A FLOOD FORECASTING AND WARNING SYSTEM FOR THE RIVER SOAR

STAGE 1 REPORT

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This report is prepared by Wallingford Water for the National Rivers Authority, Severn-Trent Region

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Executive Summary

Failure of the existing flood forecasting system in use for the Soar catchment, in the Trent basin, required a review of the situation. This Stage 1 Report aims to take a fresh approach to flood forecasting and warning for the Soar by proposing a new hydrometric network and forecasting system, under the idealised assumption that nothing exists. Any shortcomings of the existing network and system will only be examined later, under Stage 2 of the Study, which will include a comparison with the idealised design proposed here along with a final set of recommendations for action. The aim of this approach is to ensure that a fresh approach, not influenced by existing systems, emerges as the output of the Stage 1 study.

The requirements for flood warning are first reviewed and a hydrometric design and forecasting system proposed, against a background understanding of physiographic and climatic conditions and man made influences present in the Soar catchment. In particular, the choice of forecasting models has to consider the extensive areas of embanked washland and the significant backwater influences, due to artificially maintained river levels to support navigation and the presence of automatic gates used to mitigate flooding. A digital terrain model of the Soar is used to aid understanding of the physiographic conditions, the nature of the catchment response, and to support the selection of gauging station locations. Finally, the system environment used to access telemetry data, to construct forecasts and to display them to users, and to support the warning process is reviewed as a key component in influencing the success of any forecasting system.

The report concludes with recommendations for a notional implementation of the idealised system design, giving details of the proposed hydrometric network and the flood forecasting and warning system along with an outline implementation plan. Definitive recommendations for action will feature as the outcome of the Stage 2 report.

Preface

This report has been prepared by Wallingford Water, a joint venture between the Institute of Hydrology (IH) and HR Wallingford Limited. The work has been undertaken by R. J. Moore, IH, and P. Samuels, HR Wallingford under the project management of T.Parkinson, Wallingford Water. Additional support has come from V.A. Bell and G. Roberts at IH on digital terrain and Landsat analyses and from P. Hollingrake on field investigations and gauging method selection.

Particular thanks are due to Roy Ladhams, Trent Area Office, NRA-ST, for acting as NRA Project Manager and supporting the take-on of information and field investigations undertaken for this study. Other NRA members on the Project Steering Committee - Andy Johnson and Tim Harrison - are thanked for providing valuable guidance and further information, including the supply of digital data from the NRA-ST hydrometric data archive.

Contents

1. Introduction

This report concerns an investigation into the flood warning methodology appropriate for use within the Soar catchment which forms part of the Trent basin. The study is undertaken against a background of failure of the existing forecasting system to provide accurate and reliable warnings. Factors which may account for this poor performance are thought to range from the use of inappropriate models to inadequacies in the hydrometric network. Complications which are likely to affect modelling performance include a high degree of control to maintain navigation levels along the main Soar, the use of automatic gates to mitigate flooding and major areas of embanked washland. Significant backwater influences on the main channel also demands the use of special gauging methods.

In order to take a fresh approach to the flood forecasting and warning problems of the River Soar the terms of reference of Stage 1 of the study requires that the existing flood forecasting system and hydrometric network should not exert any influence on the proposed solution. This requirement demands that a new hydrometric design be proposed tailored specifically to best meet the requirements for flood warning. These warning requirements are identified in Section 2 of this report. Section 3 proceeds to consider an appropriate network design - for the measurement of rainfall, river flow and level, weather and soil moisture variables - which will best support a forecasting system tailored to meet these warning requirements. The choice of models to be used is discussed in Section 4 against a background of the particular modelling problems presented by the Soar. Consideration extends to the choice of method for real-time updating of model forecasts using the most recent observations of river flow and level. Other topics reviewed are facilities for model calibration, the need for rainfall forecasts and the relationship between forecast accuracy and the decision to issue flood warnings.

Whilst the choice of models and the design of a hydrometric network are clearly very important it is imperitive to the success of the forecasting system that the system environment within which it operates be also well designed. Section 5 considers the system environment as comprising of a shell and kernel, with the kernel responsible for forecast construction in real-time and model calibration off-line. The advantages of using a generic, configurable design for forecast construction, such as provided by IH's RFFS ICA, are outlined. The design of the Forecast System shell is addressed, bearing in mind the availability of telemetry management and Graphical User Interface software within the Sever-Trent Region. A completely fresh approach was not requested in this area.

Finally Section 6 presents an outline of the system proposed for implementation, by way of summary, together with a preliminary implementation plan.

2. Forecast Requirements

2.1 INTRODUCTION

An understanding of the requirements for flood forecasting and warning within the Soar catchment is essential, for scoping the extent of work in implementing a Flood Forecasting System, for choosing an appropriate set of models and for formulating an appropriate system configuration. This Section presents the forecast and warning points identified through discussion with NRA staff along with a summary of the flood warning procedures in present use. Other potential uses of the Forecasting System, in addition to the flood warning requirement of main concern here, are also considered to ensure maximum benefit of the System within the Soar catchment.

2.2 FORECAST AND WARNING POINTS

The NRA at the inception of the study were asked to identify points requiring forecasts within the Soar catchment. Whilst the Terms of Reference to the Study are restricted to flood warning applications it was highlighted by the contractor that the development of a forecasting system for the Soar could have additional benefits to water management in general throughout the catchment. However, since there is very little use of the Soar for water supply (see Section 3.2.4) and it was difficult to identify additional requirements, such as for water pollution and general catchment management, discharge consent and licensing purposes, the proposed list of forecast points are restricted to those serving a flood warning requirement.

Table 2.2.1 lists the forecast points nominated for inclusion and which already had been defined as part of the existing Flood Forecasting System. Whilst the list of specific forecast points are only 9, these are used as trigger points to make warnings at more distributed locations. Thus a total of 21 sites to warn are identified. Also, one "forecast point" makes use of two derived quantities, the flow at (Pillings - Rothley) and the flow at (Leicester + Syston). Whichever first exceeds the specified warning flow is used as a trigger to warn of flooding along the B5328 at Cossington. Table 2.2.1 is complemented by Table 2.2.2 which highlights the sequence of roads flooded by the Soar, downstream of Leicester, and by the rivers Wreake and Sence. Figure 2.2.1 maps point locations identified in Table 2.2.1 which require warning, highlighting that the Wreake is the main tributary along which warnings are required.

