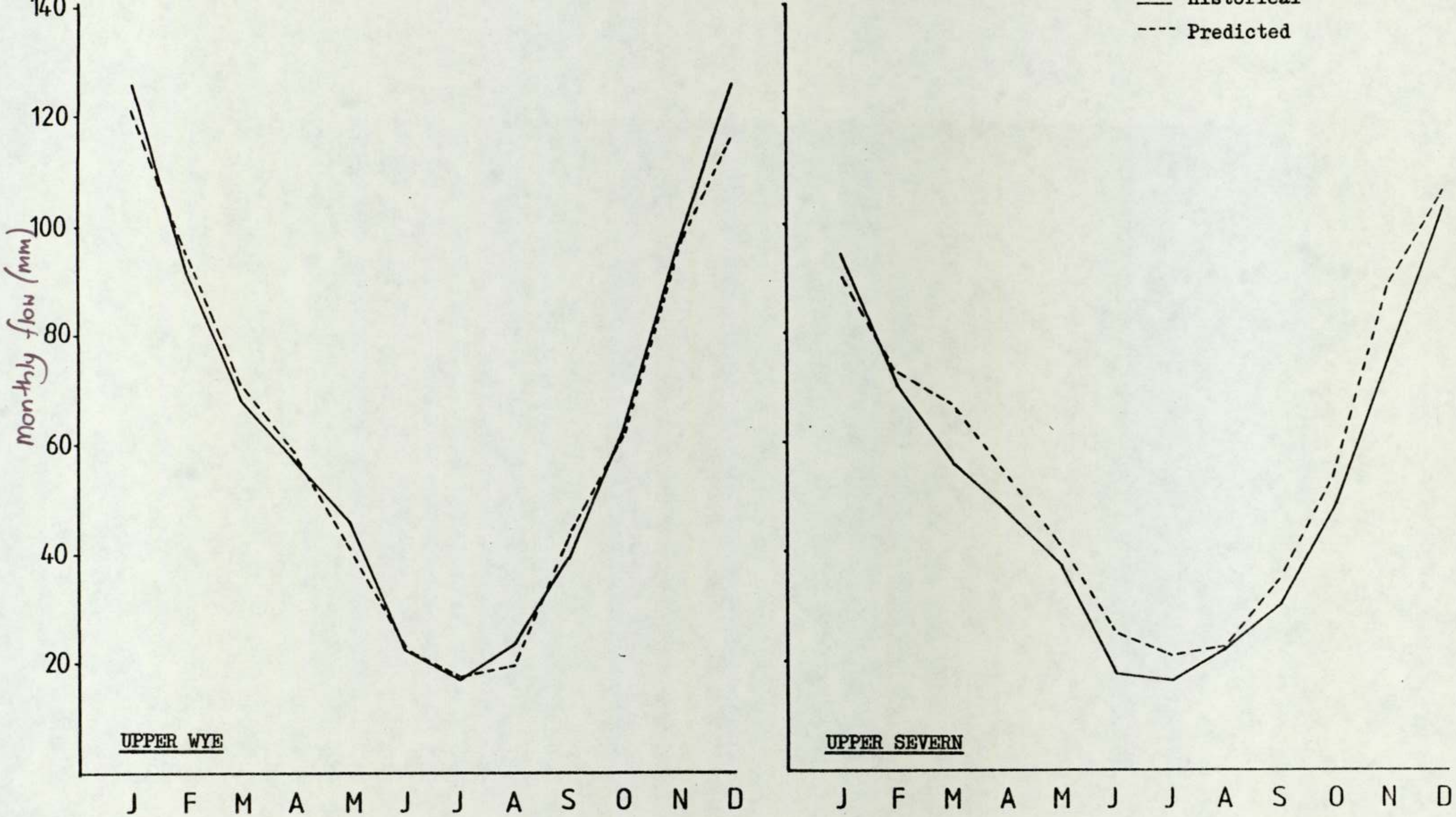


Fig 5.4.3 Historical and Predicted flow Values for 16years using MODELQf

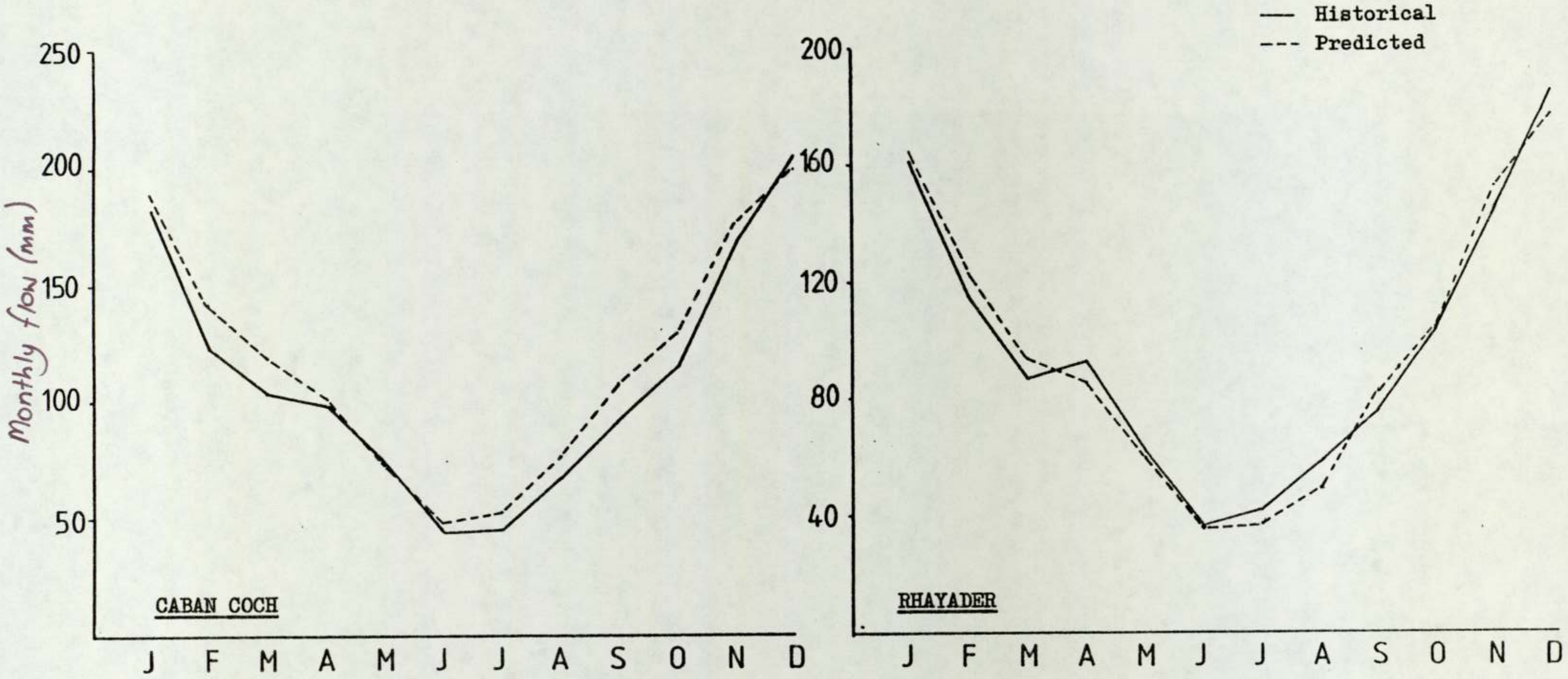


Fig 5.4.4 Historical and Predicted flow Values for 16 years using MODEL0f

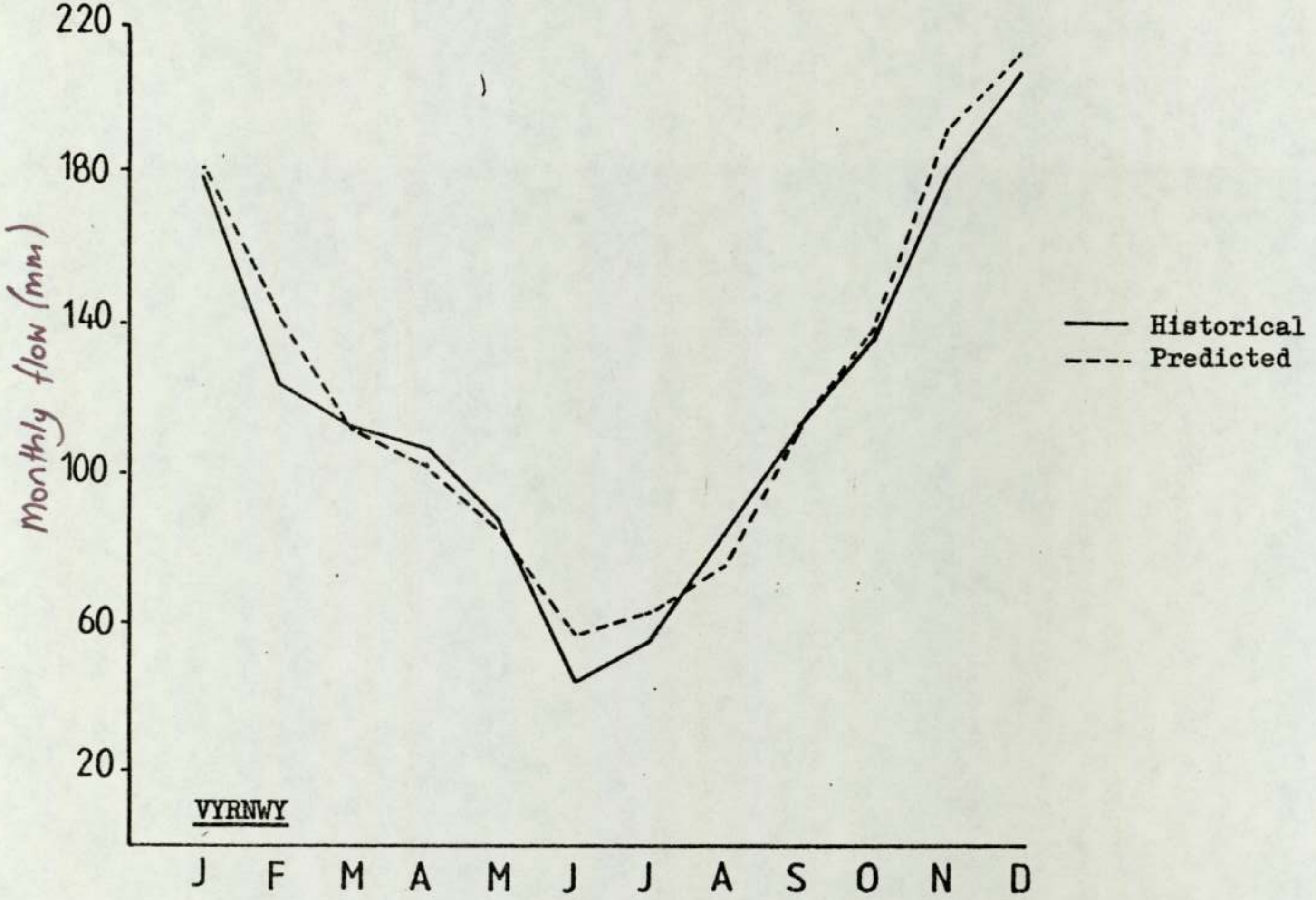


Fig 5.4.5 Historical and Predicted flow Values for 16 years using MODELQf

able 5.3 Sum of the Deviations for all MODELS

CHMENT	MEAN	BASIC	QF	MODELFAC		
				100	200	300
n Coch	103.8	117.9	104.6	101.2	87.8	95.1
vy	118.5	95.7	70.2	61.9	85.1	80.1
ader	230.0	15.1	65.5	85.3	53.2	61.3
r Wye	55.8	49.1	40.8	39.7	66.2	36.9
r Severn	67.6	56.7	66.2	72.3	69.7	76.6
Vye	98.0	55.9	52.8	70.6	42.8	73.6
Severn	71.9	68.0	67.9	69.2	69.4	69.3
ury	38.4	41.7	31.0	49.1	34.5	42.8
r Wye	37.1	49.3	36.6	42.1	41.9	65.4
ant	99.8					

and Upper Severn produced generally good fits. This is particularly true for the Upper Wye and Upper Severn. However, although predicted values for Caban Coch and Vyrnwy were a general overestimation of the historical, predicted flow values for Rhayader were a general underestimation. As with the Lowland catchments the results tended to produce a smooth curve ignoring eccentricities in the data, particularly in the April values for Rhayader. Nonetheless the predicted flow values did follow the general trends shown in the actual data.

iii) The predicted flow values for the Mid Severn continued to be values which underestimated actual flow values, whilst Mid Wye gave predicted flow values which were a close fit until August, but for September, October and November predicted flow values overestimated actual values by between 10 - 17 mm per month.

As shown by Table 5.3 the sum of the deviations were an improvement upon the results using MODELBASIC. Mid Severn continues to present problems, but this has already been discussed at length, and the problems remain the same. The Mid Wye subcatchment also exhibits problems, but the results have improved upon those using MODELBASIC.

The modification of the overland flow/interflow algorithm was expected to increase peak discharge values by allowing overland flow to occur during periods of soil moisture surplus, rather than increasing groundwater storage for later release as baseflow. This modification is therefore justified by the improvement in predicted discharge values for mid-land catchments including Upper Severn and Upper Wye. The results for the upland and lowland catchments did not exhibit such a marked change, however the modification clearly improved the capability of the model to accurately predict streamflow values.

Having considered the effect of soil saturation upon the relationship between quickflow and infiltration, it now seems pertinent to consider the effect of soil saturation upon interflow and natural recharge, since this may provide an answer to the problems of the Mid Wye.

5.4 MODIFICATION OF THE NATURAL RECHARGE/INTERFLOW ALGORITHM

5.4.1 INTRODUCTION

The proportions of surplus moisture which become natural recharge and interflow have previously been treated as constants. These constants were determined from calibration of the model using data from the Welsh catchments.

The conditions under which interflow occurs were discussed in Chapter 3, which considered the effect of soil saturation during rainfall events. When a perched saturated layer is formed in the soil body, water will escape both laterally as interflow and vertically as natural recharge. As the saturated layer grows in thickness the rate of interflow increases more rapidly than the rate of natural recharge because the saturated layer forms a barrier which reduces the flow of natural recharge and lateral movement is in the direction of greatest conductivity (Fig 5.5). This modification to the natural recharge/interflow relationship aims to take account of the degree of soil saturation and gives greater weight to the interflow component with increasing soil moisture content.

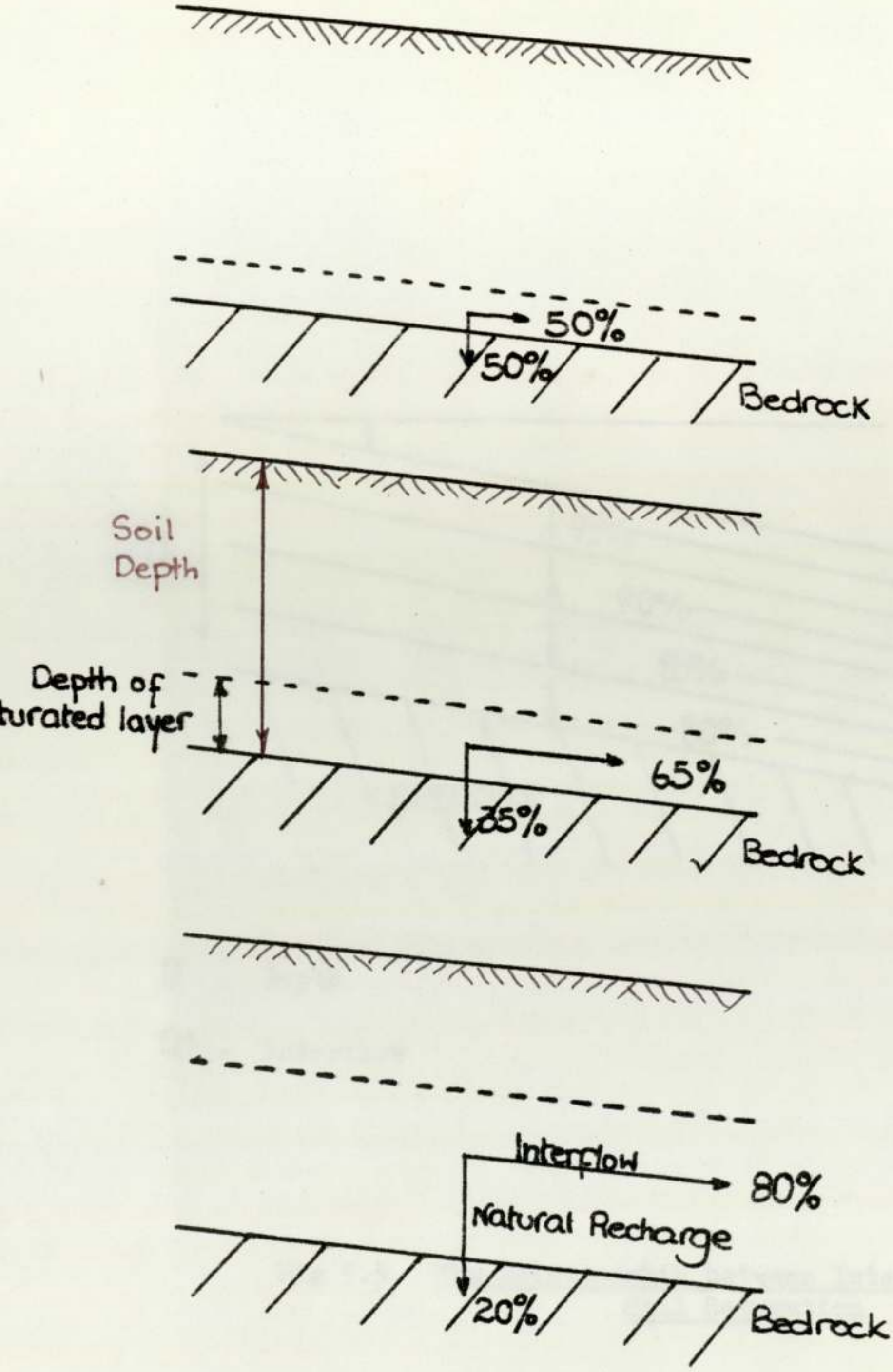


Fig. 5.5 Typical Relationship between the Depth of Saturated Layer and Natural Recharge / Interflow

5.4.2 The Proposed Natural Recharge/Interflow Algorithm

The monthly rate of interflow (QI) from a soil having a moisture surplus (SOILM) was assumed to be:-

$$QI = \frac{(SOILM)^2}{(SOILM + QIFAC)} \quad \text{(mm rainfall equivalent)}$$

where QIFAC is a constant to be determined by calibration

If the total amount of drainage during the months is unchanged from the previous model then:

$$\frac{QI + NR}{SOILM} = QICOEF + NRCOEF$$

where NR = monthly rate of natural recharge

therefore $NR = (QICOEF + NRCOEF)\ SOILM - QI$

Figure 5.6 shows the QI drainage rates for the various values of SOILM and QIFAC. This clearly illustrates how the proportion of interflow increases with increasing soil moisture surplus and demonstrates the effect which QIFAC has upon this relationship. This algorithm clearly achieves the purpose for which it was designed - to increase the proportion of quick response drainage as the soil moisture surplus increases.

When the interflow (QI) is removed from the soil moisture surplus (SOILM) the remaining surplus is available to become natural recharge (NR), thus

$$NR = NRFAC\ (SOILM - QI)$$

where NRFAC is the fraction of the remaining surplus which becomes natural recharge. Since there was no evidence to suggest that this needed modification, it was decided to retain the previously used proportion. Thus:

$$NRFAC = \frac{NRCOEF}{1 - QICOEF}$$

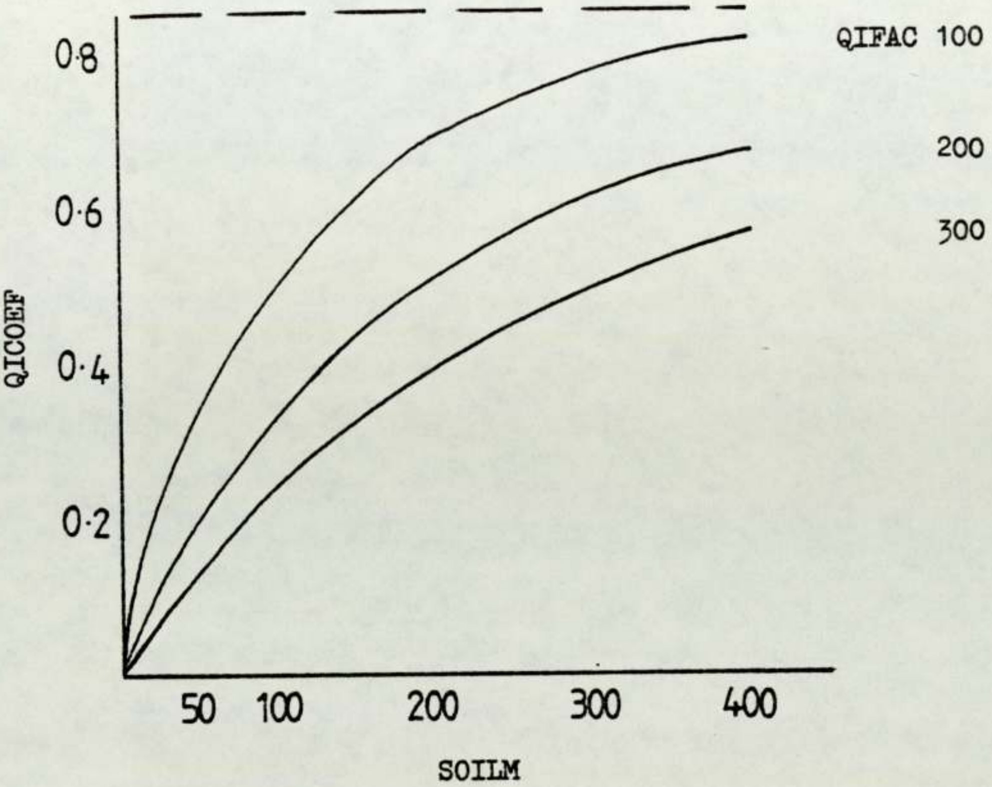


Fig 5.6 QI Drainage Rates for various Values of SOILM and QIFAC

5.4.3 Incorporation of the Modification into MODELQF

Since natural recharge and interflow only occur when soil moisture is in excess of field capacity, this modification comes into effect only when the monthly soil moisture value is in excess of field capacity and any overland flow has been removed. In this instance interflow (QI) and natural recharge (NR) are calculated as previously shown and

SOILM = SOILM - QI - NR

In the event that soil moisture is in excess of SATSTR (75 mm)

QI = QI + (SOILM - SATSTR)

and SOILM = SATSTR

5.5 RESULTS

Both catchment and subcatchment data were tested using MODELFAC and QIFAC values of 100, 200 and 300, with a view to finding the optimum values of QIFAC. Those catchments which produced the best results with a QIFAC value of 300 were subsequently tested with the values of 400 to discover whether the range of values should be extended.

5.5.1 Discussion of Results from MODELFAC

Each catchment exhibited similar results to those obtained using MODELQF and in some cases no improvement was discernible. Tables 5.4.1/9 and Figures 5.7.1/5 show predicted and historical flow values using MODELFAC. Three principal factors were highlighted by a review of the results.

i) The optimum values of QIFAC for upland and lowland catchments were found to be the reverse of what had been expected. It had been anticipated, from a purely theoretical standpoint, that upland areas would require low QIFAC values and lowland areas high values. In

Table 5.4.1 Historical and Predicted Flow Values for MODELFAC - Caban

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	183.3	123.2	101.3	99.0	72.5	44.5	45.9	68.9	95.2	119.5	165.2	203.1	1321.6
Predicted Streamflow 100 (mm)	195.46	142.06	111.11	99.74	67.47	45.4	49.07	70.32	108.15	128.34	185.25	210.36	1412.73
E	-12.16	-18.83	- 9.8	- .71	5.02	- .89	- 3.22	- 1.47	-12.92	- 8.83	-20.01	- 7.3	-91.3
Predicted Streamflow 200 (mm)	189.66	141.48	112.38	101.58	74.1	54.2	56.19	72.76	104.54	123.36	174.54	201.57	1406.4
E	6.39	-18.25	-11.07	- 2.55	- 1.61	- 9.69	-10.34	- 3.91	- 9.31	- 3.85	- 9.3	1.49	-84.8
Predicted Streamflow 300 (mm)	184.51	139.93	113.41	102.96	78.57	60.18	61.28	75.13	102.73	120.34	167.19	195.72	1401.9
E	- 1.24	-16.7	-12.1	- 3.93	- 6.08	-15.67	-15.43	- 6.28	- 7.5	- .83	- 1.95	7.34	-80.37
Stan. Dev. - Historical (mm)	82.9	62.3	54.8	46.5	33.9	32.6	23.1	32.7	61.5	62.8	59.3	103.5	
Stan. Dev. - Predicted 100 (mm)	82.6	65.4	55.8	36.2	29.4	20.1	16.8	17.2	45.3	61.2	54.3	92.5	
200	84.3	67.8	59.7	36.4	30.1	19.1	15.4	18.4	99.5	60.1	55.4	94.6	
300	79.5	61.6	54.4	33.0	27.7	18.3	13.5	15.9	44.2	55.8	51.1	90.0	

Table 5.4.2 Historical and Predicted Flow Values for MODELFAC - Vyrnwy

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	176.1	125.8	113.9	107.5	87.5	45.9	55.7	81.2	112.7	134.3	179.8	205.3	1425.7
Predicted Streamflow 100 (mm)	188.32	145.01	111.55	99.23	77.45	47.53	55.55	73.32	118.8	142.77	200.48	218.23	1478.24
E	-12.22	-19.21	2.55	8.27	10.05	- 1.63	.15	7.88	- 6.1	- 8.3	-20.68	-12.83	-52.07
Predicted Streamflow 200 (mm)	185.95	145.22	114.2	102.16	82.63	54.45	60.41	75.75	113.95	138.19	191.9	213.88	1477.69
E	- 9.85	-19.42	- .3	5.34	4.87	- 8.55	- 4.71	6.45	- 1.25	- 3.79	-12.1	- 8.48	-51.99
Predicted Streamflow 300 (mm)	183.58	143.86	112.34	102.15	85.01	58.29	63.41	75.88	112.99	136.33	190.23	212.6	1476.67
E	- 7.48	-18.06	- 1.56	5.35	2.49	-12.39	- 7.71	5.32	- .2	- 1.93	-10.43	- 7.2	-53.8
Stan. Dev. - Historical (mm)	78.4	65.6	62.1	51.4	46.3	30.0	27.5	41.6	69.3	90.5	79.8	100.9	
Stan. Dev. - Predicted 100 (mm)	94.5	79.0	67.6	42.1	45.2	23.3	24.7	32.1	73.4	98.1	79.9	113.6	
200	89.6	73.9	60.5	38.4	41.0	22.6	22.1	28.3	66.2	94.8	76.7	110.4	
300	90.7	74.8	60.3	36.4	38.9	21.9	19.6	26.9	64.7	94.8	79.8	112.7	

Table 5.4. <u>Historical and Predicted Flow Values for MODELFAC - Rhayader</u>

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	161.5	117.2	87.6	93.7	64.3	37.2	41.5	59.2	76.2	104.6	147.7	183.6	1174.3
Predicted Streamflow 100 (mm)	169.42	120.94	86.76	80.06	55.31	32.01	32.91	44.49	79.89	103.54	160.38	187.9	1153.6
E	- 7.91	- 3.72	.81	13.69	9.0	5.24	8.63	14.69	- 3.68	1.03	-12.62	- 4.26	20.9
Predicted Streamflow 200 (mm)	166.13	121.51	90.11	83.01	60.91	38.49	37.94	47.14	76.05	98.43	151.32	182.85	1153.89
E	- 4.62	- 4.29	- 2.54	10.74	3.4	- 1.29	3.6	12.04	.16	6.14	- 3.56	.79	20.57
Predicted Streamflow 300 (mm)	155.4	119.1	97.3	83.4	63.4	40.2	38.5	46.1	75.3	97.5	152	182.6	1150.8
E	6.1	- 1.9	- 9.7	10.3	.9	- 3.0	3	13.1	.9	7.1	- 4.3	1	23.5
Stan. Dev. - Historical (mm)	75.4	60.3	42.6	48.5	33.7	23.4	22.1	26.8	46.5	60.7	63.2	91.1	
Stan. Dev - Predicted 100 (mm)	76.3	61.4	41.2	31.8	34.6	17.3	15.4	13.9	49.7	65.4	64.1	98.2	
200	76.5	59.6	36.5	32.9	32.5	16.8	13.2	13.6	48.3	64.3	67.3	99.6	
300	75.2	58.3	35.0	33.1	29.2	15.6	14.3	13.3	48.6	63.1	66.5	100.8	

Table 5.4.4 Historical and Predicted Flow Values for MODELFAC - Upper Severn

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	94.3	70.4	57.2	47.6	37.7	17.8	16.8	22.2	30.2	48.3	76.5	102.6	621.6
Predicted Streamflow 100 (mm)	94.6	74.67	61.62	44.56	37.86	22.11	19.29	22.16	41.14	59.3	100.31	110.16	687.7
E	- .3	- 4.27	- 4.42	3.04	- .16	- 4.31	- 2.49	- .04	-10.94	-11.0	-23.81	- 7.56	-66.26
Predicted Streamflow 200 (mm)	92.69	76.12	64.73	49.39	42.97	26.62	22.57	23.77	38.88	55.07	91.8	103.9	688.5
E	1.61	- 5.72	- 7.53	- 1.79	- 4.27	- 8.82	- 5.77	- 1.57	- 9.68	- 6.77	- 15.3	- 1.3	-65.91
Predicted Streamflow 300 (mm)	91.48	77.02	66.65	52.28	44.35	29.13	24.39	24.72	57.79	52.74	86.83	100.01	707.39
E	- 2.82	- 6.62	- 9.45	- 4.68	- 6.65	-11.33	- 7.59	- 2.52	- 7.59	- 4.44	-10.33	2.59	- 85.79
Stan. Dev. - Historical (mm)	44.9	34.2	24.8	24.0	21.3	10.1	13.5	11.4	18.6	36.6	41.2	58.3	
Stan Dev. - Predicted 100 (mm)	39.4	34.6	30.2	13.8	22.0	8.6	9.2	10.2	22.1	35.8	39.3	45.9	
200	42.4	36.9	34.3	14.3	23.8	8.5	9.4	10.8	23.7	39.0	42.7	49.7	
300	47.4	41.5	41.6	15.6	27.3	8.6	10.0	12.3	27.2	43.7	48.1	55.0	

Table 5.4.5 Historical and Predicted Flow Values for MODELFAC - Upper Wye

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	127.7	92.9	68.3	58.8	46.1	22.4	17.1	23.1	39.4	63.0	98.4	125.9	783.1
Predicted Streamflow 100 (mm)	121.82	91.04	64.76	54.82	39.85	22.73	18.2	18.97	43.73	63.37	100.3	119.92	759.53
E	5.88	1.86	3.54	3.98	6.25	- .33	- 1.1	4.13	4.33	- .37	- 1.9	5.98	28.58
Predicted Streamflow 200 (mm)	123.27	87.95	60.03	51.21	36.09	19.39	16.18	18.24	47.26	67.43	106.96	124.73	758.7
E	4.43	4.95	8.27	7.59	10.01	3.01	1.08	4.86	7.86	4.43	8.56	1.17	24.4
Predicted Streamflow 300 (mm)	120.77	92.95	67.82	57.16	42.04	24.62	19.34	19.42	41.88	61.0	96.32	116.78	760.1
E	6.93	- .05	.48	1.64	4.06	- 2.22	- 2.24	3.68	- 2.48	2.0	2.08	9.12	23.0
Stan. Dev. - Historical (mm)	57.3	50.2	33.8	32.6	26.1	24.5	23.5	22.8	34.1	53.8	52.6	60.1	
Stan. Dev. - Predicted 100 (mm)	51.5	44.9	23.4	16.7	21.8	25.3	9.1	10.1	35.7	53.1	47.9	56.9	
200	50.9	43.2	22.5	17.8	21.0	16.3	9.3	9.9	34.2	52.2	46.1	55.3	
300	50.7	42.6	21.1	19.3	21.8	10.2	9.1	9.7	33.4	50.1	44.9	53.3	

Table 5.4.6 <u>Historical and Predicted Flow Values using MODELFAC - Mid Wye</u>

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	77.2	62.6	50.9	35.4	33.8	23.9	20.1	13.7	11.9	28.8	39.3	61.9	459.5
Predicted Streamflow 100 (mm)	80.86	58.65	47.8	35.12	29.57	18.88	16.9	13.63	25.62	43.43	57.58	62.39	490.43
E	- 3.7	3.98	3.09	.29	4.26	5.08	3.19	.11	-13.66	-14.62	-18.24	- .44	-30.66
Predicted Streamflow 200 (mm)	74.2	61.5	51.3	39.2	34.1	23.6	18.4	15.3	22.4	40.3	55.8	58.3	494.4
E	3.0	1.1	- 0.4	- 3.8	- 0.3	0.3	1.7	- 1.6	-10.5	-11.5	-16.5	3.6	-34.9
Predicted Streamflow 300 (mm)	73.09	59.83	51.45	41.21	35.13	25.17	21.1	17.11	24.27	38.24	50.22	56.1	492.92
E	4.07	2.8	-0.55	- 5.8	- 1.3	- 1.21	- 1.01	- 3.37	-12.31	- 9.43	-10.88	5.85	-33.42
Stan. Dev. - Historical (mm)	27.6	31.5	24.0	16.3	22.4	15.1	17.6	14.2	13.1	30.5	32.6	41.3	
Stan. Dev. - Predicted 100 (mm)	28.9	32.6	25.1	19.2	24.1	16.0	18.1	14.5	13.3	30.9	33.7	42.5	
200	29.1	33.8	26.5	19.6	25.3	17.4	19.2	14.8	15.6	31.5	35.2	43.1	
300	30.1	34.5	27.6	20.5	28.3	19.4	19.4	15.1	17.3	32.0	36.5	44.0	

Table 5.4.7 Historical and Predicted Flow Values for MODELFAC - Mid Severn

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	46.7	36.9	34.0	24.8	22.6	12.8	12.1	11.1	13.6	17.9	27.8	40.4	300.7
Predicted Streamflow 100 (mm)	43.42	32.29	23.25	16.38	14.66	7.02	5.68	4.42	8.84	13.99	25.87	35.9	231.72
E	3.29	4.66	10.75	8.41	7.98	5.75	6.46	6.73	4.78	3.95	1.97	4.48	69.15
Predicted Streamflow 200 (mm)	40.94	33.13	25.34	18.72	15.97	8.78	6.68	5.04	8.34	12.78	23.08	32.78	231.58
E	5.77	3.82	8.66	6.07	6.67	3.99	5.46	6.11	5.28	5.16	4.76	7.6	69.35
Predicted Streamflow 300 (mm)	39.61	33.62	26.5	19.95	16.62	9.68	7.2	5.38	8.09	12.17	21.69	31.15	231.66
E	7.1	3.33	7.5	4.84	6.02	3.09	4.94	5.77	5.53	5.77	6.15	9.23	69.27
Stan. Dev. - Historical (mm)	21.4	16.3	10.2	8.5	14.6	6.8	11.4	6.5	10.3	16.6	18.2	27.5	
Stan. Dev. - Predicted 100 (mm)	20.1	14.6	5.5	4.3	13.2	3.5	3.7	3.9	5.0	9.3	13.2	21.4	
200	22.3	15.8	7.2	6.1	15.4	3.2	3.9	4.6	5.8	13.0	15.2	23.4	
300	21.5	14.9	6.8	5.2	14.7	3.8	3.6	4.2	5.5	10.9	14.6	21.8	

Table 5.4.8 <u>Historical and Predicted Flow Values for MODELFAC</u> - TENBURY

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	67.2	50.3	47.1	30.6	28.7	13.7	11.5	9.4	12.5	24.1	39.7	52.8	387.6
Predicted Streamflow 100 (mm)	73.1	51.69	41.02	30.46	24.67	12.93	10.51	9.41	18.88	30.41	50.83	58.79	412.7
E	- 5.87	- 1.43	6.06	.16	4.0	.77	1.01	- .01	- 6.38	- 6.29	-11.13	- 5.95	-25.06
Predicted Streamflow 200 (mm)	68.62	52.93	43.56	34.06	27.79	16.58	12.88	10.93	17.98	27.93	45.69	54.42	413.37
E	- 1.39	- 2.64	3.52	- 3.44	.88	- 2.88	- 1.36	- 1.49	- 5.51	- 3.81	- 5.93	- 1.68	-25.63
Predicted Streamflow 300 (mm)	69.3	52.4	44.8	35.2	25.7	18.3	13.5	11.6	17.8	28.7	47.3	55.2	419.8
E	- 2.1	- 2.1	2.3	- 4.6	3.0	- 4.6	- 2.0	- 2.2	- 5.3	- 4.6	- 7.6	- 2.4	-30.0
Stan. Dev. - Historical (mm)	28.3	25.4	21.6	13.8	17.4	6.5	11.8	4.2	8.9	26.5	39.2	52.9	
Stan. Dev. - Predicted 100 (mm)	20.8	22.4	15.3	14.5	16.8	5.3	4.2	3.3	10.5	22.3	21.4	21.6	
200	21.4	23.6	15.2	13.1	17.3	4.5	4.4	2.9	11.6	22.5	24.1	30.3	
300	22.6	22.8	16.4	12.9	17.6	5.2	4.7	2.5	11.5	22.8	23.5	27.6	

Table 5.4.9 Historical and Predicted Flow Values for MODELFAC - Lower Wye

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	63.9	54.7	51.3	32.8	26.7	15.9	12.7	9.8	10.7	21.8	36.6	45.9	382.8
Predicted Streamflow 100 (mm)	65.08	49.38	38.89	28.79	21.2	12.44	9.21	6.87	10.87	20.02	35.49	45.31	343.57
E	- 1.12	5.34	12.4	4.05	5.55	3.45	3.47	2.95	- .2	1.87	1.15	.55	39.46
Predicted Streamflow 200 (mm)	65.09	49.35	38.88	28.78	21.2	12.43	9.2	6.87	10.81	20.04	35.51	45.31	343.49
E	- 1.19	5.35	12.42	4.02	5.5	3.47	3.5	2.93	.17	1.76	1.09	.59	39.61
Predicted Streamflow 300 (mm)	69.7	48.09	36.18	25.37	18.4	9.69	7.57	5.84	11.31	21.94	39.51	49.11	342.71
E	- 5.8	6.61	15.12	7.43	8.3	6.21	5.13	3.96	- .61	- .14	- 2.91	- 3.21	40.09
Stan. Dev. - Historical (mm)	28.2	27.5	22.4	13.5	11.43	8.2	14.7	4.3	6.2	27.8	34.4	28.9	
Stan. Dev. - Predicted 100 (mm)	28.2	25.3	13.3	11.2	11.4	4.0	4.0	2.9	8.8	23.9	28.6	25.5	
200	28.2	25.3	13.8	11.2	11.4	4.0	4.0	2.9	8.8	23.5	28.7	26.2	
300	32.4	27.9	16.8	12.3	13.5	3.0	4.2	3.6	8.2	27.7	30.9	28.6	

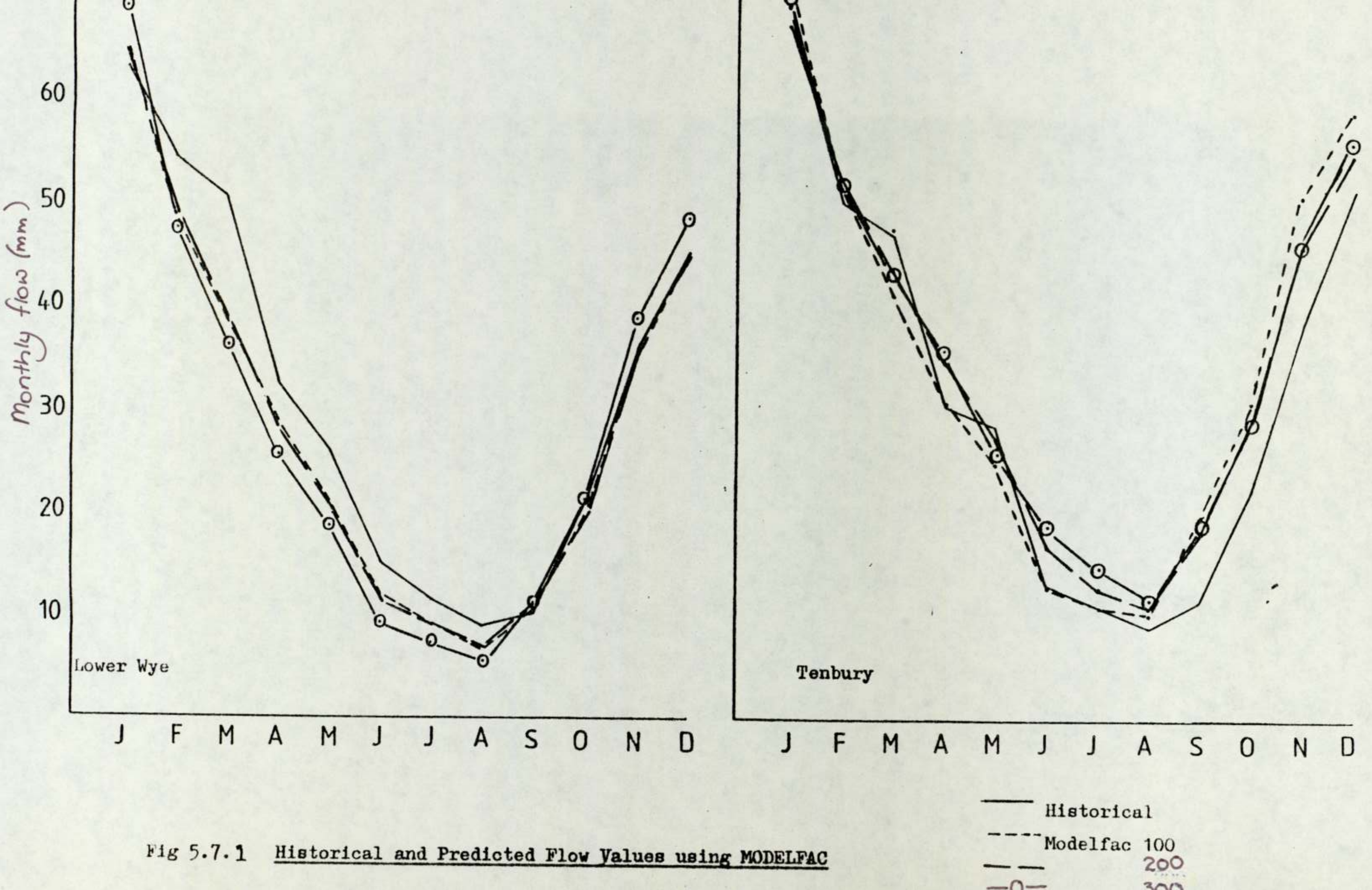


Fig 5.7.1 Historical and Predicted Flow Values using MODELFAC

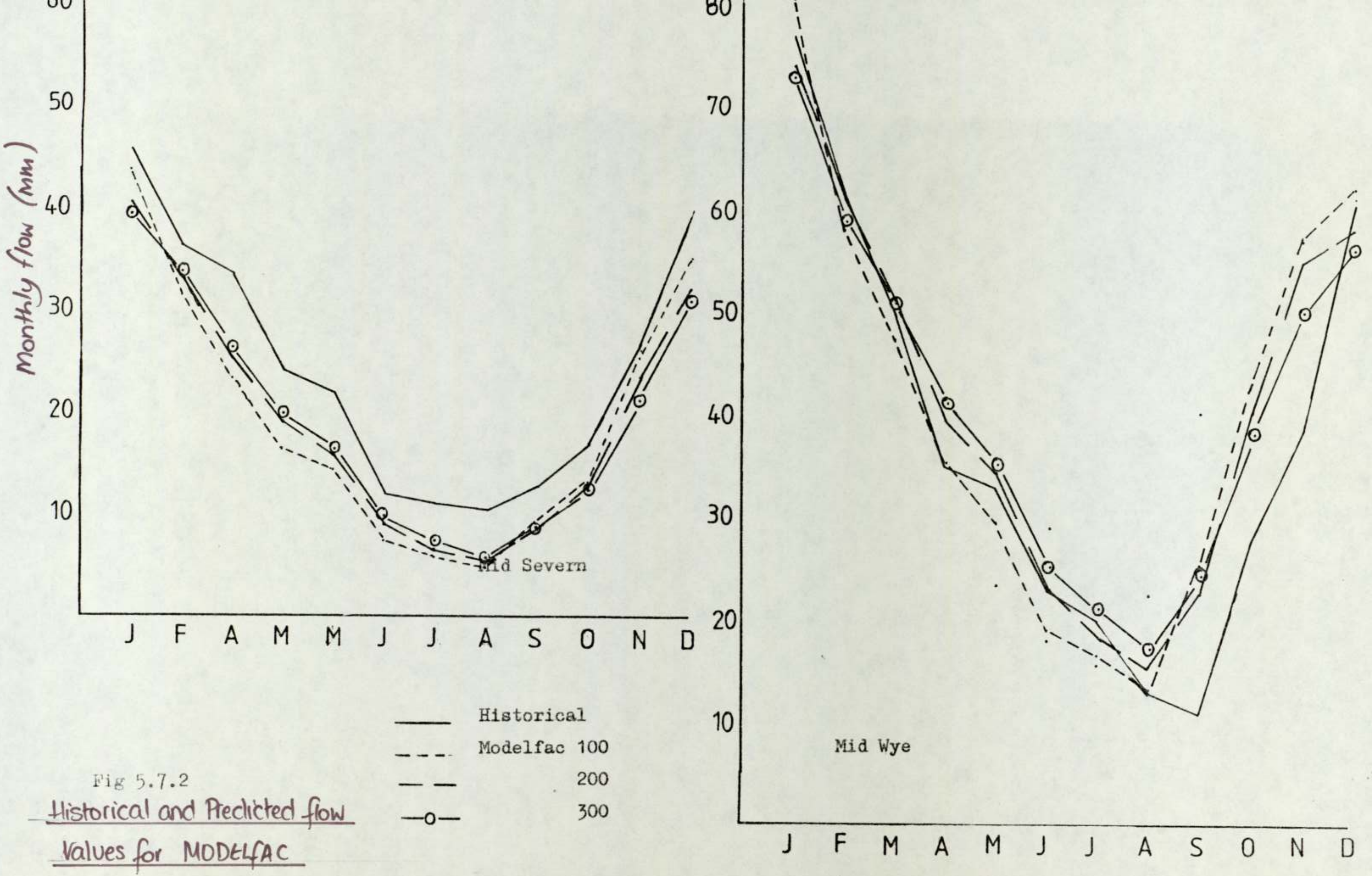


Fig 5.7.2

Historical and Predicted flow Values for MODELFAC

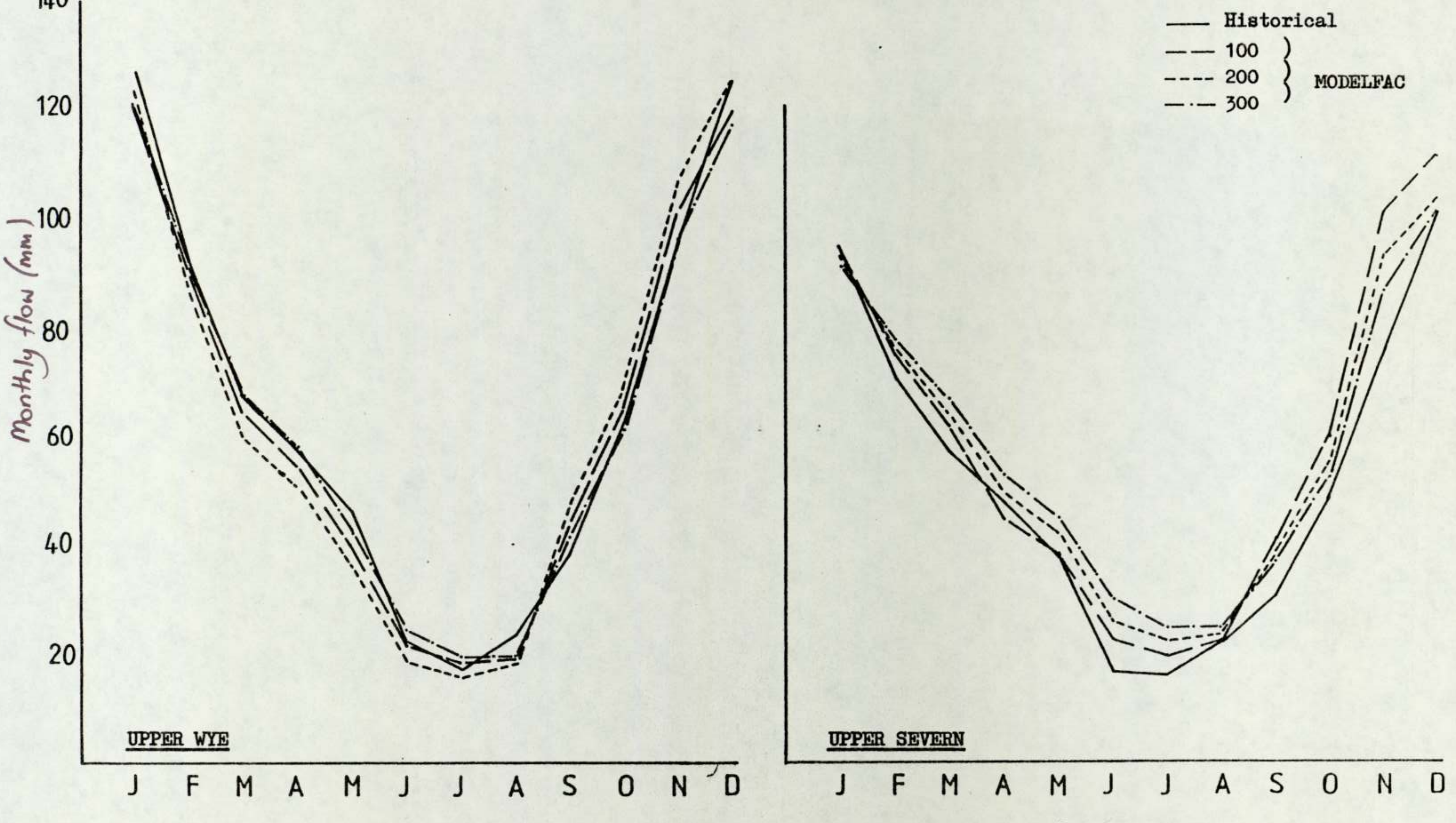


Fig 5.7.3 Historical and Predicted flow Values for MODELFAC

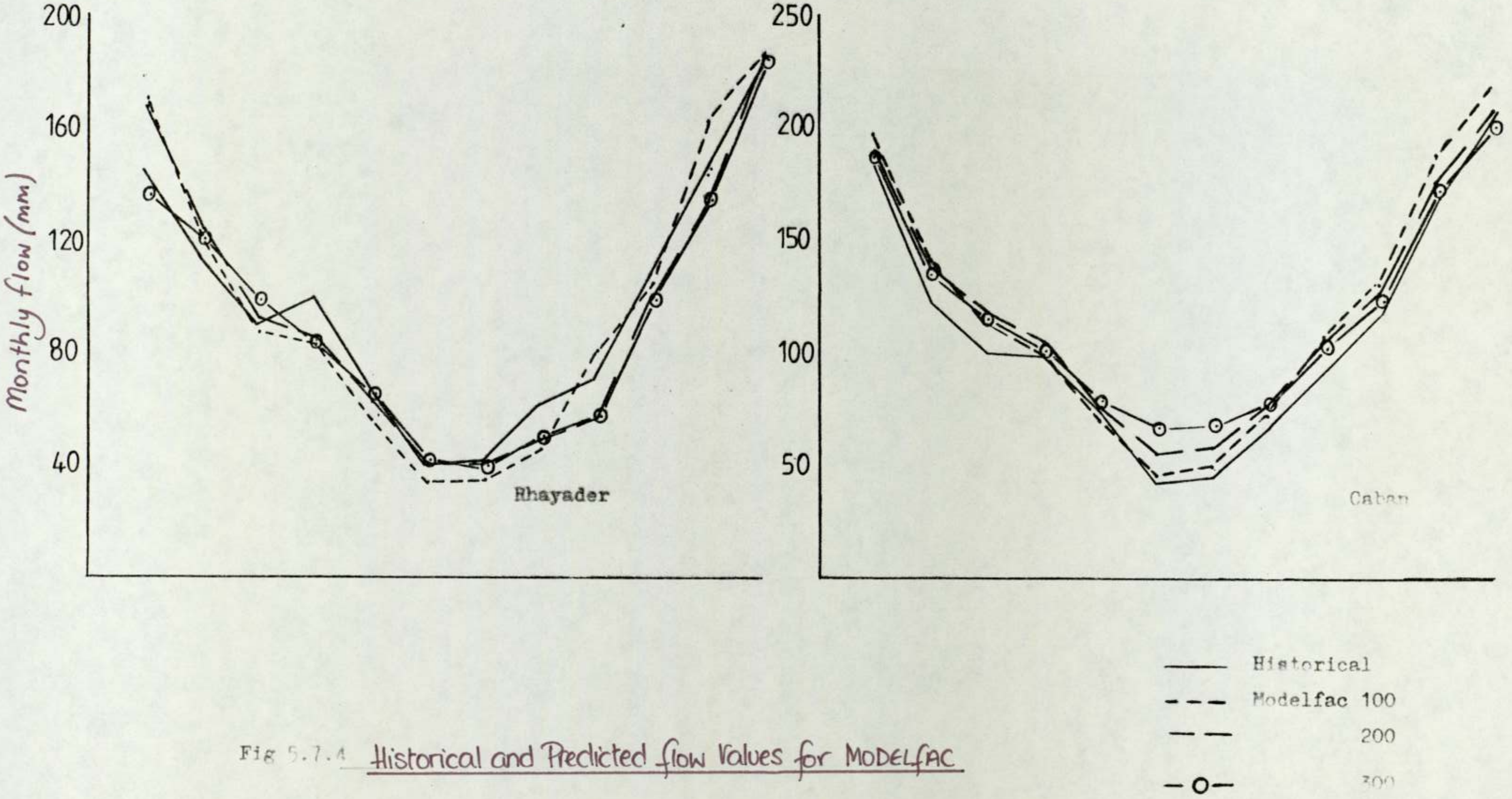


Fig 5.7.4 Historical and Predicted flow Values for MODELFAC

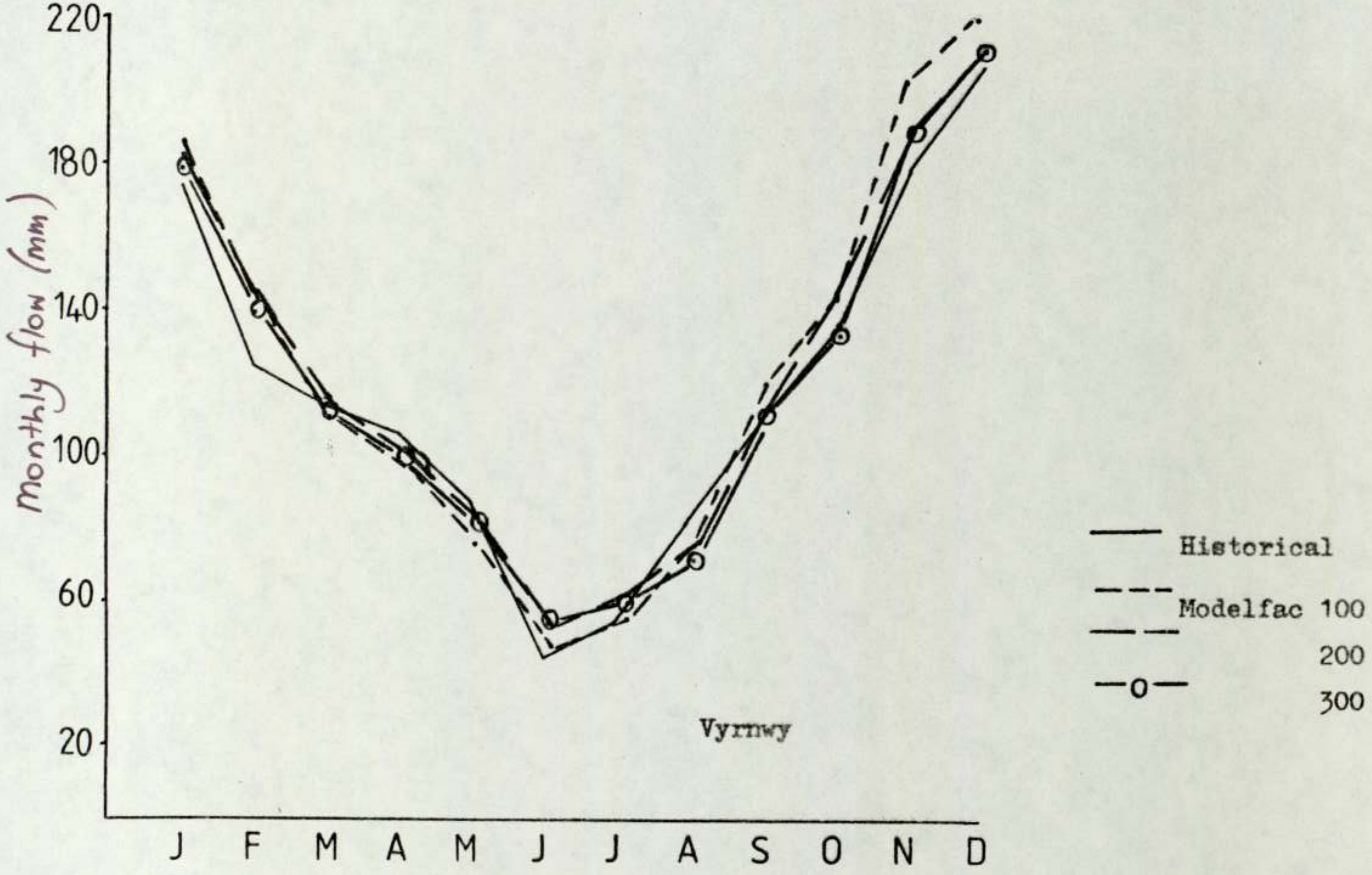


Fig 5.7.5 Historical and Predicted flow Values for MODELFAC

fact the best values of QIFAC were found to be 300 for upland catchments and 100 for lowland catchments.

ii) Although the results differed little from those obtained from MODELQF, all upland catchments showed an improvement in fit, except Upper Severn and Vyrnwy. Throughout the calibration of the catchment parameters, the values for Upper Severn were consistent with those of low and midland catchments, such as Tenbury and Lower Wye, which suggests that its name belies its catchment conditions.

iii) The similar lack of fit between real and synthetic data in the Mid-Severn and Mid Wye catchments continued, although the Mid Wye results did show signs of improvement.

It was expected that the proportion of interflow would be greatest in heavily saturated upland areas. However, the model proved this to be wrong. Lowland areas produced the best results using QIFAC values which ensured the greatest increase in the proportion of interflow. For upland catchments the predicted flow values using MODELFAC were generally an improvement upon those obtained from MODELQF, however lowland catchments produced better results using MODELQF (Table 5.3). This may possibly be because MODELFAC highlights a component of the hydrological system which is far less important to lowland than upland catchments. This may imply that MODELFAC is formulating a result to fit a theory which may not be applicable in this instance.

5.6 CONCLUSION

The predicted flow values determined using MODELQF are generally closer fitting results than those derived using MODELFAC. MODELFAC requires further investigation and although developed after MODELQF, it does not appear to improve upon it. The standard deviations of flow shown in Figs 5.8.1/4 follow a similar line to those derived from MODELBASIC. The deviations tend to be fairly close to the historical values and follow similar trends.

The validity of the models as a technique for flow prediction can only be fully understood when they have been tested in areas outside the original Mid-Wales study area. Therefore, it was necessary to find new areas in which to test the model and the various techniques for quantifying systems parameters.

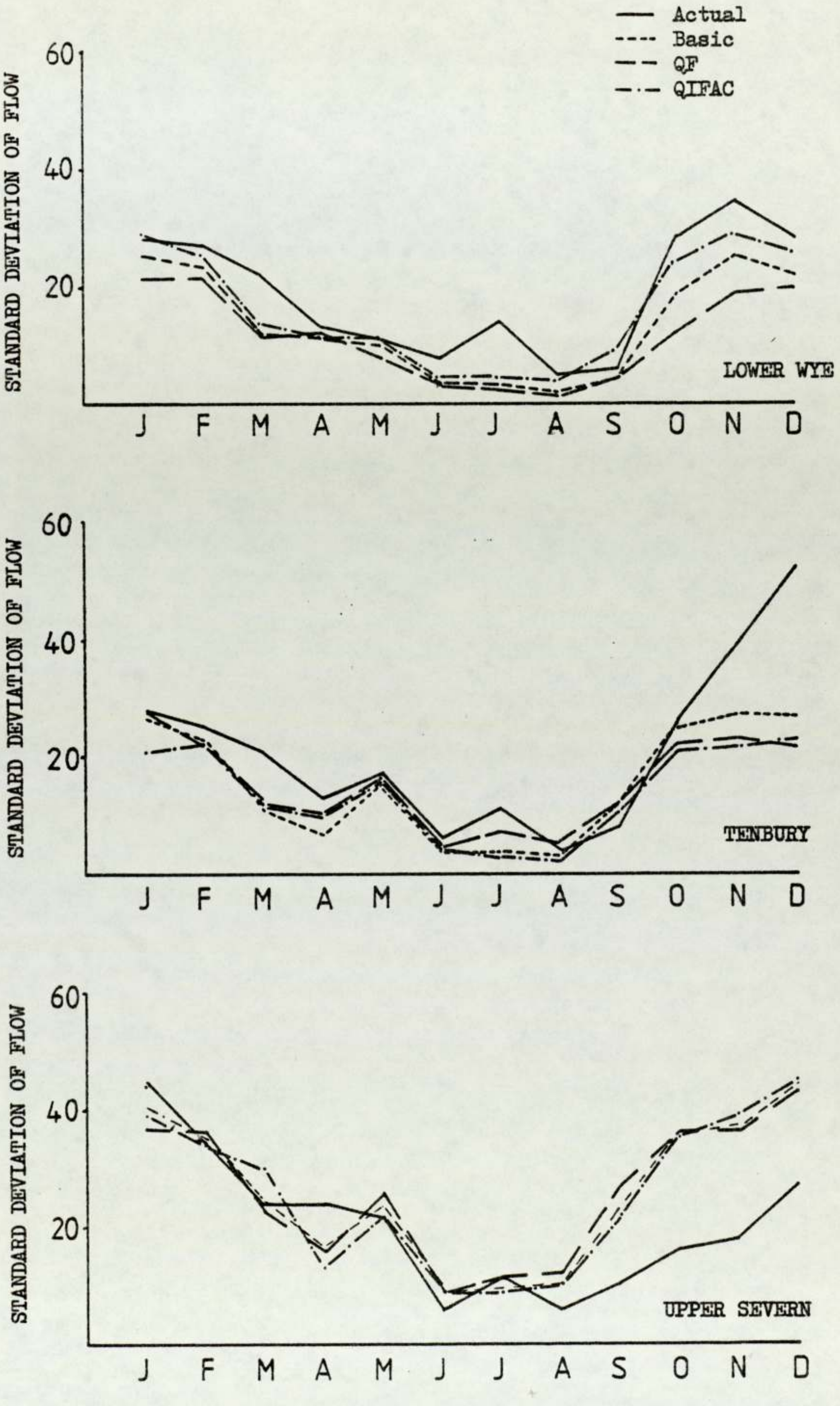


Fig 5.8.1 Standard Deviations of Actual and Predicted Flow 1960-75

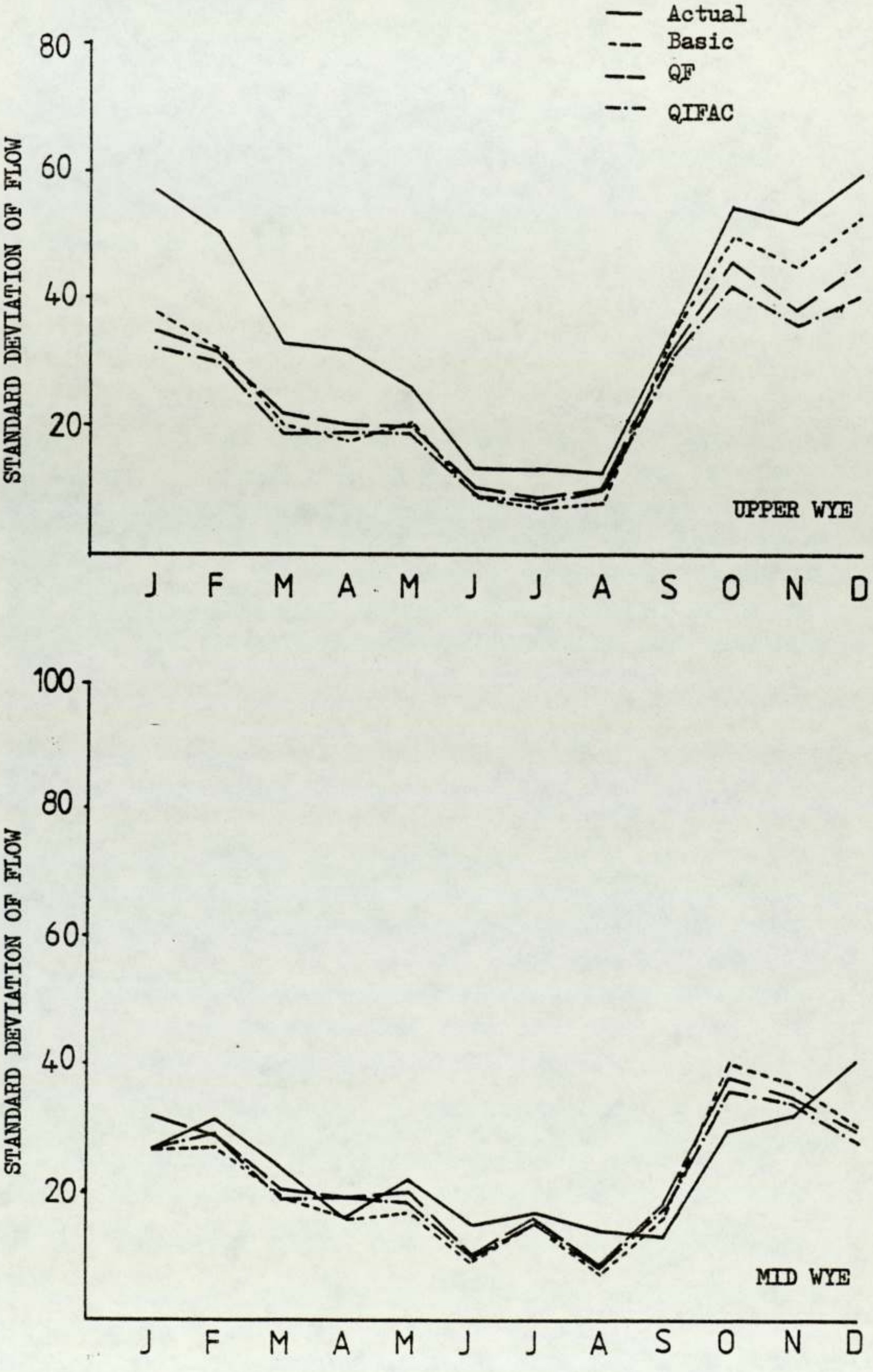


Fig 5.8.2

Standard Deviations of Actual and Predicted flows 1960-75

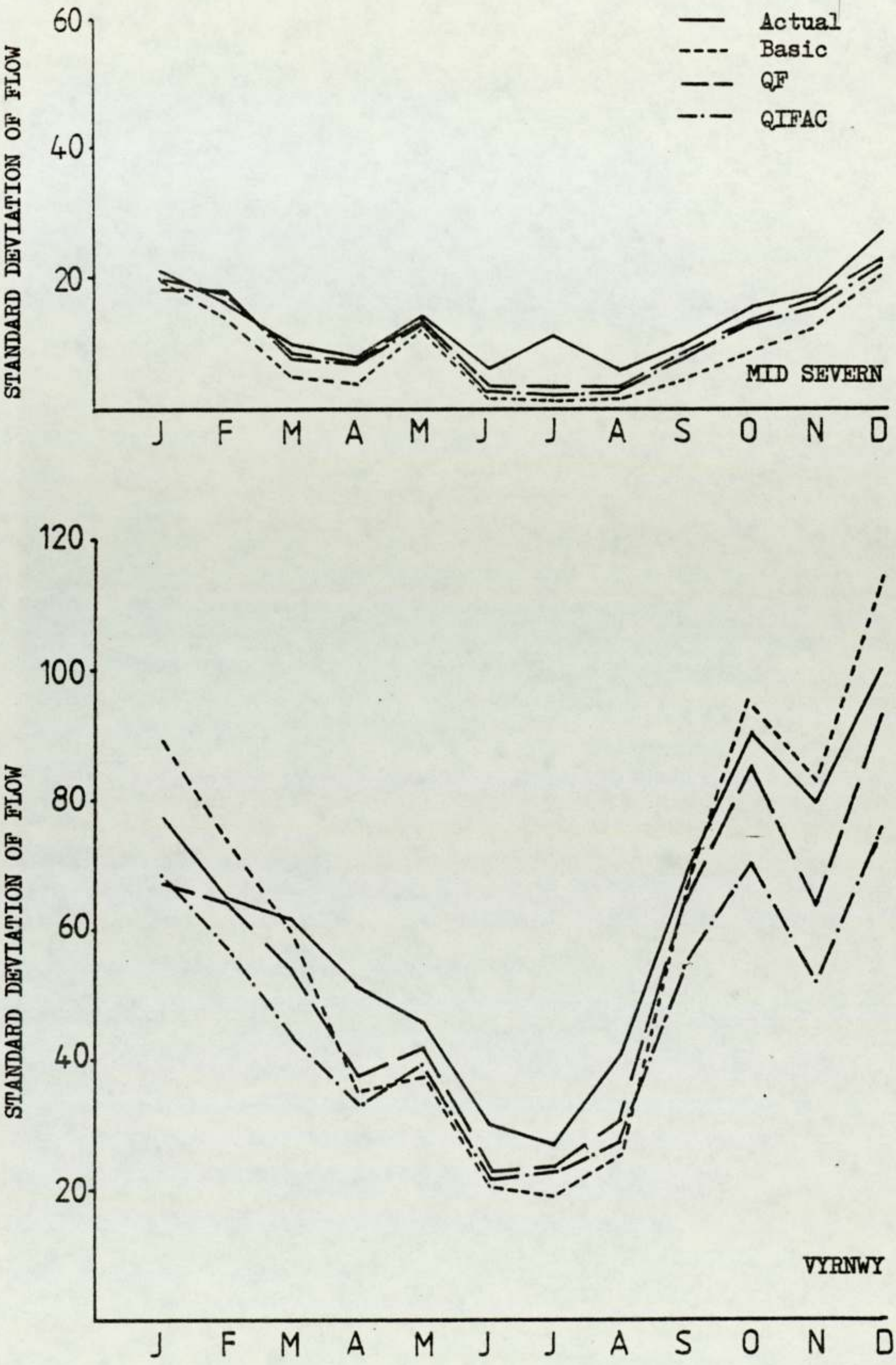
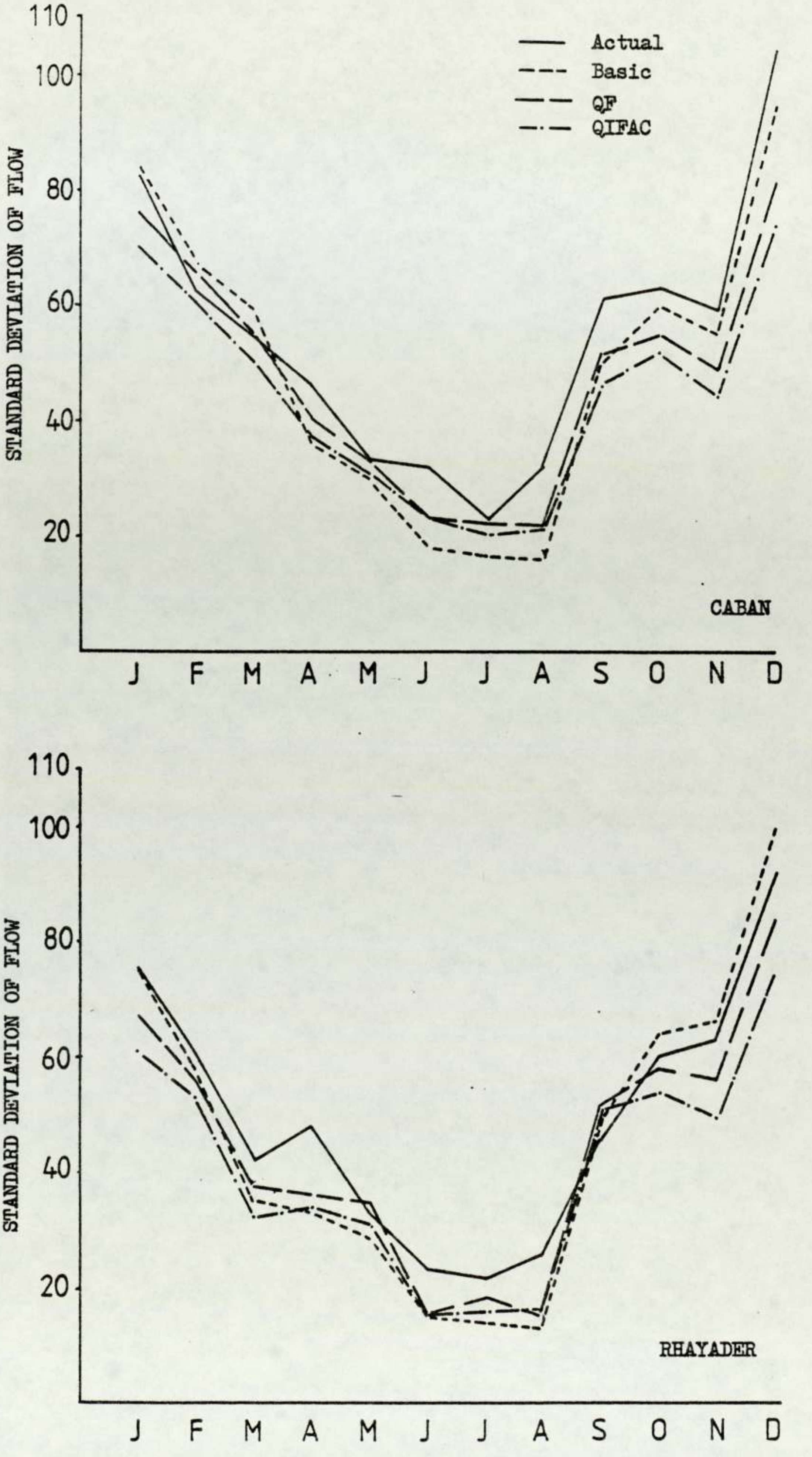


Fig 5.8.3

Standard Deviations of Actual and Predicted flows 1960-75



Standard Deviations of Actual and Predicted flows

Fig 5.8.4

1960-75

CHAPTER 6

EXAMINATION OF THE VALIDITY OF THE MODEL IN AREAS OUTSIDE MID-WALES

6.1 INTRODUCTION

The previous chapters outlined the design and development of the basic storage model. During calibration and testing of the model, data was used exclusively from the Mid-Wales, Welsh border region shown in Fig 4.14 It was, therefore, essential to examine the validity of the model and the derived calibration relationships for other regions of the U.K.

The Water Data Unit provided data for several catchments where naturalised flow data was available for a period in excess of 16 years, which was the time span previously used. Six catchments, each with reasonably reliable data were subsequently chosen, the Teifi and Towy in Wales, Spey in Scotland and the Nene, Isebrook and Stour in England.

This chapter reviews the basic storage model and its subsequent developments using catchment data from outside the Welsh region. Mention will be made of the catchments and the evaluation of the model parameters, results will be presented and conclusions discussed.

6.2 Input Data and Systems Parameters

Fig.4.14 and 6.1 and Tables 6.1.1 and 6.1.2 give details of the test catchments and their location in the British Isles. Flow and rainfall data for the Towy and Teifi covered the period 1960-75. as with other Welsh catchments, whilst data for the Nene and Stour covered the period 1948-63. Data for the River Spey was only available for 1951-60, the flow data was available for a longer period but rainfall data only matched the

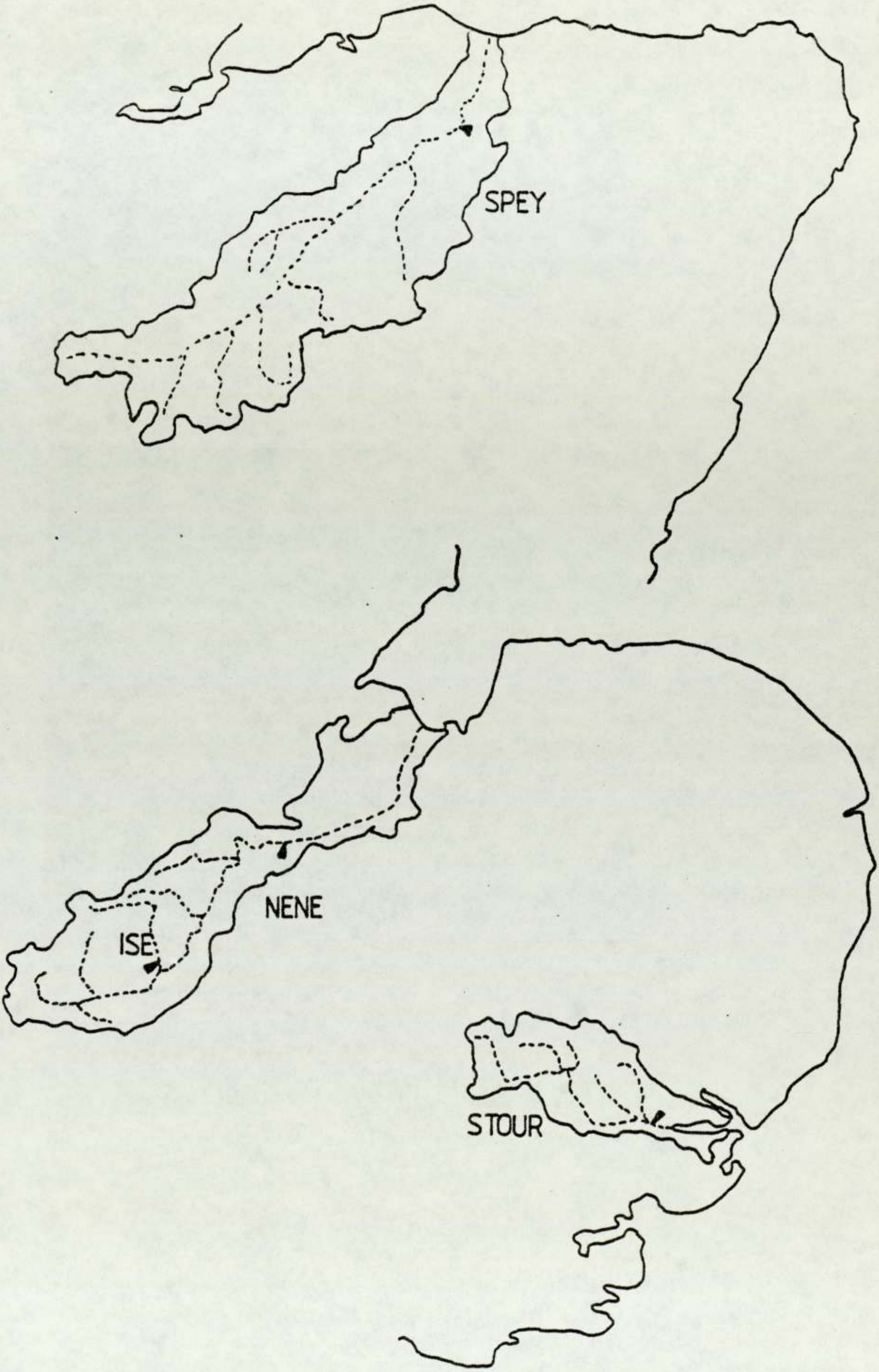


Fig 6.1 Location of Test Catchments

Table 6.1.1 **Systems Parameters**

Catchment	Gauging Station	Area (Km^2)	Discharge Coefficients				Slope	FMIN	Soil	DD	WR	BFI
			QI	NR	BF	PF						
Nene	Orton	1634.3	0.33	0.52	0.13	0.006	2.5	4.2	.346	.548	346.1	.535
Isebrook (Nene)	Harrowden Mill	195	0.33	0.52	0.23	0.005	2.6	3.5	.383	.5	360.1	.556
Stour	Stratford St. Marys	844	0.33	0.517	0.25	0.01	1.95	5.8	.379	.58	355.13	.485
Towy	Tycastell Farm	1090	0.492	0.358	0.34	0.09	9.2	3.2	.359	1.03	978.0	.461
Teifi	Glan Teifi	894	0.57	0.28	0.26	0.09	7.59	3.2	.321	1.9	843.3	.561
Spey	Aberlour	2650	0.503	0.347	0.15	0.2	13.96	4.2	.462	1.2	688.2	.596

Table 6.1.2 Systems Parameters

Catchment	Altitude Zone 1	Altitude Zone 2	Altitude Zone 3	Available Moisture Zone 1	Available Moisture Zone 2	Available Moisture Zone 3	Root Constant Zone 1	Root Constant Zone 2	Root Constant Zone 3
Nene	150	75	20	250	200	150	125	100	75
Isebrook (Nene)	150	100	40	250	200	150	125	100	76
Stour	100	50	20	250	200	150	125	100	75
Towy	400	250	100	125	115	100	65	55	50
Teifi	350	200	100	125	115	100	65	55	50
Spey	650	400	200	125	115	100	65	55	50

1951-60 period. Flow and rainfall data as used in MODELBASIC is tabulated in Appendix 4 whilst mean monthly rainfall, evaporation and temperature data as used in MODELMEAN are given in Tables 6.2.1 and 6.2.2.

Evaporation and temperature data was again based upon that from Bewdley and Hay-on-Wye respectively (Tables 4.10 and 4.11). Both sets of data were adjusted for use in the Model. Evaporation data was adjusted using annual evaporation figures from a nearby Meteorological Office recording station, whilst temperature data was adjusted using the average altitude of the three zones within each specific catchment.

The River Spey at Aberlour was the only Scottish catchment used in the study, and the data is markedly different from that recorded in England. Consequently the Meteorological Office was approached for rainfall and temperature records. They were unable to provide rainfall data, except for the annual and monthly mean rainfall (1941-70) at a number of Scottish stations, hovever, the N.E. River Purification Board were able to supply rainfall data for the period previously outlined.

The systems parameters including zonal altitude, AVMT, RTC, QICOEF, NRCOEF, BFCOEF, slope, drainage density, minimum infiltration and proportion of forest, used in the study of test catchments are given in Tables 6.1.1 and 6.1.2.

6.3 Results and Conclusions of Testing New Catchments with all MODELS

Each of the test catchments were run using the four models, MODELMEAN, MODELBASIC, MODELQF and MODELFAC. This, therefore, gave results using averaged data, and also monthly means over a period of 16 years using the basic storage model, and its

Table 6.2.1 <u>Mean Monthly Evaporation and Rainfall Values</u>

NENE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Evaporation (mm)	4.5	13.3	35.2	57.3	87.6	101.7	99.0	81.3	52.4	24.3	6.8	4.0	567.4
Rainfall (mm)	54.2	40.3	43.1	42.7	53.0	54.5	53.1	62.2	54.2	50.5	60.1	54.8	622.75
ISEBROOK (NENE)													
Evaporation (mm)	4.7	12.6	34.2	55.9	86.1	100.0	97.2	79.4	50.7	23.8	6.5	3.7	554.8
Rainfall (mm)	54.7	42.5	44.7	40.3	49.3	52.3	51.5	65.9	59.4	55.6	65.3	57.0	638.5
STOUR													
Evaporation (mm)	4.2	12.13	33.7	57.3	87.1	101.8	98.7	82.8	51.8	23.2	5.9	2.7	561.33
Rainfall (mm)	54.9	39.5	41.6	41.5	41.3	47.9	58.2	56.8	54.5	57.5	65.1	55.1	613.9

Table 6.2.2 Mean Monthly Evaporation and Rainfall Values

SPEY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Evaporation (mm)	6.1	10.1	27.5	53.4	76.9	87.5	85.4	67.1	44.0	23.6	12.1	7.8	501.5
Rainfall (mm)	104.1	89.9	72.6	69.0	50.6	77.7	92.2	113.3	102.5	115.8	109.8	127.8	1125.3
TOWY													
Evaporation (mm)	7	12	25	47	70	82	83	68	39	22	12	8	475
Rainfall (mm)	178.3	113.0	92.4	108.8	103.6	93.3	103.3	122.4	139.8	148.1	168.8	168.8	1540.6
TEIFI													
Evaporation (mm)	8	13	27	50	74	87	88	72	41	23	13	8	504
Rainfall (mm)	153.5	94.4	78.6	95.4	84.4	79.1	88.2	103.8	118.4	126.7	148.7	146.1	1317.3

subsequent developments.