In practice these forecast points would be added to by further sites for which river levels or flows are measured and made use of in forecast construction, but not specifically for warning purposes. Indeed, since a Stage 1 Project requirement is to assume that no hydrometric network exists, strictly a new set of forecast points needs to be defined which will best serve the requirement to warn at the specified locations whilst making best use of a newly designed hydrometric network. An important exception to this is the locations where control gates exist and levels are telemetered - at Frisby and Zouch - which must be included as forecast points. However, to take an extreme example, Kegworth gauging station need not necessarily be a prescribed forecast point and could be a candidate for closure from the point of view of flood warning! Practical considerations such as the existence of a gauging station and the value of preserving long term records are likely to exert a strong influence on how idealised recommenations made under the Stage 1 terms of reference carry through to final recommendations for action under Stage 2.

Table 2.2.1 Forecast points and locations requiring a flood warning

Forecast point	Grid. ref.	Level Sensor	Warning flow m^3s^{-1}	Warning level m^3s^{-1}	Location Site to Warn	Grid ref.
Frisby gate, River Wreake	SK 6955 1805	Upstream of weir Downstream of gate		62.00	Mill Lane floods	SK 6975 1795
				62.90	The Mill House, Mill Lane	
				62.90	Water Lanes floods	SK 6935 1780
		Storage lake		61.42	Ring Mr Sampson	SK 6950 1820
				63.20	Lake full - amber reach 5	
Syston Mill, River Wreake	SK 615 124	Upstream of gate Gate level	28 (yellow)		Lower gate when lake full Flooding Mill Lane The Mill House Flooding Water Lane Reach 5, Broome Lane, Ratcliffe	 SK 6975 1795 SK 6935 1780 SK 632 141
			32		Station Road, Thrussington	SK 650 157
			40		Station Lane, Asfordby (monitor situation)	SK 705 186
South Wigston, River Sence	SP 588 977	Electromagnetic	7.5 (yellow) 28 (amber)		Reach 2, Road at Craw Mill Reach 3	SP 589 977
Rothley, Rothley Brook	SK 580 121	Flat V weir				
Littlethorpe, River Soar	SP 542 973	Electromagnetic	14 (amber)		Reach 3	
Pillings Lock, River Soar	SK 565 182	Ultrasonic	25 (yellow)		Reach 7, Slash Lane, Sileby	SK 588 154
			25		B674 Mountsorrel - Sileby Road	SK 588 154

Forecast point	Grid. ref.	Level Sensor	Warning flow m^3s^{-1}	Warning level m^3s^{-1}	Location Site to Warn	Grid ref.
			55 (amber)		Reach 7, B675 Barrow	SK 571 174
			60		Warn via roster farmers upstream of Zouch	
			65		Access road, Sileby Mill	SK 594 149
Kegworth, River Soar	SK 492 263	Ultrasonic	60		Preliminary warning to Mr B Perkins	
			85 (yellow)		Reach 8, Meadow Lane, Loughborough	SK 540 216
			100 (amber)		Flood warden at Zouch, Jan 1993 flood level likely to be equalled or exceeded	
			140 (red)		Flood Warden at Zouch. 1:10 year flood defences at Zouch likely to be overtopped	
			140		Reach 8, Soar Lane, Sutton Bonnington (surfaced part only)	SK 500 258
			140		Station Road, Kegworth	SK 495 271
			140		Moor Lane, Normanton	SK 514 233
Pillings - Rothley Leicester + Syston		Derived	55		B5328 Cossington	SK 596 130
Freemans Weir, River Soar			32 (amber)		Braunstone Lane East	SK 568 012
			40		Impassable to traffic	
			130 (red)		Reach 3	

Table 2.2.2 Sequence of roads flooded by the River Soar downstream of Leicester and by the Rivers Wreake and Sence

River	Road Flooded	Grid Reference
Soar	Slash Lane, Mountsorrel	SK 588 154
	B674 Mountsorrel-Sileby	SK 588 154
	B675 Barrow to Quorn	SK 571 174
	Redhill Marine Road	SK 496 293
	B5328 Cossington	SK 596 130
	Access Road to Sileby Mill	SK 594 149
	Station Road, Kegworth	SK 495 271
	Soar Lane, Sutton Bonington (surfaced part only)	SK 500 258
	Meadow Lane, Loughborough	SK 540 216
	Moore Lane, Normanton	SK 514 233
	A6006 Zouch	SK 501 232
	B679 Kegworth	
	Braunstone Lane East	SK 568 012
	A6 at Quorn	SK 562 164
Wreake	Broome Lane, Ratcliffe	SK 632 141
	Station Road, Thrussington	SK 650 157
	Station Lane, Asfordby	SK 705 186
	Hoby to Brooksby	SK 669 164
	Fosseway Syston	SK 620 122
	Junction of Leicester Street and A607, Melton Mowbray	
Sence	Crow Mills	SP 589 977