6.3.1 Results using MODELMEAN and MODELBASIC

The results of MODELMEAN and MODELBASIC run for each of the test catchments are shown in Tables 6.3.1/6 and illustrated in Figs 6.2.1/3. The six catchments fall into two categories, three upland and three lowland catchments. The results exhibited three principal features and expressed the relationship between catchment types, similarities being discernible between upland and lowland catchment results. However, the Spey at Aberlour was slightly different since it was the only Scottish upland catchment, and showed different characteristics to those of the Welsh upland regions. The three principal features shown by the results are:

i) The Towy and Teifi catchment data predicted streamflow values which were very similar to the historical values, using both MODELMEAN and MODELBASIC. In particular the predicted values for the Towy produced a very close fit with the historical values when using MODELBASIC. However, using MODELMEAN the predicted values were not a close fit in the spring and early summer, and this was also true using both models for the Teifi. In both the Towy and Teifi MODELMEAN did not account for the similarity in historical discharge values for March and April, but tended to produce a simple curve of predicted values which did not account for eccentricities in the data. The difference in spring and summer predicted values was far more marked for the Teifi than Towy, where both January and December historical values were underestimated. This

Table 6.3.1 Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Towy

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	165.15	114.27	84.55	82.56	66.12	41.38	37.57	55.51	72.79	103.77	134.76	165.72	1124.15
	Predicted Streamflow (mm)	160.32	119.08	86.79	73.56	50.07	30.37	28.34	43.29	80.84	107.69	136.46	148.48	1065.3
	E	4.83	4.81	- 2.24	9.0	16.05	11.01	9.03	12.22	- 8.05	- 3.92	- 1.7	17.24	58.66
MODELBASIC	**Predicted Streamflow (mm)**	160.52	121.97	91.47	80.01	58.35	41.05	35.92	49.68	80.19	106.78	136.58	148.67	1111.19
	E	4.63	- 7.7	- 6.92	2.55	7.77	0.33	1.65	5.83	- 7.4	- 3.01	- 1.82	17.05	12.96
	Stan. Dev. - Historical (mm)	75.2	57.5	37.1	35.8	32.2	28.9	22.7	25.0	51.3	76.9	57.6	75.2	
	Stan. Dev. - Predicted (mm)	59.1	53.1	25.7	27.8	25.7	21.3	18.2	19.0	44.3	63.9	40.8	54.7	

TABLE 6.3.2 Historical and Predicted Flow Values for MODELMEAN AND MODELBASIC - Teifi

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	145.09	102.03	75.02	72.51	63.01	33.88	30.86	45.24	57.49	93.08	119.74	148.18	991.31
	Predicted Streamflow (mm)	133.12	94.93	67.62	56.6	31.13	17.84	15.66	26.55	50.73	83.7	113.32	123.63	814.89
	E	11.97	7.1	7.4	15.9	31.88	21.04	15.2	18.69	6.76	9.38	6.42	24.55	176.3
MODELBASIC	**Predicted Streamflow (mm)**	133.08	97.22	70.77	61.77	37.89	26.82	22.56	31.83	58.14	84.06	115.59	125.65	865.38
	E	12.01	4.81	4.25	10.74	25.12	12.06	8.3	13.41	- .65	9.02	4.15	22.53	125.75
	Stan. Dev. - Historical (mm)	65.2	44.3	34.1	27.0	25.2	30.3	21.7	25.4	47.8	66.4	47.6	59.3	
	Stan. Dev. - Predicted (mm)	50.9	43.2	38.3	24.8	16.3	13.7	11.0	14.4	38.3	50.3	37.9	41.7	

Table 6.3.3 Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Nene

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	**Historical Streamflow (mm)**	27.74	28.02	22.53	14.79	10.12	5.63	4.97	4.56	4.78	7.13	14.48	21.45	166.2
	Predicted Streamflow (mm)	23.38	20.12	12.79	7.22	6.16	5.26	4.49	3.85	3.30	2.83	6.08	11.73	107.21
	E	4.36	7.9	9.74	7.57	3.96	0.37	0.48	0.71	1.48	4.3	8.4	9.72	59.01
MODELBASIC	**Predicted Streamflow (mm)**	24.44	22.09	18.25	11.01	8.88	7.71	6.50	6.08	5.85	8.33	14.31	19.21	152.4
	E	3.3	5.93	4.28	3.78	1.24	- 2.08	- 1.53	- 1.52	- 1.07	- 1.2	.17	2.24	13.7
	Stan. Dev. - Historical (mm)	17.71	15.82	14.87	10.52	9.46	4.36	7.16	4.83	6.06	8.79	13.71	19.85	
	Stan. Dev. - Predicted (mm)	13.39	11.63	10.1	5.48	4.31	3.59	3.91	2.69	2.83	8.71	11.12	11.71	

Table 6.3.4 Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Isebrook

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	35.88	32.56	26.69	17.66	12.76	7.76	6.7	5.68	5.35	9.82	21.49	26.29	208.64
	Predicted Streamflow (mm)	30.97	27.14	18.09	9.09	6.56	4.79	3.53	2.63	1.97	1.49	8.45	17.66	132.37
	E	4.91	5.42	8.6	8.57	6.2	2.97	3.17	3.05	3.38	8.33	13.04	8.63	76.27
MODELBASIC	**Predicted Streamflow (mm)**	28.23	26.03	21.35	12.71	9.54	6.72	5.33	4.22	4.0	6.81	16.71	23.88	165.53
	E	7.65	6.53	5.34	4.95	3.22	1.04	1.37	1.46	1.35	3.01	4.78	2.41	43.11
	Stan. Dev. - Historical (mm)	20.91	16.9	11.4	5.7	5.2	3.1	2.5	1.9	2.1	9.2	18.4	16.4	
	Stan. Dev. - Predicted (mm)	35.3	32.1	26.3	15.9	12.5	7.2	6.0	4.8	4.9	9.5	21.3	26.2	

Table 6.3.5 <u>Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Stour</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	20.98	19.15	15.72	9.11	5.62	3.59	3.22	3.29	3.71	5.38	11.37	15.19	116.33
	Predicted Streamflow (mm)	18.51	16.65	12.24	6.75	4.4	3.6	2.55	2.45	3.21	7.42	13.13	16.45	107.36
	E	2.47	2.50	3.48	2.36	1.22	- 0.01	0.67	0.84	0.50	- 2.04	- 1.76	- 1.26	8.97
MODELBASIC	Predicted Streamflow (mm)	19.81	17.10	13.16	8.07	5.20	3.86	3.48	3.65	3.82	6.73	12.01	14.61	110.87
	E	1.17	2.5	2.56	1.04	0.42	- 0.27	- 0.26	- 0.36	- 0.11	- 1.35	- 0.64	0.58	8.65
	Stan. Dev. - Historical (mm)	10.3	7.13	7.54	5.02	1.76	2.48	1.95	2.03	2.90	8.75	11.04	11.12	
	Stan. Dev. - Predicted (mm)	10.29	7.92	8.76	5.22	2.10	2.22	2.75	2.31	3.49	8.91	11.64	11.02	

Table 6.3.6 Historical and Predicted Flow Values for MODELMEAN and MODELBASIC - Spey

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELMEAN	Historical Streamflow (mm)	76.17	71.83	61.51	55.29	43.38	33.08	39.18	51.65	42.69	61.02	63.9	83.8	683.5
	Predicted Streamflow (mm)	25.92	21.06	179.56	55.63	31.1	22.3	22.4	31.84	41.59	61.24	78.97	52.71	624.32
	E	50.25	50.77	-118.05	- 0.34	12.28	10.78	16.78	19.81	1.1	- .22	-15.07	31.09	- 130.82
MODELBASIC	Predicted Streamflow (mm)	64.94	57.31	78.32	62.77	37.04	28.28	36.58	45.64	44.85	73.22	72.71	95.23	696.80
	E	11.23	14.52	-16.81	- 7.48	6.34	4.8	2.6	6.01	- 2.16	-12.2	- 8.81	-11.43	-13.39
	Stan. Dev. - Historical (mm)	21.71	34.0	19.07	13.7	11.13	13.05	16.8	22.6	17.9	23.7	17.15	21.2	
	Stan. Dev. - Predicted (mm)	28.93	25.77	29.43	33.4	16.38	7.26	16.95	25.01	20.88	20.45	21.43	30.9	

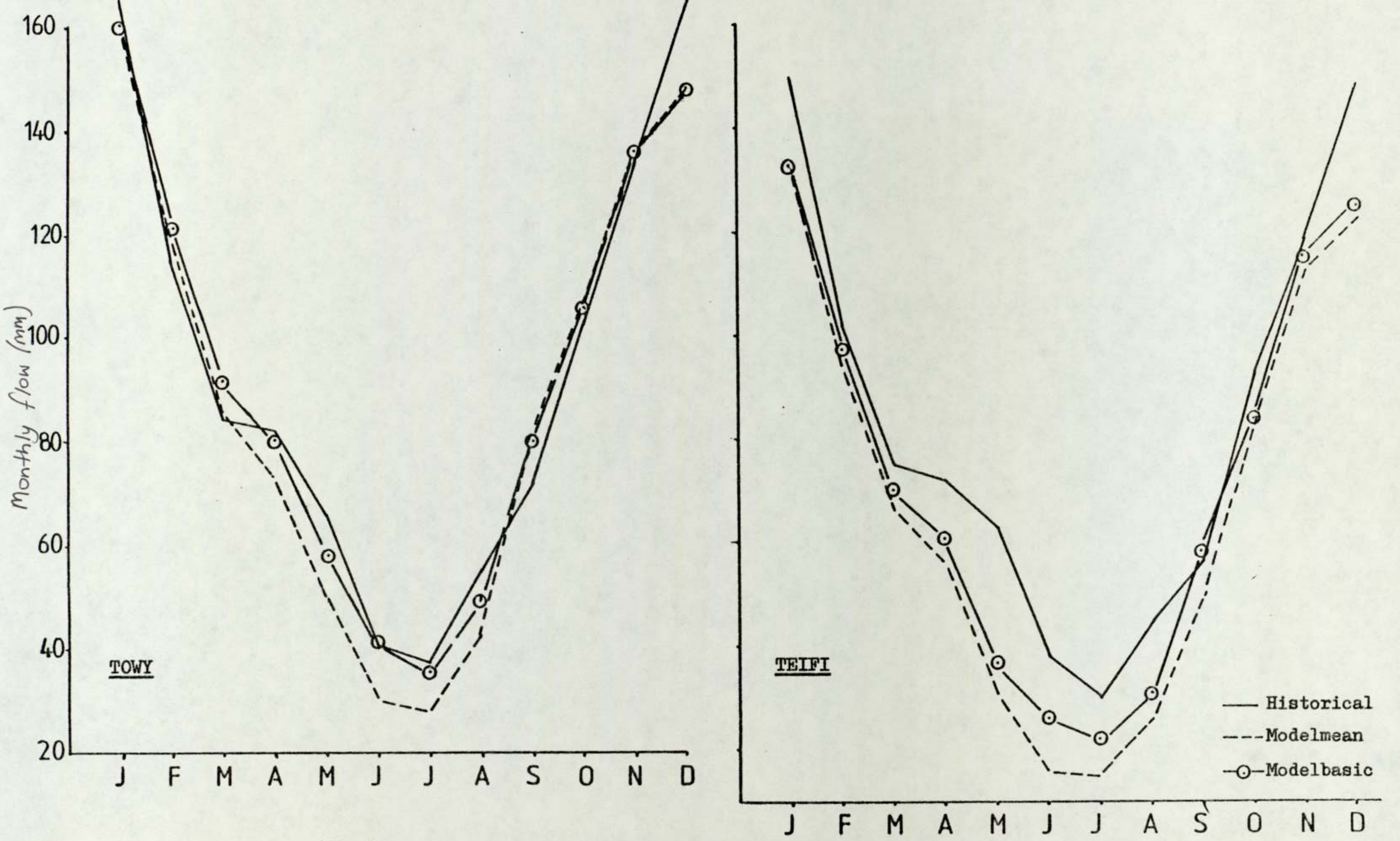


Fig 6.3.1 Historical and Predicted Mean Monthly Flow for MODELMEAN and MODELBASIC

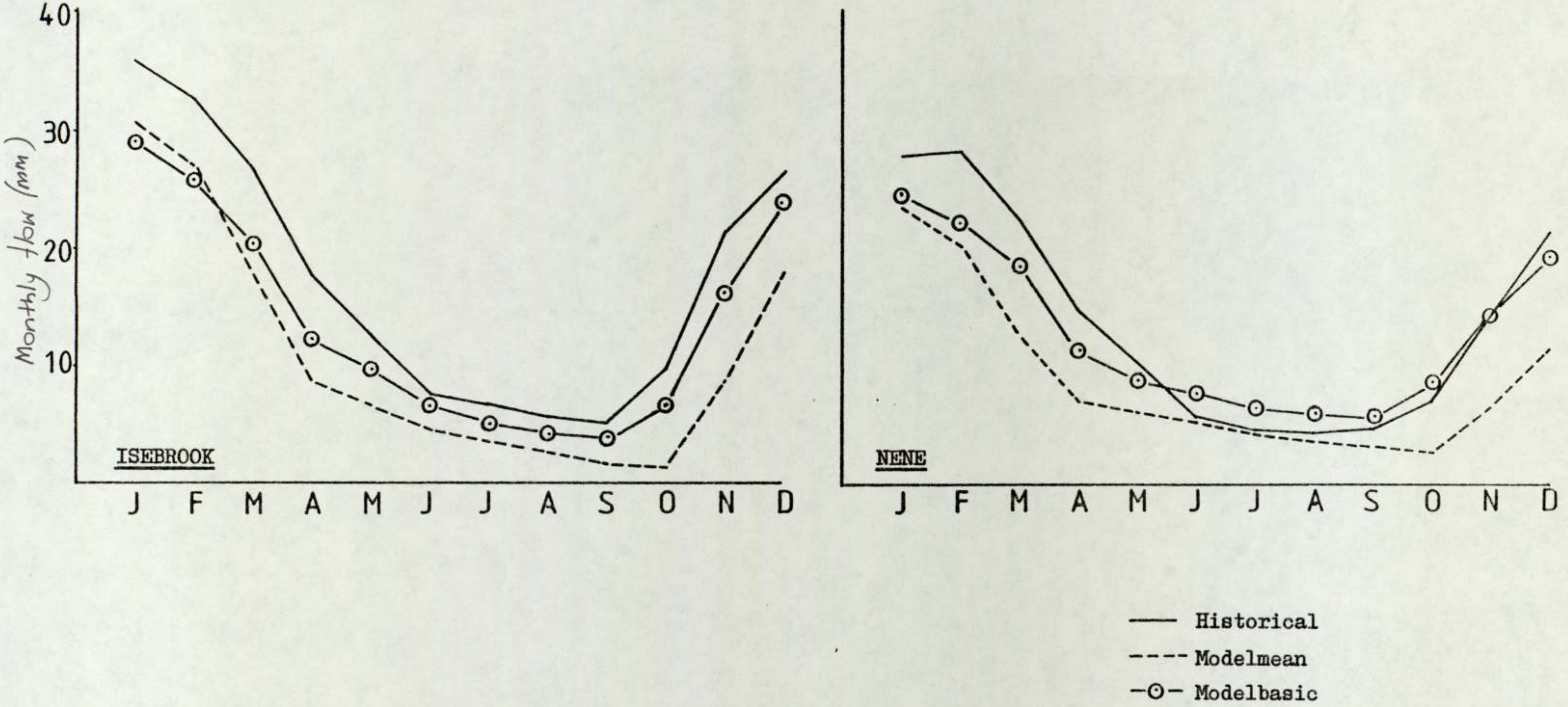


Fig 6.2.2 Historical and Predicted Mean Monthly Flow for MODELMEAN and MODELBASIC

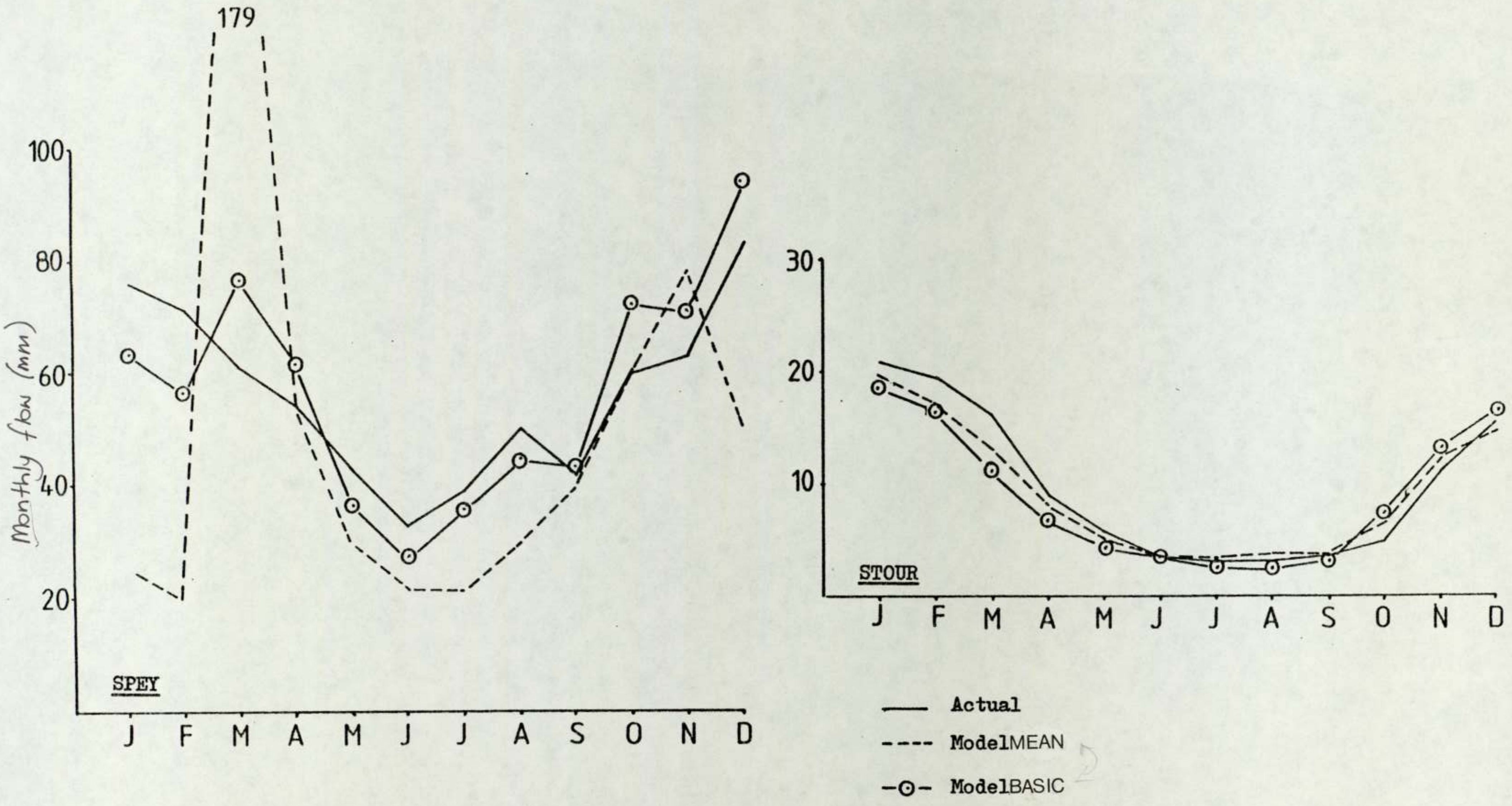


Fig 6.2.3 Historical and Predicted Monthly Flows for MODELMEAN and MODELBASIC

tends to suggest a gauging error in one or more of the sets of input data, particularly as annual rainfall minus evaporation is considerably less than the annual streamflow value. Although the close fit of the predicted values during winter and autumn does not suggest that the problem is due to inflow from an adjoining catchment.

ii) The results for the Isebrook at Harrowden and the Nene at Orton produced generally good fits, the values for MODELBASIC being an improvement upon those produced by MODELMEAN. The predicted discharge of the Isebrook was noticeably less than actually recorded. This was because, although the annual predicted discharges using MODELMEAN and MODELBASIC were 132.37 mm and 165.53 mm respectively, the total annual recorded discharge was 208.64 mm. However,. the total annual rainfall minus evaporation was only 83.7, which suggests that there is either an influx of water across the catchment groundwater boundary or a gauging error in the rainfall, evaporation or streamflow values. The Stour at Stratford St. Marys and the Nene at Orton both produced predicted values for both MODELMEAN and MODELBASIC which were a reasonably good fit.

iii) The Spey catchment is not only farthest removed from the Mid-Wales region by distance, but it also contains the Cairngorms and is therefore markedly higher in altitude than any of the other Welsh 'upland' catchments. The difference in altitude means that on the upper slopes of the Spey snow lies for a period in excess of one month. It is snowmelt that accounts for the marked increase in discharge predicted for the month of March by both MODELMEAN and MODELBASIC and the snowstore accounts for the underestimation of streamflow in the months of January and February. However, the degree to which the predicted values differed from the historical was far grester using MODELMEAN than MODELBASIC. MODELMEAN tends to ignore fluctuations in the data which become apparent when running MODELBASIC. Less hard winters with smaller snowstores are overlooked whereas the snowstore and snowmelt values differ from month to month and year to year and tend to moderate the averaged streamflow values. Snowmelt is further discussed in Section 6.3.2 which discusses predictions using MODELQF and MODELFAC.

6.3.2 Results of MODELQF and MODELFAC

All catchments exhibited very similar results for both MODELQF and MODELFAC four basic features were discernible, but unlike the results for MODELMEAN and MODELBASIC they do not fall into categories based upon terrain. The results tabulated in Tables 6.3.7/12and 6.3.13/18and illustrated in figures 6.3.1/3

i) The results for the Teifi and the Stour, although dissimilar catchments, both exhibited very close fits for both MODELQF and MODELFAC.

ii) The results for Isebrook and the Nene were an improvement upon those obtained using MODELMEAN and MODELBASIC. The total annual volume of discharge was not necessarily altered, although the results were less erratic than those previously obtained. In both catchments the fit was very close for the latter seven

Table 6.3.7 <u>Historical and Predicted Flow Values for MODELQF - Towy</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	165.15	114.27	84.55	82.56	66.12	41.38	37.57	55.51	72.79	103.77	134.76	165.72	1124.15
	Predicted Streamflow (mm)	162.09	116.85	86.65	78.57	57.72	41.5	36.94	49.86	81.78	108.69	139.69	151.08	1111.42
	E	3.06	2.58	2.1	3.99	8.4	0.12	0.63	5.65	8.99	4.92	4.93	14.64	12.73
	Stan. Dev. - Historical (mm)	75.2	56.5	37.1	35.8	32.6	28.9	22.8	25.6	51.4	76.3	58.2	75.1	
	Stan. Dev. - Predicted (mm)	66.0	56.26	29.96	30.27	28.74	22.4	17.38	18.82	49.41	71.86	46.17	62.84	

Table 6.3.8 <u>Historical and Predicted Flow Values for MODELQF - Teifi</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	145.09	102.03	75.02	72.51	63.01	38.88	30.86	45.24	57.49	93.08	119.74	148.18	991.13
	Predicted Streamflow (mm)	134.39	94.39	68.16	61.01	37.76	27.5	23.76	31.94	58.46	84.66	117.95	127.49	867.47
	E	10.7	7.64	6.86	11.5	25.23	11.13	7.1	13.3	1.0	8.42	1.79	20.69	125.36
	Stan. Dev. - Historical (mm)	65.2	45.0	34.1	27.8	25.7	30.5	21.3	25.4	47.9	66.3	47.2	59.1	
	Stan. Dev. - Predicted (mm)	55.77	44.91	31.36	25.97	17.75	13.53	10.23	14.99	40.77	54.21	41.51	50.97	

Table 6.3.9 Historical and Predicted Flow Values for MODELQF - Nene

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	27.74	28.02	22.53	14.79	10.12	5.63	4.97	4.56	4.78	7.13	14.48	21.45	166.2
	Predicted Streamflow (mm)	22.78	20.82	16.72	10.05	8.34	6.85	5.89	5.15	5.02	6.59	13.12	18.75	140.08
	E	4.92	7.18	5.78	4.75	1.76	-1.25	-0.99	-0.55	-0.22	0.51	1.38	2.75	26.12
	Stan. Dev. - Historical (mm)	17.71	15.82	14.87	10.52	9.46	4.36	7.16	4.83	6.06	8.79	13.71	19.85	
	Stan. Dev.- Predicted (mm)	12.73	11.44	9.44	5.07	4.09	3.1	2.63	2.24	2.18	5.0	3.87	11.75	

Table 6.3.10 <u>Historical and Predicted Flow Values for MODELQF - Stour</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	20.98	19.15	15.72	9.11	5.62	3.59	3.22	3.29	3.71	5.38	11.37	15.19	116.33
	Predicted Streamflow (mm)	23.53	22.65	16.11	9.72	6.45	4.72	3.52	2.93	2.57	3.67	10.68	17.72	124.27
	E	- 2.55	- 3.5	- 0.39	- 0.61	- 0.83	- 1.13	- 0.3	0.36	1.14	1.71	0.69	- 2.53	- 7.94
	Stan. Dev. - Historical (mm)	10.3	7.13	7.54	5.02	1.76	2.48	1.95	2.03	2.9	8.75	11.04	11.12	
	Stan. Dev. - Predicted (mm)	13.5	13.2	10.48	7.14	3.78	2.66	1.99	2.09	2.93	5.31	10.63	13.61	

Table 6.3.11 Historical and Predicted Flow Values for MODELQF - Spey

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	76.17	71.83	61.51	55.29	43.38	33.08	39.18	51.65	42.69	61.02	63.9	83.8	683.5
	Predicted Streamflow (mm)	59.28	53.28	82.38	65.54	38.55	31.98	40.1	46.54	43.05	74.1	71.3	99.93	706.03
	E	16.89	18.55	-20.57	-10.25	4.83	1.1	- 0.92	5.11	- 0.36	-13.08	- 7.4	-16.13	-22.23
	Stan. Dev. - Historical (mm)	21.71	34.0	19.07	13.7	11.13	13.05	16.8	22.6	17.9	23.7	17.15	21.1	
	Stan. Dev. - Predicted (mm)	22.89	29.3	38.0	42.9	18.33	6.65	18.5	25.23	19.58	24.46	26.74	37.19	

Table 6.3.12 <u>Historical and Predicted Flow Values for MODELQF - Isebrook</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
MODELQF	Historical Streamflow (mm)	35.88	32.56	26.69	17.66	12.76	7.76	6.70	5.68	5.35	9.82	21.49	26.29	208.64
	Predicted Streamflow (mm)	28.28	25.94	21.28	12.58	9.68	6.81	5.36	4.38	3.93	6.79	16.83	23.85	165.71
	E	7.6	6.62	5.41	5.08	3.08	0.95	1.34	1.3	1.42	3.03	4.66	2.44	42.93
	Stan. Dev.- Historical (mm)	20.96	16.9	16.57	10.1	7.97	5.23	8.87	4.39	4.63	14.44	21.04	19.03	
	Stan. Dev. - Predicted (mm)	16.4	14.3	11.5	6.2	5.0	3.5	2.5	2.3	2.7	7.6	14.2	14.3	

Table 6.3.13 Historical and Predicted Flow Values for MODELFAC - Towy

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	165.15	114.27	84.55	82.56	66.12	41.38	37.57	55.51	72.79	103.77	134.76	165.72	1124.15
Predicted Streamflow 100 (mm)	166.36	108.12	76.42	72.59	53.91	39.54	35.6	48.34	85.34	115.32	147.95	138.01	1087.5
E	- 1.21	6.15	8.13	9.97	12.21	1.84	1.97	7.17	-12.55	-11.55	-13.19	7.71	36.65
Predicted Streamflow 200 (mm)	163.72	112.29	82.22	76.66	59.13	44.1	38.85	48.54	80.25	109.22	140.16	153.37	1109.51
E	1.43	1.98	2.33	5.9	6.99	- 2.72	- 1.28	6.97	- 7.46	- 5.45	- 5.4	12.35	14.64
Predicted Streamflow 300 (mm)	161.76	114.97	86.12	79.52	62.36	46.86	40.78	48.86	77.43	105.37	135.27	150.05	1109.1
E	3.39	- 0.7	- 1.57	5.03	4.24	- 5.48	- 3.21	6.65	- 4.64	- 1.6	- 0.51	15.67	17.27
Stan. Dev. - Historical (mm)	75.2	57.5	37.1	33.8	32.2	28.9	22.7	25.0	51.3	76.9	57.6	75.2	
Stan. Dev. - Predicted 100 (mm)	74.2	58.3	34.0	28.3	26.7	22.1	15.8	17.9	51.5	82.6	55.3	74.8	
200	72.0	56.7	31.0	27.8	25.9	20.3	15.2	17.4	49.9	80.5	54.0	72.3	
300	67.6	54.3	275	26.4	24.8	19.7	15.0	16.5	43.8	76.1	53.8	70.1	

Table 6.3.14 Historical and Predicted Flow Values for MODELFAC - Teifi

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	145.09	102.03	75.02	72.51	63.01	38.88	30.86	45.24	57.49	93.08	119.74	148.18	991.13
Predicted Streamflow 100 (mm)	137.26	88.37	61.89	57.28	36.88	27.96	24.16	31.05	58.62	86.47	122.11	131.78	863.3
E	7.83	13.66	13.13	15.23	26.13	10.92	6.7	14.19	- 1.13	6.61	- 2.37	16.4	127.3
Predicted Streamflow 200 (mm)	133.36	91.57	67.42	61.63	43.2	33.27	28.18	32.55	54.91	80.21	112.78	125.39	864.47
E	11.73	10.46	7.6	10.88	19.81	5.61	2.68	12.69	2.58	12.87	6.96	22.79	126.66
Predicted Streamflow 300 (mm)	130.54	93.53	71.01	64.67	47.09	36.51	30.63	33.64	53.01	76.45	107.05	121.0	865.22
E	14.55	8.48	4.01	7.84	15.92	2.37	0.23	11.6	4.48	16.63	12.69	27.18	125.98
Stan. Dev. - Historical (mm)	65.2	44.3	34.1	27.0	25.2	30.3	21.7	25.4	47.8	66.4	47.6	59.3	
Stan. Dev. - Predicted 100 (mm)	66.4	46.4	36.4	23.9	16.4	12.1	0.3	13.9	42.1	62.4	51.1	63.7	
200	59.5	43.2	31.8	21.2	15.1	11.9	8.0	12.6	38.7	57.6	47.9	56.5	
300	54.6	39.8	26.5	20.4	13.5	11.7	8.3	11.3	33.8	52.5	43.2	51.9	

Table 6.3.15 <u>Historical and Predicted Flow Values for MODELFAC - **Nene**</u>

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	27.7	28.0	22.5	14.8	10.1	5.6	4.9	4.6	4.8	7.1	14.5	21.5	166.1
Predicted Streamflow 100 (mm)	23.82	20.88	15.54	9.16	7.79	6.57	6.65	4.92	4.67	6.94	14.47	19.13	139.54
E	3.95	7.12	6.96	5.64	2.31	- 0.97	- 0.75	- 0.32	0.13	0.16	0.03	2.31	26.57
Predicted Streamflow 200 (mm)	20.65	19.33	15.82	11.05	9.55	8.15	7.02	6.11	5.59	7.01	12.58	16.38	139.24
E	7.12	8.67	6.68	3.75	0.55	- 2.55	- 2.12	- 1.51	- 0.79	0.009	1.92	5.12	26.85
Predicted Streamflow 300 (mm)	19.12	18.58	15.97	11 97	10.39	8.91	7.67	6.68	6.05	7.05	11.66	15.1	139.15
E	8.58	10.58	6.53	2.83	- 0.29	- 3.31	- 2.77	- 2.08	- 1.7	0.05	2.9	6.4	27.72
Stan. Dev. - Historical (mm)	17.71	15.82	14.87	10.52	9.46	4.36	7.16	4.83	6.06	8.79	13.71	19.85	
Stan. Dev. - Predicted 100 (mm)	16.8	14.6	9.4	4.2	3.4	2.8	2.3	1.9	2.0	6.4	14.0	13.5	
200	13.5	11.4	8.1	4.7	4.1	3.4	3.1	2.5	2.2	5.00	10.8	11.0	
300	11.9	10.3	7.7	5.3	4.6	4.0	3.2	2.8	2.4	4.3	9.4	9.8	

Table 6.3.16 **Historical and Predicted Flow Values for MODELFAC - Isebrook**

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	33.7	31.4	23.4	17.1	11.3	7.0	6.0	4.9	4.9	8.5	21.5	25.2	194.9
Predicted Streamflow 100 (mm)	29.41	25.4	19.83	11.41	9.1	6.56	5.12	4.18	3.71	7.21	18.72	24.72	165.38
E	4.29	6.0	3.57	5.68	2.2	1.56	0.88	0.72	1.19	1.29	2.78	0.48	30.64
Predicted Streamflow 200 (mm)	26.63	24.6	20.59	13.66	10.92	8.08	6.25	5.06	4.30	6.81	16.11	21.74	164.75
E	7.07	6.8	2.81	3.44	0.38	- 1.08	- .25	- 0.16	0.6	1.69	5.44	3.46	30.2
Predicted Streamflow 300 (mm)	25.25	24.21	21.0	14.75	11.81	8.82	6.79	5.48	4.58	6.62	14.81	20.32	164.4
E	8.45	7.19	2.4	2.35	- .51	- 1.82	- .79	- .58	.32	1.88	6.69	4.88	30.46
Stan. Dev. - Historical (mm)	20.9	16.9	16.6	10.1	8.0	5.2	8.9	4.4	4.6	14.4	21.1	19.6	
Stan. Dev. - Predicted 100 (mm)	19.4	16.9	11.4	5.7	5.2	3.1	2.5	1.9	2.1	9.2	18.4	16.4	
200	16.4	13.8	10.7	6.34	5.9	3.9	3.0	2.3	2.2	7.5	15.1	14.6	
300	15.7	13.5	10.1	6.9	6.2	4.3	3.3	2.5	2.3	6.6	13.5	13.5	

Table 6.3.17 <u>Historical and Predicted Flow Values for MODELFAC - Stour</u>

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	20.98	19.15	15.72	9.11	5.62	3.59	3.22	3.29	3.71	5.38	11.37	15.19	116.33
Predicted Streamflow 100 (mm)	20.15	20.97	16.63	11.78	8.47	6.26	4.65	3.65	3.08	3.65	9.06	14.73	123.08
E	0.75	- 1.82	- 0.93	- 2.67	- 2.85	- 2.67	- 1.43	- 0.36	0.62	1.73	2.31	0.46	- 6.86
Predicted Streamflow 200 (mm)	21.35	21.46	16.18	10.98	7.78	5.75	4.27	3.39	2.93	3.67	9.84	15.79	123.39
E	- 0.45	- 2.31	- 0.48	- 1.87	- 2.18	- 2.16	- 1.05	- 0.1	0.77	1.71	1.53	0.6	- 7.06
Predicted Streamflow 300 (mm)	23.91	22.48	15.23	9.3	6.33	4.67	3.47	2.86	2.61	3.71	11.45	18.04	124.06
E	- 3.72	- 3.33	0.47	0.19	- 0.71	- 1.08	- 0.25	0.43	1.09	1.67	- 0.08	- 2.85	- 7.73
Stan. Dev. - Historical (mm)	10.3	7.13	7.54	5.02	1.76	2.48	1.95	2.03	2.9	8.75	11.04	11.12	
Stan. Dev. - Predicted 100 (mm)	11.4	11.3	9.2	6.9	4.6	3.5	2.5	2.1	2.72	4.6	9.3	12.5	
200	12.0	13.4	9.8	6.5	4.3	2.8	1.9	2.0	3.15	4.9	11.2	13.7	
300	14.2	15.6	10.8	6.2	4.0	2.3	1.7	1.8	3.1	5.8	12.3	15.5	

Table 6.3.18 <u>Historical and Predicted Flow Values for MODELFAC - Spey</u>

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL
Historical Streamflow (mm)	76.17	71.83	61.51	55.29	43.38	33.08	39.18	51.65	42.69	61.02	63.9	83.8	683.5
Predicted Streamflow 100 (mm)	56.85	51.37	85.27	67.72	37.65	32.3	39.44	45.87	41.19	72.38	69.75	104.07	703.86
E	19.32	20.46	-23.76	-12.43	5.73	.78	- .26	5.78	1.5	-11.36	- 5.85	-20.27	-20.36
Predicted Streamflow 200 (mm)	57.43	52.23	82.05	69.17	42.92	37.15	42.46	47.26	42.11	68.12	65.89	96.33	703.12
E	18.74	19.6	-20.54	-13.88	.46	- 4.07	- 3.28	4.39	.58	- 7.1	- 1.99	-12.53	-19.62
Predicted Streamflow 300 (mm)	57.51	52.77	80.19	69.7	45.8	39.82	44.24	48.14	42.75	66.11	63.88	92.92	702.82
Σ E	18.66	19.06	-18.68	-14.41	- 2.42	- 6.74	- 5.06	3.51	- .06	- 5.09	.02	- 8.11	-19.32
Stan. Dev. - Historical (mm)	21.71	34.0	19.07	13.7	11.13	13.05	16.08	22.6	17.9	23.7	17.15	21.2	
Stan. Dev. - Predicted 100 (mm)	37.9	30.2	42.6	50.8	15.2	6.1	17.4	22.9	18.3	26.4	30.0	43.0	
200	33.25	25.2	36.44	43.88	14.3	5.37	16.33	22.05	16.65	23.02	25.6	38.48	
300	30.66	22.6	32.95	39.74	13.85	5.06	15.86	20.9	15.87	21.19	23.3	35.7	

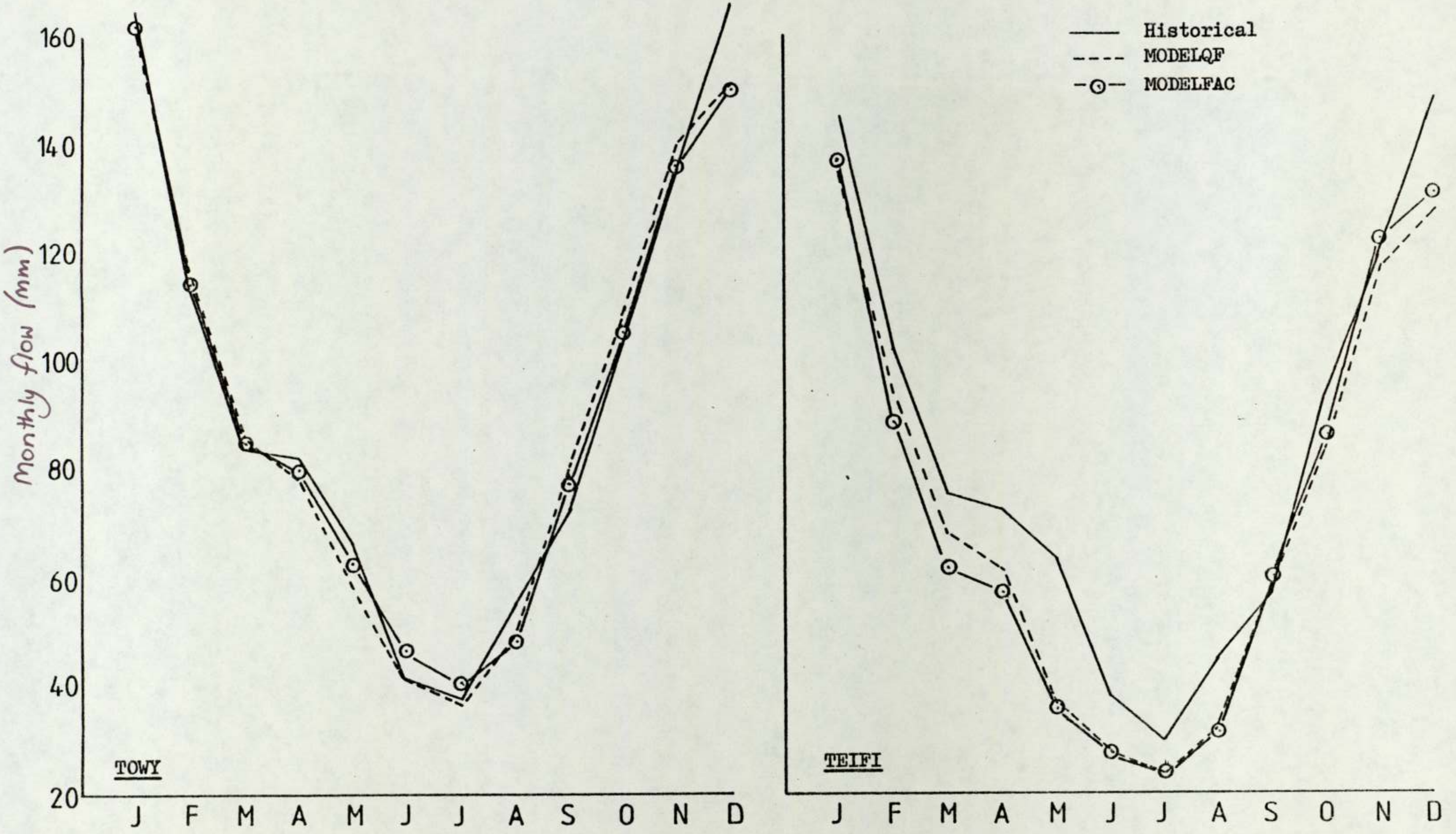


Fig 6.3.1 Historical and Predicted Flows using MODELQF and MODELFAC

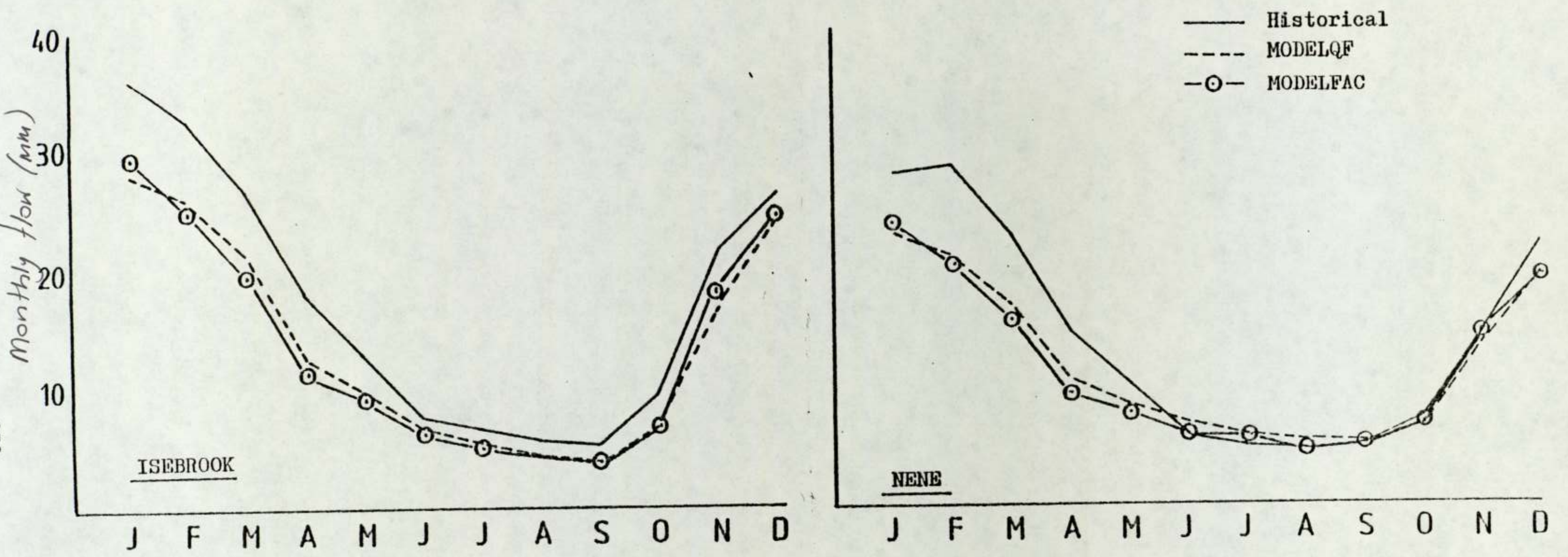


Fig 6.3.2 Historical and Predicted flows using MODELQf and MODELFAC

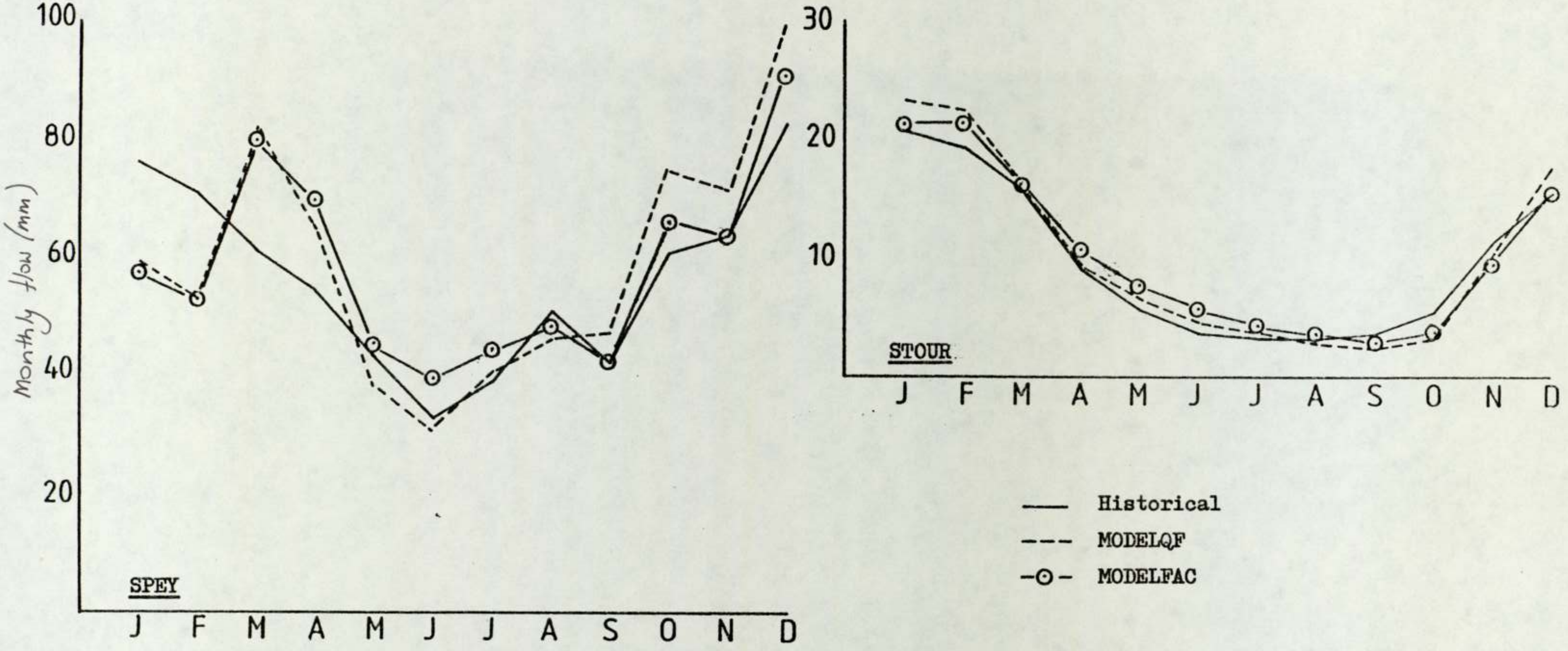


Fig 6.3.3 Historical and Predicted flow Values for MODELQf and MODELFAC

months of the year, but as with previous results the earlier part of the year did not exhibit such a close fit. The data shows a marked difference between total annual historical streamflow and rainfall minus evaporation (R - E) for both the Nene and Isebrook. Taking this into account it is probable that if the problem is not due to a gauging error, there is an inflow of moisture across catchment boundaries. If this is so, low flow periods would not necessarily be affected, but infilling of stores would be more rapid following the summer deficit and therefore the quantity of winter quickflow would increase markedly.

iii) Unlike its adjoining catchment, the Teifi again exhibited results which were an underestimation of the actual discharge for April - August. Although an improvement was discernible from the results produced by MODELMEAN and MODELBASIC the fit was nonetheless poor, the slight improvement in the summer months being due to an improvement in winter predictions due to the inclusion of the infiltration/overland flow division.

iv) The Spey at Aberlour produced a fairly good fit for the middle of the year, yet whereas the results using MODELFAC were relatively close during the latter months, the values obtained from MODELQF were poor. The most distinct feature of all the Spey results is the erratic nature of predictions for the first four months. In all cases January and February predicted values have underestimated historical discharges, whilst March and April figures exceeded predicted values to a similar extent.

When illustrating the predicted discharge values determined from each of the 'MODELS' the results were generally encouraging. Excluding Aberlour the results tend to be fairly good and suggest that the catchment parameters as adopted for the 'MODELS' are applicable in areas of the country other than that of Mid-Wales and the border countries for which they were originally designed.

Spey at Aberlour is a particularly difficult catchment since the accumulation and melting of snow extends over several months, and these processes are highly temperature sensitive. This rarely occurs in the Welsh catchments as was discussed earlier, yet in the Spey catchment the Cairngorms are known to store snow, and consequently this has provided the first real test of the snowstore routine. As can be seen from the results the snowstore reduces the discharge in January and February, and then releases the snow as melt in the months of March and April, whilst the actual discharge suggests a far more constant gradual release. This suggests that the snowstore routine lacks sophistication and more work is needed to reconsider the effect of altitude and temperature upon the quantity of snow in store. It should also be considered whether in the case of large catchments such as the Spey (2650 km^2) three zones is adequate. In the upland zone of the Spey the Cairngorms cover a significant area, but not the total area. Consequently it is conceivable that the small area which is at a particularly high altitude causes the average altitude of the zone to be misleadingly high. This would, therefore, lower the zonal temperature and artificially increase the quantity of snowfall. The only solution to this problem would therefore be to either increase the overall number of zones, or simply breakdown the upland zone into separate, smaller zones to compensate for the range in altitude.

As with the predictions for the Mid-Wales region, the standard deviations of flow as predicted for the test catchments reflected marked similarities in the general trends expressed by the historical deviations. The standard deviations of flow are illustrated in Figs 6.4.1/3

6.4 COMPARISON OF RESULTS USING EL GUSBI'S (1979) RAINFALL/ STREAMFLOW RELATIONSHIPS AND MODELMEAN

6.4.1 INTRODUCTION

A stated aim of El Gusbi's (1979) project was to devise methods of estimating streamflow parameters for ungauged catchments. For this reason he investigated rainfall/streamflow relationships, in particular mean annual areal rainfall/monthly streamflow and mean monthly areal rainfall/monthly streamflow. The rainfall/streamflow relationship assumed the general form -

$$Q_i = b_i + m_i R$$

where Q_i - mean monthly streamflow in ith month

b_i - intercept coefficient in ith month

m_i - slope coefficient in ith month

R - rainfall

Linear regression equations with smoothed intercept and slope coefficients were obtained from the above investigation (Table 6.4) and used with monthly and annual rainfall data for each of the six new catchments. The aim of this exercise was to examine the validity of El Gusbi's rainfall/streamflow relationships in predicting streamflow patterns outside the area for which they were designed, compared with the results of predictions using the four 'MODELS' and in particular MODELMEAN.

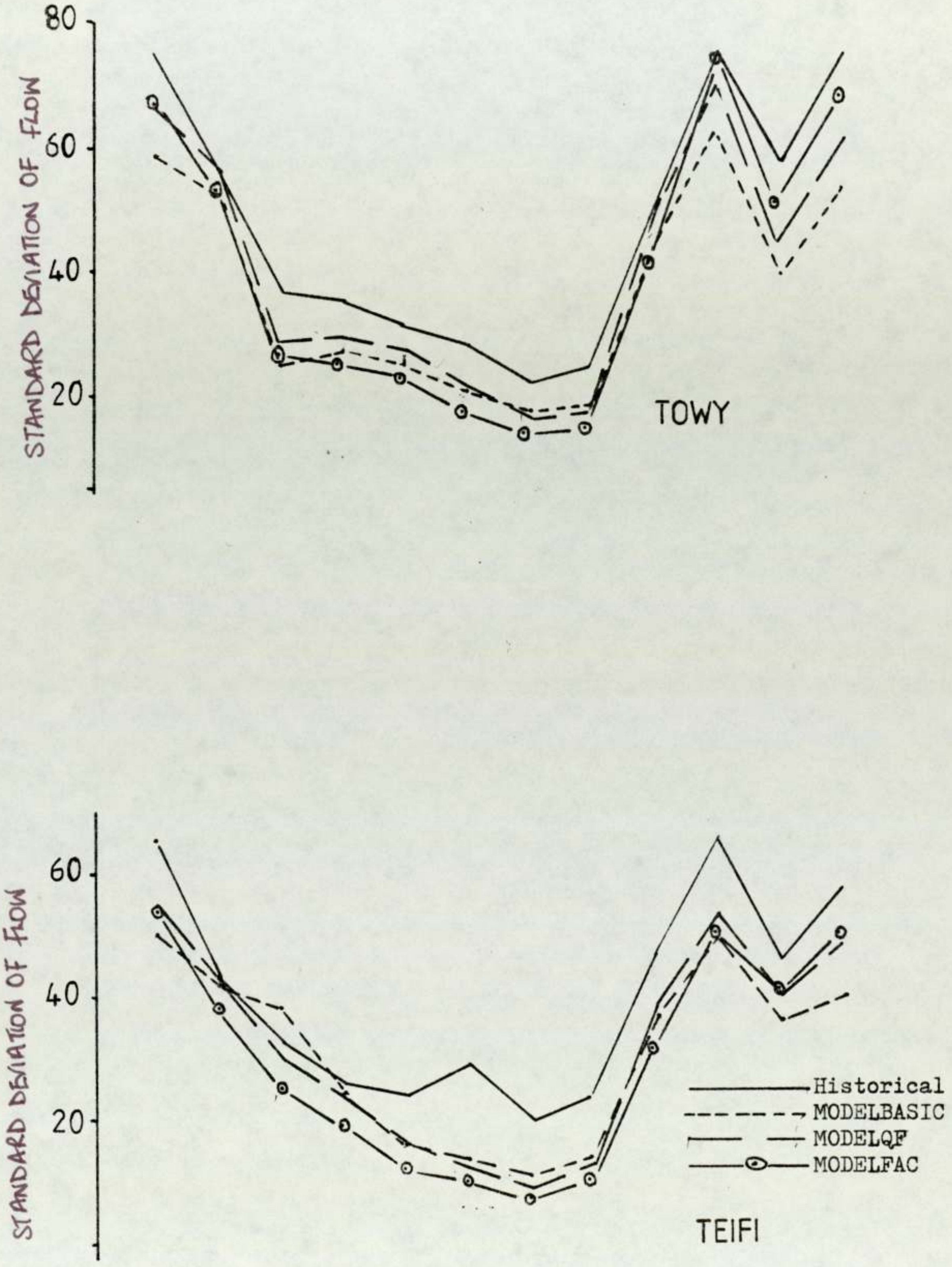


Fig 6.4.1 Standard deviations of Historical and Predicted flows

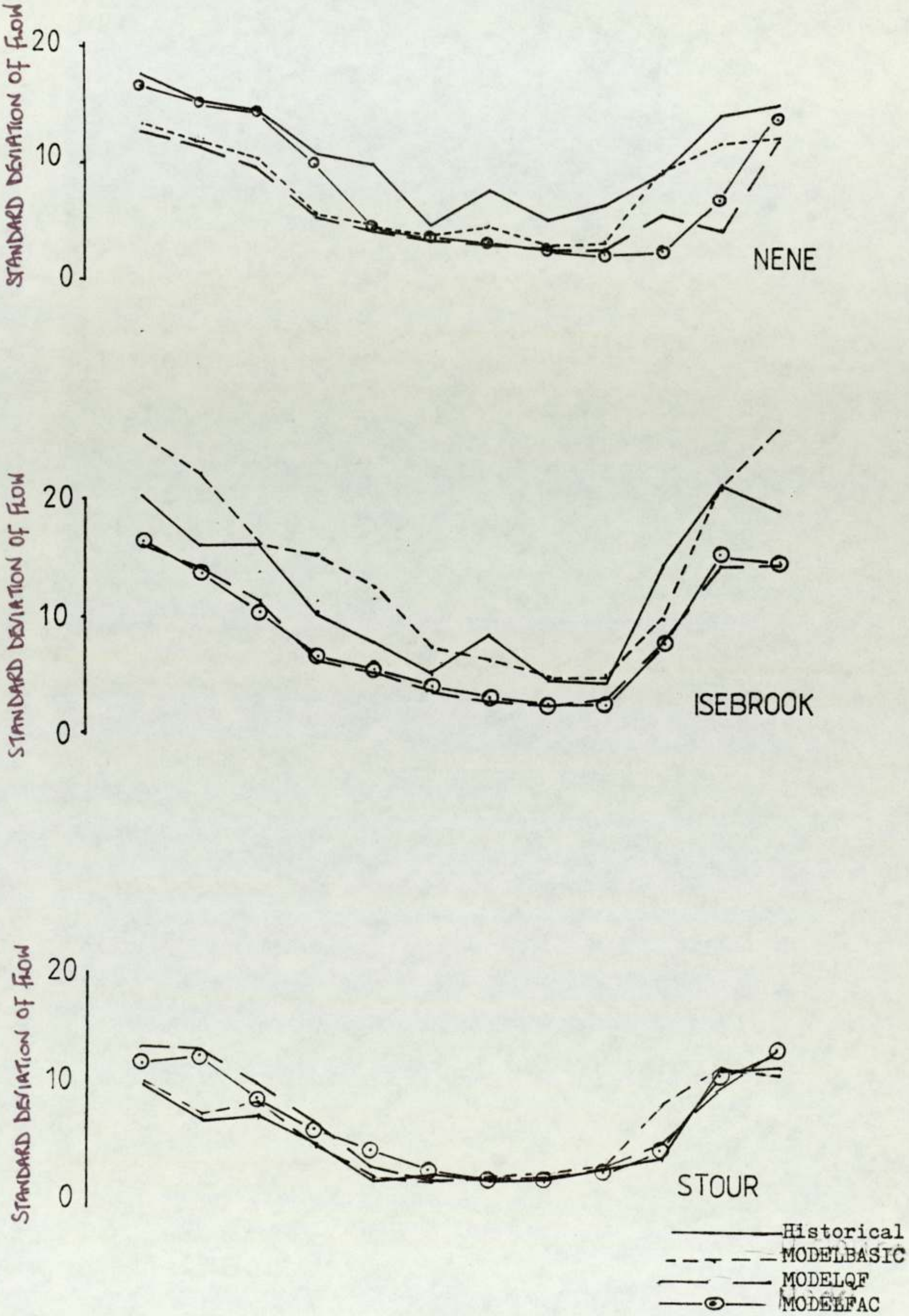


Fig 6.4.2 Standard deviations of Historical and Predicted flows

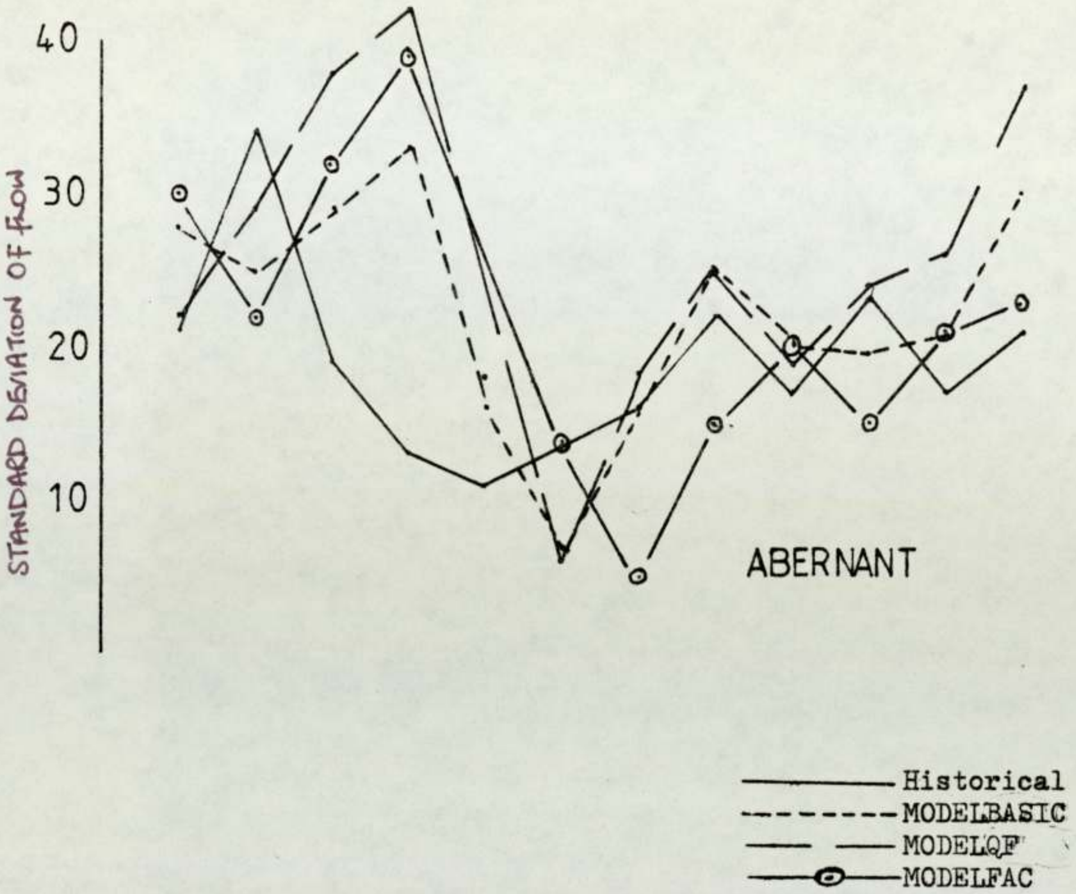


FIG.6.4.3 Standard deviations of Historical and Predicted flows

Table 6.4 **Linear Regression Equations for Predictions (A) and (B) - El Gusbi**

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
ANNUAL RAINFALL 1960 - 1975	b	-32.71	-11.34	- 5.19	-29.4	-16.53	-11.95	-20.32	-45.92	-62.22	-62.22	-71.48	-74.62
		-16.38	- 7.41	-12.69	-16.22	- 2.54	-11.54	1.83	-18.64	-33.77	-18.52	- 1.96	-26.14
	m	0.1208	0.0785	0.061	0.0724	0.0525	0.0322	0.381	0.0648	0.0869	0.1038	0.1326	0.1549
		0.055	0.0412	0.381	0.0364	0.0229	0.0232	0.0128	0.0293	0.052	0.0542	0.0397	0.0722
MONTHLY MEAN RAINFALL 1960 - 1975	b	-17.23	1.42	- 9.58	-29.3	-45.23	-27.69	-36.25	-61.01	-67.03	-55.56	-53.42	-28.04
		- 8.65	- 0.78	-15.66	-10.08	-15.85	-22.6	- 3.66	-25.37	-36.64	-16.0	3.56	- 3.82
	m	0.9703	0.8777	0.9589	0.9841	1.0367	0.7869	0.7474	0.9869	1.0286	1.0218	1.0723	1.0805
		0.4371	0.4675	0.6014	0.4938	0.4602	0.5632	0.2525	0.4462	0.6147	0.6002	0.3205	0.499

6.4.2 Results

The actual and predicted streamflow values for each of the six catchments are tabulated in Tables 6.5.1 and 6.5.2 and 6.5.3 illustrated in Figs 6.5.1/3. It includes predictions using MODELBASIC compared with predictions (A) and (B) where (A) is -

$$Q_i = b_i + m_i R_m$$

where R_m - mean monthly areal rainfall

and (B) is

$$Q_i = b_i + m_i R_a$$

where R_a - mean annual areal rainfall

Three principle features were discernible from the results -

i) for the three lowland catchments, the Nene, Isebrook and Stour, the predicted values using (A) and (B) were erratic during the summer months, particularly in June where streamflow values were overestimated and September where they were underestimated. The inaccuracy of the predictions is most probably due to the exclusion of such low lying catchments from the original study.

ii) The validity of El Gusbi's relationships within the Welsh region are proven by the results for the Towy and Teifi, for both catchments the results were a good fit and an improvement upon the values predicted by 'MODELBASIC'.

iii) for Aberlour both predictions (A) and (B) are an improvement upon the prediction of MODELBASIC, although (A) has produced a more erratic curve than (B). It is, however, true that developments in the MODEL have produced a curve which improves upon both predictions

Table 6.5.1 <u>Historical and Predicted Flow Values using El Gusbi's Predictions (A) and (B)</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Actual	Mean	145.09	102.03	75.02	72.51	63.01	38.88	30.86	45.24	57.49	93.08	119.74	148.18	Teifi Rainfall 1960-75
	Stan. Dev.	65.79	44.67	34.96	27.60	25.68	30.67	21.24	25.74	48.68	66.39	47.78	59.53	
Pred (A)	Mean	131.72	84.29	65.73	64.61	42.28	34.55	29.70	41.44	54.79	73.87	106.03	129.84	
	Stan. Dev.	58.44	43.36	31.57	37.04	23.00	21.94	18.62	20.95	36.17	60.03	51.22	69.09	
Pred (B)	Mean	126.43	92.08	75.17	65.98	52.63	30.47	29.87	39.45	52.26	73.22	103.21	129.45	
	Stan. Dev.	56.07	46.87	37.50	31.73	27.63	19.02	18.69	19.96	34.73	52.88	50.34	68.98	
Actual	Mean	165.15	114.27	84.55	82.56	66.12	41.38	37.57	55.51	72.79	103.77	134.76	165.72	Towy Rainfall 1960-75
	Stan. Dev.	75.36	57.39	37.03	36.95	32.73	29.3	23.32	25.68	51.01	77.35	58.59	75.14	
Pred (A)	Mean	155.76	100.62	79.0	77.80	62.20	45.74	40.93	59.81	76.81	95.72	127.62	154.3	
	Stan. Dev.	69.28	52.06	39.90	43.66	31.84	29.96	22.41	29.25	49.32	72.86	57.67	80.39	
Pred (B)	Mean	153.39	109.6	88.79	82.14	64.35	37.66	38.38	53.91	71.66	96.39	132.80	164.03	
	Stan. Dev.	68.36	56.06	46.01	39.86	32.74	24.20	21.55	26.50	46.34	64.98	59.20	85.09	

(A) $Q = b_i + m_i \; Rm$

(B) $Q = b_i + m_i \; Ra$

Table 6.5.2 Historical and Predicted Flow Values using El Gusbi's Predictions (A) and (B)

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Actual	Mean	76.17	71.83	61.51	55.29	43.38	33.08	39.18	51.65	42.69	61.02	63.9	83.8	Spey Rainfall 1951-60
	Stan. Dev.	21.71	34.0	19.07	13.7	11.13	13.05	16.08	22.6	17.9	23.7	17.15	21.2	
Pred (A)	Mean	82.81	78.66	49.58	37.42	28.89	33.06	37.82	47.15	16.9	63.48	58.96	130.79	
	Stan. Dev.	36.41	40.36	21.45	23.40	17.05	20.88	21.36	23.53	13.52	53.92	37.15	69.53	
Pred (B)	Mean	99.59	74.63	61.62	49.89	40.97	23.32	21.41	25.04	32.95	50.15	73.74	95.02	
	Stan. Dev.	43.85	37.71	29.04	23.64	22.54	13.87	15.85	13.45	23.18	40.84	41.52	52.93	
Actual	Mean	20.98	19.15	15.72	9.11	5.62	3.59	3.22	3.29	3.71	5.38	11.37	15.19	Stour Rainfall 1948-63
	Stan. Dev.	10.3	7.13	7.54	5.02	1.76	2.48	1.95	2.03	2.90	8.75	11.04	11.12	
Pred (A)	Mean	36.10	36.04	30.29	11.54	- 2.45	9.98	7.30	- 4.95	-11.02	3.14	16.35	31.51	
	Stan. Dev.	15.37	17.66	24.21	10.41	3.14	15.07	11.04	- 0.03	- 3.17	18.48	24.41	23.68	
Pred (B)	Mean	41.43	36.84	32.25	15.03	15.69	7.81	3.06	- 6.15	- 8.88	0.176	9.90	20.45	
	Stan. Dev.	17.37	17.88	10.69	6.12	11.51	- 2.52	9.69	- 0.66	- 1.86	14.74	22.41	18.17	

(A) $Q = b_i + m_i \; Rm$

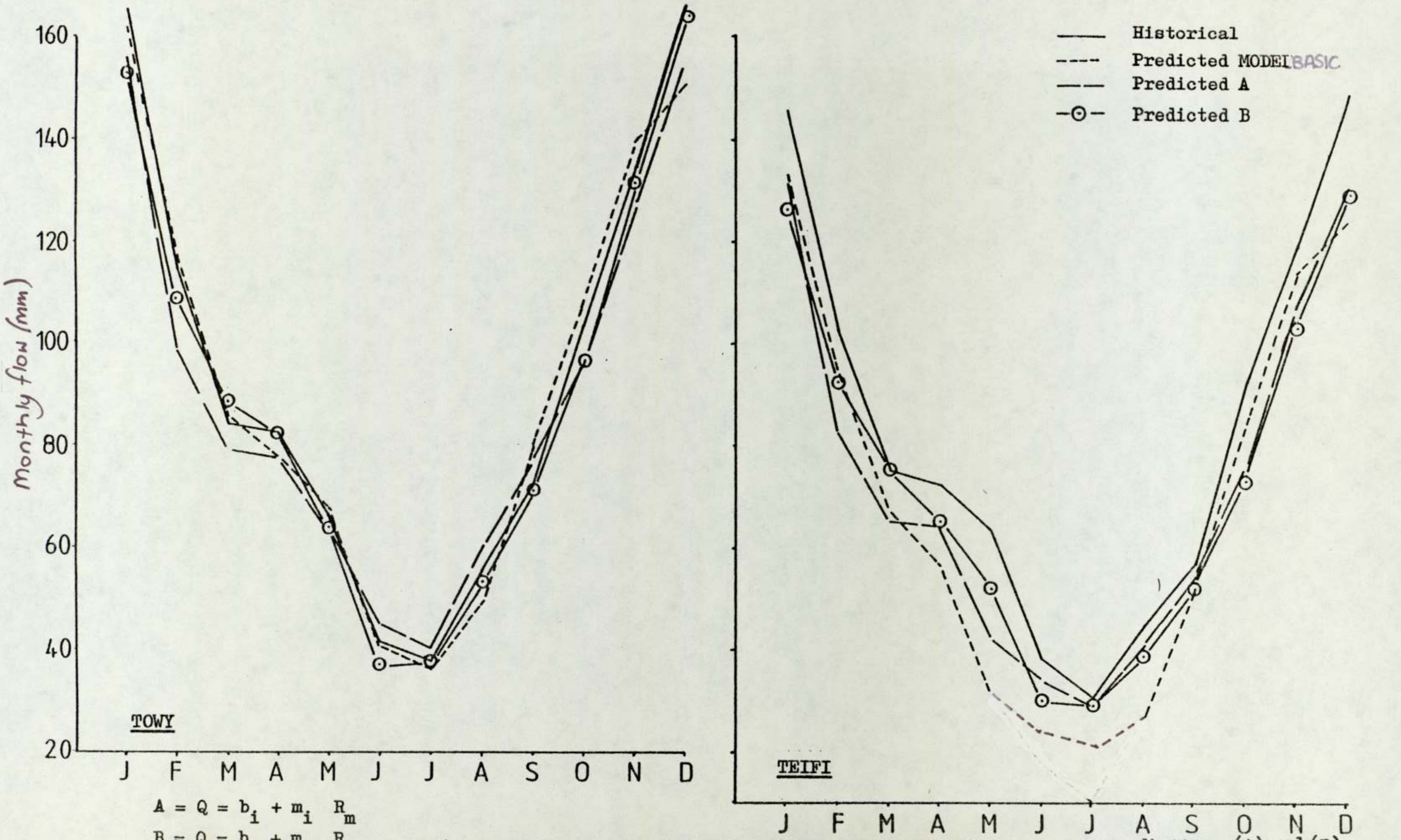
(B) $Q = b_i + m_i \; Ra$

Table 6.5.3 <u>Historical and Predicted Flow Values using El Gusbi's Predictions (A) and (B)</u>

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Actual	Mean	27.74	28.02	22.53	14.79	10.12	5.63	4.97	4.56	4.78	7.13	14.48	21.45	Nene Rainfall 1948-63
	Stan. Dev.	17.71	15.82	14.87	10.52	9.46	4.36	7.16	4.83	6.06	8.79	13.71	19.85	
Pred (A)	Mean	42.51	37.54	31.74	12.74	9.68	15.20	3.40	0.36	-11.30	- 1.99	11.56	30.61	
	Stan. Dev.	15.06	18.05	10.25	- 9.58	8.53	8.09	9.97	2.37	- 3.33	14.29	22.98	23.48	
Pred (B)	Mean	35.4	36.77	32.81	15.70	16.18	8.11	3.42	- 5.55	- 8.08	1.14	11.13	21.88	
	Stan. Dev.	17.89	18.26	11.04	6.46	11.73	25.99	9.80	- 0.38	- 1.37	15.25	22.77	18.84	
Actual	Mean	35.88	32.56	26.69	17.66	12.76	7.76	6.7	5.68	5.35	9.82	21.49	26.29	Isebrook Rainfall 1948-63
	Stan. Dev.	20.96	27.14	18.09	9.09	6.56	4.79	3.53	2.63	1.97	1.49	8.45	17.66	
Pred (A)	Mean	35.84	38.7	33.28	10.35	5.88	13.46	2.24	4.03	- 5.93	1.25	16.60	33.55	
	Stan. Dev.	15.26	19.09	11.22	9.82	6.84	6.86	9.34	4.03	- 0.13	17.37	24.49	24.62	
Pred (B)	Mean	44.42	38.78	33.76	16.83	16.99	8.61	4.01	- 4.54	- 6.73	2.75	13.18	24.28	
	Stan. Dev.	18.74	18.89	11.64	7.02	12.08	3.27	10.00	0.07	- 0.57	16.09	23.38	19.96	

(A) $Q = b_i + m_i \; Rm$

(B) $Q = b_i + m_i \; Ra$


160
140
120
100
80
60
40
20
Monthly flow (mm)
J
F
M
A
M
J
J
A
S
O
N
D
TOWY
TEIFI
Historical
Predicted MODEL BASIC
Predicted A
Predicted B

$A = Q = b_i + m_i \ R_m$

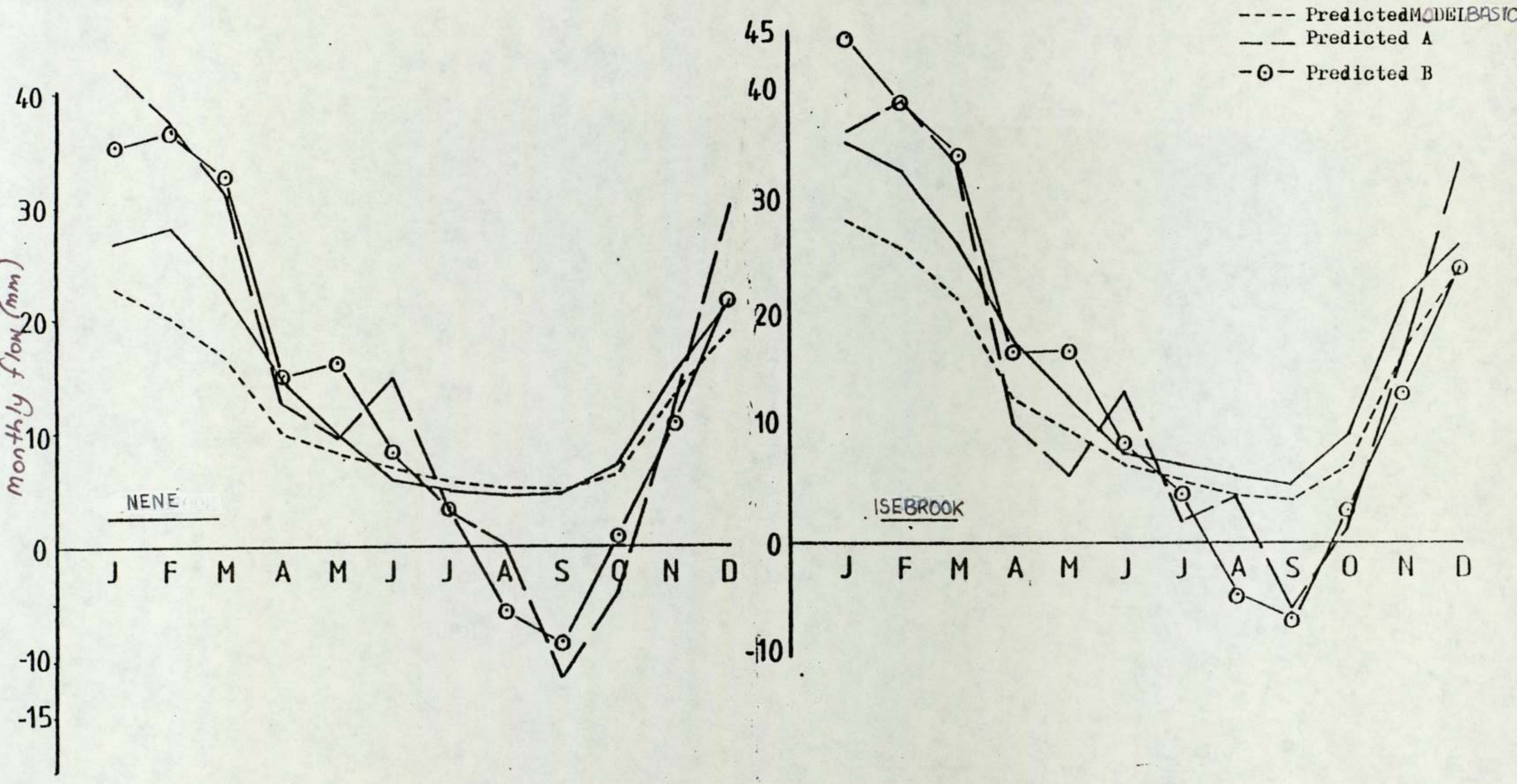


Fig 6.4.2 Historical and Predicted flow Values for MODELBASIC and Predictions (A) and (B)

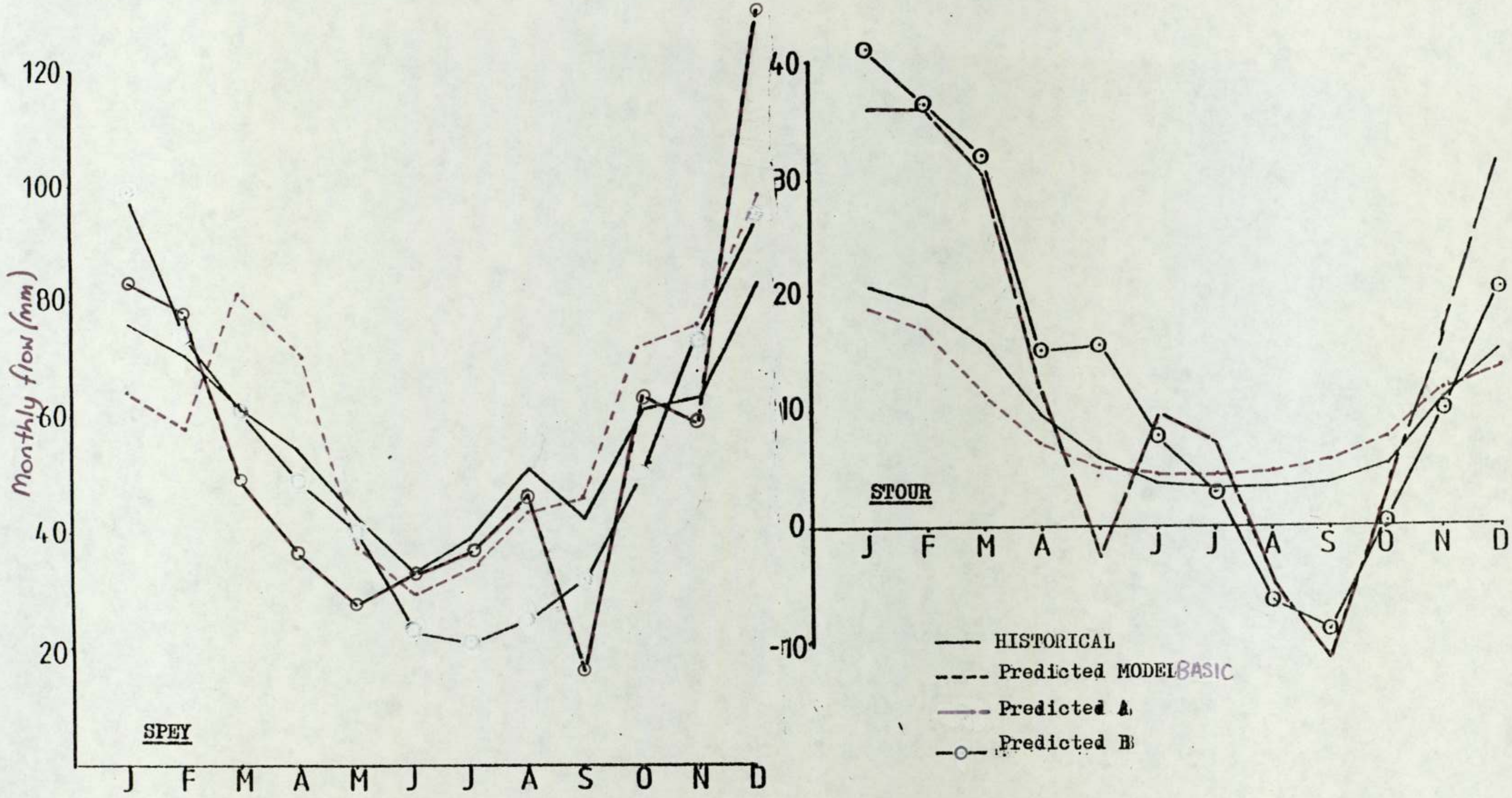


Fig 6.4.3 Historical and Predicted flow Values for MODELBASIC and Predictions (A) and (B)

(A) and (B).

The validity of El Gusbi's rainfall/streamflow relationship is therefore only proven by streamflow predictions for those catchments within the Welsh region. This is in contrast to results using the 'MODELS' which produce far more consistent closer fitting predictions when compared with historical streamflow values for catchments both internal and external to the Welsh region. This is to be expected since predictions based upon regression analysis are usually specific to the area from which they were derived and their application is consequently limited.

CHAPTER SEVEN

DISCUSSION AND CONCLUSION

The principal aim of this project has been to develop a method of estimating monthly mean flows of any given point on a river in a region of sparse hydrometric data. The approach has been to develop simple conceptual models of the rainfall/run-off process which utilise monthly mean areal rainfall and evaporation estimates as input, and then convert these into monthly mean flows. The use of catchment characteristics for the calibration of the model is the most original aspect of the project. The development and testing of the models and their calibration procedures form the bulk of the project.

7.1 THE ESSENTIAL CHARACTERISTICS

The first stage was to identify those aspects of the hydrological cycle and the physical form of the catchments which were most important in shaping the catchments response to rainfall.

The most important of the hydrological stores were clearly the soil moisture store and the groundwater store, while the most important processes were interflow/natural recharge and baseflow, and to a lesser degree the infiltration/overland flow relationship. The latter, no doubt, would have been of much greater importance had the time step of the model been shorter. The most significant catchment characteristics were considered to be relief, slope, soil type, drainage density, solid geology and vegetation. All of these were incorporated into the proposed method, except solid geology which could not be expressed in terms of a quantifiable index. However, it was felt that so many of the other characteristics were closely related to solid geology that its influence was well represented through their inclusion. The characteristics which were found to be most useful were relief (i.e. altitude), soil (as defined by Soil Survey), drainage density and slope. However, it should be said that the method adopted for the definition of slope, which was based upon the average number of contours within 1 km grid squares, can contain directional bias and should therefore be replaced by a similar method based upon a 1 km diameter circle.

It was decided in the early stages of the project that the model should be as simple as possible, bearing in mind the need for adequate precision. The reason for this was not related to computer time or size, but to the fact that a complex model could not possibly be calibrated using catchment characteristics alone. The assumed total absence of hydrometric data and the consequent reliance upon catchment characteristics for the calibration of the model dictated that the model contain relatively few systems parameters. On the otherhand, the need to represent spatial variability of rainfall, evaporation, soil type, slope, etc., required that a distributed and not a lumped model be used.

7.2 DEVELOPMENT AND CALIBRATION OF THE BASIC MODEL

The basic model therefore comprised three zones: upland, mid-land and lowland zones of equal area. These were used to represent spatial variability in the hydrological and physical character of the catchment. Each zone was represented by a soil moisture store draining into a groundwater store, both of which were assumed to behave as linear reservoirs with two drainage outlets. The soil moisture store drains by interflow and natural recharge while the groundwater store drains by baseflow and transmission flow. The latter represents the lateral transfer of water from the groundwater store in an upper zone to that in a lower zone. However, due to calibration difficulties this was assumed to be zero in all simulations thus effectively reducing groundwater drainage to baseflow only. Problems relating to the coincidence or other wise of the surface water and groundwater basins did arise and are discussed later.

The basic model was applied in two ways:

i) Using a three year sequence of mean monthly rainfall formed by repeating the annual cycle of mean monthly rainfalls three times; and

ii) Using a 16 year record of monthly rainfall

The first method is intended for situations where only short or unreliable records exist but where a reasonable estimate of the seasonal distribution of rainfall can be made. The first two years of input were used to allow the model to 'warm up' and the output from the third year was taken as the estimated distribution of monthly flows. This method cannot give any indication of the likely standard deviation of the flows, since there was no variability in the seasonal distribution of the rainfall inputs. This lack of variability in the input can, and often does, lead to errors in the estimated monthly mean flows. The reason for this is that an unusually wet summer month has a greater impact upon the mean monthly flow than it does on the mean monthly rainfall. This effect is lost if actual rainfall sequences are replaced by their long term mean.

The second method utilised actual rainfall sequences as input and therefore provided, through the operation of the model, a flow sequence of the same length. This sequence was used as a synthetic flow sequence in its own right, however, the validity of the model for use in this way was not demonstrated. What was demonstrated is that the basic model, used in this way, provided a simple and fairly reliable means of estimating mean monthly flows and their standard deviations throughout the British Isles.

These models were developed and calibrated using rainfall and flow data for a number of Welsh catchments. Calibration of the system parameters was achieved by fitting the predicted flows to the historical flows by repeated simulation.

7.3 CALIBRATION USING CATCHMENT CHARACTERISTICS

Having calibrated the model for a number of catchments, calibration functions were then developed using linear regression analysis to relate where appropriate the system parameter to the catchment characteristics. The most important of these were those relating to the linear reservoir discharge coefficients for interflow, natural recharge and baseflow. These gave -

Interflow coefficient QICOEF = 018 + 0.73 (Soil x Drainage Density (1/km))

Natural Recharge Coefficient NRCOEF = 0.85 - QICOEF

Baseflow Coefficient BFCOEF = 0.075 + 0.002 ((ERMAX-ERMIN) x NRCOEF)

where SOIL = Soil index defined by Soil Survey in WRAP

(ERMAX-ERMIN) = Winter Rainfall - Summer Rainfall

The size of the available soil moisture store (AVMT) may be determined by reference to the predominant soil type and its thickness in each zone. However, the values of available soil moisture used throughout this study were based upon typical lowland, mid-land, upland or mountainous zones, varying within a range of 250 - 75 (mm) (rainfall equivalent mm) respectively. The root constant values were calculated as 0.5 of the available moisture.