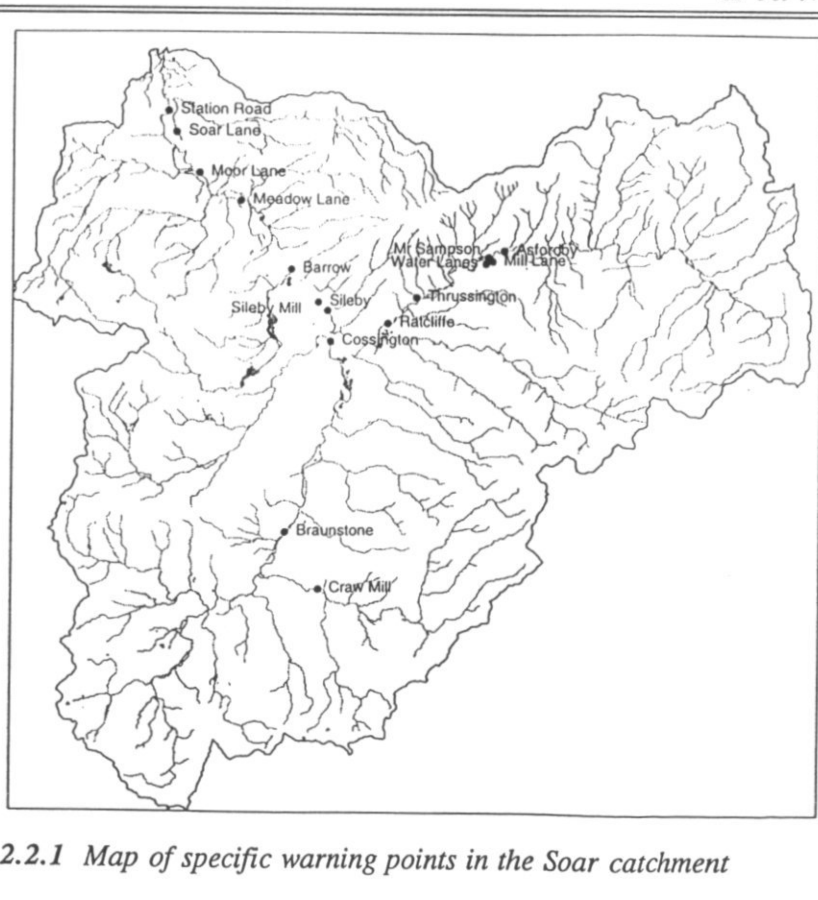


Figure 2.2.1 Map of specific warning points in the Soar catchment

2.3 FLOOD WARNING PROCEDURES

A target "Level of Service" for main river flood warning which provides 4 hours prior notice of flooding with forecasts accurate to within ±10% of the flood peak, whilst not mandatory, is aspired to by the NRA Severn-Trent Region. This target can be approached, or indeed exceeded, through an appropriate choice of hydrometric network and forecasting and warning system. The level of service can be expected to be met where the flood generation process is well monitored but in complex situations, for example on headwater streams during rain-on-snow conditions, it can only be viewed as an ideal to strive towards.

Flood duty officers in the Soar aim to operate the NRA Flood Warning Service prescribed for the NRA nationally. This system is based on three colour-coded warning phases - yellow, amber and red - each associated with increasing flood risk. Table 2.3.1 summarises the service as applied to non-tidal rivers such as the Soar. Note that the three warning phases are based on a mixture of flood severity, as judged by associated impacts, and flood risk (or likelihood) criteria.

In addition to issuing specific warnings the NRA is responsible for monitoring weather forecasts, weather radar, rainfall and river levels round the clock in anticipation of the need to detect and forecast flooding incidents. Flood warning notices are issued to the Police who in turn inform Local Authorities, other emergency services and the general public, often achieving local dissemination through the operation of a flood warden system.

Use of computer fax can be an important aid in warning dissemination. A modern forecasting and warning system should be provided with computer-assisted fax dissemination facilities based on warning proformas and pre-configured groups of fax numbers associated with given areas of inundation.

Table 2.3.1 NRA Flood Warning Service warning phases, flood risk, nature of flooding and warning for non-tidal rivers

Warning Phase	Flood risk	Nature of flooding and warning
Yellow	Flooding is possible	River catchments are in a state susceptible to flooding due to continuing or imminent rainfall and above normal river levels. Minor flooding of roads and agricultural land in low-lying areas is forecast but flooding of property is not expected. The NRA warning will specify which rivers and coastal areas are likely to be affected.
Amber	Flooding is likely	Rivers are likely to overtop banks. Flooding of a number of roads, considerable areas of agricultural land and some high risk properties is forecast. The NRA warning will specify which rivers are likely to be affected.
Red	Serious flooding is likely	Overtopping of river banks and possible breaching of flood defences is possible. Flooding of a significant number of properties, roads and large areas of agricultural land is forecast. NRA warnings will specify which areas are likely to be affected and there may be recommendations to the Police to issue flood warnings to the general public. Throughout England and Wales the NRA aims to issue a Red warning to the Police before flooding is likely to occur.

2.4 OTHER REQUIREMENTS

Whilst no requirements, other than for flood warning were specified by the NRA, it is likely that other water management functions within the Soar can benefit from the flow forecasts produced. These might include uses for catchment monitoring and licence and discharge management. Probably the other major area for potential application is in support of water quality management. At its simplest level the Forecasting System can be seen as a source of information on time-of-travel and flow dilution capacity, of particular relevance to pollution spill and effluent discharge management. The System to be proposed should be sufficiently generic in nature so as to allow extension of forecasts of river level and flow to include explicit forecasting of water quality variables. This would usually be accomplished through a generic model algorithm interface which permits inclusion of a water quality model as an integral part of the Forecasting System. Suffice it to say that the proposed System must be able to accommodate new Forecast Requirements, such as those mentioned above, with ease as and when new applications are felt to be needed.

2.5 SUMMARY OF REQUIREMENTS

(i) Flood warning is seen at present as the only use of the Forecasting System. Point locations and river reaches requiring warning have been identified on the main Soar and its tributaries.

(ii) Flood warning procedures to be followed conform to the NRA national standard. This uses a colour-coded system in which the three flood risk levels reflect primarily the severity of impact, but are also related to the likelihood of flooding.

(iii) Whilst no applications for forecasting, other than for flood warning, have been identified by the NRA it is recommended that the proposed Forecasting System be sufficiently generic to accommodate new requirements as they are recognised and become needed. Future uses might include support to water quality management within the Soar catchment.

3. Hydrometric Network Design for Flood Forecasting

3.1 INTRODUCTION

A specific requirement of the Stage 1 Study is to arrive at a fresh approach to flood forecasting for the Soar through not being influenced by the existing system, referred to here as the ST-FFS, or the associated hydrometric network used to support it. The latter requirement implies the need to undertake a completely new hydrometric design for the Soar tailored specifically to best support the flood warning requirements identified in Section 2. The measurement of rainfall, river level and flow, climatic variables and soil water are each considered in turn in Sections 3.3 to 3.7. However, as a foundation to the design, Section 3.2 attempts to gain a general understanding of the Soar catchment through a review of its topography and river network, its geology, soils and land use, its meteorology and climate and the effect of any artificial influences. A Digital Terrain Model and Landsat satellite imagery for the Soar are used to support the catchment review and aspects of the network design.

3.2 THE RIVER SOAR CATCHMENT

3.2.1 Topography and the river network

The River Soar drains an area of 1360 km^2, rising 20 km south-west of Leicester, just within Warwickshire, at an altitude of 140 m and flows northwards for 52 km joining the River Trent, at an altitude of 30 m, at Ratcliffe. The highest point in the catchment is 279 m, at Bardon Hill in the Charnwood Forest, but in general the catchment has very subdued relief and low gradients. The IH Digital Terrain Model (DTM) for the Soar catchment and a relief map derived from it are shown in Figures 3.2.1 and 3.2.2. Figure 3.2.3 shows a map of the slope variation, again derived from the 50 m grid DTM; a logarithmic grey scale is used with steepest slopes lightest. Whilst the Charnwood Forest area is an exception with youthful incised valleys, the lower Wreake has mature meander belts and the lower Soar is characterised by a broad flood plain, sweeping meanders and abandoned ox-bow lakes.