During this phase of the study several algorithms were developed which required once only calibration. The rainfall/snowfall algorithm for example, was developed and calibrated after a study of years of daily meteorological reports from Edgbaston Observatory. Much more work could be done on this subject but time did not permit it here. The main criticism of its application must be that the analysis was done on daily mean data yet it has been applied to monthly mean data. However, the combined effects of the need to keep the model simple and the actual complexity and sensitivity of this process dictate that its simulation must remain quite crude. It was, therefore, felt that a more extensive study during the course of this project could not be justified.

The snowmelt algorithm took the form of a linear mathematical equation for the rate of snowmelt, based upon constants derived following calibration using data from Rhayader catchment. Although the results did not appear particularly sensitive the constants were validated to some extent by semi-empirical equations of basin-wide melt estimates designed by U.S. Corps of Engineers (1956). These equations were derived for Canadian catchments but nonetheless confirmed that the initial values used for the constants were of the right order of magnitude.

7.4 IMPROVEMENTS TO THE BASIC MODEL

The basic model was then extended to incorporate two modifications to the model -

i) modification of the overland flow/interflow algorithm
ii) modification of the natural recharge/interflow algorithm

The modification to the overland flow/interflow algorithm utilised a generalised rainfall intensity/duration curve, which offered some measure of the amount of rainfall during the month which is likely to have become overland flow. The rainfall intensity/duration curve was calibrated for the model using field data from Plynlimon. It was also necessary to incorporate into the model the effect of catchment characteristics such as slope, vegetation and soil saturation since these factors ultimately effect infiltration and consequently the respective proportion of overland flow and interflow. The procedure devised for the evaluation of monthly overland flow was based upon the assumption that all rainfall in excess of a critical intensity (RCRIT) would become overland flow, and rainfall less than this intensity would infiltrate the ground surface. RCRIT was defined as -

$$\text{RCRIT} = \underset{\text{FACTOR}}{\text{SLOPE}} \times \underset{\text{FACTOR}}{\text{VEGETATION}} \times \text{INFILTRATION ON A FLAT SURFACE}$$

The results using MODELQF which contained the overland flow/interflow modification were a marked improvement upon those produced by MODELMEAN and MODELBASIC.

Data for Plynlimon was readily available and although limited it did permit the formulation of a non-linear algorithm describing the infiltration/overland flow relationship which was clearly of the correct form. It must, however, be said that both the rainfall intensity/duration curves and the equation for RCRIT are based upon very limited field evidence and more detailed work on this algorithm is clearly needed.

The modification of the natural recharge/interflow algorithm was the second development to the model. It aimed to take account of the degree of soil saturation by giving greater weight to the interflow component and less to the natural recharge component as soil moisture content increased. This modification came into effect when the monthly soil moisture value was in excess of field capacity after removal of the overland flow component. A basic assumption of the alteration was that the interflow/natural recharge ratio would be greatest in heavily saturated upland areas, but calibration showed that this ratio was highest in lowland areas. This may possibly be because the basic assumption ignores the effect of field drains in lowland areas which tend to encourage increased interflow. Further work on this algorithm is clearly required.

7.5 RESULTS OF TESTS OUTSIDE THE CALIBRATION AREA

During calibration and testing of the model, data had been used exclusively from the Welsh region. It was, therefore, essential to test the validity of the model and the derived calibration relationships for other regions of the U.K. Each of the test catchments were run using the four models, MODELMEAN, MODELBASIC, MODELQF and MODELFAC using systems parameters evaluated from catchment characteristics. The predicted discharge values determined from each of the MODELS were generally encouraging. Excluding Spey, the results suggested that the catchment parameters adopted for the models are applicable in areas other than that for which they were originally designed. The Spey catchment was unusual in that it was the only catchment to store snow for a period in excess of one month. The results suggested that there is scope for improvement in the snowstore/snowmelt routine. However, the snowfall and snowmelt processes are so sensitive to small changes in temperature that it is doubtful whether a significant improvement can be made without the introduction of highly sophisticated routines. It is nonetheless clear that the effects of temperature distribution throughout the month and further zoning on an altitude basis requires further consideration.

In conclusion comparison was made of the precision of predictions made by the various models. El Gusbi's rainfall/streamflow relationships only produced close fitting predictions for catchments within the area from which the relationships were derived. In contrast, predictions using the four models, especially MODELQF produced far more consistent close fitting results for catchments both within the Welsh region and outside it.

7.6 Recommendations for Further Study

There are several aspects of this project which would benefit from further study either because they require more detailed field validation or because there is scope for improved simulation of one or more hydrological processes.

1) The effect of interception was not included as a separate process in any of the models because it was felt that interception loss was adequately represented by total evapotranspiration loss. However, inclusion of interception as a separate process would enable a greater distinction to be made between forested and non-forested areas, and thereby permit greater use to be made of the catchment characteristic "PF" (i.e. proportion of forest).
2) The rainfall/overland flow/interception algorithm which proved to be of great value in the formulation of MODELQF could nevertheless benefit from further work in two areas. Firstly, rainfall intensity/duration curves for many more places in the British Isles could be derived and used to improve the form and calibration of the generalised rainfall

intensity/duration curve. Secondly, more field evidence needs to be collected and used to improve the method used to evaluate RCRIT.

3) The natural recharge/interflow algorithm proved to be of little real value and therefore requires a complete re-appraisal of the general assumptions and form of the basic functions. There is clearly scope here for a significant improvement in the model.

4) The precision of the model when applied to catchments which store snow for one or more months depends to a large extent upon the precision of the snowfall and snowmelt algorithms. Unfortunately, both of these processes are highly dependent upon temperature over a relatively small range. This fact alone makes it very difficult to model these processes with a high degree of precision, especially when using a one month time step. However, it is felt that there is still room for improvement in these algorithms. Firstly, the mean monthly temperature used in these algorithms could be replaced by a typical distribution of daily mean temperature giving the same overall monthly mean temperature. Snowmelt could then be evaluated on a daily basis and summed to give the monthly value. In this way the algorithm would more effectively take account of the few warm days within a relatively cold month. The algorithm could also benefit from the use of sub-zones based upon altitude which would be utilised only when snow was known to be lying.

5) There is a need for a fuller investigation of the degree of coincidence between surface and groundwater catchments, in order to adequately account for the movement of groundwater across catchment boundaries. This could possibly be achieved

by the use of coefficients to adjust groundwater storage, but this requires further consideration.

6) The slope index used in the model should be replaced by one based upon a 1 km circle and not a 1 km grid square. This would make little difference, if any, to the results of this project, but it would eliminate the potential for directional bias contained within the present definitions.

7) Since this project is seen as one step towards the development of a model which has general applicability throughout the world, one of the next steps must be to calibrate and test the model using flow data from a number of European rivers.

7.7 Conclusion

Throughout this project a number of rainfall/run-off models have been developed which utilise information extracted or extrapolated from historical hydrometeorological and topographic data. A basic rainfall/run-off model which utilises catchment characteristics for its calibration and estimates of mean areal rainfall and evapotranspiration as input data, has been developed and tested. An improved version of the basic model (MODELQF) has been shown to provide fairly reliable estimates of mean monthly river flows and their standard deviations for rivers in mainland Britain. Although several of the procedures and algorithms are based on limited field evidence, their use has clearly been justified by the results of the final simulation tests. The use of a simple rainfall/run-off model which is calibrated by means of catchment characteristics has been shown to provide a potentially useful means of deriving basic flow data from limited meteorological data. This method has been shown to be superior to the regression method developed by El Gusbi when used for catchments lying outside the calibration zone. This suggests that although catchment characteristics may be a relatively poor substitute for hydrometric data, they are nonetheless a convenient and useful source of data for flow prediction. Several problems remain unresolved and have been fully discussed. There is clearly much scope for further improvement to, and extension of the model, but nevertheless the basic aims of the project have been fulfilled.

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APPENDIX 1

"MODELS"

```
ENT     MODEL MEAN

LIST(LP)
PROGRAM(FXXX)
INPUT 1=CR3
INPUT 3=CR1
INPUT 5=CR2
INPUT 7=TR0
OUTPUT 6=LP0
OUTPUT 2=LP1
COMPRESS INTEGER AND LOGICAL
COMPACT PROGRAM
EXTENDED DATA
TRACE 2
END
TRACE 1
TRACE 2
MASTER MODEL2
REAL INF,INFL,NR,NRCOEF
INTEGER MTH,YR,CATCH
DIMENSION R(50,12),E(50,12),T(50,12),SM(3),SN(3),B1(12)
DIMENSION GW(3),QI(3),QB(3),QF(3),Z(3),RFAC(3)
DIMENSION NR(3),QFL(50,12),QIN(50,12),QBF(50,12),Q(50,12)
DIMENSION SNSTR(50,12),GWSTR(50,12),SMSTR(50,12)
DIMENSION RATIO(50,12),AVMT(3),RTC(3),QICOEF(40,3)
DIMENSION NRCOEF(40,3),BFCOEF(40,3),QHIST(12)
READ(1,54)CATCH
WRITE(2,53)CATCH
READ(1,17)NYRS,NTEST,B2,T1,T2
WRITE(2,20)NYRS,NTEST,B2,T1,T2
READ(5,10)((E(I,J),J=1,12),I=1,NYRS)
WRITE(2,21)((E(I,J),J=1,12),I=1,NYRS)
READ(1,10)(B1(I),I=1,12)
WRITE(2,22)(B1(I),I=1,12)
READ(5,10)((T(I,J),J=1,12),I=1,NYRS)
WRITE(2,23)((T(I,J),J=1,12),I=1,NYRS)
READ(5,10)((R(I,J),J=1,12),I=1,NYRS)
WRITE(2,24)((R(I,J),J=1,12),I=1,NYRS)
READ(1,11)(Z(I),I=1,3)
WRITE(2,25)(Z(I),I=1,3)
READ(1,11)(RFAC(I),I=1,3)
WRITE(2,26)(RFAC(I),I=1,3)
READ(1,12)ZESTAT,A1,A2,SATSTR,TRCOEF,ZBIRM
WRITE(2,27)ZESTAT,A1,A2,SATSTR
WRITE(2,28)TRCOEF,ZBIRM
READ(1,11)(AVMT(I),I=1,3)
WRITE(2,29)(AVMT(I),I=1,3)
READ(1,11)(RTC(I),I=1,3)
WRITE(2,50)(RTC(I),I=1,3)
READ(3,11)((QICOEF(I,J),J=1,3),I=1,NTEST)
READ(3,11)((NRCOEF(I,J),J=1,3),I=1,NTEST)
READ(3,11)((BFCOEF(I,J),J=1,3),I=1,NTEST)
READ(1,10)(QHIST(I),I=1,12)
WRITE(2,58)(QHIST(I),I=1,12)
WRITE(2,59)
DO 85 ITEST=1,NTEST
WRITE(2,55)(QICOEF(ITEST,J),J=1,3),(NRCOEF(ITEST,J),J=1,3),
(BFCOEF(ITEST,J),J=1,3)
WRITE(6,1)
WRITE(6,2)
WRITE(6,3)
WRITE(6,4)
WRITE(2,19)
```

```
SN(1)=0.0
SN(2)=0.0
SN(3)=0.0
SM(1)=0.0
SM(2)=0.0
SM(3)=0.0
SW(1)=0.0
SW(2)=0.0
SW(3)=0.0
YR=0
MTH=0
DO 45 I=1,NYRS
YR=YR+1
DO 45 J=1,12
IF(MTH.EQ.12)MTH=0.0
MTH=MTH+1
DO 46 K=1,3
QF(K)=0.0
RL=RFAC(K)*R(I,J)
EP=E(I,J)-B1(J)*(Z(K)-ZESTAT)
EL=EP
TL=T(I,J)-B2*(Z(K)-ZBIRM)
RTCL=RTC(K)
AVMTL=AVMT(K)
IF(TL.GT.T2)GO TO 83
IF(TL.LE.T1)GO TO 6
SNS=RL*((T2-TL)/(T2-T1))
GO TO 7
SNS=RL
GO TO 7
SNS=0.0
SNMS=SN(K)+SNS
IF(SNMS.EQ.0.0)GO TO 41
ES=EL
EL=0.0
RSNM=A1+A2*TL
IF(RSNM.LT.0.0)GO TO 41
GO TO 42
RSNM=0.0
ES=0.0
SN(K)=SNMS-RSNM-ES
SS=SN(K)
IF(SS.GE.0.0)GO TO 49
SN(K)=0.0
FRAC=SNMS/(RSNM+ES)
RSNM=FRAC*RSNM
ES=FRAC*ES
EL=EP-ES
INF=RL-SNS+RSNM
SOILM=SM(K)-EL+INF
IF(SOILM.GE.-RTCL)GO TO 30
IF(RL.GE.EL)GO TO 30
PHI=(AVMTL+SOILM)/(AVMTL-RTCL)
EA=EL*0.9
WRITE(2,93)EP,EA
SOILM=SOILM+(EL-EA)
CONTINUE
IF(SOILM.LE.0.0)GO TO 32
NR(K)=NRCOEF(ITEST,K)*SOILM
QI(K)=QICOEF(ITEST,K)*SOILM
TOTL=QI(K)+NR(K)
SOILM=SOILM-TOTL
IF(SOILM.LT.SATSTR)GO TO 62
QF(K)=SOILM-SATSTR
SOILM=SATSTR
GO TO 62
NR(K)=0.0
QI(K)=0.0
```

```
WRITE(2,18)RL,SNS,EP,TL,EL,ES,EA,RSNM,INFL,SOILM
CONTINUE
GW(1)=GW(1)+NR(1)
QB(1)=BFCOEF(ITEST,1)*GW(1)
TRANS1=TRCOEF*GW(1)
GW(1)=GW(1)-QB(1)-TRANS1
GW(2)=GW(2)+TRANS1+NR(2)
QB(2)=BFCOEF(ITEST,2)*GW(2)
TRANS2=TRCOEF*GW(2)
GW(2)=GW(2)-QB(2)-TRANS2
GW(3)=GW(3)+TRANS2+NR(3)

QB(3)=BFCOEF(ITEST,3)*GW(3)
GW(3)=GW(3)-QB(3)
WRITE(2,5)YR,MTH,SN(1),SM(1),GW(1),QF(1),QI(1),QB(1),
                 SN(2),SM(2),GW(2),QF(2),QI(2),QB(2),
                 SN(3),SM(3),GW(3),QF(3),QI(3),QB(3)
QFL(I,J)=(QF(1)+QF(2)+QF(3))/3.0
QIN(I,J)=(QI(1)+QI(2)+QI(3))/3.0
QBF(I,J)=(QB(1)+QB(2)+QB(3))/3.0
Q(I,J)=(QFL(I,J)+QIN(I,J)+QBF(I,J))
SNSTR(I,J)=(SN(1)+SN(2)+SN(3))/3.0
GWSTR(I,J)=(GW(1)+GW(2)+GW(3))/3.0
SMSTR(I,J)=(SM(1)+SM(2)+SM(3))/3.0
QTEST=Q(I,J)
IF(QTEST.GT.0.0)GO TO 45
RATIO(I,J)=0.0
GO TO 48
RATIO(I,J)=QBF(I,J)/Q(I,J)
CONTINUE
SUMD2=0.0
DO 33 IM=1,12
SUMD2=SUMD2+(Q(3,IM)-QHIST(IM))**2
WRITE(2,60)SUMD2
WRITE(2,6)((QFL(I,J),J=1,12),I=1,NYRS)
WRITE(2,7)((QIN(I,J),J=1,12),I=1,NYRS)
WRITE(2,8)((QBF(I,J),J=1,12),I=1,NYRS)
WRITE(2,9)((Q(I,J),J=1,12),I=1,NYRS)
WRITE(2,13)((SNSTR(I,J),J=1,12),I=1,NYRS)
WRITE(2,14)((GWSTR(I,J),J=1,12),I=1,NYRS)
WRITE(2,15)((SMSTR(I,J),J=1,12),I=1,NYRS)
WRITE(2,16)((RATIO(I,J),J=1,12),I=1,NYRS)
WRITE(2,59)
CONTINUE
STOP
FORMAT(///49X,'CATCHMENT ZONES')
FORMAT(///23X,'ZONE 1',32X,'ZONE 2',32X,'ZONE 3')
FORMAT(10F8.2)
FORMAT(///4X,'RL',5X,'SNS',6X,'EP',6X,'TL',6X,'EL',6X,
          'ES',6X,'EA',4X,'RSNM',4X,'INFL',4X,'SOILM')

FORMAT(1X,'NYRS =',I4,3X,'NTEST =',I4,3X,'B2 =',F8.3,3X,
'T1 =',F8.3,3X,'T2 =',F8.3)
FORMAT(/49X,'EVAPORATION',//(12F9.2))
FORMAT(/55X,'B1',//(12F9.2))
FORMAT(///49X,'TEMPERATURE',//(12F9.2))
FORMAT(///49X,'RAINFALL',//(12F9.2))
FORMAT(/9X,'ALTITUDE Z',//(3F9.2))
FORMAT(/9X,'RAINFALL RFAC',//(3F9.2))
FORMAT(1X,'ZESTAT =',F8.3,3X,'A1 =',F8.3,3X,'A2 =',F8.3,
3X,'SATSTR =',F8.3)
FORMAT(5F9.2)
FORMAT(1X,'TRCOEF =',F8.3,3X,'ZBIRM =',F8.3)
FORMAT(/9X,'AVAIL MOIST AVMT',//(3F9.2))
FORMAT(/9X,'ROOT CONST RTC',//(3F9.2))
FORMAT(3F9.2)
FORMAT(I8)
```

```
FORMAT(1X,'CATCHMENT AREA =',I8)
FORMAT(11X,'QICOEF',12X,'NRCOEF',12X,'BFCOEF',//(9F9.2))
FORMAT(1H1)
FORMAT(/49X,'HISTORICAL DIS',//(12F9.2))
FORMAT(3X,'SUMD2 =',F8.3)
FORMAT(//2X,'DATE',3(8X,'STORES',12X,'FLOWS',7X))
FORMAT(1X,'YR',1X,'MTH',3(4X,'SN',4X,'SM',4X,'GW',4X,
                     'QF',4X,'QI',4X,'QB',2X))
ORMAT(I2,2X,I2,3(2X,6F6.1))
ORMAT(2I0,3F0.0)
ORMAT(///49X,'QUICK FLOW',//(12F9.2))
ORMAT(///49X,'INTERFLOW',//(12F9.2))
ORMAT(///49X,'BASEFLOW',//(12F9.2))
ORMAT(///49X,'DISCHARGE',//(12F9.2))
ORMAT(12F0.0)
ORMAT(3F0.0)
ORMAT(6F0.0)
ORMAT(///49X,'SNOWSTORE',//(12F9.2))
ORMAT(///49X,'GROUND WATER STORE',//(12F9.2))

ORMAT(2(F8.3))
ORMAT(///49X,'SOIL MOISTURE STORE',//(12F9.2))
ORMAT(///49X,'RATIO',//(12F9.2))
ND
INISH
```

```
NT     MODEL BASIC


 LIST(LP)
 PROGRAM(FXXX)
 INPUT 1=CR3
 INPUT 3=CR2
 INPUT 5=CR1
 INPUT 7=TR1
 OUTPUT 6=LP0
 OUTPUT 2=LP1
 COMPRESS INTEGER AND LOGICAL
 COMPACT PROGRAM
 EXTENDED DATA
 TRACE 2
 END
 TRACE 1
 MASTER MODEL2
 THIS MODEL CALCULATES DISCHARGE FOR ANY NO.OF YEARS BASED
 ON ANY NO.OF YEARS RAIN.EVAP.AND TEMP.CATA
 REAL INF,INFL,NR,NRCOEF
 INTEGER MTH,YR
 DIMENSION R(50,12),E(50,12),T(50,12),SM(3),SN(3),B1(12)
 DIMENSION GW(3),QI(3),QB(3),QF(3),Z(3),RFAC(3)
 DIMENSION NR(3),QFL(50,12),QIN(50,12),QBF(50,12),Q(50,12)
 DIMENSION SNSTR(50,12),GWSTR(50,12),SMSTR(50,12)
 DIMENSION RATIO(50,12),AVMT(3),RTC(3),QICOEF(3),NRCOEF(3)
 DIMENSION XQFL(12),XQIN(12),XQBF(12),XQ(12),XSNSTR(12)
 DIMENSION XGWSTR(12),XSMSTR(12),RCRIT(3),QHIST(12)
 READ(1,17)NYRS,B2,T1,T2,RAT,SLOPE,PF,FMIN
 READ(5,101)((E(I,J),J=1,12),I=1,NYRS)
 READ(1,10)(B1(I),I=1,12)
 READ(3,10)((T(I,J),J=1,12),I=1,NYRS)
 READ(3,10)((R(I,J),J=1,12),I=1,NYRS)
 READ(1,11)(Z(I),I=1,3)
 READ(1,11)(RFAC(I),I=1,3)
 READ(1,12)ZESTAT,A1,A2,SATSTR,BFCOEF,TRCOEF,ZBIRM
 READ(1,11)(AVMT(I),I=1,3)
 READ(1,11)(RTC(I),I=1,3)
 READ(1,11)(QICOEF(I),I=1,3)
 READ(1,11)(NRCOEF(I),I=1,3)
 READ(1,10)(QHIST(I),I=1,12)
 NYRS IS NO OF YEARS,B2 IS TEMP CHANGE PER 100M
 T1 IS TEMP WHERE ALL PRECIP IS SNOW
 T2 IS TEMP WHERE ALL PRECIP IS RAIN,RAT ADAPTS BEWDLEY,
 EVAP DATA,SLOPE IS SLOPE INDEX
 PF IS PROPN FOREST,FMIN IS MIN.INFIL,E IS EVAPORATION DATA,
 B1 ADJUSTS EVAP FOR ALT
 T TEMPDATA,Z ALT.OF ZONES,RFAC ADJUSTS RAIN
 ZESTAT ALT.OF EVAP READINGS,A1&A2 CALC.SNOWMELT
 SATSTR SAT.STORE,BFCOEF BASE FLOW COEF,TRCOEF TRANS.STORE COEF
 ZBIRM ALT OF TEMP READINGS
 AVMT AVAILABLE MOISTURE,RTC ROOT CONSTANT,QICOEF INTERFLOW COEF
 NRCOEF NAT RECHARGE COEF,QHIST HISTORICAL DISCHARGE
 THIS LOOP ALTERS THE EVAP DATA DEPENDING ON THE CATCHMENT
 DO 51 I=1,NYRS
  0 51 J=1,12
 E(I,J)=RAT*E(I,J)
 RITE(2,101)((E(I,J),J=1,12),I=1,NYRS)
  RITE(2,1)
  RITE(2,2)
  RITE(2,3)
  RITE(2,4)
```

```
SN(1)=0.0
SN(2)=0.0
SN(3)=0.0
SM(1)=0.0
SM(2)=0.0
SM(3)=0.0
GW(1)=0.0
GW(2)=0.0
GW(3)=0.0
YR=0
MTH=0
HIS MAIN LOOP CALCULATES ZONAL SNOW,SOIL,AND GROUND STORES
DO 45 I=1,NYRS
YR=YR+1
DO 45 J=1,12
IF(MTH.EQ.12)MTH=0.0
MTH=MTH+1
DO 46 K=1,3
QF(K)=0.0
RCRIT(K)=0.0
RL=RFAC(K)*R(I,J)
EP=E(I,J)-B1(J)*(Z(K)-ZESTAT)
EL=EP
TL=T(I,J)-B2*(Z(K)-ZBIRM)
RTCL=RTC(K)
AVMTL=AVMT(K)
BEGINNING OF SNOWSTORE ROUTINE
IF(TL.GT.T2)GO TO 83
IF(TL.LE.T1)GO TO 6
SNS=RL*((T2-TL)/(T2-T1))
GO TO 7
SNS=RL
GO TO 7
SNS=0.0
SNMS=SN(K)+SNS
IF(SNMS.EQ.0.0)GO TO 41
ES=EL
EL=0.0
RSNM=A1+A2*TL
IF(RSNM.LT.0.0)GO TO 41
GO TO 42
RSNM=0.0
ES=0.0
SN(K)=SNMS-RSNM-ES
SS=SN(K)
IF(SS.GE.0.0)GO TO 49
SN(K)=0.0
FRAC=SNMS/(RSNM+ES)
RSNM=FRAC*RSNM
ES=FRAC*ES
EL=EP-ES
BEGINNING OF SOILSTORE ROUTINE
INF=RL-SNS+RSNM
SOILM=SM(K)-EL+INF
IF(SOILM.GE.-RTCL)GO TO 30
IF(RL.GE.EL)GO TO 30
PHI=(AVMTL+SOILM)/(AVMTL-RTCL)
EA=RL+PHI*(EL-RL)
SOILM=SOILM+(EL-EA)
CONTINUE
IF(SOILM.LE.0.0)GO TO 32
NR(K)=NRCOEF(K)*SOILM
QI(K)=QICOEF(K)*SOILM
TOTL=QI(K)+NR(K)
SOILM=SOILM-TOTL
IF(SOILM.LT.SATSTR)GO TO 62
QF(K)=SOILM-SATSTR
SOILM=SATSTR
```

```
WRITE(2,50)(XGWSTR(I),I=1,12)
WRITE(2,15)((SMSTR(I,J),J=1,12),I=1,NYRS)
WRITE(2,50)(XSMSTR(I),I=1,12)
WRITE(2,16)((RATIO(I,J),J=1,12),I=1,NYRS)
STOP
FORMAT(3X,'SUMDZ =',F6.3)
FORMAT(3F6.2)
FORMAT(///44X,'CATCHMENT ZONES')
FORMAT(///23X,'ZONE 1',32X,'ZONE 2',32X,'ZONE 3')
FORMAT(//2X,'DATE',3(8X,'STORES',12X,'FLOWS',7X))
FORMAT(1X,'YR',1X,'MTH',3(4X,'SN',4X,'SM',4X,'GW',4X,
                          'QF',4X,'QI',4X,'QB',2X))
FORMAT(I2,2X,I2,3(2X,6F6.1))
FORMAT(I0,7F0.0)
FORMAT(///49X,'QUICK FLOW',//(12F9.2))
FORMAT(///49X,'INTERFLOW',//(12F9.2))
FORMAT(///49X,'BASEFLOW',//(12F9.2))
FORMAT(///49X,'DISCHARGE',//(12F9.2))
FORMAT(12F0.0)
FORMAT(3F0.0)
FORMAT(7F0.0)
FORMAT(///49X,'SNOWSTORE',//(12F9.2))
FORMAT(///49X,'GROUND WATER STORE',//(12F9.2))

FORMAT(12F6.1)
FORMAT(///47X,'MEAN',//(12F9.2))
FORMAT(///49X,'SOIL MOISTURE STORE',//(12F9.2))
FORMAT(///49X,'RATIO',//(12F9.2))
END
TRACE 0
SUBROUTINE MEANS(X,NYRS,XBAR)
DIMENSION X(50,12),SUM1(12),XBAR(12)
DO 73 I=1,12
SUM1(I)=0.0
DO 74 J=2,NYRS
SUM1(I)=SUM1(I)+X(J,I)
XBAR(I)=SUM1(I)/FLOAT(NYRS-1)
RETURN
END
SUBROUTINE TAPEB(R,NYRS)
INTEGER F19XX,SKIP,T19XX,STATNO,STATON
DIMENSION R(50,12)
DATA FINISH/'        '/
WRITE(6,1)
READ(1,2)STATON
IF(STATON.EQ.FINISH)GO TO 6
WRITE(6,3)
READ(1,4)F19XX,T19XX
IF(F19XX.LT.1936.OR.T19XX.GT.1976.OR.F19XX.GT.T19XX)GO TO 9
NYRS=T19XX-F19XX+1
CALL GAP(2)
READ(7,5,END=999)STATNO
WRITE(2,5)STATNO
IF(STATON.EQ.STATNO)GO TO 8
CALL GAP(43)
GO TO 7
SKIP=F19XX-1936+2
CALL GAP(SKIP)
READ(7,11)((R(I,J),J=1,12),I=1,NYRS)
WRITE(2,100)((R(I,J),J=1,12),I=1,NYRS)
IJK=1976-T19XX
CALL GAP(IJK)
END FILE 7
RETURN
NYRS=0
GO TO 15
WRITE(6,12)
END FILE 7
```

```
STOP 2000
FORMAT('WHICH STATION NUMBER?'/)
FORMAT(I6)
FORMAT(' BETWEEN WHAT YEARS (1936-1976)?'/)
FORMAT(2I6)
FORMAT(17X,I6)
FORMAT(10X,12F6.0)
FORMAT(' END OF DATA. INCORRECT STATION NUMBER.')
FORMAT(10X,12F9.3)
END
SUBROUTINE GAP(J)
DO 1 I=1,J
READ(7,2)A
FORMAT(A6)
CONTINUE
RETURN
END
FINISH
```

```
ENT     MODELQF


 LIST(LP)
 PROGRAM(FXXX)
 INPUT 1=CR3
 INPUT 3=CR2
 INPUT 5=CR1
 INPUT 7=TR1
 OUTPUT 6=LP0
 OUTPUT 2=LP1
 COMPRESS INTEGER AND LOGICAL
 COMPACT PROGRAM
 EXTENDED DATA
 TRACE 2
 END
 TRACE 1
 MASTER MODEL2
 THIS MODEL CALCULATES DISCHARGE FOR ANY NO.OF YEARS BASED
.ON ANY NO.OF YEARS RAIN.EVAP.AND TEMP.DATA
 REAL INF,INFL,NR,NRCOEF
 INTEGER MTH,YR
 DIMENSION R(50,12),E(50,12),T(50,12),SM(3),SN(3),B1(12)
 DIMENSION GW(3),QI(3),QB(3),QF(3),Z(3),RFAC(3)
 DIMENSION NR(3),QFL(50,12),QIN(50,12),QBF(50,12),Q(50,12)
 DIMENSION SNSTR(50,12),GWSTR(50,12),SMSTR(50,12)
 DIMENSION RATIO(50,12),AVMT(3),RTC(3),QICOEF(3),NRCOEF(3)
 DIMENSION XQFL(12),XQIN(12),XQBF(12),XQ(12),XSNSTR(12)
 DIMENSION XGWSTR(12),XSMSTR(12),RCRIT(3),QHIST(12)
 READ(1,17)NYRS,B2,T1,T2,RAT,SLOPE,PF,FMIN
 READ(5,101)((E(I,J),J=1,12),I=1,NYRS)
 READ(1,10)(B1(I),I=1,12)
 READ(3,10)((T(I,J),J=1,12),I=1,NYRS)
 READ(3,10)((R(I,J),J=1,12),I=1,NYRS)
 READ(1,11)(Z(I),I=1,3)
 READ(1,11)(RFAC(I),I=1,3)
 READ(1,12)ZESTAT,A1,A2,SATSTR,BFCOEF,TRCOEF,ZBIRM
 READ(1,11)(AVMT(I),I=1,3)
 READ(1,11)(RTC(I),I=1,3)
 READ(1,11)(QICOEF(I),I=1,3)
 READ(1,11)(NRCOEF(I),I=1,3)
 READ(1,10)(QHIST(I),I=1,12)
 NYRS IS NO OF YEARS,B2 IS TEMP CHANGE PER 100M
 T1 IS TEMP WHERE ALL PRECIP IS SNOW
 T2 IS TEMP WHERE ALL PRECIP IS RAIN,RAT ADAPTS BEWDLEY,
.EVAP DATA,SLOPE IS SLOPE INDEX
 PF IS PROPN FOREST,FMIN IS MIN.INFIL,E IS EVAPORATION DATA,
.B1 ADJUSTS EVAP FOR ALT
 T TEMPDATA,Z ALT.OF ZONES,RFAC ADJUSTS RAIN
 ZESTAT ALT.OF EVAP READINGS,A1&A2 CALC.SNOWMELT
 SATSTR SAT.STORE,BFCOEF BASE FLOW COEF,TRCOEF TRANS.STORE COEF
 ZBIRM ALT OF TEMP READINGS
 AVMT AVAILABLE MOISTURE,RTC ROOT CONSTANT,QICOEF INTERFLOW COEF
 NRCOEF NAT RECHARGE COEF,QHIST HISTORICAL DISCHARGE
 THIS LOOP ALTERS THE EVAP DATA DEPENDING ON THE CATCHMENT
 DO 51 I=1,NYRS
 DO 51 J=1,12
 E(I,J)=RAT*E(I,J)
 WRITE(2,101)((E(I,J),J=1,12),I=1,NYRS)
 WRITE(2,1)
 WRITE(2,2)
 WRITE(2,3)
 WRITE(2,4)
```

```
  EA=RL+PHI*(EL-RL)
  SOILM=SOILM+(EL-EA)
0 CONTINUE
  IF(SOILM.LE.0.0)GO TO 32
  NR(K)=NRCOEF(K)*SOILM
  QI(K)=QICOEF(K)*SOILM
  TOTL=QI(K)+NR(K)
  SOILM=SOILM-TOTL
  IF(SOILM.LT.SATSTR)GO TO 62
  SOILM=SATSTR
  GO TO 62
2 NR(K)=0.0
  QI(K)=0.0
2 SM(K)=SOILM
  CONTINUE
  WRITE(2,416)(RCRIT(K),K=1,3)
  BEGINNING OF GROUND WATER STORE ROUTINE
  GW(1)=GW(1)+NR(1)
  QB(1)=BFCOEF*GW(1)
  TRANS1=TRCOEF*GW(1)
  GW(1)=GW(1)-QB(1)-TRANS1
  GW(2)=GW(2)+TRANS1+NR(2)
  QB(2)=BFCOEF*GW(2)
  TRANS2=TRCOEF*GW(2)
  GW(2)=GW(2)-QB(2)-TRANS2
  GW(3)=GW(3)+TRANS2+NR(3)

  QB(3)=BFCOEF*GW(3)
  GW(3)=GW(3)-QB(3)
  WRITE(2,5)YR,MTH,SN(1),SM(1),GW(1),QF(1),QI(1),QB(1),
 .                 SN(2),SM(2),GW(2),QF(2),QI(2),QB(2),
 -                 SN(3),SM(3),GW(3),QF(3),QI(3),QB(3)
  QFL(I,J)=(QF(1)+QF(2)+QF(3))/3.0
  QIN(I,J)=(QI(1)+QI(2)+QI(3))/3.0
  QBF(I,J)=(QB(1)+QB(2)+QB(3))/3.0
  Q(I,J)=(QFL(I,J)+QIN(I,J)+QBF(I,J))
  SNSTR(I,J)=(SN(1)+SN(2)+SN(3))/3.0
  GWSTR(I,J)=(GW(1)+GW(2)+GW(3))/3.0
  SMSTR(I,J)=(SM(1)+SM(2)+SM(3))/3.0
  CALL MEANS(QFL,NYRS,XQFL)
  CALL MEANS(QIN,NYRS,XQIN)
  CALL MEANS(QBF,NYRS,XQBF)
  CALL MEANS(Q,NYRS,XQ)
  CALL MEANS(SNSTR,NYRS,XSNSTR)
  CALL MEANS(GWSTR,NYRS,XGWSTR)
  CALL MEANS(SMSTR,NYRS,XSMSTR)
  QTEST=Q(I,J)
  IF(QTEST.GT.0.0)GO TO 45
  RATIO(I,J)=0.0
  GO TO 48
  RATIO(I,J)=QBF(I,J)/Q(I,J)
  CONTINUE
  SUMD2=0.0
  DO 33 IM=1,12
  SUMD2=SUMD2+(Q(3,IM)-QHIST(IM))**2
  WRITE(2,60)SUMD2
  WRITE(2,6)((QFL(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XQFL(I),I=1,12)
  WRITE(2,7)((QIN(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XQIN(I),I=1,12)
  WRITE(2,8)((QBF(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XQBF(I),I=1,12)
  WRITE(2,9)((Q(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XQ(I),I=1,12)
  WRITE(2,13)((SNSTR(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XSNSTR(I),I=1,12)
  WRITE(2,14)((GWSTR(I,J),J=1,12)      ,NYRS)
  WRITE(2,50)(XGWSTR(I),I=1,12)
```

```
 SN(1)=0.0
 SN(2)=0.0
 SN(3)=0.0
 SM(1)=0.0
 SM(2)=0.0
 SM(3)=0.0
 GW(1)=0.0
 GW(2)=0.0
 GW(3)=0.0
 YR=0
 MTH=0
 ALPHA=((15-SLOPE)/15)**1.5+0.2
 BETA=1+PF
THIS MAIN LOOP CALCULATES ZONAL SNOW,SOIL,AND GROUND STORES
 DO 45 I=1,NYRS
 YR=YR+1
 DO 45 J=1,12
 IF(MTH.EQ.12)MTH=0.0
 MTH=MTH+1
 DO 46 K=1,3
 QF(K)=0.0
 RCRIT(K)=0.0
 RL=RFAC(K)*R(I,J)
 EP=E(I,J)-B1(J)*(Z(K)-ZESTAT)
 EL=EP
 TL=T(I,J)-B2*(Z(K)-ZBIRM)
 RTCL=RTC(K)
 AVMTL=AVMT(K)
 BEGINNING OF SNOWSTORE ROUTINE
 IF(TL.GT.T2)GO TO 83
 IF(TL.LE.T1)GO TO 6
 SNS=RL*((T2-TL)/(T2-T1))
 GO TO 7
 SNS=RL
 GO TO 7
 SNS=0.0
 SNMS=SN(K)+SNS
 IF(SNMS.EQ.0.0)GO TO 41
 ES=EL
 EL=0.0
 RSNM=A1+A2*TL
 IF(RSNM.LT.0.0)GO TO 41
 GO TO 42
 RSNM=0.0
 ES=0.0
 SN(K)=SNMS-RSNM-ES
 SS=SN(K)
 IF(SS.GE.0.0)GO TO 49
 SN(K)=0.0
 FRAC=SNMS/(RSNM+ES)
 RSNM=FRAC*RSNM
 ES=FRAC*ES
 EL=EP-ES
 BEGINNING OF SOILSTORE ROUTINE
 INF=RL-SNS+RSNM
 AA1=5.75+0.0229*INF
 BB1=9.88/(INF+4.0)+0.121
 CC2=14.9+0.288*INF
 RCRIT(K)=ALPHA*BETA*FMIN*(1+((SATSTR-SM(K))/(SATSTR+AVMTL))**2)
 IF(RCRIT(K).LT.1.0)RCRIT(K)=1.0
 QF(K)=CC2*(ALOG(CC2/(AA1*(RCRIT(K)+BB1)))-1.0)+AA1*(RCRIT(K)+BB1)
 RMAX=CC2/AA1-BB1
 IF(RCRIT(K).GE.RMAX)QF(K)=0.0
 INFL=INF-QF(K)
 IF(INFL.LT.0.0)INFL=0.0
 SOILM=SM(K)-EL+INFL
 IF(SOILM.GE.-RTCL)GO TO 30
 IF(RL.GE.EL)GO TO 30
 PHI=(AVMTL+SOILM)/(AVMTL-RTC
```

```
    WRITE(2,15)((SMSTR(I,J),J=1,12),I=1,NYRS)
    WRITE(2,50)(XSMSTR(I),I=1,12)
    WRITE(2,16)((RATIO(I,J),J=1,12),I=1,NYRS)
    STOP
    FORMAT(3X,'SUMD2 =',F8.3)
    FORMAT(3F6.2)
    FORMAT(///49X,'CATCHMENT ZONES')
    FORMAT(///23X,'ZONE 1',32X,'ZONE 2',32X,'ZONE 3')
    FORMAT(//2X,'DATE',3(8X,'STORES',12X,'FLOWS',7X))
    FORMAT(1X,'YR',1X,'MTH',3(4X,'SN',4X,'SM',4X,'GW',4X,
                             'QF',4X,'QI',4X,'QB',2X))
    FORMAT(I2,2X,I2,3(2X,6F6.1))
    FORMAT(I0,7F0.0)
    FORMAT(///49X,'QUICK FLOW',//(12F9.2))
    FORMAT(///49X,'INTERFLOW',//(12F9.2))
    FORMAT(///49X,'BASEFLOW',//(12F9.2))
    FORMAT(///49X,'DISCHARGE',//(12F6.2))
    FORMAT(12F0.0)
    FORMAT(3F0.0)
    FORMAT(7F0.0)
    FORMAT(///49X,'SNOWSTORE',//(12F9.2))
    FORMAT(///49X,'GROUND WATER STORE',//(12F9.2))

    FORMAT(12F6.1)
    FORMAT(///47X,'MEAN',//(12F9.2))
    FORMAT(///49X,'SOIL MOISTURE STORE',//(12F9.2))
    FORMAT(///49X,'RATIO',//(12F9.2))
    END
    TRACE 0
    SUBROUTINE MEANS(X,NYRS,XBAR)
    DIMENSION X(50,12),SUM1(12),XBAR(12)
    DO 73 I=1,12
    SUM1(I)=0.0
    DO 74 J=2,NYRS
  4 SUM1(I)=SUM1(I)+X(J,I)
  3 XBAR(I)=SUM1(I)/FLOAT(NYRS-1)
    RETURN
    END
    SUBROUTINE TAPEB(R,NYRS)
    INTEGER F19XX,SKIP,T19XX,STATNO,STATON
    DIMENSION R(50,12)
    DATA FINISH/'          '/
    WRITE(6,1)
    READ(1,2)STATON
    IF(STATON.EQ.FINISH)GO TO 6
  9 WRITE(6,3)
    READ(1,4)F19XX,T19XX
    IF(F19XX.LT.1936.OR.T19XX.GT.1976.OR.F19XX.GT.T19XX)GO TO 9
    NYRS=T19XX-F19XX+1
  7 CALL GAP(2)
    READ(7,5,END=999)STATNO
    WRITE(2,5)STATNO
    IF(STATON.EQ.STATNO)GO TO 8
    CALL GAP(43)
    GO TO 7
  8 SKIP=F19XX-1936+2
    CALL GAP(SKIP)
    READ(7,11)((R(I,J),J=1,12),I=1,NYRS)
    WRITE(2,100)((R(I,J),J=1,12),I=1,NYRS)
    IJK=1976-T19XX
    CALL GAP(IJK)
  5 END FILE 7
    RETURN
  6 NYRS=0
    GO TO 15
 99 WRITE(6,12)
    END FILE 7
```

```
FORMAT('WHICH STATION NUMBER?'/)
FORMAT(I8)
FORMAT(' BETWEEN WHAT YEARS (1936-1976)?'/)
FORMAT(2I0)
FORMAT(17X,I8)
FORMAT(10X,12F0.0)
FORMAT(' END OF DATA. INCORRECT STATION NUMBER.')
FORMAT(10X,12F9.3)
END
SUBROUTINE GAP(J)
DO 1 I=1,J
READ(7,2)A
FORMAT(A8)
CONTINUE
RETURN
END
FINISH
```

```
ENT    MODELFAC


 LIST(LP)
 PROGRAM(FXXX)
 INPUT 1=CR3
 INPUT 3=CR2
 INPUT 5=CR1
 INPUT 7=TR1
 OUTPUT 6=LP0
 OUTPUT 2=LP1
 COMPRESS INTEGER AND LOGICAL
 COMPACT PROGRAM
 EXTENDED DATA
 TRACE 2
 END
 TRACE 1
 MASTER MODEL2
 THIS MODEL CALCULATES DISCHARGE FOR ANY NO.OF YEARS BASED
.ON ANY NO.OF YEARS RAIN.EVAP.AND TEMP.DATA
 REAL INF,INFL,NR,NRFAC
 INTEGER MTH,YR
 DIMENSION R(50,12),E(50,12),T(50,12),SM(3),SN(3),B1(12)
 DIMENSION GW(3),QI(3),QB(3),QF(3),Z(3),RFAC(3)
 DIMENSION NR(3),QFL(50,12),QIN(50,12),QBF(50,12),Q(50,12)
 DIMENSION SNSTR(50,12),GWSTR(50,12),SMSTR(50,12)
 DIMENSION RATIO(50,12),AVMT(3),RTC(3),QIFAC(3),NRFAC(3)
 DIMENSION XQFL(12),XQIN(12),XQBF(12),XQ(12),XSNSTR(12)
 DIMENSION XGWSTR(12),XSMSTR(12),RCRIT(3),QHIST(12)
 READ(1,17)NYRS,B2,T1,T2,RAT,SLOPE,PF,FMIN
 READ(5,101)((E(I,J),J=1,12),I=1,NYRS)
 READ(1,10)(B1(I),I=1,12)
 READ(3,10)((T(I,J),J=1,12),I=1,NYRS)
 READ(3,10)((R(I,J),J=1,12),I=1,NYRS)
 READ(1,11)(Z(I),I=1,3)
 READ(1,11)(RFAC(I),I=1,3)
 READ(1,12)ZESTAT,A1,A2,SATSTR,BFCOEF,TRCOEF,ZBIRM
 READ(1,11)(AVMT(I),I=1,3)
 READ(1,11)(RTC(I),I=1,3)
 READ(1,11)(QIFAC(I),I=1,3)
 READ(1,11)(NRFAC(I),I=1,3)
 READ(1,10)(QHIST(I),I=1,12)
 NYRS IS NO OF YEARS,B2 IS TEMP CHANGE PER 100M
 T1 IS TEMP WHERE ALL PRECIP IS SNOW
 T2 IS TEMP WHERE ALL PRECIP IS RAIN,RAT ADAPTS BEWDLEY,
.EVAP DATA,SLOPE IS SLOPE INDEX
 PF IS PROPN FOREST,FMIN IS MIN.INFIL,E IS EVAPORATION DATA,
.B1 ADJUSTS EVAP FOR ALT
 T TEMPDATA,Z ALT.OF ZONES,RFAC ADJUSTS RAIN
 ZESTAT ALT.OF EVAP READINGS,A1&A2 CALC.SNOWMELT
 SATSTR SAT.STORE,BFCOEF BASE FLOW COEF,TRCOEF TRANS.STORE COEF
 ZBIRM ALT OF TEMP READINGS
 AVMT AVAILABLE MOISTURE,RTC ROOT CONSTANT,QICOEF INTERFLOW COEF
 NRCOEF NAT RECHARGE COEF,QHIST HISTORICAL DISCHARGE
 THIS LOOP ALTERS THE EVAP DATA DEPENDING ON THE CATCHMENT
 DO 51 I=1,NYRS
 DO 51 J=1,12
 E(I,J)=RAT*E(I,J)
 WRITE(2,101)((E(I,J),J=1,12),I=1,NYRS)
 WRITE(2,1)
 WRITE(2,2)
 WRITE(2,3)
 WRITE(2,4)
```

```
 SN(1)=0.0
 SN(2)=0.0
 SN(3)=0.0
 SM(1)=0.0
 SM(2)=0.0
 SM(3)=0.0
 GW(1)=0.0
 GW(2)=0.0
 GW(3)=0.0
 YR=0
 MTH=0
 ALPHA=((15-SLOPE)/15)**1.5+0.2
 BETA=1+PF
THIS MAIN LOOP CALCULATES ZONAL SNOW,SOIL,AND GROUND STORES
 DO 45 I=1,NYRS
 YR=YR+1
 DO 45 J=1,12
 IF(MTH.EQ.12)MTH=0.0
 MTH=MTH+1
 DO 46 K=1,3
 QF(K)=0.0
 RCRIT(K)=0.0
 RL=RFAC(K)*R(I,J)
 EP=E(I,J)-B1(J)*(Z(K)-ZESTAT)
 EL=EP
 TL=T(I,J)-B2*(Z(K)-ZBIRM)
 RTCL=RTC(K)
 AVMTL=AVMT(K)
 BEGINNING OF SNOWSTORE ROUTINE
 IF(TL.GT.T2)GO TO 83
 IF(TL.LE.T1)GO TO 6
 SNS=RL*((T2-TL)/(T2-T1))
 GO TO 7
 SNS=RL
 GO TO 7
 SNS=0.0
 SNMS=SN(K)+SNS
 IF(SNMS.EQ.0.0)GO TO 41
 ES=EL
 EL=0.0
 RSNM=A1+A2*TL
 IF(RSNM.LT.0.0)GO TO 41
 GO TO 42
 RSNM=0.0
 ES=0.0
 SN(K)=SNMS-RSNM-ES
 SS=SN(K)
 IF(SS.GE.0.0)GO TO 49
 SN(K)=0.0
 FRAC=SNMS/(RSNM+ES)
 RSNM=FRAC*RSNM
 ES=FRAC*ES
 EL=EP-ES
 BEGINNING OF SOILSTORE ROUTINE
 INF=RL-SNS+RSNM
 AA1=5.75+0.0229*INF
 BB1=9.86/(INF+4.0)+0.121
 CC2=14.9+0.288*INF
 RCRIT(K)=ALPHA*BETA*FMIN*(1+((SATSTR-SM(K))/(SATSTR+AVMTL))**2)
 IF(RCRIT(K).LT.1.0)RCRIT(K)=1.0
 QF(K)=CC2*(ALOG(CC2/(AA1*(RCRIT(K)+BB1)))-1.0)+AA1*(RCRIT(K)+BB1)
 RMAX=CC2/AA1-BB1
 IF(RCRIT(K).GE.RMAX)QF(K)=0.0
 INFL=INF-QF(K)
 IF(INFL.LT.0.0)INFL=0.0
 SOILM=SM(K)-EL+INFL
 IF(SOILM.GE.-RTCL)GO TO 30
 IF(RL.GE.EL)GO TO 30
```

```
  PHI=(AVMTL+SOILM)/(AVMTL-TCL)
  EA=AL+PHI*(EL-AL)
  SOILM=SOILM+(EL-EA)
  CONTINUE
  IF(SOILM.LE.0.0)GO TO 32
  QI(K)=SOILM-QIFAC(K)+QIFAC(K)**2/(QIFAC(K)+SOILM)
  NR(K)=(SOILM-QI(K))*NRFAC(K)
  SOILM=SOILM-QI(K)-NR(K)
  IF(SOILM.LT.SATSTR)GO TO 62
  QI(K)=QI(K)+(SOILM-SATSTR)
  SOILM=SATSTR
  GO TO 62
  NR(K)=0.0
  QI(K)=0.0
2 SM(K)=SOILM
  CONTINUE
  WRITE(2,416)(RCRIT(K),K=1,3)
  BEGINNING OF GROUND WATER STORE ROUTINE
  GW(1)=GW(1)+NR(1)
  QB(1)=BFCOEF*GW(1)
  TRANS1=TRCOEF*GW(1)
  GW(1)=GW(1)-QB(1)-TRANS1
  GW(2)=GW(2)+TRANS1+NR(2)
  QB(2)=BFCOEF*GW(2)
  TRANS2=TRCOEF*GW(2)
  GW(2)=GW(2)-QB(2)-TRANS2
  GW(3)=GW(3)+TRANS2+NR(3)

  QB(3)=BFCOEF*GW(3)
  GW(3)=GW(3)-QB(3)
  WRITE(2,5)YR,MTH,SN(1),SM(1),GW(1),QF(1),QI(1),QB(1),
.                  SN(2),SM(2),GW(2),QF(2),QI(2),QB(2),
.                  SN(3),SM(3),GW(3),QF(3),QI(3),QB(3)
  QFL(I,J)=(QF(1)+QF(2)+QF(3))/3.0
  QIN(I,J)=(QI(1)+QI(2)+QI(3))/3.0
  QBF(I,J)=(QB(1)+QB(2)+QB(3))/3.0
  Q(I,J)=(QFL(I,J)+QIN(I,J)+QBF(I,J))
  SNSTR(I,J)=(SN(1)+SN(2)+SN(3))/3.0
  GWSTR(I,J)=(GW(1)+GW(2)+GW(3))/3.0
  SMSTR(I,J)=(SM(1)+SM(2)+SM(3))/3.0
  CALL MEANS(QFL,NYRS,XQFL)
  CALL MEANS(QIN,NYRS,XQIN)
  CALL MEANS(QBF,NYRS,XQBF)
  CALL MEANS(Q,NYRS,XQ)
  CALL MEANS(SNSTR,NYRS,XSNSTR)
  CALL MEANS(GWSTR,NYRS,XGWSTR)
  CALL MEANS(SMSTR,NYRS,XSMSTR)
  QTEST=Q(I,J)
  IF(QTEST.GT.0.0)GO TO 45
  RATIO(I,J)=0.0
  GO TO 43
5 RATIO(I,J)=QBF(I,J)/Q(I,J)
  CONTINUE
  SUMD2=0.0
  DO 33 IM=1,12
3 SUMD2=SUMD2+(Q(3,IM)-QHIST(IM))**2
  WRITE(2,60)SUMD2
  WRITE(2,6)((QFL(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XQFL(I),I=1,12)
  WRITE(2,7)((QIN(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XQIN(I),I=1,12)
  WRITE(2,8)((QBF(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XQBF(I),I=1,12)
  WRITE(2,9)((Q(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XQ(I),I=1,12)
  WRITE(2,13)((SMSTR(I,J),J=1,12),I=1,NYRS)
  WRITE(2,50)(XSMSTR(I),I=1,12)
  WRITE(2,14)((GWSTR(I,J),J=1,12 YRS)
```

```
      GO TO 62
2     NR(K)=0.0
      QI(K)=0.0
2     SM(K)=SOILM
6     CONTINUE
      BEGINNING OF GROUND WATER STORE ROUTINE
      GW(1)=GW(1)+NR(1)
      QB(1)=BFCOEF*GW(1)
      TRANS1=TRCOEF*GW(1)
      GW(1)=GW(1)-QB(1)-TRANS1
      GW(2)=GW(2)+TRANS1+NR(2)
      QB(2)=BFCOEF*GW(2)
      TRANS2=TRCOEF*GW(2)
      GW(2)=GW(2)-QB(2)-TRANS2
      GW(3)=GW(3)+TRANS2+NR(3)

      QB(3)=BFCOEF*GW(3)
      GW(3)=GW(3)-QB(3)
      WRITE(2,5)YR,MTH,SN(1),SM(1),GW(1),QF(1),QI(1),QB(1),
     .                 SN(2),SM(2),GW(2),QF(2),QI(2),QB(2),
     .                 SN(3),SM(3),GW(3),QF(3),QI(3),QB(3)
      QFL(I,J)=(QF(1)+QF(2)+QF(3))/3.0
      QIN(I,J)=(QI(1)+QI(2)+QI(3))/3.0
      QBF(I,J)=(QB(1)+QB(2)+QB(3))/3.0
      Q(I,J)=(QFL(I,J)+QIN(I,J)+QBF(I,J))
      SNSTR(I,J)=(SN(1)+SN(2)+SN(3))/3.0
      GWSTR(I,J)=(GW(1)+GW(2)+GW(3))/3.0
      SMSTR(I,J)=(SM(1)+SM(2)+SM(3))/3.0
      CALL MEANS(QFL,NYRS,XQFL)
      CALL MEANS(QIN,NYRS,XQIN)
      CALL MEANS(QBF,NYRS,XQBF)
      CALL MEANS(Q,NYRS,XQ)
      CALL MEANS(SNSTR,NYRS,XSNSTR)
      CALL MEANS(GWSTR,NYRS,XGWSTR)
      CALL MEANS(SMSTR,NYRS,XSMSTR)
      QTEST=Q(I,J)
      IF(QTEST.GT.0.0)GO TO 45
      RATIO(I,J)=0.0
      GO TO 48
5     RATIO(I,J)=QBF(I,J)/Q(I,J)
3     CONTINUE
      SUMD2=0.0
      DO 33 IM=1,12
3     SUMD2=SUMD2+(Q(3,IM)-QHIST(IM))**2
      WRITE(2,60)SUMD2
      WRITE(2,6)((QFL(I,J),J=1,12),I=1,NYRS)
      WRITE(2,50)(XQFL(I),I=1,12)
      WRITE(2,7)((QIN(I,J),J=1,12),I=1,NYRS)
      WRITE(2,50)(XQIN(I),I=1,12)
      WRITE(2,8)((QBF(I,J),J=1,12),I=1,NYRS)
      WRITE(2,50)(XQBF(I),I=1,12)
      WRITE(2,9)((Q(I,J),J=1,12),I=1,NYRS)
      WRITE(2,50)(XQ(I),I=1,12)
      WRITE(2,13)((SNSTR(I,J),J=1,12),I=1,NYRS)
      WRITE(2,50)(XSNSTR(I),I=1,12)
      WRITE(2,14)((GWSTR(I,J),J=1,12),I=1,NYRS)
      WRITE(2,50)(XGWSTR(I),I=1,12)
      WRITE(2,15)((SMSTR(I,J),J=1,12),I=1,NYRS)
      WRITE(2,50)(XSMSTR(I),I=1,12)
      WRITE(2,16)((RATIO(I,J),J=1,12),I=1,NYRS)
      STOP
0     FORMAT(3X,'SUMD2 =',F8.3)
6     FORMAT(3F6.2)
1     FORMAT(///49X,'CATCHMENT ZONES')
2     FORMAT(///23X,'ZONE 1',32X,'ZONE 2',32X,'ZONE 3')
3     FORMAT(//2X,'DATE',3(8X,'STORES',12X,'FLOWS',7X))
4     FORMAT(1X,'YR',1X,'MTH',3(4X,'SN',4X,'SM',4X,'GW',4X,
     .                        'QF',4X,'QI',4X,'QB',2X))
```

```
FORMAT(I2,2X,I2,3(2X,6F6.1))
FORMAT(I3,7F0.0)
FORMAT(///49X,'QUICK FLOW',//(12F9.2))
FORMAT(///49X,'INTERFLOW',//(12F9.2))
FORMAT(///49X,'BASEFLOW',//(12F9.2))
FORMAT(///49X,'DISCHARGE',//(12F9.2))
FORMAT(12F0.0)
FORMAT(3F0.0)
FORMAT(7F0.0)
FORMAT(///49X,'SNOWSTORE',//(12F9.2))
FORMAT(///49X,'GROUND WATER STORE',//(12F9.2))

FORMAT(12F6.1)
FORMAT(///47X,'MEAN',//(12F9.2))
FORMAT(///49X,'SOIL MOISTURE STORE',//(12F9.2))
FORMAT(///49X,'RATIO',//(12F9.2))
END
TRACE 0
SUBROUTINE MEANS(X,NYRS,XBAR)
DIMENSION X(50,12),SUM1(12),XBAR(12)
DO 73 I=1,12
SUM1(I)=0.0
DO 74 J=2,NYRS
SUM1(I)=SUM1(I)+X(J,I)
XBAR(I)=SUM1(I)/FLOAT(NYRS-1)
RETURN
END
FINISH
```

APPENDIX 2

RAINFALL AND STREAMFLOW RECORDS

WELSH CATCHMENTS

```
                      WATER    DATA   UNIT    RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
          05400300      RIVER  VYRNWY                 AT  VYRNWY RESERVOIR
YEAR     JAN      FEB      MAR      APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC

1936    7.403    3.016    4.489    2.505    0.848    3.101    5.981    1.404    4.332    3.727    7.381    7.921
1937    8.209    9.670    4.832    3.437    0.979    1.733    0.912    0.407    0.556    1.362    1.976    5.508
1938   10.524    3.111    2.137    0.658    1.358    4.401    3.876    3.353    0.902   10.671    8.761    5.907
1939   10.435    5.848    5.051    2.370    0.837    1.174    7.798    2.184    0.709    1.684   10.765    6.199
1940    1.389    7.412    4.417    3.766    1.746    0.250    1.436    0.853    2.307    6.806   13.994    5.297
1941    1.424    9.567    4.551    2.132    2.457    0.911    0.431    3.195    1.342    6.086    4.311    5.420
1942    5.782    3.880    3.502    4.464    3.367    0.715    1.851    4.028    3.079    5.783    1.185    5.920
1943   10.261    5.830    1.153    1.725    4.801    4.951    2.513    3.825    6.040    4.810    4.069    3.724
1944    8.659    3.013    1.454    1.537    1.198    2.554    2.290    1.103    5.446    8.546   10.754    7.402
1945    5.589   10.757    2.277    3.463    2.912    4.553    1.984    1.923    3.630    6.280    1.086    6.435
1946    8.912   12.340    2.800    0.710    0.570    3.875    1.448    5.264    8.114    2.117    9.575    7.118
1947    6.545    0.783   12.673    5.624    2.683    1.705    1.867    0.405    0.743    0.599    7.794    5.260
1948   15.867    7.000    2.804    2.854    1.343    0.832    1.606    5.225    4.361    2.590    4.775    6.169
1949    5.188    3.393    2.220    5.966    2.504    1.812    0.815    1.050    0.466    7.080    8.394    9.482
1950    3.105   11.401    3.817    3.885    1.557    0.621    3.756    6.171   10.434    4.347    5.585    4.186
1951    7.174    6.871    6.554    4.753    2.064    0.827    0.652    3.424    5.293    1.521   11.350   10.166
1952    6.498    4.347    3.398    1.928    2.084    1.570    0.958    2.474    1.893    9.234    4.054    6.287
1953    2.144    4.590    3.642    3.542    2.052    1.835    4.617    3.056    5.409    2.206    9.033    2.457
1954    4.009    5.937    5.131    2.247    2.508    3.649    3.657    4.281    6.370   13.066   10.894    8.241
1955    4.847    3.266    3.819    2.460    6.469    4.424    1.083    0.296    0.360    1.653    3.307    6.821
1956    7.812    1.309    2.979    0.844    1.084    0.898    3.452    6.372    4.556    3.669    2.733    7.525
1957    9.042    4.563    6.159    0.792    1.369    0.493    5.561    5.901    7.976    5.496    4.153    4.980
1958    6.464    9.232    2.003    1.459    5.201    2.826    2.460    3.820    8.161    4.511    2.296    4.369
1959    7.692    1.111    3.019    4.885    1.069    1.104    2.525    0.670    0.180    4.397    5.954   13.345
1960    9.150    7.541    3.498    4.044    0.775    1.107    3.070    3.761    5.127    5.977   12.579    8.549
1961    7.064    6.494    1.333    4.468    2.983    0.537    0.912    3.268    3.065    7.750    5.580    6.770
1962    8.894    5.164    2.023    7.458    2.830    0.801    0.842    6.029    4.896    2.049    4.526    5.588
1963    0.756    0.600   10.105    5.241    3.871    2.364    2.215    2.338    3.355    2.810   11.339    2.248
1964    2.070    2.154    2.985    2.801    3.298    1.315    2.178    1.201    1.477    3.518    4.361   13.298
1965    8.182    1.299    4.421    3.408    3.703    3.970    2.106    2.273    5.222    3.021    4.730   14.053
1966    4.117    9.107    3.694    5.877    3.714    2.175    1.533    2.912    2.810    4.295    5.793   10.320
1967    4.037    7.193    3.383    2.164    6.421    1.038    1.610    3.693    7.214   13.712    3.756    6.969
1968    9.350    2.637    8.142    2.608    3.688    2.141    3.509    1.390    7.220    6.700    4.077    4.565
1969    6.538    3.487    4.337    3.724    4.903    1.708    0.547    0.890    1.205    1.337    8.297    6.570
1970    5.870    7.942    3.837    6.348    1.357    0.851    1.586    3.074    4.058    6.475   11.356    3.721
1971    6.385    4.640    3.022    1.721    0.760    2.185    0.828    3.368    1.118    6.732    5.344    2.872
1972    6.107    4.236    4.508    6.023    4.797    4.041    2.217    3.300    0.647    0.724    6.356   10.010
1973    2.533    4.461    2.947    3.054    3.397    1.006    2.250    5.187    4.775    4.250    4.120    5.430
1974    8.920    7.300    3.090    0.630    0.580    1.080    4.090    2.300    9.820    3.790    7.771   10.249
1975    9.192    3.532    2.807    3.064    2.203    0.358    1.934    0.815    3.604    2.540    4.730    4.450
1976    6.660    3.970    3.070    1.490    1.310    0.490    0.290    0.000    0.000    7.100    3.860    3.380
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                                  WATER  DATA  UNIT  RETRIEVAL  LISTING (I.C.L. MAG. TAPE  TYPE B FORMAT )
          05400530         RIVER  SEVERN           AT  UPPER SEVERN  IE  MONTFORD - VYRNWY
YEAR     JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1937    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1938    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1939    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1940    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1941    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1942    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1943    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1944    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1945    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1946    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1947    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1948    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1949    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1950    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1951    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1952    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1953    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1954    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1955    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1956    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1957   55.719    76.565    48.096     9.623     8.808     6.538    21.148    60.587    86.178    42.501    60.608    40.667
1958   72.314    98.288    23.950     9.334    24.815    34.043    32.965    39.335    71.976    62.968    27.522    47.835
1959   96.906    17.003    20.699    39.771    18.577     8.614    12.259     6.984     2.255    18.163    43.148   101.027
1960  105.930    76.360    42.092    34.071     9.739     5.873     9.115    21.736    41.454    68.100   116.490    99.452
1961   65.116    64.553    15.207    30.390    30.035     4.325     4.797    14.815    13.636    46.024    31.770    80.786
1962   90.499    55.123    21.404    67.271    22.259     7.722     4.841    26.640    40.893    14.012    37.780    57.870
1963   13.074    13.955    89.599    49.071    24.673    13.460    15.800    11.141    19.253    17.406   106.235    25.219
1964   19.593    23.467    35.838    20.929    24.286    12.376    11.644     8.268     4.962    18.187    30.780   107.049
1965  116.951    16.190    49.183    34.622    31.863    22.832    17.716    16.297    46.088    26.364    54.103   190.372
1966   56.199    94.875    41.190    64.197    30.099    17.023     9.295    14.677    14.316    39.316    60.930   121.217
1967   44.444    71.116    97.054    18.416    55.676    16.906     8.133     9.837    33.828   112.611    53.477    65.669
1968  110.272    30.436    47.824    24.738    38.030    17.451    46.090    10.705    40.694    47.732    47.160    50.961
1969   71.172    59.156    58.331    34.324    69.550    21.387     5.625     8.168     5.037    14.485    54.043    52.995
1970   51.837    98.036    44.396    55.227    14.710     5.984     5.695    15.849    17.388    22.072   107.937    44.508
1971   64.057    49.791    32.002    19.328    13.153    12.811     8.069    21.279     7.899    31.404    39.471    30.407
1972   60.488    49.595    36.962    37.913    22.772    31.180    15.619    17.762     7.385     5.045    34.856    93.410
1973   24.060    47.392    24.399    20.650    23.258     8.801    14.846    40.049    25.420    43.082    29.435    43.908
1974   97.861    98.543    30.415     9.275     5.674     5.818     9.968    11.813    33.180    39.408    85.826    88.059
1975   93.106    39.613    32.432    25.552    17.636     7.986     6.246     6.520     7.685    10.736    19.015    28.908
1976    6.660     3.970     3.070     1.490     1.310     0.490     0.290     0.000     0.000     7.100     3.860     3.380
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                              WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE   TYPE B FORMAT )
          05400150   .  RIVER  SEVERN          AT  MID-SEVERN   IF.  BEWDLEY - MONTFORD
YEAR     JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1937    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1938    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1939    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1940    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1941    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1942    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1943    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1944    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1945    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1946    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1947    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1948    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1949    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1950    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1951    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1952    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1953    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1954    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1955    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1956    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1957   34.660    48.451    33.528    14.844    10.211     6.420     8.064    21.748    36.557    23.220    43.665    22.654
1958   38.341    65.270    33.343    16.928    11.044    12.034    16.593    18.151    40.069    54.935    29.025    38.597
1959   81.128    26.202    25.808    39.162    22.801    12.369     8.917     7.920     4.899     7.286    17.330    49.187
1960   78.806    63.637    33.131    24.720    12.678     8.396     7.014     9.220    29.733    59.777    76.852    70.368
1961   45.302    47.373    19.196    24.976    21.690    10.854     8.393     4.967     4.339    11.440    10.251    27.496
1962   42.362    24.607    13.753    24.919    14.187     7.561     5.474     7.164    11.043     9.169    16.961    20.049
1963    8.455    15.036    39.644    24.806    12.176     7.453     9.226     3.228     5.001     7.025    19.312    14.102
1964    8.466    11.446    26.051    12.629    10.276     5.876     2.970     2.169     2.594     4.686     5.644    11.254
1965   39.463    11.762    26.684    15.291    10.491     7.093     4.140     0.198    15.150    10.995    16.966    95.237
1966   37.179    51.133    29.354    41.607    24.755    12.727     9.329    15.257    11.656    24.142    27.242    58.306
1967   29.217    29.314    39.897    11.716    27.803    15.109     7.236    11.083     4.505    23.881    27.556    31.681
1968   65.958    27.354    20.624    17.508    28.868    16.324    44.560    14.755    22.992    21.909    30.068    31.843
1969   43.181    47.199    44.282    20.235    58.149    25.243    11.284    13.556    10.540     0.143    25.890    31.301
1970   49.236    48.682    36.901    28.375    14.726     7.668     7.547    15.637     9.753     5.383    35.539    30.871
1971   43.607    30.640    30.299    21.625    11.452    15.833     6.989    12.891     6.483    15.562    22.275    21.162
1972   48.137    40.724    30.777    24.058    16.166    16.779    13.280    12.650     7.567     8.480    20.692    45.266
1973   20.987    23.691    18.788    18.026    19.754     9.294    12.672    16.386     8.879    17.248    16.495    20.852
1974   40.629    43.107    26.055    11.435     8.016     7.912     7.922     9.387    34.680    12.618    24.832    22.421
1975   27.658    27.900    22.289    22.314    13.551     3.451     5.350     1.525     4.557     9.010    10.602    11.288
1976   81.786    56.120    45.398    23.294    17.497     9.020     5.555     3.645    31.699   109.054    56.809    83.120
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                                            WATER    DATA    UNIT    RETRIEVAL    LISTING
             05400800              RIVER    TEME                         AT   TENBURY
YEAR      JAN        FEB        MAR        APR        MAY        JUN        JUL        AUG        SEP        OCT        NOV        DEC

1936     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1937     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1938     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1939     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1940     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1941     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1942     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1943     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1944     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1945     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1946     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1947     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1948     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1949     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1950     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1951     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1952     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1953     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1954     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1955     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1956     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1957    15.871     29.393     17.871      6.377      3.304      2.121      1.838     16.702     25.032     11.282     26.189     14.828
1958    23.827     42.004     14.286      7.332      4.314      8.182      6.637      8.035     29.695     36.105     13.585     21.124
1959    35.793     10.154     11.628     17.318      9.047      3.676      2.283      1.574      1.086      1.350      8.273     38.175
1960    51.704     36.530     21.195     16.007      4.793      2.640      1.707      2.082     10.528     43.195     50.229     42.061
1961    25.829     21.617      7.944     16.586     15.174      3.494      2.411      1.690      1.529      8.381      6.858     19.414
1962    35.651     14.524      9.005     21.062      8.957      4.490      3.021      5.967     11.702      7.921     15.908     15.426
1963     9.709      8.826     45.180     21.717      8.534      4.583      5.701      2.632      2.465      2.133     24.542     10.188
1964     6.201      9.507     20.588     10.332      7.377      5.392      3.264      1.855      1.495      1.668      3.154     16.413
1965    28.314      8.024     19.442     10.071      7.451      5.315      4.260      2.910     11.231     10.037     16.328     57.376
1966    25.514     40.898     21.013     26.402     22.267      7.553      4.725      5.840      6.339     20.809     30.200     31.340
1967    19.085     31.652     24.037      8.148     19.831      9.600      5.644      4.246      7.885     25.945     19.848     20.965
1968    40.160     15.423     15.313     12.011     16.960      8.168     21.955      5.204      8.962     13.690     17.180     22.230
1969    30.500     29.190     31.810      6.690     35.380     13.089      4.487      4.569      3.233      2.463     15.343     21.353
1970    35.427     37.987     20.392     15.753      7.939      3.671      2.385      7.208      4.864      2.474     30.193     17.030
1971    32.419     17.264     17.176      9.366      5.902      4.709      2.368      3.441      1.706      5.290      9.046     11.538
1972    35.555     28.816     24.677     12.303     10.528     10.664      6.001      5.636      3.534      3.216     10.607     39.918
1973    12.560     14.778      9.882      8.897     11.749      6.458      5.390      7.275      3.668      6.558      6.338     10.204
1974    40.182     41.064     14.419      6.313      4.041      2.972      2.583      1.864      6.906      8.129     19.631     17.251
1975    26.894     17.364     17.172     12.824      7.553      3.269      2.256      1.527      1.373      1.576      3.089      5.574
1976     8.847      9.136      7.452      4.701      2.575      1.563      1.012      0.746      6.988     31.770     15.794     26.268
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                                      WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
         05507654       . RIVER  WYE        AT  UPPER  WYE  IE  ERW. ¬( CAB. + RHAY. + ABER.)
 YEAR     JAN      FEB      MAR      APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC

 1936    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1937    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1938   50.844   19.827   10.860    2.105    2.375    5.900   13.252    4.979    2.355   35.057   48.681   48.865
 1939   70.814   35.792   32.355   18.307    4.619    1.580   26.808   16.936    2.891    2.853   56.161   37.687
 1940   19.820   44.408   24.727   14.320   14.348    2.823    4.121    1.686    1.770   10.502   95.688   34.358
 1941   18.989   54.384   33.977   12.161    8.260   12.714    3.591    8.364    7.023   19.123   22.963   32.702
 1942   29.485   22.646   12.714   26.886   19.082    9.181    4.444    4.436    6.043   16.586    9.535   35.795
 1943   58.449   59.292    6.912    5.060   12.674   10.840    4.525    6.352   28.094   29.241   38.314   25.645
 1944   45.120   16.416    6.612    6.088    3.190    2.978    4.296    7.657   11.663   39.707   58.243   47.776
 1945   20.616   60.679   11.063   16.102    7.820   21.854    7.821    6.893   15.476   42.343   21.604   56.286
 1946   63.052   95.503   15.165    6.765    4.825   15.813    6.726   19.239   55.342   14.217   63.795   42.138
 1947   35.629    6.194   85.124   28.719   11.707    5.088    3.376    1.655    1.474    1.499   14.672   20.384
 1948   89.036   39.118    8.058   16.625    7.914   12.155    4.766    6.576   18.798   12.961   17.444   51.668
 1949   34.958   11.356   13.014   22.394    6.741    6.947    0.757    0.988    0.783   18.557   46.868   54.210
 1950   16.171   71.297   17.490   15.184   10.182    2.756    8.107   21.831   41.371   22.321   40.412   29.342
 1951   44.671   39.747   38.417   31.782    8.893    4.133    1.495    3.990   14.401    4.703   68.766   44.551
 1952   44.758   33.193   14.560   12.737   16.642    6.888    4.456   11.486   10.008   28.412   23.754   37.176
 1953   12.821   27.124   15.451   23.691   10.137    4.285    5.256    7.500   18.561   13.462   31.400   14.678
 1954   21.846   40.308   20.974   16.894    5.032   25.218    6.947   26.968   14.394   44.113   68.141   52.101
 1955   24.875   20.640   18.880   11.058   28.565   31.572    4.414    1.790    1.270    3.549   14.813   29.800
 1956   43.347   11.076   14.667    5.000    3.386    2.996    4.303   13.254   31.346   15.667   11.161   37.316
 1957   33.918   48.876   29.503    5.380    3.881    2.089    3.374   14.028   41.254   16.525   30.762   20.101
 1958   36.773   59.925   12.559    5.681    9.982   14.411   12.807   16.702   35.513   38.276   17.796   22.809
 1959   49.052    7.383   15.015   25.513   10.429    4.615    3.881    1.904    0.678    7.924   32.409   66.373
 1960   59.602   53.628   26.507   30.539    5.166    3.537    3.637    7.559   20.471   43.413   66.710   54.284
 1961   43.537   37.712    7.842   26.170   17.670    3.372    2.999    3.928    5.363   39.135   20.466   41.532
 1962   52.306   30.855    8.169   35.818   14.330    4.602    3.089   17.150   28.381   13.150   22.217   28.221
 1963   10.579    8.913   55.353   25.359   15.492    7.496   11.444    3.840    6.712    8.998   56.472   12.243
 1964    7.005   10.180   17.297   10.446   11.310    7.802    2.919    2.288    1.442    7.133   17.215   51.649
 1965   57.568    6.321   21.532   15.699   14.462    9.988    5.813    4.545   24.581   14.840   28.490   82.303
 1966   27.749   52.782   19.361   27.836   15.654    5.768    3.433   10.244    7.753   29.588   28.025   60.433
 1967   26.429   44.689   23.097    6.905   24.656    6.417    5.182   10.385   29.044   67.086   26.196   30.255
 1968   53.951   14.158   23.173   13.285   23.523   13.899   19.540    3.780   15.950   27.914   25.287   32.898
 1969   45.508   29.939   23.599   14.892   35.996   11.593    3.540   10.714    4.421    3.265   33.046   36.697
 1970   44.598   57.143   26.014   29.002    8.398    2.957    2.913    8.310   10.485   10.019   67.770   22.375
 1971   45.186   26.181   41.274    8.094    4.667   10.929    2.615    6.265    2.157   14.659   21.684   20.588
 1972   42.674   33.981   26.023   37.097   19.032   20.404    7.123    4.501    2.508    1.508   28.925   63.454
 1973   13.196   30.170   13.361   11.540   15.367    4.376    5.067   14.298    6.976   12.167   14.319   30.270
 1974   65.865   61.377   17.731    3.532    3.106    3.347    5.846    8.607   36.842   22.137   45.236   57.174
 1975   57.404   23.591   18.829   14.368    6.755    1.919    2.201    1.642    5.150    6.968   18.078   19.701
 1976   27.246   20.971   13.895    6.712    4.087    1.752    0.820    0.510    7.153   38.787   25.961   33.643
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                                WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
            05500270         RIVER  WYE                      AT  MID-WYE  I.E BELMONT - ERWOOD
YEAR      JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1937     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1938    17.257    10.248     4.504     1.777     1.777     5.325     9.803     7.105     3.102    12.688    14.901    17.505
1939    25.421    14.827    16.738    11.435     4.729     2.230     8.600     5.113     2.130     0.747    26.285    20.045
1940     6.785    16.474    17.126    11.451    10.573     6.191     5.976     2.451     0.211     3.798    29.914     9.836
1941    12.403    34.111    22.797    11.351     4.666     3.719     1.494     8.516     2.488    14.271     5.760    13.618
1942    12.779    12.140    11.856    13.277    13.561     8.595     5.949     4.813     4.876    15.481     8.011    15.138
1943    18.642    21.887     1.268     3.314    11.998    10.388     6.207     2.556    10.116     6.433     8.700     7.032
1944    10.831     4.566     1.830     1.820     1.820     1.615     2.325     1.004     4.571    14.318    21.061    18.399
1945     5.444    24.748     5.359     5.145     1.530     8.227     6.544     4.934     5.496     6.385     3.613     7.370
1946     3.041    22.728    10.152     5.439     7.443    18.823    10.326    24.701    33.275    14.075    38.945    31.844
1947    29.787    11.720    64.388    32.334    10.294     1.173     0.058     1.199     0.511    -0.073     6.438     7.264
1948    39.502    23.896     5.323    11.761     4.392     9.047     2.573     3.908    11.614    11.093    14.660    23.139
1949    23.728     8.721    10.272    12.729     5.639     3.335     1.288     0.442     0.683     9.978    16.386    17.011
1950     5.839    31.554     7.058     5.871     5.750     1.762     3.451     6.944    14.797    12.871    19.762    19.562
1951    26.852    18.232    21.719    17.747    11.362     3.703     2.688     2.199     4.876     3.661    16.674     5.897
1952    10.178     7.684     7.132     8.226    10.773     4.366     1.467     4.445     0.926     4.650    10.036    20.188
1953     7.816     7.033     3.003     8.821     5.649     2.772     3.772     2.861     4.481     4.383    10.307     7.577
1954     7.617    13.734    11.922     5.862     2.712     4.758     4.414    10.818     8.156    30.894    30.667    24.919
1955    12.711    13.983    13.624     6.785     9.912    21.076     5.699     1.607     1.933     1.377     4.940     6.917
1956    15.990     9.773    13.014     4.364     2.235     2.190     1.632     3.758     4.053     5.267     3.457    12.262
1957    10.987    29.139    13.280     5.836     5.173     4.392     5.825     8.920     6.796     6.314    15.404    12.516
1958    14.668    20.473    10.534     5.304     1.761     4.584     2.603     7.447    10.194    21.125    10.250    12.176
1959    21.804     8.490     8.127     8.693     8.883     2.719     1.923     2.189     1.354     0.255     4.729    23.277
1960    19.307    19.482    15.801    15.546     4.763     2.761     0.258    -0.793     0.935    19.595    24.211    29.903
1961    18.774    19.402     5.174     9.345     9.605     1.614     0.515    -0.012    -0.328     3.823     1.331    20.049
1962    21.307    10.647     2.424     4.406     3.906     2.483     1.158     1.629     3.863     4.576     6.382     7.009
1963     6.698     2.224    24.664    12.431     9.968     6.535    12.131     7.606     5.165     5.366    22.880    10.732
1964     5.504     7.600    11.865     7.150     6.621    10.642     8.006     3.602     1.149     1.860     1.543     8.652
1965    16.756     9.460    11.080     5.076     4.802     4.059     5.363     5.810     2.026     5.618    12.082    34.606
1966    21.051    20.115    19.512    17.484    23.663     8.519     6.531    12.226    13.239    24.428    16.405    18.168
1967    14.586    18.874    17.258     7.252    10.581    14.323     6.648     1.430     2.654    14.177    13.474     9.611
1968    14.174    10.308     7.512     7.541     7.221     6.178    14.745     2.142     3.006     9.876    14.547    16.835
1969    22.196    17.571    12.685     6.738    15.131     9.248     2.495    -0.639     2.266     1.504     3.959     9.423
1970    16.046    19.973     8.437     4.340     5.559     1.871     1.170     1.034     0.761    -0.995    11.204     9.251
1971    24.238    15.089    11.974     6.798     4.011     6.222     2.315     3.629     2.392     3.681     2.695     7.677
1972    21.939    21.664    13.739    13.010     3.450     7.438     3.860     2.486     2.631     2.561     3.796    28.502
1973    11.529    12.500     9.677     4.630     6.317     3.827     3.181     5.839     0.039     2.987     3.788     1.486
1974    30.511    37.442     5.130     7.268     2.531     3.078     2.859     3.337     6.112     6.661    12.647    12.533
1975    20.975    12.186    11.514     6.543     7.191     2.901     3.009     1.621    -0.169     1.008     0.402     5.026
1976     3.472     1.860     1.874     2.314     2.964     3.140     0.926     0.463     2.300    16.323     5.417    13.172
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                                      WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE H FORMAT )
            05500120         RIVER  WYE                          AT  LOWER  WYE  I.E CADORA - BELMONT
YEAR     JAN        FEB        MAR.       APR        MAY        JUN        JUL        AUG        SEP        OCT        NOV        DEC

1936      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1937      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
1938     37.304     26.805     17.811     10.246     13.074     11.498      3.193      4.876      4.913     10.215     30.605     61.969
1939    106.442     39.998     32.549     28.104     13.639      7.911     16.153     14.286      9.032     11.072     44.594     47.561
1940     30.424     80.452     36.263     20.919     25.848      9.189      8.200      5.744      6.522     11.535     68.806     21.456
1941     48.219     91.230     57.886     28.009     15.159     24.880     10.237      5.344      9.463      2.677     18.710     22.591
1942     28.759     36.615     29.751     26.447     10.982     11.156      3.535      3.861      5.822      1.530      9.599     34.233
1943     86.358     73.561     19.472      8.268      6.801      4.518      2.846      2.252      7.163     11.067     13.712     23.602
1944     23.080     18.862      9.815      6.639      4.124      2.882      1.478      3.304      5.087     12.718     44.126     50.507
1945     24.901     70.584     23.776     16.448     15.549     21.639     19.209     18.042     25.059     44.195     38.030     67.138
1946     64.756     59.354     22.686     15.059     13.618     13.141      4.718     15.601     49.723     16.669     61.932     53.746
1947     52.516     22.644    133.409     60.169     30.566     18.284     13.329      7.785      5.512      5.221      9.952      9.661
1948     48.243     39.868     16.694     20.617     20.231     12.542      8.838      9.737     16.027      9.855     18.399     50.261
1949     48.153     23.415     23.851     26.218     11.969     10.379      5.374      3.822      5.229     11.520     33.810     25.964
1950     16.511     77.212     30.235     15.858     12.808      6.244      4.582     -0.358     10.262     18.084     32.435     29.072
1951     49.213     59.322     58.396     44.505     21.729     16.154      6.601      4.418      3.244      5.324     78.101     42.022
1952     52.868     34.111     23.612     21.587     32.364     11.867      6.817     13.481      9.815     20.517     34.969     67.484
1953     25.888     28.679     16.753     35.782     19.541     12.149      4.293      5.904     11.284     10.778     24.268     20.105
1954     18.151     48.563     38.879     21.492     11.041     38.228      9.600     13.252      5.380      7.277     90.985     89.538
1955     49.275     43.189     43.633     25.191     32.451     61.837     14.004      8.816      6.050      0.858     12.555     28.299
1956     49.933     26.742      8.430     11.226      8.290      5.573      5.626      6.978     26.734     16.226      8.798     36.217
1957     38.851     76.512     36.020     15.897      7.405      2.719      0.793      3.964     20.218     12.828     39.135     32.508
1958     44.401     88.802     32.621     15.056     13.221     22.229     11.997      8.807     41.910     68.017     32.338     42.731
1959     96.222     24.230     27.864     29.761     26.606     12.397      7.379      5.060      3.157      5.635     19.794     87.697
1960     90.247     77.985     57.625     48.224     14.229      7.796      5.870      7.255     15.631     90.331    122.216     80.675
1961     60.825     53.746     22.316     41.626     30.129     11.907      7.167      5.913      7.481      9.203      9.684     30.214
1962     53.983     25.740     14.371     32.632     13.891      5.780      4.486      9.188      5.963     10.488     17.518     20.458
1963      2.503     14.952     83.705     41.173     17.103      7.216      1.982     -0.487      2.820      1.614     37.661     22.654
1964     11.959     14.819     38.879     18.901     10.675      5.745      1.159      1.642      2.847      5.518      8.902     22.666
1965     53.526     14.353     36.163     22.363     14.734     13.201     10.371      8.265     26.093     15.493     16.529     68.833
1966     45.465     67.213     34.441     45.207     27.895     10.661      4.411      1.876      8.349     14.495     38.847     36.125
1967     38.416     53.125     53.920     14.462     30.920     12.616      3.980     11.732      6.165     50.491     48.170     39.882
1968     69.837     37.178     51.170     22.471     29.899     16.972     52.806     15.999     12.030     23.432     40.905     62.395
1969     70.809     59.778     64.314     23.902     38.880     26.480      9.573     11.249      5.145      5.015     17.442     27.781
1970     75.650     77.365     40.712     25.089     20.277     10.336      6.492      8.106      7.618      3.909     48.728     33.527
1971     57.210     42.707     38.510     20.888     16.046     25.895     14.023     13.656      8.256     12.090     13.235     20.798
1972     57.288     67.768     51.852     26.728     32.407     24.599     14.031     10.656      7.523      5.683     14.799     76.830
1973     26.643     22.735     15.726     14.321     18.832     13.210      8.528      8.274      6.705     12.709     14.144     12.283
1974     63.351     88.004     33.116     13.503     13.403      9.360      9.775      6.758     12.608     13.605     28.202     21.453
1975     39.912     48.164     38.799     22.485     12.612      8.164      7.370      5.593      5.694      4.891      7.084      9.610
1976     11.835     13.114     14.479     11.837      4.622      2.755      3.195      1.598     15.046     64.113     34.228     59.931
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                                   WATER    DATA    UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE   TYPE B FORMAT )
           05500500        RIVER  WYE                    AT  RHAYADER
YEAR     JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1937     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1938    14.202     6.207     4.173     1.738     1.121     4.763     5.855     3.115     1.352     8.970    14.676    10.527
1939    18.313    10.433     7.039     3.214     1.557     0.772     8.471     4.049     1.094     1.806    22.013    11.337
1940     1.931     8.057     5.357     3.476     2.180     0.965     4.173     0.872     3.154     6.229    19.310     8.721
1941     3.364    12.207     6.354     3.218     2.990     1.995     0.685     5.046     2.382     8.222     5.214     7.475
1942     8.347     5.635     7.911     3.407     4.298     1.159     2.803     2.803     3.476    10.589     2.124     9.094
1943    11.960     9.793     1.370     2.124     3.987     5.536     2.429     3.551     9.011     6.727     9.140     5.855
1944    12.583     5.393     1.869     2.060     1.308     2.253     2.492     1.059     5.407    12.271    13.260    10.340
1945     6.104    14.414     2.865     4.184     2.741     4.055     2.118     2.056     3.540     6.229     1.995     8.098
1946    10.020    18.000     1.620     1.159     1.121     4.763     3.052     9.032    16.800     3.675    12.101     9.530
1947     7.973     1.448    17.068     5.021     2.865     1.480     2.554     0.810     0.901     0.747     9.719     8.596
1948    20.930     8.257     3.426     4.827     1.931     5.536     2.928     4.360     6.887     4.423     6.694     9.406
1949     9.780     3.793     5.544     7.788     3.052     1.674     1.121     2.056     1.352     9.406    13.710    16.320
1950     5.170    16.689     4.111     5.922     2.492     0.772     2.429     8.658    15.770     6.852    10.106     7.849
1951    11.275    10.620    12.209     8.689     2.305     1.287     0.997     2.616     5.278     1.744    16.735    12.209
1952    11.088     7.357     4.173     2.575     3.177     3.090     1.308     3.426     4.119     6.665     7.273    10.839
1953     3.737     7.034     6.229     4.699     2.367     1.223     5.170     4.983     6.630     3.177    10.556     3.488
1954     7.973     8.306     5.357     5.021     1.495     5.664     6.540     8.471     7.595    15.510    15.384    14.202
1955     6.167     5.241     5.606     4.892     6.977     7.788     1.682     0.436     1.867     3.177     5.342     8.534
1956    12.707     2.197     6.665     1.545     1.121     1.094     3.177     9.032     8.110     5.855     4.634    10.839
1957     9.530    10.552     8.347     1.223     1.682     1.287     5.419    10.340    14.740     8.970     7.981     9.032
1958    10.963    16.069     3.177     2.060     3.800     3.991     3.924     5.232     8.883     8.783     5.021     5.544
1959    13.704     1.793     4.236     6.437     2.554     1.674     3.301     0.872     0.322     7.288    10.106    17.005
1960    14.451     9.538     5.544     7.402     1.184     1.287     4.485     4.672     8.432     8.160    14.997    14.701
1961     9.593     9.034     2.305     6.308     3.987     0.579     1.184     4.423     2.832     9.530     6.823     8.970
1962    12.396     9.724     1.931    10.234     3.239     1.030     0.685     6.977     7.209     3.052     5.085     9.655
1963     2.616     1.362    13.455     8.046     5.419     2.768     2.928     3.488     5.471     5.544    15.963     1.931
1964     2.492     3.396     4.049     2.639     4.049     2.124     3.426     3.239     1.995     6.354     8.496    15.884
1965    12.084     1.793     4.672     5.214     4.360     3.154     2.616     2.803     7.853     3.675     5.278    23.919
1966     6.354    11.379     5.606     6.050     4.796     4.570     2.429     3.862     3.218     6.354     8.303    19.933
1967     6.291     9.793     5.731     3.283     7.101     1.802     2.305     5.232     7.080    17.379     7.917    10.029
1968    17.130     3.795     7.101     4.699     6.790     3.540     4.423     0.934     5.342     7.973     5.214     6.977
1969    10.839     6.138     6.478     6.244     7.350     3.476     0.872     3.924     2.124     2.990    11.007    10.153
1970     8.285    16.207     7.039    11.007     1.744     0.708     2.928     4.423     3.862     8.160    19.053     7.039
1971    10.465     8.276     5.046     1.995     1.121     3.862     0.685     3.115     1.159     6.727     8.947     5.108
1972    10.402     7.524     6.291    11.972     4.236     5.600     2.928     2.056     0.901     0.685     9.398    13.143
1973     5.668    11.172     4.423     5.342     5.170     1.480     2.678     5.731     5.664     7.724     7.595    11.150
1974    17.005    13.655     3.613     0.965     0.872     1.931     5.295     3.613    11.843     6.852    11.779    17.130
1975    15.074     5.034     4.049     5.214     2.803     0.451     1.495     0.623     3.605     3.115     6.501     7.537
1976    10.029     6.792     3.737     2.124     2.056     0.644     0.436     0.187     1.609     9.157     5.793     6.914
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                                WATER    DATA    UNIT    RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
             05500600          RIVER  ELAN                    AT  CARAN COCH
YEAR      JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936    11.930     6.315     4.950     5.590     2.285     5.148     9.390     2.019     5.516     6.434    13.057    13.833
1937    17.650    17.152    11.018     9.427     1.991     1.506     2.061     0.479     2.313     3.843     3.458    11.004
1938    16.101     5.918     3.619     1.920     1.883     7.572     7.176     4.109     2.087    14.328    16.611    12.881
1939    16.653    11.302     7.388     4.788     1.195     1.011    10.885     3.732     0.951     2.200    23.826    10.715
1940     4.078    11.279     6.507     4.392     2.330     0.442     7.813     0.895     3.424     9.036    23.257     9.778
1941     3.322    16.374     8.730     3.786     4.834     2.322     1.017     8.750     1.880     8.778     8.167    10.418
1942    11.044     7.436     5.856     5.092     7.946     1.215     4.726     4.112     6.082    12.624     2.441    13.618
1943    15.710    10.331     1.560     2.886     7.076     5.491     3.231     5.035    10.817     9.036    11.641     6.388
1944    12.151     5.510     1.945     2.212     1.665     2.447     4.134     1.390     7.872    15.741    15.883    12.089
1945     7.450    14.512     3.664     4.044     3.792     6.776     3.616     2.747     6.697     7.200     2.140    11.356
1946    11.882    21.455     3.003     1.351     1.819     6.948     3.466    10.925    16.421     4.497    17.037    12.266
1947     9.741     1.130    24.490     6.348     3.671     2.046     3.224     0.704     1.162     1.167    12.955     9.767
1948    23.470     9.332     4.302     5.102     2.398     7.590     3.697     5.028     8.947     6.890     6.706    14.333
1949     8.994     3.366     6.606     7.074     5.523     1.451     0.320     1.225     0.883    11.303    14.380    15.543
1950     5.565    16.537     4.918     5.822     2.719     0.710     3.071     9.851    15.027     6.454    12.271     9.473
1951    12.445    12.229    12.371    10.520     3.024     1.167     0.867     5.044     8.258     1.872    21.850    13.407
1952    11.750     7.474     5.165     3.382     4.802     3.971     1.720     5.840     5.260     9.604     8.268    12.965
1953     5.107     7.858     7.253     7.469     3.829     2.072     6.569     5.640     8.579     4.794    11.465     4.723
1954     9.231    11.279     6.810     5.796     2.736     8.877     8.719    10.571     8.733    18.743    20.997    16.359
1955     7.985     6.187     8.436     6.292     9.313     9.546     1.453     0.249     2.608     5.675     7.911    10.609