The mean discharge of the Soar is about 9 m^{3}s^{-1} (780 Ml/d). Of this 20% derives from public supplies imported from the Dove and Derwent and returned to the Soar as effluent returns (see Section 3.2.4). In extreme drought years these imports can account for as much as 50% of the annual flow.

The Soar's majoı tributaries are the Upper Soar, Sence, Wreake and Rothley Brook: these can all produce floods on the lower Soar. Unprotected washlands on the lower Soar are flooded on average every two years. An indication of the time-of-travel to the confluence with the Trent can be obtained using the DTM by first inferring flow paths (Figure 3.2.4) and then making an assumption concerning water velocity along the paths. Here, it has been assumed

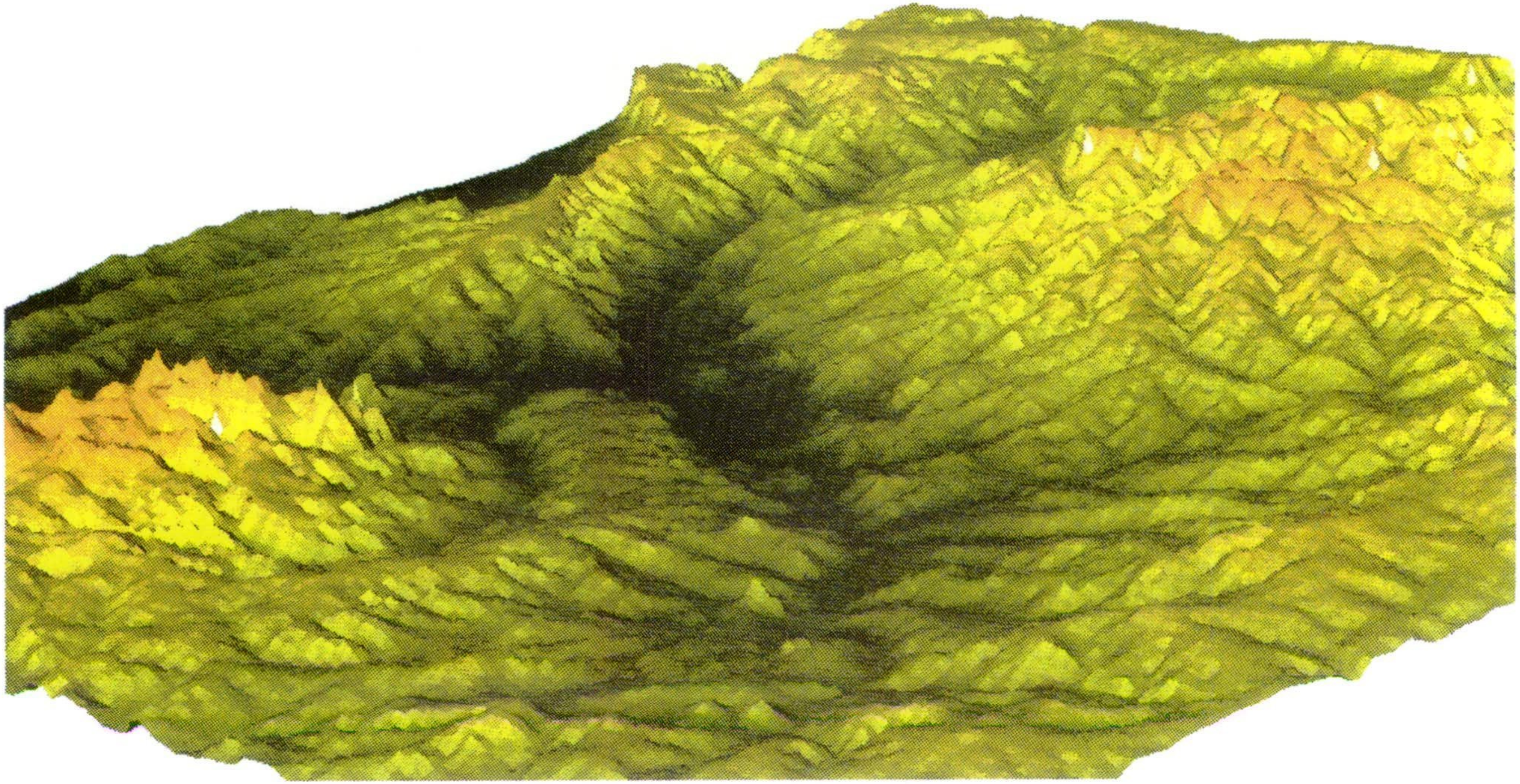


Figure 3.2.1 Digital terrain model of the Soar catchment

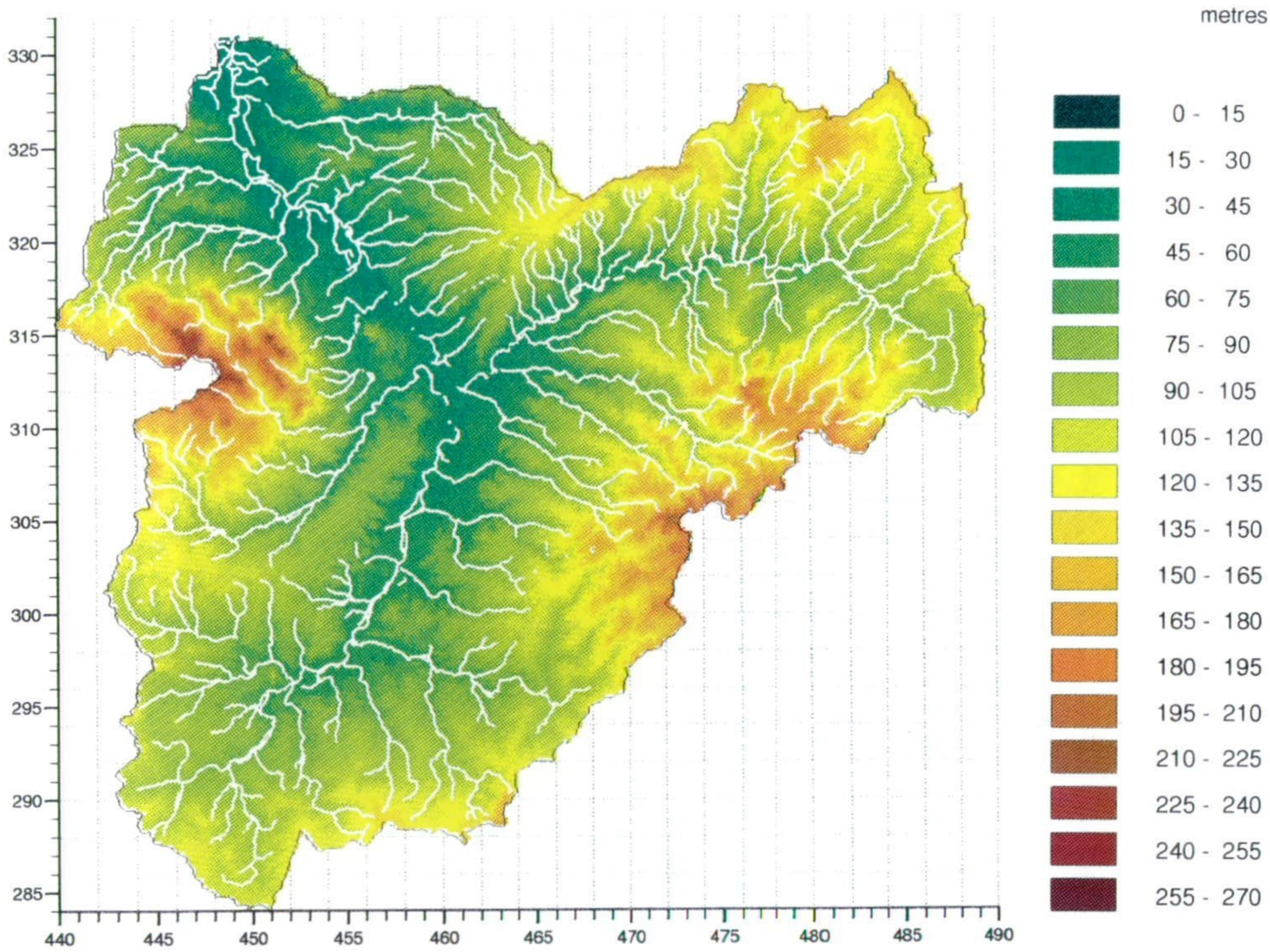


***Figure 3.2.2** Relief map of the Soar catchment*

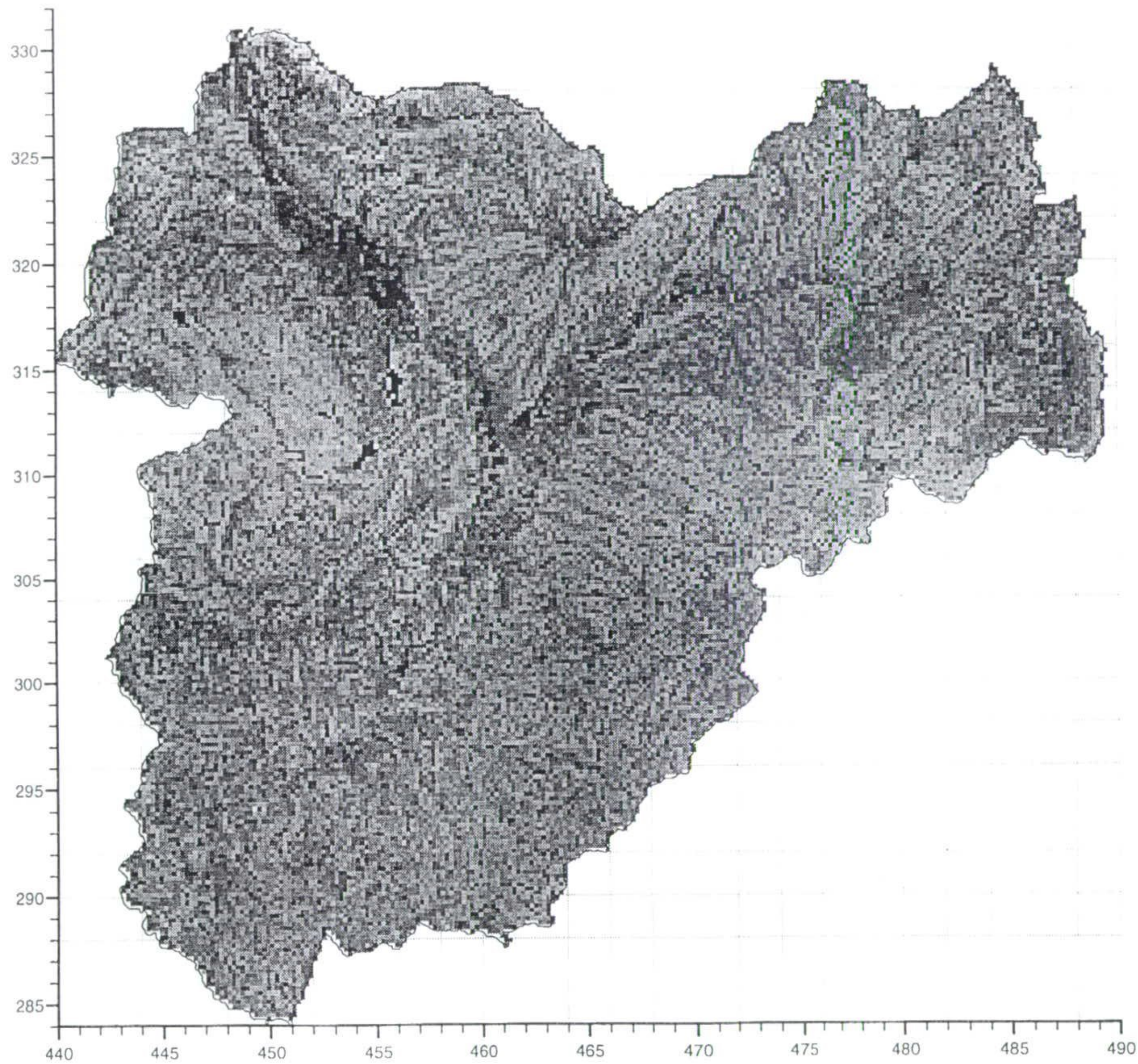


Figure 3.2.3 *Slope map of the Soar catchment*

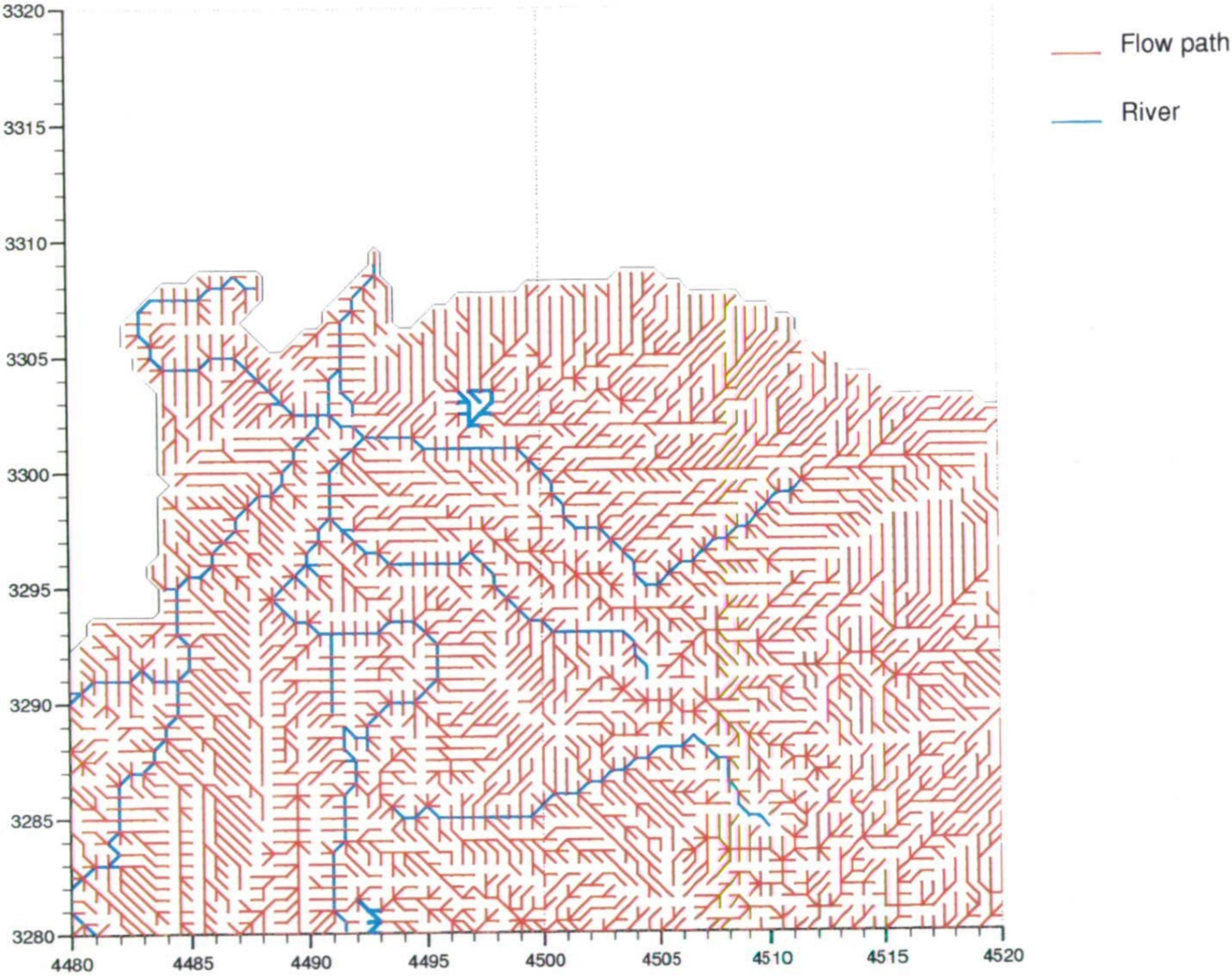


Figure 3.2.4 DTM-derived flow pahts for part of the Soar catchment to the confluence with the River Trent