1956    14.722     2.677     8.295     2.324     1.215     1.362     3.624    12.902    10.009     6.479     5.576    13.360
1957     9.274    13.615     8.920     1.005     2.200     1.484     8.804    13.601    19.901     9.481     9.622     9.362
1958    11.760    18.049     3.200     2.345     5.029     6.026     4.848     6.493    11.160    12.236     7.419     7.561
1959    15.152     2.113     6.428     9.424     2.679     1.286     3.763     0.714     0.096    11.423    12.972    18.225
1960    17.641    13.991     6.250     8.269     1.815     1.826     5.338     4.330     9.752    11.468    19.196    17.472
1961    12.485    10.154     2.724     9.888     4.086     0.787     2.897     5.032     4.732    14.750     7.566    10.432
1962    15.603    11.389     2.506    12.202     5.615     1.198     0.824     9.902    11.001     4.474     6.932    11.672
1963     1.065     0.719    19.111     9.410     6.513     3.610     3.296     4.590     7.629     6.632    16.529     2.246
1964     3.673     4.270     6.462     3.806     4.627     2.721     3.684     3.981     2.553     8.838     9.917    20.235
1965    15.639     2.302     7.125     7.085     4.876     4.299     2.908     4.013    13.640     4.809     8.402    29.081
1966     8.278    13.340     6.767     7.931     6.227     5.641     3.173     5.729     4.777     8.725    10.080    25.830
1967     8.519    11.023     5.565     3.194     9.412     1.633     2.336     7.213    11.642    18.823     9.938    12.434
1968    19.441     4.406     9.274     5.182     7.213     4.756     4.534     1.374     8.093     9.537     6.507     8.297
1969    14.201     8.481     7.260     7.102     7.980     4.941     1.076     5.924     2.149     3.486    13.694    13.731
1970    12.777    15.453     9.127    11.650     2.070     0.767     4.474     6.300     4.780     9.333    20.725     6.946
1971    12.440     9.171     6.612     2.911     1.917     7.034     0.854     3.613     1.116     8.038    11.855     6.389
1972    14.495    10.428     7.488    10.648     5.977     6.886     3.366     2.885     1.349     0.950    13.891    16.532
1973     7.102    10.876     4.522     5.673     6.548     1.343     3.619     5.604     5.343     8.072     9.551    14.682
1974    21.022    16.809     5.839     0.923     1.924     2.840     6.526     4.534    14.694     8.862    13.133    18.068
1975    17.037     5.324     4.740     6.531     2.817     0.284     1.511     0.618     5.040     4.603     9.725     9.137
1976    11.541     8.386     4.946     2.414     3.229     0.639     0.275     0.069     3.407    14.083     7.809     8.244
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                              WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
           05500400        RIVER  WYE                      AT  ABERNANT
YEAR      JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1937     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1938     6.880     2.830     1.523     0.702     0.870     3.597     3.726     1.931     0.955     6.200    11.661     4.759
1939     7.315     4.396     3.345     1.883     0.408     0.871     6.173     2.040     0.618     0.952     8.964     4.759
1940     1.523     4.157     3.127     1.939     0.761     0.225     1.387     0.218     0.646     3.236     8.093     3.535
1941     1.387     5.118     3.018     1.549     1.468     1.152     0.408     2.583     0.702     3.426     2.979     3.698
1942     3.345     2.198     2.012     2.332     3.263     0.590     1.061     2.040     2.304     3.916     1.096     5.112
1943     5.683     3.523     0.462     0.618     2.284     2.108     1.197     1.904     3.962     3.535     4.046     2.230
1944     4.569     1.948     0.625     0.927     0.517     0.927     1.849     0.897     3.035     6.336     6.941     4.813
1945     2.828     6.563     2.012     2.248     1.632     3.035     1.251     1.115     2.838     2.719     0.871     4.269
1946     4.514     7.677     1.115     0.450     0.598     2.810     1.278     3.073     5.564     1.686     6.070     4.025
1947     3.617     0.632     8.131     2.838     1.197     0.759     0.734     0.218     0.365     0.489     3.934     3.154
1948     9.509     3.663     1.414     1.855     0.843     3.007     1.332     2.067     4.749     3.046     3.119     6.554
1949     4.106     2.288     2.556     3.288     1.768     1.152     0.190     0.517     0.422     3.997     6.098     6.581
1950     2.665     8.430     2.937     2.585     1.496     0.590     2.556     4.560     7.699     3.018     5.648     3.916
1951     6.227     4.426     4.704     4.665     1.142     0.787     0.354     2.257     4.243     0.843     8.121     5.955
1952     5.439     3.808     2.991     1.883     2.237     1.546     0.979     2.556     1.742     4.052     3.400     5.248
1953     1.931     3.372     2.311     2.838     1.577     0.899     2.040     2.203     3.765     2.257     5.367     1.985
1954     3.454     5.269     2.991     2.220     1.142     3.962     2.801     4.677     3.513     8.539     7.868     6.282
1955     3.562     2.649     3.154     2.473     4.133     4.018     0.952     0.218     0.422     1.822     2.894     5.140
1956     5.547     1.192     2.638     0.815     0.816     0.955     1.278     4.351     3.850     2.638     1.770     5.058
1957     5.384     5.961     4.569     0.618     1.061     0.534     3.046     4.025     8.037     4.215     3.625     3.726
1958     5.320     7.587     1.197     0.731     2.311     2.023     1.822     2.665     3.513     4.786     2.782     2.937
1959     6.363     0.783     2.638     3.822     0.952     0.365     0.979     0.290     0.141     3.154     5.451     8.267
1960     6.934     6.192     2.475     3.175     0.925     1.236     1.876     2.284     3.962     4.269     8.514     6.309
1961     5.602     4.576     0.925     4.215     2.257     0.393     0.897     1.840     2.248     7.179     3.203     5.384
1962     6.708     4.185     0.870     4.440     2.910     0.787     0.544     4.133     4.946     2.148     3.484     3.943
1963     1.033     1.204     8.104     3.625     3.073     1.995     2.284     1.659     2.332     2.910     6.323     1.278
1964     1.224     2.033     2.774     1.855     2.475     1.180     1.441     1.006     1.124     3.481     3.878     7.859
1965     6.853     1.024     2.991     2.726     2.300     3.300     3.000     2.020     4.500     1.958     2.248    12.591
1966     3.861     7.858     3.889     4.833     4.133     2.164     1.251     3.644     2.304     4.079     3.962    11.367
1967     4.161     3.389     2.883     1.433     3.753     1.012     1.169     3.454     4.580    10.877     4.637     5.847
1968     8.403     2.703     3.861     2.136     3.209     2.641     2.175     0.780     3.344     4.514     3.681     3.345
1969     5.248     3.071     2.311     2.389     3.345     1.686     0.544     2.012     1.040     1.251     5.957     5.847
1970     5.547     5.901     3.698     4.637     1.169     0.506     1.632     1.985     2.108     3.073     8.008     2.828
1971     5.983     3.462     2.910     1.321     0.897     2.866     0.625     1.822     0.506     3.073     3.934     2.801
1972     5.547     3.750     3.209     4.974     2.774     3.653     1.876     1.550     0.674     0.680     5.564     8.185
1973     2.230     4.396     2.067     2.136     2.067     0.702     1.061     3.997     1.770     3.100     3.597     5.547
1974     8.892     8.159     2.447     0.506     0.789     1.265     2.883     3.518     6.744     3.726     5.901     7.886
1975     7.886     2.559     2.012     2.529     1.006     0.309     1.006     0.462     2.501     2.040     4.215     3.290
1976     3.753     3.198     1.795     1.096     1.142     0.422     0.381     0.190     1.658     5.357     3.400     3.290
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                                WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE 8 FORMAT )
            06000100       RIVER  TOWY                         AT  TY CASTELL
YEAR      JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1937     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1938     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1939     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1940     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1941     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1942     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1943     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1944     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1945     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1946     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1947     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1948     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1949     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1950     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1951     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1952     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1953     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1954     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1955     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1956     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1957     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1958     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1959    84.977    12.268    33.923    47.657    14.048     4.437     7.071     3.652     1.607    28.600    89.083    96.106
1960    97.268    94.238    32.932    38.880    10.755     9.557    12.771    30.897    61.363    58.161   109.810    87.639
1961    70.706    62.918    18.839    54.083    34.632     8.030     7.400    12.361    25.630    86.903    35.907    52.045
1962    73.368    41.114     9.719    46.070    30.384     7.253     4.777    35.284    59.860    26.097    43.977    37.123
1963     9.487    19.629    78.577    40.607    33.439    16.063    26.313    12.248    20.403    31.868    77.650    19.516
1964    12.687    16.738    27.642    18.010    29.613    12.850    14.177    11.913    10.513    35.639    36.880    97.406
1965    78.197    19.732    34.910    33.060    28.616    39.523    24.300    13.694    48.010    20.984    39.580   128.432
1966    48.961    84.679    42.635    33.380    43.074    22.040    16.726    37.726    24.760    58.700    41.640   105.439
1967    59.839    67.854    41.255    22.840    47.474    14.433    14.968    31.232    49.847   130.658    53.457    60.865
1968    78.239    33.907    40.932    29.790    41.219    31.400    42.197    15.061    33.617    48.116    43.353    55.913
1969    84.577    44.318    25.977    26.650    43.700    27.087    13.206    23.806    12.203     8.168    56.967    68.026
1970    76.916    65.218    38.890    51.093    15.200     5.360    11.168    23.430    24.390    29.329   111.587    40.116
1971    74.200    34.732    36.681    16.240    11.203    27.267     7.206    22.258     5.457    37.503    42.063    40.365
1972    63.445    58.362    43.529    60.107    21.539    40.407    16.739    25.484     7.803     6.281    59.320   105.655
1973    25.404    37.782    27.968    21.817    22.471     7.237     6.948    27.455    14.373    21.752    34.167    59.626
1974   120.710    95.796    25.990     6.867     7.448     6.870    18.910    26.032    74.027    53.965    74.107    80.800
1975   101.313    38.936    24.023    35.873     9.777     3.080     6.894     3.487    17.563    21.597    46.203    40.106
1976     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
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                              WATER    DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
              06000200    .  RIVER  TEIFI                   AT  GLAN TEIFI
 YEAR      JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

 1936     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1937     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1938     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1939     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1940     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1941     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1942     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1943     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1944     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1945     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1946     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1947     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1948     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1949     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1950     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1951     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1952     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1953     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1954     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1955     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1956     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1957     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1958     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1959     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1960    72.347    62.218    24.916    31.330     8.205     5.411     5.837    15.844    46.564    47.597    75.896    57.103
 1961    45.162    42.283    10.073    32.054    23.649     4.033     5.070     7.638    16.441    69.211    29.676    39.559
 1962    55.736    31.315     8.305    29.503    16.110     5.687     2.969    15.677    38.086    24.916    40.188    31.087
 1963     7.038    18.095    58.805    30.710    19.746     9.547    14.910     5.837     7.169    15.743    61.178    17.778
 1964     9.640    12.051    22.014    17.578    22.548     9.099     8.472    11.774     5.342    22.615    20.060    64.141
 1965    54.569    11.152    22.615    20.129    17.278    15.062    11.107     9.073    42.015    21.214    35.053    93.927
 1966    38.125    59.361    29.352    35.466    34.322    27.539    17.311    29.319    13.235    44.028    33.674    81.386
 1967    41.127    47.638    30.186    14.545    29.219    12.580     8.305    25.016    38.051    81.986    45.772    43.661
 1968    56.203    25.315    21.481    21.955    33.822    16.682    25.983     6.671    12.477    29.719    29.538    40.326
 1969    59.205    37.298    15.710    16.785    29.152    20.266     6.504    11.040     6.204     6.471    35.225    58.338
 1970    57.604    45.791    34.322    41.153    24.916     7.272     6.804    31.420    13.373    26.484    77.688    36.724
 1971    47.908    32.866    33.188    20.473    11.708    21.714     7.205    25.049     7.031    18.845    35.776    37.324
 1972    51.467    53.126    27.284    36.638    28.819    43.014    25.183    17.511     4.756     3:969    35.604    69.378
 1973    20.480    29.469    20.547    14.476    15.577     6.066     5.270    15.076     8.789    19.879    29.917    39.826
 1974    90.292    58.347    24.583     7.824     8.639     6.549    10.373    11.774    50.942    52.234    43.325    45.629
 1975    67.944    31.131    17.244    29.503    12.708     3.964     3.569     2.935     6.755    12.275    32.261    35.123
 1976    30.686    30.735    21.280    13.373     6.871     3.550     1.868     1.134     4.481     0.000     0.000     0.000
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                                   WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
              05400300       RIVER  VYRNWY                        AT  VYRNWY RESERVOIR
 YEAR     JAN        FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

 1936    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1937    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1938    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1939    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1940    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1941    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1942    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1943    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1944    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1945    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1946    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1947    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1948    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1949    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1950    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1951    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1952    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1953    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1954    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1955    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1956    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1957    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1958    0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1959  238.800    27.900   119.400   170.200    50.800    96.500   170.200    35.600    15.200   243.800   199.400   431.800
 1960  284.500   229.100    76.700   130.600    59.900    89.700   191.000   173.500   167.100   203.200   398.800   271.800
 1961  238.800   177.800    40.600   165.100    86.400    53.300   106.700   180.300   147.300   271.800   177.800   198.100
 1962  292.100   137.200    88.900   188.000   127.000    58.400    76.200   251.500   180.300    88.900   114.300   182.900
 1963   63.500    58.400   266.700   167.600   144.800   139.700    71.100   149.900   142.200   101.600   360.700    76.200
 1964   58.400    58.400    91.400   121.900   121.900    73.700   127.000    83.800    83.800   140.000   157.000   446.000
 1965  328.000    26.000   154.000   136.000   150.000   171.000   121.000   118.000   194.000   122.000   177.000   491.000
 1966  119.000   283.000   135.000   160.000   151.000   117.000   116.000   104.000   118.000   153.000   225.000   313.000
 1967  136.000   226.000   111.000    70.000   249.000    54.000   132.000   146.000   274.000   468.000   125.000   217.000
 1968  269.000    56.000   262.000   102.000   128.000   123.000   124.000   108.000   277.000   230.000   130.000   154.000
 1969  151.000   187.000   103.000   143.000   207.000    93.000    49.000    88.000    80.000    64.000   279.000   188.000
 1970  190.000   277.000   138.000   231.000    58.000    88.000   103.000   144.000   155.000   217.000   333.000   116.000
 1971  212.000   142.000    95.000    66.000    52.000   131.000    73.000   177.000    57.000   237.000   196.000    73.000
 1972  194.000   124.000   163.000   190.000   198.000   151.000   127.000    99.000    42.000    65.000   246.000   283.000
 1973   88.000   143.000    78.000   124.000   163.000    41.000   137.000   213.000   204.000   130.000   153.000   173.000
 1974  311.000   221.000    88.000    16.000    61.000   106.000   211.000    97.000   346.000   154.000   281.000   328.000
 1975  328.000    68.000   101.000   141.000    48.000    39.000   152.000    86.000   203.000    74.000   176.000   137.000
 1976  226.000   106.000   112.000    42.000   111.000    31.000    59.000     7.000   274.000   224.000   134.000   115.000
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                                           WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
     DATA    IN    MM.
              05406530        RIVER   SEVERN                         AT   UP SEVERN
 YEAR       JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

 1936      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1937      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1938      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1939      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1940      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1941      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1942      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1943      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1944      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1945      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1946      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1947      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1948      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1949      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1950      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1951      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1952      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1953      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1954      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1955      0.000     0.000   . 0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1956      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1957      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
 1958    124.183   179.247    37.339    30.941   109.499   102.136   141.489   101.004   203.580    98.591    66.601   111.911
 1959    142.831    14.580    66.119   116.919    81.498    75.208    92.900    30.251     7.229   131.993   120.842   218.675
 1960    177.938   111.315    52.157    68.194    42.384    67.569   113.176   146.020   130.391   160.617   206.967   165.238
 1961    126.135    79.209    22.035   101.121    54.410    34.735    74.710   103.105    83.425   151.917    84.558   104.858
 1962    150.926    73.221    59.637   113.322    84.417    29.137    68.229   142.211   137.717    46.317    66.368   116.299
 1963     36.659    29.137   122.799    98.376    70.227   102.361    49.808    85.921    86.297    56.290   219.526    30.890
 1964     34.486    37.108    75.458    68.619    63.270    60.380    81.690    57.159    51.810    92.802    86.728   197.424
 1965    157.039    16.560   101.558    86.704    93.363   108.069    89.535    64.509   154.144    51.728   125.607   279.134
 1966     71.802   157.139    61.581   112.802    91.216    86.584    74.046    84.072    61.363   128.877   135.848   175.602
 1967     65.728   145.239    77.437    36.437   175.581    41.414    84.802    70.483   154.432   232.010    66.265   134.141
 1968    143.139    38.170   106.771    34.179   117.512   100.974   141.830    93.316   163.725   105.188    83.851    95.265
 1969    112.193   113.581    93.560    82.167   193.365    44.753    50.049    95.342    68.463    31.486   170.969   101.995
 1970    115.532   137.504    98.144   107.237    35.974    65.974    68.388   133.512    74.239    91.139   214.481    52.021
 1971    138.581    58.693    64.584    57.609    55.219   101.632    43.632   128.753    38.121   107.992   117.337    53.072
 1972    120.581    87.291   100.069   103.995   102.555   103.802    94.486    55.997    40.951    51.365   120.139   157.139
 1973     47.095    72.728    33.949    95.681   112.656    29.463   133.853   124.897   123.239    83.851    66.995    82.800
 1974    180.944   126.504    50.242     9.707    46.316    75.584   100.872    65.535   190.771    90.021   157.237   129.769
 1975    154.941    38.632    71.632    71.776    49.049    19.072    76.483    62.925    90.774    50.925    80.555    74.069
 1976      0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
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                                       WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
      DATA    IN    MR.
              05400150         RIVER   SEVERN                        AT   MID SEVERN
   YEAR      JAN       FEB      MAR      APR       MAY       JUN      JUL      AUG       SEP       OCT       NOV       DEC

   1936     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1937     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1938     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1939     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1940     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1941     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1942     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1943     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1944     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1945     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1946     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1947     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1948     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1949     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1950     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1951     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1952     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1953     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1954     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1955     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1956     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1957     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
   1958    62.927   107.529   26.010   12.200    56.073   104.980  124.746   91.975   144.268    34.410    44.320    82.818
   1959    94.336     5.798   63.711   90.629    41.820    57.020   53.626   30.500     2.899    60.666   100.618   123.484
   1960   130.248    54.746   39.009   32.927    47.901    59.010   78.627  109.127   127.211   138.713   115.673    84.264
   1961    70.046    50.328    8.421   99.399    36.720    26.010   76.200   63.638    57.629    76.265    31.547    71.027
   1962    30.966    28.437   27.528   73.926    62.518    16.209   63.711  109.127    96.638    19.529    54.309    47.755
   1963    28.510    16.209   62.745   53.837    35.339    75.517   41.210   45.838    50.727    44.109    97.102     9.118
   1964    11.718    28.310   71.499   47.218    47.008    51.410   45.627   34.518    10.426    51.750    37.348    71.728
   1965    69.098    11.359   75.793   53.272    50.870    67.750   92.880   42.554   144.717    19.272    90.391   142.326
   1966    40.152    93.424   36.793   90.554    69.554    80.478   70.359   85.000    39.554   107.435    76.065   106.783
   1967    37.033    70.022   45.152   21.076   137.630    28.837   43.750   40.152    92.304   113.250    46.435    70.304
   1968    68.141    33.359   36.902   58.674    86.033    70.033  118.435   41.348   103.185    58.348    50.272    62.272
   1969    59.467    77.511   54.511   49.272   178.957    26.315   48.120   91.239    18.228    12.315   102.304    57.109
   1970    81.391    63.141   64.272   64.109    14.435    42.554   54.957  113.315    38.511    33.065   142.902    30.554
   1971    89.348    24.391   67.880   58.000    51.043    82.315   31.837  112.196    25.837    66.989    79.630    29.554
   1972    95.913    58.913   65.391   32.783    65.630    60.870   64.033   41.076    46.641    46.359    56.424    95.304
   1973    78.315    36.511   20.957   66.913    83.033    35.641  105.793   59.424    63.065    55.913    50.315    43.750
   1974    94.859    65.185   44.478   10.000    31.957    48.793   51.467   59.478    98.337    64.793    76.500    41.217
   1975    72.739    24.957   52.315   61.837    35.837    20.000   55.554   43.315    47.109    20.033    45.511    43.152
   1976     0.000     0.000    0.000    0.000     0.000     0.000    0.000    0.000     0.000     0.000     0.000     0.000
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                                      WATER   DATA   UNIT   RETRIEVAL   LISTING
               03400800         RIVER  TEME                    AT  TENBURY
YEAR       JAN       FEB       MAR      APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC

1936      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1937      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1938      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1939      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1940      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1941      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1942      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1943      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1944      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1945      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1946      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1947      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1948      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1949      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1950      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1951      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1952      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1953      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1954      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1955      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1956      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
1957     58.400    81.300    61.000    7.600   45.700   48.300   83.800  165.100  160.000   50.800   71.100   66.000
1958    109.200     7.600    68.600  101.600   53.300   55.900   58.400   35.600    2.500   91.400  121.900  182.900
1959     73.700   132.100    38.100   12.700   68.600  109.200  109.200   76.200  170.200   88.900   58.400   86.400
1960    157.500    96.500    58.400   53.300   40.600   53.300   86.400  119.400  106.700  182.900  160.000  116.800
1961     86.400    53.300     5.100  114.300   38.100   27.900   53.300   63.500   66.000  111.800   50.800   83.800
1962    121.900    35.600    45.700   94.000   71.100   12.700   63.500  124.500  119.400   25.400   68.600   55.900
1963     25.400    35.600   104.100   78.700   50.800   71.100   50.800   61.000   45.700   40.600  147.300   22.900
1964     22.900    40.600    73.700   38.400   43.200   53.300   43.200   35.600   22.900   59.000   48.000  103.000
1965     89.000    10.000    81.000   55.000   60.000   70.000   71.000   44.000  130.000   26.000   93.000  161.000
1966     51.000   116.000    45.000   97.000   87.000   70.000   55.000   81.000   48.000  121.000  104.000   98.000
1967     53.000   104.000    38.000   28.000  133.000   35.000   56.000   57.000  124.000  153.000   49.000   88.000
1968     82.000    32.000    70.000   72.000   90.000   73.000  116.000   51.000  116.000   81.000   60.000   82.000
1969     85.000    99.000    76.000   54.000  174.000   37.000   47.000   91.000   39.000   21.000  116.000   78.000
1970    118.000    82.000    74.000   73.000   27.000   58.000   52.000  127.000   54.000   38.000  169.000   43.000
1971    120.000    32.000    69.000   46.000   43.000   80.000   22.000  108.000   28.000   81.000   79.000   44.000
1972    122.000    84.000    82.000   60.000   86.000   72.000   67.000   40.000   46.000   49.000   79.000  131.000
1973     36.000    43.000    24.000   79.000   94.000   32.000   91.000   62.000   75.000   44.000   46.000   49.000
1974    154.000   102.000    42.000    9.000   43.000   59.000   61.000   60.000  116.000   60.000   93.000   67.000
1975    108.000    32.000    74.000   61.000   37.000   17.000   66.000   63.000   70.000   34.000   53.000   43.000
1976      0.000     0.000     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
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                                  WATER    DATA    UNIT    RETRIEVAL    LISTING  (I.C.L. MAG. TAPE   TYPE B FORMAT )
             05500400        RIVER   WYE                        AT  ABERNANT
YEAR      JAN       FEB       MAR       APR        MAY       JUN        JUL        AUG        SEP        OCT        NOV        DEC

1936   241.000    86.000   117.000   102.000     66.000   152.000    257.000     41.000    175.000    152.000    229.000    297.000
1937   312.000   305.000   145.000   165.000     74.000    64.000     99.000     48.000    150.000    104.000     61.000    160.000
1938   338.000   124.000    48.000    20.000    122.000   175.000    180.000     94.000     79.000    287.000    328.000    180.000
1939   269.000   188.000   137.000   117.000     25.000   122.000    284.000     86.000     28.000     94.000    419.000    160.000
1940    99.000   140.000   160.000    94.000     56.000    23.000    183.000     43.000    109.000    211.000    371.000    175.000
1941   109.000   185.000   112.000    58.000    122.000    48.000     97.000    226.000     30.000    201.000    147.000    173.000
1942   193.000    48.000   124.000    99.000    224.000    20.000    168.000    165.000    124.000    193.000     36.000    279.000
1943   193.000    48.000   124.000    99.000    224.000    20.000    168.000    165.000    124.000    193.000     36.000    279.000
1944   224.000    71.000    23.000    76.000     71.000   109.000    114.000    107.000    170.000    277.000    277.000    183.000
1945   145.000   198.000    94.000    79.000    127.000   170.000     89.000    107.000    142.000    140.000     28.000    196.000
1946   208.000   302.000    38.000    51.000     91.000   165.000    109.000    236.000    244.000     71.000    328.000    203.000
1947   152.000    74.000   315.000   155.000     97.000    74.000    104.000     20.000    102.000     46.000    203.000    178.000
1948   437.000   127.000    97.000    94.000     89.000   201.000    109.000    165.000    196.000    137.000    119.000    302.000
1949   122.000    71.000   107.000   150.000    145.000    25.000     36.000     97.000     64.000    218.000    234.000    246.000
1950    99.000   302.000   102.000   163.000     64.000    79.000    142.000    241.000    305.000     94.000    229.000    152.000
1951   221.000   170.000   198.000   173.000     79.000    46.000     61.000    183.000    145.000     43.000    325.000    234.000
1952   224.000   127.000   104.000    99.000     94.000   117.000     74.000    168.000    117.000    198.000    107.000    198.000
1953    76.000   112.000   137.000   119.000     94.000    66.000    185.000    147.000    160.000    119.000    193.000     69.000
1954   147.000   183.000   150.000    46.000    104.000   185.000    160.000    201.000    196.000    320.000    356.000    221.000
1955   142.000    99.000   137.000   117.000    193.000   224.000     28.000     48.000    135.000    137.000    124.000    229.000
1956   224.000    23.000   109.000    53.000     43.000   104.000    130.000    220.000    183.000    117.000    104.000    196.000
1957   196.000   175.000   175.000    18.000     81.000    64.000    201.000    221.000    323.000    183.000    112.000    175.000
1958   191.000   284.000    38.000    61.000    142.000   127.000    160.000    130.000    264.000    185.000    112.000    160.000
1959   221.000    30.000   147.000   191.000     41.000    84.000    145.000     13.000     15.000    239.000    236.000    358.000
1960   292.000   251.000    71.000   135.000     71.000   102.000    175.000    165.000    183.000    206.000    371.000    267.000
1961   244.000   168.000    48.000   191.000     84.000    64.000    107.000    155.000    163.000    292.000    155.000    173.000
1962   279.000   122.000    74.000   185.000    173.000    64.000     84.000    241.000    249.000     91.000    109.000    188.000
1963    46.000    81.000   175.000   173.000    135.000   132.000     99.000    137.000    130.000    114.000    290.000     41.000
1964    61.000    74.000   117.000    99.000    107.000    86.000    122.000    109.000     94.000    163.000    191.000    302.000
1965   272.000    18.000   132.000   142.000    117.000   150.000    135.000    127.000    236.000    108.000    179.000    412.000
1966   118.000   273.000   140.000   185.000    170.000   121.000    133.000    143.000    117.000    192.000    194.000    196.000
1967   182.000   210.000   115.000    69.000    229.000    45.000    144.000    146.000    261.000    447.000    141.000    206.000
1968   287.000    59.000   196.000   133.000    146.000   161.000     97.000    113.000    215.000    202.000    116.000    143.000
1969   223.000   129.000   123.000   119.000    177.000   108.000     70.000    140.000     82.000     81.000    222.000    225.000
1970   247.000   219.000   162.000   219.000     31.000    74.000    141.000    125.000    125.000    187.000    347.000     93.000
1971   268.000   127.000   122.000    65.000     87.000   154.000     60.000    157.000     53.000    167.000    187.000    100.000
1972   219.000   163.000   170.000   209.000    154.000   165.000    102.000     93.000     68.000     82.000    271.000    271.000
1973    98.000   159.000    57.000   132.000    133.000    43.000    137.000    171.000    140.000    119.000    150.000    213.000
1974   367.000   270.000    89.000    19.000     92.000   110.000    174.000    129.000    289.000    153.000    228.000    297.000
1975   331.000    54.000   112.000   118.000     42.000    25.000    130.000     78.000    205.000     92.000    196.000    123.000
1976   142.000   167.000    86.000    43.000    101.000    22.000     85.000     26.000      0.000      0.000      0.000      0.000
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                                      WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
            05500500       RIVER  WYE                     AT  RHAYADER
YEAR       JAN        FEB        MAR        APR        MAY        JUN        JUL        AUG        SEP        OCT        NOV        DEC

1936   244.000     89.000    102.000     97.000     66.000    175.000    221.000     33.000    142.000    150.000    201.000    279.000
1937   246.000    257.000    135.000    122.000     56.000     89.000    102.000     48.000     84.000     97.000     66.000    142.000
1938   297.000    107.000     53.000     15.000     99.000    142.000    160.000    109.000     56.000    267.000    254.000    170.000
1939   267.000    180.000    107.000    112.000     36.000     84.000    284.000     97.000     30.000     91.000    381.000    124.000
1940   117.000    119.000    107.000    104.000     76.000     30.000    180.000     41.000    112.000    180.000    381.000    170.000
1941   107.000    145.000    114.000     58.000    109.000     38.000     81.000    218.000     53.000    206.000    119.000    142.000
1942   203.000     41.000     97.000    104.000    185.000     30.000    150.000    124.000    137.000    193.000     30.000    218.000
1943   234.000    145.000     46.000     48.000    140.000    140.000     97.000    168.000    221.000    165.000    191.000     86.000
1944   241.000     79.000     28.000     66.000     71.000    102.000     99.000     97.000    157.000    241.000    267.000    147.000
1945   135.000    193.000     81.000     66.000    112.000    168.000     71.000    114.000    112.000    157.000     33.000    185.000
1946   229.000    310.000     41.000     53.000     94.000    145.000    107.000    246.000    272.000     76.000    297.000    170.000
1947   137.000     69.000    310.000    117.000     97.000     86.000    119.000     13.000     79.000     30.000    193.000    203.000
1948   386.000    124.000    109.000    107.000     89.000    157.000     79.000    150.000    142.000    140.000     97.000    262.000
1949   104.000     84.000     81.000    150.000    124.000     25.000     76.000     84.000     74.000    229.000    236.000    274.000
1950    69.000    284.000     84.000    142.000     43.000     58.000    142.000    226.000    323.000    112.000    224.000    119.000
1951   183.000    183.000    203.000    147.000     97.000     38.000     84.000    170.000    142.000     51.000    318.000    244.000
1952   211.000     86.000     69.000     79.000     94.000     97.000     69.000    142.000    142.000    173.000    132.000    191.000
1953    76.000     94.000    145.000    124.000     76.000     46.000    203.000    168.000    157.000     97.000    165.000     58.000
1954   168.000    155.000    145.000     53.000    102.000    160.000    170.000    196.000    198.000    287.000    305.000    241.000
1955   112.000     97.000    112.000    114.000    183.000    180.000     30.000     48.000    122.000    119.000    104.000    191.000
1956   236.000     30.000    107.000     58.000     38.000     94.000    135.000    211.000    170.000    114.000    104.000    180.000
1957   165.000    157.000    160.000     15.000     84.000     76.000    201.000    231.000    305.000    185.000    117.000    180.000
1958   163.000    267.000     48.000     56.000    130.000    130.000    170.000    124.000    249.000    152.000     99.000    155.000
1959   218.000     28.000    117.000    160.000     74.000    117.000    142.000     23.000     13.000    218.000    183.000    300.000
1960   249.000    178.000     74.000    127.000     56.000     86.000    183.000    150.000    155.000    178.000    310.000    264.000
1961   193.000    137.000     53.000    135.000     76.000     46.000     84.000    150.000    107.000    231.000    119.000    155.000
1962   229.000    135.000     71.000    183.000    130.000     38.000     69.000    211.000    206.000     74.000     81.000    168.000