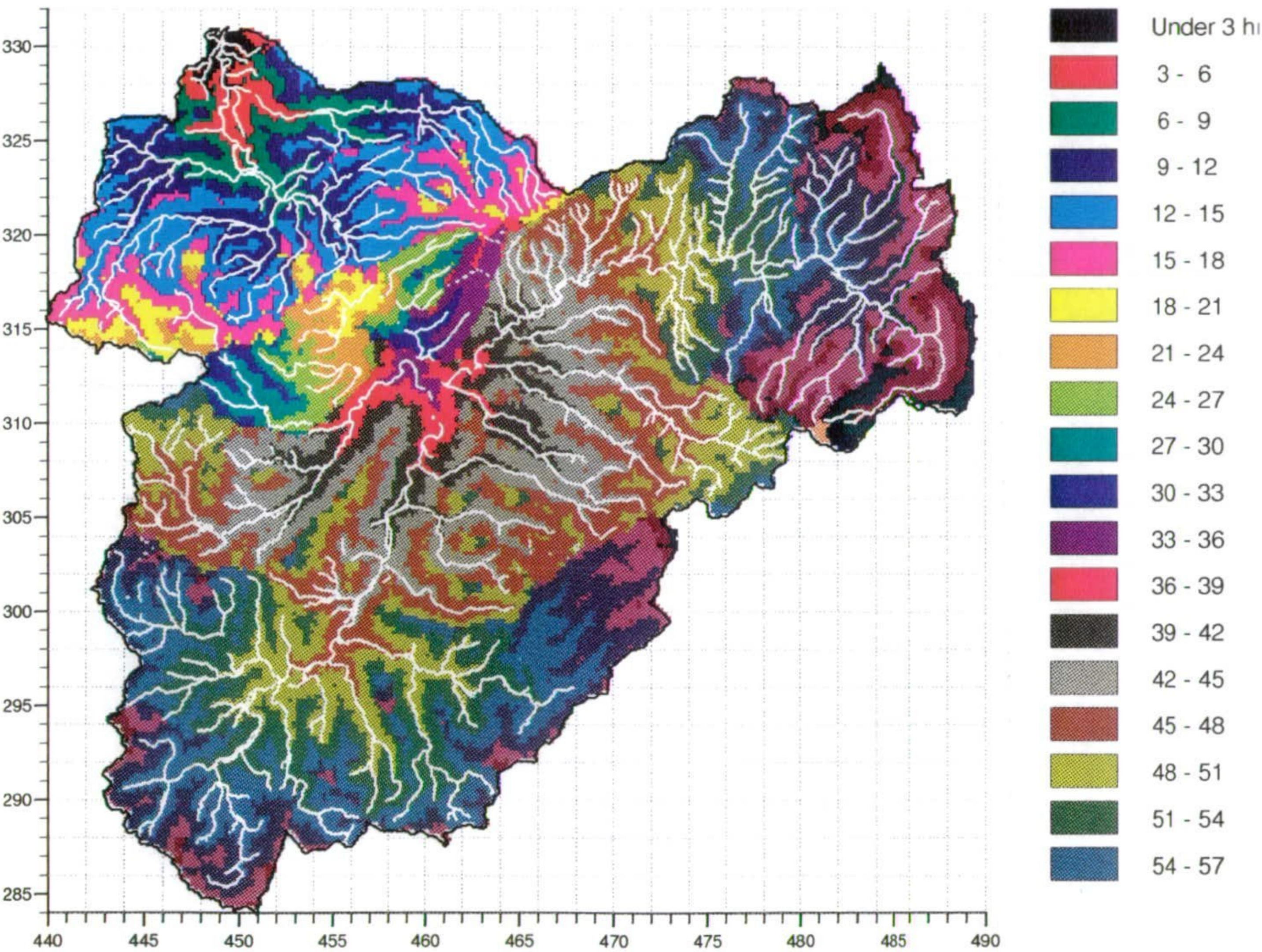


***Figure 3.2.5** Isochrone map for the Soar catchment*

that velocities for river and hillslope paths are 0.5 and 0.1 m s^{-1} respectively. The resulting isochrone map - showing lines joining points of equal time-of-travel to the Trent confluence - is shown in Figure 3.2.5. This isochrone map can be used in turn to infer an approximate unit hydrograph (UH) for the Soar catchment based on the time area method. This UH does not incorporate additional attenuation due to channel storage effects. The resulting UH, shown in Figure 3.2.6, is seen to peak initially at about 12 hrs and to be followed by later peaks at 47, 51 and 56 hrs as runoff contributions from the more distant locations arrive at the Soar's confluence with the River Trent.

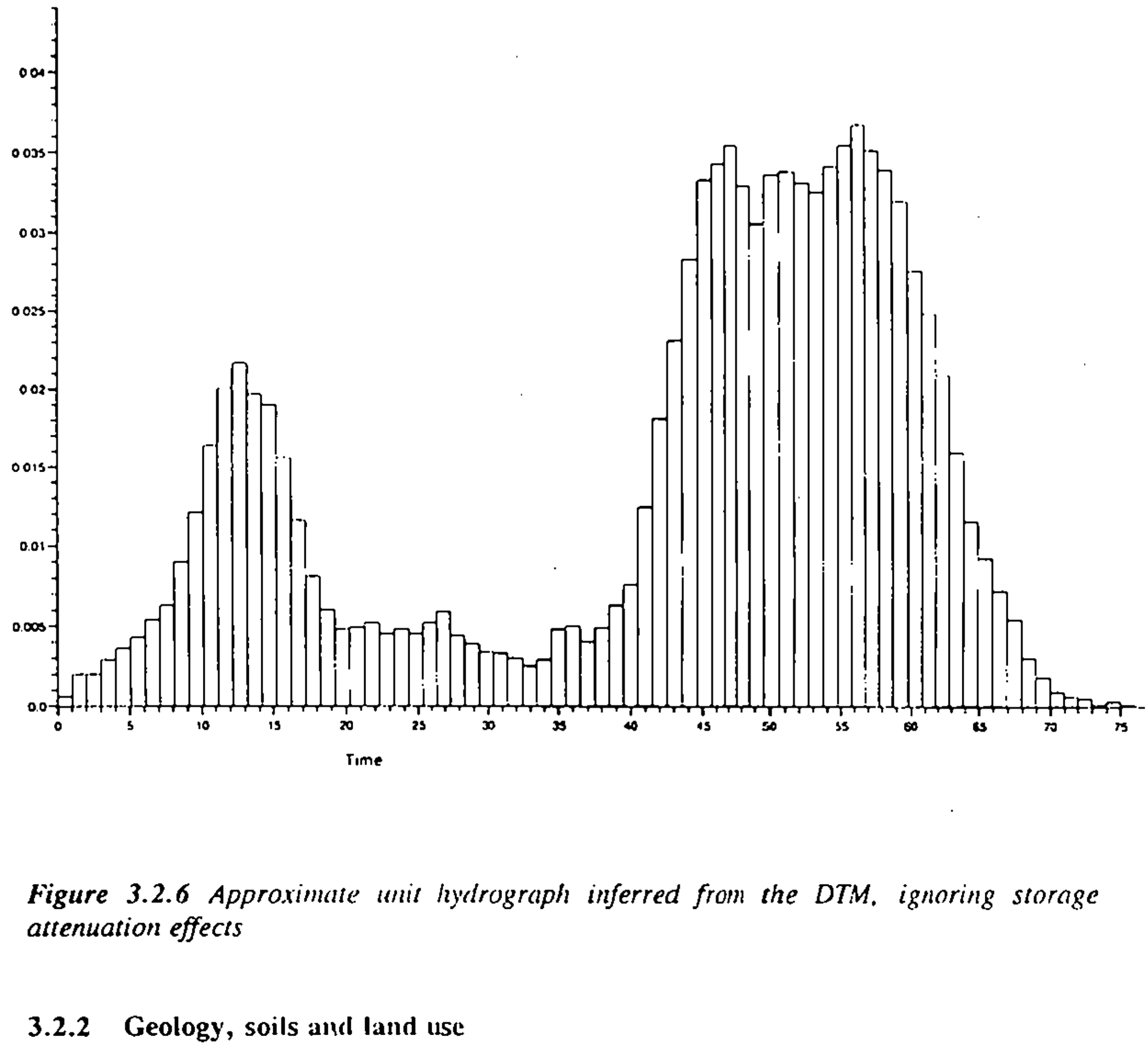


Figure 3.2.6 Approximate unit hydrograph inferred from the DTM, ignoring storage attenuation effects

3.2.2 Geology, soils and land use

The catchment is underlain by impervious strata, principally Liassic Clays, which with low slopes impeding drainage makes the Soar catchment particularly vulnerable to flooding. There is little or no groundwater to support baseflows. Figure 3.2.7 provides a summary of the land use over part of the Soar catchment, as inferred from classification of a Landsat satellite image. Table 3.2.1 summarises the percentage of the catchment under each land use type. A classification for the entire Soar catchment is not currently available on account of the need to composite more than one Landsat image.