1963    41.000     58.000    201.000    135.000    122.000    137.000     58.000    135.000    130.000     97.000    300.000     28.000
1964    61.000     58.000     81.000     89.000     99.000     79.000    109.000    107.000     66.000    147.000    160.000    292.000
1965   241.000     18.000    124.000    132.000    117.000    117.000    109.000    107.000    206.000     77.000    143.000    451.000
1966    95.000    224.000    106.000    120.000    132.000    139.000    113.000    119.000    100.000    159.000    188.000    355.000
1967   120.000    193.000    111.000     63.000    211.000     48.000    151.000    120.000    216.000    329.000    130.000    197.000
1968   235.000     48.000    173.000    110.000    159.000    126.000     90.000     81.000    190.000    157.000     90.000    129.000
1969   195.000    120.000    111.000    123.000    201.000     90.000     65.000    139.000     71.000     61.000    221.000    156.000
1970   156.000    242.000    130.000    206.000     25.000     80.000    109.000    129.000    115.000    179.000    300.000    104.000
1971   195.000    113.000    101.000     56.000     62.000    127.000     49.000    137.000     43.000    156.000    184.000     94.000
1972   195.000    131.000    148.000    196.000    136.000    120.000     75.000     81.000     55.000     63.000    210.000    227.000
1973    95.000    168.000     58.000    135.000    144.000     30.000    149.000    139.000    152.000    105.000    145.000    169.000
1974   341.000    214.000     72.000     13.000     75.000    102.000    150.000    105.000    266.000    142.000    235.000    284.000
1975   270.000     49.000     98.000    109.000     43.000     22.000     99.000     93.000    179.000     73.000    135.000    125.000
1976   158.000     97.000     94.000     26.000     96.000     22.000     52.000     18.000      0.000      0.000      0.000      0.000
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                                                 WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
                05500600            RIVER  ELAN                               AT  CARAN COCH
YEAR       JAN        FEB        MAR        APR        MAY        JUN        JUL        AUG        SEP        OCT        NOV        DEC

1936   231.000     97.000    104.000    104.000     71.000    163.000    226.000     36.000    155.000    170.000    216.000    287.000
1937   305.000    269.000    122.000    162.000     64.000     66.000     91.000     33.000    107.000    119.000     58.000    165.000
1938   312.000    119.000     51.000     25.000    112.000    170.000    178.000    122.000     71.000    274.000    287.000    215.000
1939   282.000    221.000    114.000    127.000     33.000     91.000    264.000     99.000     30.000    102.000    437.000    157.000
1940   104.000    132.000    130.000    109.000     61.000     20.000    234.000     53.000    119.000    213.000    376.000    183.000
1941   109.000    193.000    137.000     66.000    124.000     46.000     94.000    241.000     38.000    193.000    147.000    173.000
1942   213.000     53.000    127.000    117.000    216.000     23.000    173.000    137.000    132.000    229.000     33.000    269.000
1943   272.000    157.000     53.000     64.000    168.000    135.000    122.000    165.000    101.000    168.000    196.000    104.000
1944   226.000     97.000     28.000     66.000     89.000     97.000    114.000     94.000    170.000    292.000    284.000    196.000
1945   142.000    213.000     81.000     84.000    119.000    178.000     86.000    114.000    130.000    145.000     28.000    198.000
1946   218.000    318.000     46.000     61.000     91.000    137.000    112.000    269.000    264.000     84.000    320.000    206.000
1947   157.000     79.000    351.000    137.000    102.000     79.000    114.000     20.000    102.000     43.000    213.000    185.000
1948   411.000    135.000    112.000    112.000     89.000    191.000     99.000    157.000    170.000    145.000    109.000    290.000
1949   127.000     81.000    114.000    155.000    163.000     20.000     48.000     99.000     69.000    236.000    257.000    292.000
1950   107.000    284.000     97.000    157.000     51.000     64.000    130.000    231.000    323.000    107.000    234.000    152.000
1951   198.000    201.000    224.000    178.000     94.000     41.000     79.000    178.000    140.000     51.000    353.000    251.000
1952   226.000    130.000     91.000     86.000    102.000    112.000     69.000    160.000    142.000    198.000    137.000    203.000
1953    86.000     99.000    160.000    127.000     94.000     58.000    198.000    140.000    180.000    107.000    175.000     71.000
1954   157.000    175.000    142.000     66.000    104.000    178.000    191.000    185.000    208.000    287.000    323.000    257.000
1955   140.000    102.000    122.000    124.000    188.000    191.000     33.000     43.000    137.000    147.000    117.000    203.000
1956   244.000     41.000    135.000     74.000     43.000     94.000    130.000    246.000    178.000    127.000    122.000    213.000
1957   188.000    180.000    163.000     15.000     89.000     74.000    231.000    287.000    345.000    191.000    112.000    193.000
1958   196.000    279.000     48.000     66.000    122.000    132.000    145.000    124.000    239.000    193.000    107.000    163.000
1959   236.000     33.000    132.000    183.000     56.000     94.000    142.000     20.000     15.000    267.000    216.000    348.000
1960   282.000    249.000     89.000    157.000     64.000     86.000    191.000    150.000    155.000    196.000    328.000    277.000
1961   201.000    155.000     66.000    165.000     69.000     58.000    127.000    147.000    127.000    262.000    147.000    165.000
1962   277.000    163.000     76.000    196.000    142.000     51.000     71.000    226.000    224.000     81.000    102.000    213.000
1963    69.000    109.000    244.000    178.000    132.000    132.000     64.000    150.000    150.000    112.000    290.000     30.000
1964    76.000     66.000    114.000    102.000     94.000     89.000    117.000    114.000     89.000    165.000    188.000    295.000
1965   264.000     23.000    127.000    145.000    119.000    112.000    107.000    117.000    231.000     97.000    163.000    434.000
1966   119.000    244.000    119.000    147.000    135.000    137.000    119.000    117.000    122.000    165.000    206.000    422.000
1967   155.000    196.000    127.000     64.000    213.000     43.000    122.000    150.000    249.000    343.000    150.000    218.000
1968   297.000     53.000    180.000    142.000    147.000    135.000    104.000     99.000    203.000    186.000    107.000    150.000
1969   219.000    135.000    127.000    132.000    185.000    107.000     62.000    156.000     77.000     74.000    227.000    214.000
1970   237.000    260.000    178.000    217.000     31.000     75.000    126.000    140.000    122.000    193.000    331.000    106.000
1971   222.000    143.000    120.000     69.000     76.000    141.000     50.000    149.000     49.000    165.000    205.000    101.000
1972   234.000    157.000    173.000    205.000    145.000    148.000     66.000     96.000     60.000     76.000    262.000    260.000
1973   116.000    178.000     62.000    127.000    151.000     31.000    144.000    147.000    150.000    129.000    172.000    243.000
1974   399.000    261.000     91.000     14.000     98.000     95.000    164.000    112.000    266.000    146.000    230.000    337.000
1975   328.000     58.000    112.000    135.000     46.000     20.000    118.000     63.000    168.000     91.000    189.000    121.000
1976     0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000      0.000
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                                    WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE   TYPE B FORMAT )
          06000100        RIVER  TOWY                          AT  TY CASTELL
 YEAR      JAN      FEB      MAR      APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC

 1936     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1937     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1938     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1939     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1940     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1941     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1942     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1943     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1944     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1945     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1946     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1947     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1948     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1949     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1950     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1951     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1952     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1953     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1954     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1955     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1956     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1957     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1958     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
 1959   203.200   25.400  149.900  160.000   35.600   78.700  124.500   30.500   15.200  228.600  261.600  304.800
 1960   236.200  221.000   61.000  127.000   61.000   83.800  162.600  177.800  170.200  203.200  322.600  203.200
 1961   188.000  119.400   30.500  175.300   76.200   50.800   83.800  137.200  160.000  279.400  104.100  127.000
 1962   223.500   78.700   61.000  132.100  147.300   53.300   86.400  188.000  218.400   76.200  111.800  104.100
 1963    22.900   61.000  195.600  132.100  109.200  129.500   88.900  116.800   96.500   94.000  243.800   45.700
 1964    33.000   53.300   94.000   83.800   91.400   73.700   96.500   94.000   86.400  142.000  130.000  251.000
 1965   179.000   10.000  101.000   95.000   98.000  159.000  121.000  105.000  194.000   93.000  142.000  346.000
 1966    94.000  211.000   85.000  159.000  143.000  115.000  112.000  131.000   95.000  212.000  140.000  283.000
 1967   165.000  175.000   98.000   46.000  212.000   41.000  150.000  109.000  218.000  396.000  104.000  154.000
 1968   178.000   50.000  136.000  106.000  120.000  145.000  117.000  103.000  171.000  165.000  105.000  119.000
 1969   211.000   82.000   71.000   93.000  160.000   99.000   59.000  121.000   68.000   50.000  192.000  182.000
 1970   215.000  142.000  118.000  161.000   30.000   74.000  108.000  115.000  107.000  160.000  273.000   69.000
 1971   221.000   72.000  104.000   62.000   70.000  132.000   45.000  145.000   43.000  129.000  167.000   88.000
 1972   177.000  145.000  122.000  147.000  133.000  168.000   82.000   89.000   49.000   77.000  215.000  265.000
 1973    70.000  105.000   51.000   89.000  109.000   43.000   91.000  140.000  130.000   62.000  117.000  159.000
 1974   339.000  225.000   62.000   17.000   71.000  101.000  134.000  131.000  255.000  152.000  181.000  218.000
 1975   300.000   58.000   88.000  116.000   27.000   25.000  115.000   56.000  176.000   78.000  153.000   86.000
 1976     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
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                                  WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
          06000200          RIVER   TEIFI                          AT  GLAN TEIFI
YEAR      JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1937     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1938     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1939     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1940     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1941     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1942     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1943     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1944     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1945     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1946     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1947     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1948     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1949     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1950     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1951     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1952     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1953     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1954     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1955     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1956     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1957     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1958     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
1959   160.000    22.900   114.300   121.900    38.100    58.400    91.400    30.500    10.200   211.000   243.000   223.000
1960   202.000   164.000    53.000   111.000    57.000    66.000   140.000   168.000   171.000   188.000   279.400   167.600
1961   154.900    99.100    25.400   162.600    61.000    50.800    96.500   127.000   147.300   243.800    94.000   111.800
1962   177.800    63.500    50.800   124.500   101.600    48.300    71.100   152.400   198.100    63.500   106.700   106.700
1963    27.900    66.000   180.300   116.800    94.000   114.300    50.800    96.500    86.400    86.400   231.100    27.900
1964    35.600    38.100    76.200    61.000    76.200    71.100    91.400    94.000    53.300   137.000   107.000   209.000
1965   160.000    12.000    98.000    91.000    78.000   106.000    98.000    80.000   179.000    62.000   136.000   315.000
1966    81.000   163.000    64.000   124.000   101.000   101.000   102.000    86.000    80.000   180.000   115.000   242.000
1967   129.000   141.000    70.000    40.000   168.000    40.000   125.000    94.000   183.000   271.000   108.000   140.000
1968   154.000    44.000    88.000   110.000   100.000   105.000    90.000    65.000   134.000   128.000    76.000   119.000
1969   182.000    83.000    66.000    85.000   128.000    90.000    48.000   107.000    52.000    43.000   175.000   169.000
1970   179.000   134.000   113.000   134.000    29.000    75.000    86.000   102.000    83.000   143.000   244.000    66.000
1971   179.000    62.000    89.000    57.000    53.000   130.000    63.000   150.000    42.000   107.000   153.000    99.000
1972   167.000   140.000   107.000   115.000   106.000   147.000    77.000    67.000    44.000    74.000   160.000   196.000
1973    75.000    77.000    43.000    68.000    88.000    22.000    87.000   114.000   113.000    70.000   117.000   134.000
1974   326.000   183.000    67.000    19.000    80.000    80.000   104.000    91.000   210.000   160.000   142.000   156.000
1975   226.000    41.000    66.000   108.000    30.000    19.000    82.000    67.000   119.000    70.000   135.000    79.000
1976    95.000    72.000    83.000    27.000    84.000    17.000    30.000    16.000     0.000     0.000     0.000     0.000
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                                       WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
    DATA    IN    MM.
              05503270      RIVER  WYE                           AT   MID WYE
YEAR      JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936   152.087    75.165    95.251    65.545    51.814   125.713   157.086     9.554    74.390   -20.525    55.617   134.492
1937   123.515   137.491   111.982    47.216    86.963    -3.775   114.869    57.612    44.661   165.749    50.992    66.480
1938    42.577    -1.308   -12.064     3.822    56.836    32.952    80.655   127.867    57.257    63.905   103.520   119.093
1939   137.082    38.885    43.839    36.542    18.731    58.547   148.667    43.105    24.996   111.870   116.565    17.511
1940   113.692    73.100    42.217    79.721    70.255    24.996    88.210     3.378    49.282   109.384   206.770    55.949
1941   143.364    75.212   101.983    32.551    58.836    58.434    75.988    88.499    36.816    60.504    75.656    51.038
1942    77.768    12.554    69.278    48.927    98.942     8.732    56.393    87.275    47.660    50.506    14.554   110.673
1943   163.516    52.216    26.729    21.266    81.832    73.100    37.662    65.214   104.829    90.565    49.328    48.104
1944    79.767    15.932    17.997    37.550     9.667    49.282    49.282    88.986    60.214   104.875   129.493    54.683
1945    51.395    58.504    36.373    27.108    91.541    95.653    81.431   144.131    48.838   131.535    18.819   118.649
1946    77.324    37.578    31.817    57.168   103.250    71.834    54.281   190.525   140.379    27.108   192.926    60.504
1947    31.921    54.725   150.424    93.541    64.368    45.549    54.281    24.262    40.106    18.731    64.681    64.770
1948   142.270    43.395    38.928    60.102    84.809    74.390    30.107   132.422    76.922    82.365    53.103   174.107
1949    74.575    36.373    24.664    56.393    70.657    13.731    35.994    29.663    76.432   156.643   100.320    34.288
1950     5.490   143.224    41.283    52.216    52.169    46.815   103.539   137.823   100.610    48.104   132.469    38.396
1951    74.034    99.829   103.207    49.683   105.693    23.730    22.108    85.210    82.365    22.552   192.482    81.501
1952    66.059     8.460    49.370    60.546    90.985    64.279    31.373   172.037    51.393   118.649    86.542    74.768
1953    15.937    58.839    25.510    82.365    50.548    36.728    64.770    71.479    79.389    79.809    46.773    41.727
1954    72.656    71.390    71.923     2.023    55.103   108.650    41.773    91.499    59.682   111.052   227.631    82.678
1955   102.806    54.370    62.658    20.398   127.825   124.825    17.464    16.287    28.397    53.837    98.984   109.384
1956    73.499     4.555    15.399    46.815    12.554    55.103   113.981    72.324    95.653    43.927    24.664   114.916
1957    65.214    96.830    66.391     9.998    49.370    36.373    99.829   108.940   122.428    60.214    63.835    96.096
1958    68.947   143.757    37.994    16.287    87.364    91.097   120.359    73.100   201.701    90.565    68.545    90.565
1959   131.647     8.732    73.100    85.210    73.988    64.279    71.834    38.438     7.999    86.500   133.646   226.365
1960   151.200   123.648    60.546    81.099    50.992    60.546    86.383    93.097   130.712   217.675   201.747   126.493
1961   104.941    62.658     8.377   140.799    35.106    40.993    38.839    65.657    76.833   129.493    48.394   106.095
1962   110.236    29.217    30.107    80.122    67.657    11.288    64.723   110.762    92.232    20.931    75.988    58.948
1963    55.994    46.726   134.090   102.352    58.836    61.481    54.725    47.572    41.395    50.104   198.369    42.259
1964    15.110    57.257    80.987    63.546    50.104    68.989    39.662    33.840    20.931    66.391    49.683   129.049
1965    69.789     3.733    93.541    42.217    47.572    76.100    92.807    37.662   132.824    40.194   108.272   146.471
1966    71.655   115.850    45.838   131.156    91.275    64.835    48.660   104.161    44.838   156.063   103.562    76.660
1967    76.011   135.001    66.279    26.463   168.440   111.024    50.950    51.127   131.292   215.656    52.660    82.856
1968    65.437    28.905    71.035    84.631    87.831    98.274   177.102    48.104   120.826   103.007    93.162   102.717
1969   116.560   121.513    75.544    39.395   171.794    38.017    50.637    82.921    47.637    19.198    96.764    87.299
1970   167.150    63.083    62.658    36.886    50.613    58.813    52.837    86.364    60.925    41.507   173.486    22.487
1971   155.087    15.955    69.367    55.080    67.167   107.894    51.436   138.333    42.082    66.125    54.594    46.016
1972   129.302   117.892    78.478    46.796    99.362    83.099    36.195    25.842    62.256    51.814    59.261   174.995
1973    31.541    15.890    17.198    60.569   101.540    49.613    56.126    59.392    11.269    16.044    48.216    40.063
1974   164.040   103.231    46.548     8.910    62.723    81.720    53.860    73.367   137.403    34.597    55.084    26.136
1975   110.436    55.257   102.516    43.572    28.729    13.909    82.543    73.899    83.388    45.460    24.066    34.219
1976     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
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                                          WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
   DATA   IN   MM.
              05507654       RIVER  WYE                        AT  UP WYE
YEAR      JAN       FEB       MAR   .   APR        MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

1936   155.942    57.671    76.405    71.181    52.981   119.786   167.593    19.731   118.494   126.129   153.595   189.141
1937   190.422   201.075   102.590    90.366    48.279    49.754    77.730    33.294    83.928   102.145    45.737   101.195
1938   151.743    61.171    12.037     4.966    91.277    76.451   105.163    89.565    38.887   172.705   195.850   130.068
1939   190.438   121.251    68.607    93.427    25.628    64.343   206.149    63.156    22.703    73.454   252.275    84.006
1940    79.497    92.032    93.096    81.375    58.510    25.270   123.369    14.364    54.004   147.897   288.834   102.573
1941    91.468   119.373    91.219    41.351    89.749    42.904    69.390   148.175    43.231   121.099   115.105    98.378
1942   130.021    18.420    83.800    74.756   152.647    14.427    86.794    99.816    74.957   101.653    28.848   161.574
1943   214.398   104.358    22.951    37.259    99.994    97.434    66.207   107.667   122.156   124.647   129.895    55.322
1944   120.209    36.952    13.490    45.738    44.741    60.662    57.178    84.848   100.842   185.201   186.344   115.524
1945    96.836   116.605    45.549    49.092   101.761   126.858    58.792    99.659    71.250   146.079    22.548   151.413
1946   145.027   163.517    34.007    48.468    94.897    95.736    63.943   182.182   162.589    47.828   240.159   125.137
1947   104.560    58.966   236.572    97.544    79.501    51.182    61.607    13.893    60.173    22.870   116.181   117.879
1948   225.804    84.053    60.092    83.136    91.987   105.659    45.288    97.945    89.604    85.420    73.148   218.259
1949    52.747    46.916    56.788    92.178   103.407    23.085    25.656    67.735    56.505   139.604   167.452   159.017
1950    41.384   215.270    52.806    95.189    43.985    47.466   110.223   151.972   167.717    65.315   163.189    71.793
1951   130.267   116.027   142.173   112.763    75.275    29.212    40.726   132.834    85.424    32.264   251.662   129.848
1952   147.466    40.238    64.304    71.323    87.805    80.142    44.681   125.483    91.850   153.574    88.246   129.591
1953    39.508    69.001    93.181    93.913    55.682    41.732   114.499   110.072   118.961    76.564    99.252    43.827
1954    98.961   105.523    91.456    25.419    77.507   146.555    90.183   171.052   109.408   173.689   250.521   122.780
1955    91.975    64.397   103.256    54.852   158.679   151.510    38.487    38.618    60.933    74.137    92.051   146.377
1956   151.672    13.302    47.066    47.528    21.570    81.205   105.134   133.275   125.367    61.677    50.859   129.755
1957   160.692   120.676   101.335     7.279    63.768    50.565   103.472   143.681   206.789    89.798    99.081    98.487
1958   119.204   194.289    33.914    31.031    99.335   117.878   134.390    93.623   193.121   122.493    73.782   130.460
1959   154.151    11.825    91.827   133.027    86.656    82.912    96.943    24.491     4.935   138.513   166.953   257.912
1960   184.518   144.645    74.026    97.491    45.546    69.709   120.734   109.899   130.224   194.169   254.673   184.795
1961   160.079    38.698    16.289   141.742    61.888    34.435    65.366    93.469   112.899   196.782    87.545   124.449
1962   180.124    64.391    54.740   123.294    95.887    30.022    74.766   170.892   171.614    47.163    66.658    99.909
1963    27.108    42.132   140.226   102.248    84.406   104.147    62.198    74.866    76.431    68.449   234.294    33.936
1964    35.384    39.794    70.574    70.432    72.512    61.329    71.834    56.047    46.749   104.450   106.568   199.410
1965   173.705     9.461   100.277    86.550    86.703   100.339    92.290    68.812   148.815    56.644   120.726   289.194
1966    71.478   164.782    70.462   116.168   104.240    90.179    83.137    86.032    71.442   145.955   131.364   215.235
1967    92.307   155.073    77.363    35.395   173.203    37.379   114.500   103.643   166.282   266.710    78.485   131.999
1968   153.085    37.035   118.773    81.777   116.378   116.623   105.820    71.442   141.785   117.100    79.671    97.924
1969   144.173    90.634    76.685    79.595   172.116    57.949    62.232   106.897    52.354    35.610   149.439   122.784
1970   141.377   175.875    85.637   111.441    29.179    59.179    78.748    95.620    87.264    99.157   229.634    61.195
1971   169.532    65.554    80.213    46.477    55.386    97.815    28.438   116.304    34.892   115.803   110.547    71.083
1972   136.817   107.780   115.388   136.219   110.143   101.222    58.212    54.366    49.839    51.135   162.320   189.315
1973    55.896   100.909    37.813    99.634   103.110    25.696   109.274    98.730   137.019    67.307    86.520   109.086
1974   244.226   176.777    51.552    10.783    64.149    86.394   112.109    86.530   205.806   104.368   170.955   190.894
1975   198.633    42.167    72.904    78.770    34.975    14.707    90.806    76.807   129.131    54.090   104.813    82.718
1976     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
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                           WATER   DATA   UNIT   RETRIEVAL   LISTING  (I.C.L. MAG. TAPE  TYPE B FORMAT )
   DATA    IN    MM.
           05500120        RIVER  WYE                          AT  LOW WYE
YEAR     JAN      FEB      MAR      APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC

1936   129.662   67.232   70.158   62.810   27.736  107.505  138.431    6.810   78.084   48.315   91.662  111.978
1937   123.167  133.820   93.158   55.084   52.695   22.926   84.579   33.579   53.389  101.389   41.579   68.084
1938   104.052   24.736    3.579    2.347   59.505   48.968   78.084   88.158   41.579   97.820  113.399  106.084
1939   124.662   53.589   42.736   66.852   21.232   48.273  146.473   48.926   21.232   77.610  157.325   47.736
1940    81.926   75.158   50.084   86.000   64.000   25.000   81.010    2.926   28.315  118.736  204.746   51.241
1941   121.421   92.505   68.084   29.810   63.389   57.421   62.810   99.894   31.579   66.241   82.505   53.662
1942    86.662   14.579   72.810   49.505  114.968    5.579   37.473  100.232   50.736   52.473   21.232  121.662
1943   177.084   50.662   27.347   28.579   95.810   46.894   38.852   58.010   79.241   76.894   63.010   44.505
1944    66.052   20.273    8.579   34.810   25.926   41.505   47.158   70.158   71.852  115.820  125.820   71.315
1945    51.315   54.820   26.505   34.810   68.084   83.662   76.653  107.579   53.389  113.736   17.347  134.926
1946    91.010   83.978   24.695   53.000   97.000   61.315   42.736  161.431  115.820   29.158  178.820   86.968
1947    73.084   51.579  190.010   85.158   82.768   46.579   57.810   27.421   36.505   11.810   71.894   64.241
1948   177.978   48.968   39.505   62.158   89.000   72.431   26.505   97.505   71.852   72.505   49.505  161.473
1949    35.389   35.926   37.158   69.505   68.084   16.232   24.695   36.505   62.232  172.926  104.589   58.325
1950    16.505  155.241   48.579   56.315   44.232   41.579   95.158  112.241   98.978   35.084  137.852   53.389
1951    81.010  103.158  111.084   66.315   89.000   16.810   24.158   89.315   76.273   23.579  213.315   81.589
1952    82.241   15.852   52.695   57.810   87.232   48.968   30.926  143.232   70.158  121.736   91.347   70.473
1953    16.505   41.505   40.662   81.926   51.579   43.000   73.662   82.505   88.736   68.926   55.662   38.579
1954    66.662   71.315   72.505   11.210   62.810  109.852   50.662  106.662   61.241  108.399  193.052   80.473
1955    51.926   44.505   69.505   35.389  130.505  123.736   26.232   17.926   37.736   52.736   95.232  109.315
1956   114.315   11.232   34.158   51.000   17.347   53.389   91.389   95.431   93.084   44.505   31.505  109.852
1957    63.662   95.736   66.315    0.579   48.926   32.158   74.241  106.126  147.589   49.241   68.389   83.084
1958    74.315  152.662   38.000   17.926   71.852   83.736   91.662   75.158  164.662   95.736   69.579   95.736
1959   123.431    5.579   78.926   89.315   55.158   48.968   61.315   22.347    2.347   77.167  131.084  201.820
1960   145.894   96.589   61.579   62.431   41.579   52.158   73.126   91.389  118.158  204.768  163.556  103.978
1961    89.820   60.084    4.158  145.000   31.505   41.000   41.505   48.010   66.315  101.325   38.894   93.084
1962    99.630   14.473   41.579   67.473   61.315    9.158   61.579  114.010  100.473   21.505   66.579   63.662
1963    24.695   39.810  107.894   79.315   48.315   72.505   45.926   67.810   45.084   42.736  154.978   24.695
1964    20.926   35.926   81.000   49.505   46.505   53.926   33.315   36.505   21.505   56.894   47.473   98.135
1965    87.746   10.000   79.505   50.084   52.736   66.852   97.000   35.084  131.736   28.852   93.547  144.103
1966    61.158  113.894   39.084   96.852   74.084   59.968   44.199   86.810   41.852  121.968   93.662   94.598
1967    63.199   99.589   60.389   22.042  150.852   -2.948   31.167   64.852  114.473  166.367   50.084   76.473
1968    86.052   35.347   56.704   72.273   84.852   67.894  117.579   35.084  108.431   93.968   70.158   86.389
1969    93.473   71.315   72.010   50.621  143.968   45.926   47.695   68.431   40.926   17.273   92.473   62.936
1970   149.926   73.978   58.199   57.241   37.884   63.000   57.389  106.653   55.852   35.936  167.936   39.158
1971   140.199   33.852   72.695   43.579   44.158   98.695   22.158   94.199   36.232   72.315   71.431   38.852
1972   118.084   97.389   76.315   69.241   91.389   66.315   39.926   32.273   50.347   54.116   86.704  143.357
1973    42.042   38.126   22.810   67.621   89.389   36.884   71.736   55.547   70.736   43.158   50.431   54.357
1974   168.209  113.357   40.042    7.232   44.505   61.621   64.431   67.273  133.936   49.547   96.126   64.135
1975   105.441   39.579   76.810   50.621   29.347   14.116   74.158   55.273   85.199   33.505   44.010   43.968
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APPENDIX 3

GENERALISED RAINFALL INTENSITY/ DURATION CURVE

Appendix 3 W.J.Walley Rainfall intensity/duration curve

The rainfall intensity/duration curve for a typical month takes the general form shown in Fig5.1 and may be approximately represented by a parabolic equation of the following form -

$$(r + b)\ (t + a) = C^2 \qquad (1)$$

where a, b and c are constants

Re-arranging (1) gives $\underline{r = \frac{C^2}{(t + a)} - b}$ (2)

Now, when $r = o$, $t = t_m$

therefore $\frac{C^2}{t_m + a} = b$ or $\underline{t_m = (\frac{C^2}{b}) - a}$ (3)

Also, when t_o, $r = r_m$

therefore $r_m = (\frac{C^2}{a}) - b$ (4)

Since heavy rainfall is more likely to cause overland flow than is light rainfall, it is useful to know what amount of rainfall during the whole month exceeds a given intensity r_c (mm/hr). (see Fig 1)

Now,

$$Q = \int_{r_c}^{r_m} r\,dr = \int_{r_c}^{r_m} \left[\frac{C^2}{r + b} - a\right] dr = C^2 \int_{r_c}^{r_m} \left[\frac{1}{r + b} - \frac{a}{2}\right] dr$$

$$\text{therefore} \left[\log_e (r + b) - \frac{ar}{C^2}\right]_{r_c}^{r_m}$$

$$= C^2 \log_e \left(\frac{r_m + b}{r_c + b}\right) - a\,(r_m - r_c) \qquad (5)$$

Substituting (3) into (5) and re-arranging gives

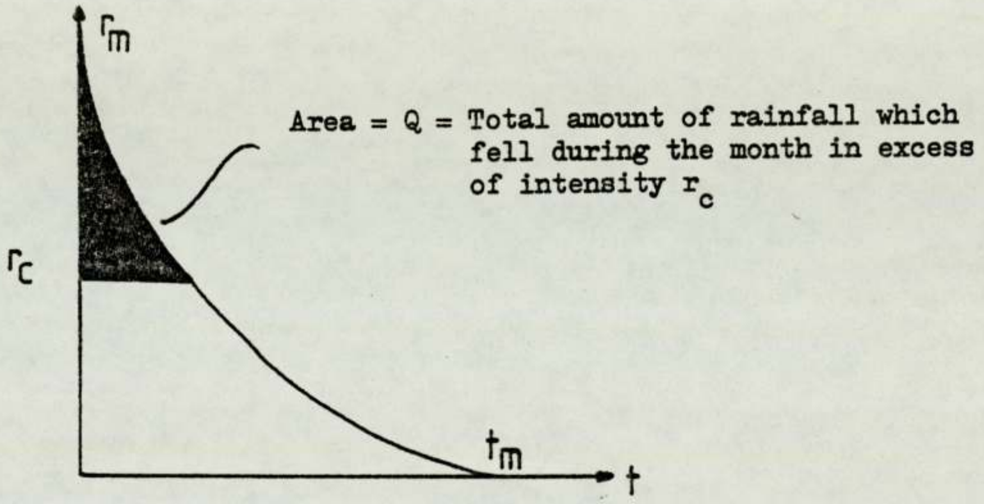

Fig 5.1 Rainfall in Excess of a Given Intensity

$$Q(\mathrm{mm}) = C^2 \left[\log_e \left[\frac{C^2}{a(r_c + b)} \right] - 1 \right] + a(r_c + b) \qquad (6)$$

When $r_c = 0$, $Q = R_m$ (Total monthly rainfall)

$$\text{therefore } R_m = C^2 \left[\log_e \left(\frac{C^2}{ab}\right) - 1 \right] + ab \qquad (7)$$

Dividing both sides of equation (7) by ab gives

$$\frac{Rm}{ab} = \left(\frac{C^2}{ab}\right) \left[\log_e \left(\frac{C^2}{ab}\right) - 1 \right] + 1 \qquad (8)$$

Now, multiplying equation (4) by $^1/b$ and re-arranging gives

$$\left(\frac{C^2}{ab}\right) = \frac{r_m + b}{b} \qquad (9)$$

Substituting (9) into the first part of (8) only gives

$$\frac{Rm}{ab} = \frac{(r_m + b)}{b} \left[\log_e \left(\frac{C^2}{ab}\right) - 1 \right] + 1 \qquad (10)$$

Re-arranging (10) gives

$$r_m = \frac{\left(\frac{Rm}{a} - b\right)}{\log_e \frac{(C^2)}{ab}} - b \qquad (11)$$

APPENDIX 4

RAINFALL AND STREAMFLOW RECORDS

NEW CATCHMENTS

RAINFALL (mm) - Nene

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT	OCT.	NOV.	DEC.
1948	109.0	25.0	18.0	38.0	89.0	66.0	36.0	81.0	69.0	84.0	41.0	69.0
1949	25.0	25.0	30.0	46.0	63.0	15.0	48.0	33.0	36.0	117.0	66.0	38.0
1950	20.0	91.0	23.0	51.0	71.0	51.0	86.0	48.0	86.0	15.0	99.0	33.0
1951	61.0	81.0	86.0	69.0	79.0	28.0	23.0	109.0	41.0	25.0	117.0	46.0
1952	43.0	15.0	69.0	46.0	61.0	33.0	10.0	91.0	58.0	74.0	74.0	58.0
1953	25.0	41.0	23.0	48.0	41.0	63.0	61.0	69.0	33.0	58.0	38.0	18.0
1954	23.0	58.0	63.0	8.0	69.0	63.0	69.0	107.0	58.0	63.0	127.0	66.0
1955	51.0	48.0	56.0	20.0	97.0	66.0	8.0	18.0	38.0	46.0	30.0	46.0
1956	94.0	15.0	23.0	25.0	15.0	63.0	91.0	109.0	48.0	33.0	18.0	74.0
1957	30.0	61.0	46.0	8.0	41.0	53.0	74.0	66.0	127.0	36.0	43.0	61.0
1958	69.0	79.0	41.0	20.0	56.0	127.0	74.0	66.0	56.0	56.0	43.0	61.0
1959	94.0	3.0	61.0	56.0	10.0	18.0	51.0	23.0	3.0	43.0	51.0	104.0
1960	91.0	48.0	43.0	13.0	33.0	76.0	84.0	86.0	97.0	130.0	81.0	76.0
1961	58.0	46.0	5.0	66.0	18.0	28.0	46.0	41.0	46.0	58.0	48.0	89.0
1962	58.0	15.0	25.0	50.0	48.0	5.0	41.0	66.0	79.0	25.0	41.0	41.0
1963	28.0	15.0	79.0	48.0	36.0	51.0	38.0	79.0	58.0	36.0	97.0	13.0

RAINFALL (mm) - Isebrook

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1948	112.0	25.0	18.0	38.0	79.0	61.0	38.0	81.0	74.0	79.0	41.0	69.0
1949	23.0	25.0	36.0	48.0	63.0	13.0	48.0	28.0	43.0	130.0	66.0	43.0
1950	18.0	94.0	25.0	58.0	69.0	48.0	84.0	51.0	94.0	15.0	104.0	33.0
1951	58.0	79.0	84.0	71.0	91.0	36.0	25.0	109.0	38.0	20.0	124.0	48.0
1952	46.0	18.0	69.0	48.0	74.0	28.0	10.0	91.0	56.0	66.0	69.0	58.0
1953	25.0	41.0	23.0	48.0	36.0	63.0	61.0	63.0	38.0	51.0	41.0	18.0
1954	25.0	56.0	61.0	8.0	69.0	61.0	66.0	104.0	56.0	66.0	130.0	71.0
1955	46.0	48.0	58.0	20.0	91.0	61.0	5.0	18.0	38.0	48.0	30.0	51.0
1956	94.0	15.0	23.0	25.0	15.0	69.0	94.0	117.0	51.0	36.0	18.0	76.0
1957	36.0	63.0	51.0	8.0	41.0	51.0	71.0	63.0	127.0	33.0	43.0	61.0
1958	69.0	81.0	43.0	20.0	58.0	135.0	84.0	66.0	51.0	61.0	46.0	58.0
1959	99.0	3.0	63.0	58.0	10.0	15.0	43.0	20.0	3.0	43.0	53.0	107.0
1960	94.0	43.0	51.0	15.0	28.0	66.0	81.0	99.0	94.0	137.0	81.0	81.0
1961	69.0	48.0	5.0	66.0	15.0	28.0	48.0	38.0	51.0	71.0	56.0	97.0
1962	63.0	20.0	23.0	61.0	53.0	5.0	33.0	79.0	84.0	25.0	38.0	41.0
1963	23.0	15.0	81.0	48.0	36.0	61.0	38.0	89.0	56.0	36.0	102.0	13.0

RAINFALL (mm), Stour

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1948	94.0	28.0	23.0	41.0	61.0	61.0	36.0	109.0	38.0	46.0	41.0	41.0
1949	28.0	28.0	20.0	41.0	58.0	18.0	41.0	38.0	20.0	117.0	53.0	38.0
1950	30.0	76.0	13.0	41.0	46.0	36.0	102.0	56.0	91.0	10.0	99.0	38.0
1951	51.0	94.0	81.0	81.0	63.0	30.0	41.0	76.0	81.0	20.0	97.0	46.0
1952	56.0	18.0	76.0	33.0	28.0	41.0	20.0	74.0	71.0	56.0	104.0	61.0
1953	23.0	30.0	10.0	56.0	41.0	86.0	71.0	58.0	41.0	63.0	33.0	18.0
1954	36.0	53.0	58.0	8.0	56.0	63.0	76.0	91.0	38.0	51.0	94.0	53.0
1955	53.0	46.0	36.0	8.0	69.0	61.0	8.0	43.0	51.0	104.0	18.0	43.0
1956	84.0	18.0	18.0	23.0	18.0	53.0	66.0	117.0	41.0	48.0	20.0	51.0
1957	33.0	53.0	38.0	5.0	25.0	43.0	71.0	69.0	84.0	46.0	58.0	48.0
1958	56.0	76.0	20.0	28.0	56.0	124.0	79.0	84.0	79.0	53.0	36.0	76.0
1959	56.0	3.0	41.0	53.0	10.0	43.0	58.0	20.0	0	43.0	53.0	94.0
1960	56.0	30.0	41.0	13.0	20.0	48.0	91.0	86.0	102.0	140.0	79.0	74.0
1961	66.0	53.0	8.0	46.0	30.0	33.0	38.0	53.0	63.0	84.0	46.0	79.0
1962	61.0	15.0	36.0	38.0	43.0	3.0	104.0	41.0	69.0	30.0	41.0	46.0
1963	25.0	18.0	63.0	58.0	53.0	33.0	48.0	86.0	46.0	46.0	97.0	13.0

RAINFALL (mm) - Spey

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1951	107.0	109.0	74.0	136.0	44.0	72.0	94.0	131.0	46.0	41.0	186.0	122.0
1952	105.0	73.0	64.0	56.0	70.0	80.0	58.0	103.0	103.0	131.0	109.0	138.0
1953	69.0	74.0	31.0	82.0	81.0	109.0	139.0	80.0	88.0	49.0	124.0	128.0
1954	94.0	76.0	71.0	44.0	141.0	85.0	88.0	88.0	114.0	183.0	153.0	221.0
1955	61.0	126.0	66.0	33.0	98.0	39.0	17.0	39.0	83.0	158.0	43.0	193.0
1956	110.0	85.0	63.0	57.0	54.0	93.0	139.0	173.0	122.0	123.0	76.0	158.0
1957	136.0	89.0	93.0	37.0	53.0	79.0	151.0	148.0	77.0	88.0	80.0	144.0
1958	110.0	109.0	70.0	65.0	98.0	68.0	145.0	107.0	84.0	96.0	33.0	122.0
1959	123.0	33.0	53.0	78.0	47.0	77.0	87.0	47.0	20.0	161.0	155.0	150.0
1960	116.0	106.0	32.0	90.0	29.0	70.0	73.0	180.0	79.0	135.0	89.0	94.0

Naturalised flow data (mm) - Nene

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV	DEC.
1948	44.35	19.3	130.6	41.2	10.6	4.9	4.1	2.4	1.8	1.92	2.1	3.1
1949	16.9	12.2	4.4	4.11	4.6	3.7	2.2	2.8	3.1	7.1	10.1	20.5
1950	28.3	11.2	14.0	8.6	5.4	3.4	2.7	1.7	1.6	5.5	11.1	13.6
1951	7.4	48.2	12.4	8.2	12.6	4.6	4.2	2.7	2.7	3.8	18.1	18.6
1952	43.9	50.4	50.6	42.6	24.1	7.3	4.4	4.5	3.4	3.4	32.4	18.9
1953	28.2	16.3	26.2	22.6	14.4	5.4	2.3	3.6	2.3	4.5	12.7	34.8
1954	23.2	29.6	10.5	10.3	5.8	3.9	3.3	2.8	2.4	3.3	5.4	3.1
1955	5.03	19.2	16.1	11.6	5.8	11.8	3.0	13.5	4.5	6.4	59.1	70.0
1956	43.1	27.2	36.3	15.6	21.3	13.1	4.3	2.8	2.6	3.3	3.1	17.2
1957	20.5	21.9	9.3	5.1	2.4	2.9	3.5	12.5	7.6	6.2	3.3	24.6
1958	23.8	35.8	23.6	8.7	3.8	1.3	2.9	1.9	9.2	5.1	17.4	22.8
1959	38.0	52.6	31.7	15.7	6.7	18.5	26.4	7.8	5.0	13.5	16.4	8.3
1960	77.8	16.1	27.6	17.3	7.7	4.4	3.6	2.9	2.7	3.5	4.6	57.9
1961	24.0	31.9	17.4	10.9	7.4	5.9	6.01	5.3	10.7	38.7	20.4	12.7
1962	40.0	29.3	18.1	12.4	5.5	3.2	1.7	0.9	1.0	1.7	2.8	5.3
1963	38.8	15.1	5.5	11.7	5.9	1.4	.36	1.3	1.4	1.7	3.6	11.5

NATURALISED FLOW DATA (mm) - ISEBROOK

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1948	23.61	15.3	5.4	4.5	5.8	4.3	2.4	2.9	4.0	7.3	12.4	24.0
1949	30.1	13.2	15.7	10.4	6.5	4.4	2.8	1.3	1.1	8.4	17.6	20.4
1950	9.8	58.5	14.8	11.1	17.3	5.6	6.1	3.9	4.1	3.3	23.3	21.9
1951	49.6	52.6	59.8	48.9	33.8	10.6	5.9	5.4	4.4	2.5	34.1	26.4
1952	35.5	20.7	32.3	24.9	21.4	4.9	2.5	3.0	2.1	3.2	12.2	38.8
1953	25.7	35	11.6	14.4	7.2	4.9	4.1	3.0	2.3	3.5	8.2	4.0
1954	7.7	26.5	23.5	13.0	8.6	12.0	5.2	13.9	5.6	13.3	70.9	72.1
1955	46.9	36.8	43.8	18.0	26.1	15.0	5.4	3.6	2.4	5.3	5.6	5.9
1956	25.3	18.9	10.6	8.2	6.4	6.8	6.6	16.7	14.8	10.6	7.9	26.5
1957	28.7	48.7	33.3	14.6	9.1	6.7	7.6	6.8	13.8	7.7	21.2	28.2
1958	47.5	64.2	35.1	19.6	10.6	23.4	39.4	9.9	6.5	19.2	20.8	33.0
1959	87.3	20.9	29.6	20.0	9.8	3.2	3.0	2.2	0.13	2.1	2.8	13.7
1960	49.7	39.0	26.2	14.8	8.6	6.6	5.1	5.1	13.5	61.0	69.9	64.5
1961	50.9	38.5	19.5	15.8	9.3	6.3	3.5	2.2	2.1	2.9	4.5	19.5
1962	50.7	24.7	8.1	17.6	11.9	4.4	2.0	3.3	3.2	2.9	5.9	7.3
1963	5.1	7.9	57.8	26.6	12.0	5.2	5.5	4.7	5.5	4	26.7	14.6

NATURALISED FLOW DATA - STOUR

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1948	15.9	11.2	4.9	4.3	3.6	2.8	2.5	4.6	2.2	2.7	4.9	4.9
1949	11.1	6.5	4.4	3.3	2.0	2.1	1.6	1. 3	1.3	3.1	4.2	6.5
1950	5.4	23.8	5.8	4.0	7.3	1.9	1.6	1.2	1.4	1.7	5.5	9.1
1951	20.3	35.7	26.8	24.6	6.0	4.1	3.0	3.2	3.6	3.4	11.9	10.5
1952	18.7	13.0	19.1	11.1	4.7	2.9	2.1	2.5	2.4	3.8	12.0	27.4
1953	16.7	15.1	5.8	4.7	5.2	6.1	3.4	2.7	2.3	3.1	8.7	4.1
1954	12.1	21.3	14.7	6.9	4.4	5.1	3.3	9.9	3.7	3.4	25.2	30.2
1955	28.6	22.1	14.4	6.1	5.4	4.6	2.5	2.3	2.2	8.4	4.4	6.5
1956	25.2	18.5	9.9	5.3	3.4	2.8	2.6	4.3	4.0	4.5	5.2	11.6
1957	11.7	19.9	9.2	4.9	3.2	2.2	2.3	2.8	2.7	3.5	11.4	13.0
1958	19.0	21.7	17.9	5.2	4.7	11.0	13.2	8.2	15.4	17.4	14.6	29.8
1959	33.6	4.8	8.0	7.2	5.3	3.1	2.4	2.3	1.78	2.32	3.1	9.1
1960	17.5	17.7	9.0	8.0	3.8	2.5	2.7	3.1	8.4	37.1	48.6	40.8
1961	36.1	22.7	16.0	11.4	6.0	3.9	2.9	3.1	3.3	5.0	6.5	13.6
1962	39.5	13.4	8.2	10.5	5.7	3.1	4.5	3.6	3.1	3.6	4.9	8.6
1963	5.6	6.3	36.6	11.6	11.7	3.5	5.1	3.3	3.3	4.6	21.3	8.2

NATURALISED FLOW DATA (mm) - SPEY

	JAN.	FEB.	MAR.	APL.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
1951	83.2	47.6	69.4	95.4	107.6	54.1	43.3	54.1	25.4	19.0	85.0	74.9
1952	60.6	78.1	60.5	40.6	30.1	28.3	18.1	33.6	33.8	66.7	74.0	58.2
1953	105.2	89.7	34.1	54.1	41.9	67.2	63.1	40.4	52.0	36.2	68.2	78.4
1954	66.3	50.2	71.8	45.5	74.8	40.6	44.8	46.8	96.1	95.1	93.5	170.9
1955	64.8	40.8	63.1	87.7	65.4	24.6	16.0	10.0	18.3	57.4	37.0	90.2
1956	74.5	70.4	75.7	42.5	38.1	35.8	53.1	99.1	72.8	73.8	52.3	111.9
1957	92.3	81.7	78.4	39.6	34.4	22.3	61.8	76.7	54.3	40.3	74.2	77.5
1958	81.1	81.4	55.4	75.7	50.4	34.4	51.0	68.0	40.0	55.2	30.0	42.3
1959	55.8	78.5	50.6	49.8	29.3	22.2	24.3	61.1	14.0	41.9	83.9	69.2
1960	84.8	75.7	64.1	62.0	26.1	22.6	20.4	71.2	53.8	87.5	62.2	55.9