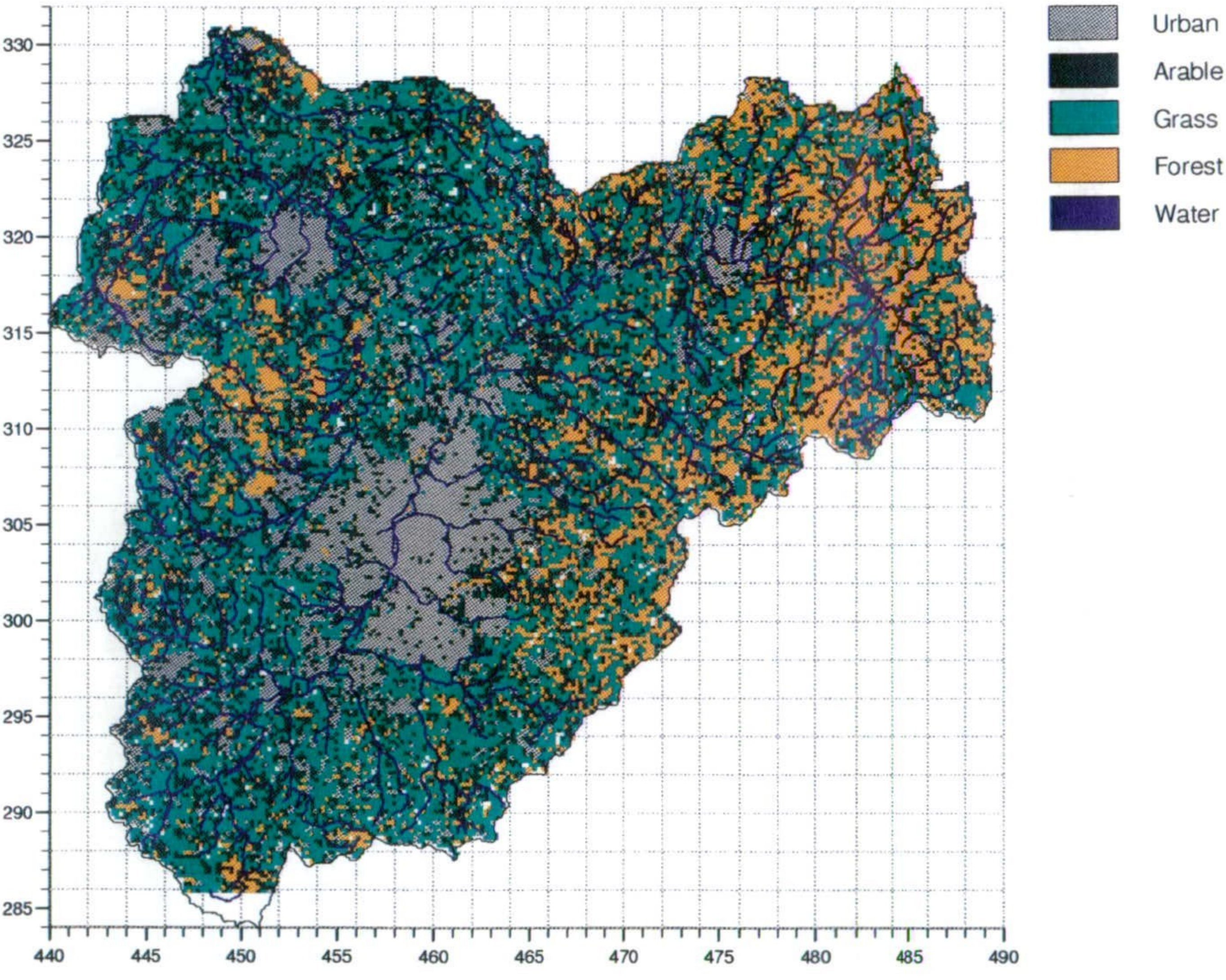


Figure 3.2.7 Land use over the Soar catchment inferred from Landsat

Table 3.2.1 Land use over the Soar catchment as inferred from Landsat imagery

Land use	% cover
Grass	43.2
Arable	23.3
Urban	16.7
Forest	15.6
Water	0.1
Unclassified	1.1

3.2.3 Meteorology and climate

The Soar is one of the driest catchments in the Severn-Trent region with an annual average rainfall of 650 mm, which falls fairly uniformly over the whole area. Exceptions are some increase over the higher ground of Charnwood Forest (800 mm) and over the limestone escarpment forming the south-east divide (750 mm). About 75% is said to be lost to evaporation although this figure would seem to be high. Soil moisture deficits of 100 mm can develop in summer. There is little seasonal variation in rainfall.

3.2.4 Artificial influences

Urban centres

The catchment falls almost entirely within the county of Leicestershire with the main centres of population being the industrial centres of Leicester and Loughborough and the market town of Melton Mowbray. The concentration of population in the middle reaches of the Soar means that the largest effluent returns occur between Leicester and Loughborough, with the main outfall near Wanlip. However, their magnitude forms a negligible contribution to flows at times of flood and are consequently not of concern to the present study. More important is the effect of paved and roofed areas on runoff production, although urban centres are provided with storage attenuation facilities to balance out this effect.

Water resource schemes

There is a paucity of local sources of water within the Soar catchment. As a consequence the majority of water used for public supply is imported from outside the basin from the Derwent Valley reservoirs and the River Dove. The Derwent supply comes via the Hallgate Service Reservoirs to the north-west of Leicester with an entitlement of 69 Ml/d (the aqueduct capacity is 82 Ml/d). A yield of 180 Ml/d can be maintained by the Dove source via Hallgate and Ragdale. The main local source are the impounded reservoirs on the slopes of the Charnwood Forest comprising of the Blackbrook, Cropston, Swithland and Thornton reservoirs with a combined storage of 8500 Ml. Their yield, including the stream intake at Nanpantan, is 22 Ml/d but the average draw-off is as high as 30-35 Ml/d.

There are also a few scattered borehole sources, with small yields, around the edge of the basin. The Triassic Sandstone aquifer crops out only as a small disjointed area on the western edge of the basin near Coalville: resources are only of local significance. Lincolnshire Limestone, Lower Estuarine Series, Northampton Sands and Middle Lias Marlstone aquifers have very small outcrop areas over the eastern edge of the basin around Melton Mowbray. Licensed abstractions are minimal. In addition to these there are a few other minor localised sources; for example, a few industrial boreholes in Leicester tap sandstone horizons in the Keuper Marl and the Soar River Gravels. Again these small resource schemes will not be of concern to this flood forecasting study.

Navigation

Locks and weirs on the Soar Navigation act to enhance water levels and aggravate flooding. They are of particular concern to this study and are discussed in more detail in Section 4.2.

3.3 RAINFALL MEASUREMENT NETWORK

3.3.1 Raingauge network

The design of a raingauge network to support flood warning is not a straightforward task if it is to be done objectively to achieve a given level of accuracy at least cost. Clearly accuracy will be dependent on weather conditions as well as the application context within which the rainfall information is to be used. Design also raises questions of gauge configuration as well as number and also the optimal method of sampling.

For flood forecasting it is best to use a tipping-bucket raingauge recording time-of-tip, giving the opportunity to resolve the data to any time interval appropriate to the application. Under UK climatic conditions a 0.2 mm bucket size is preferred to a 0.5 mm one, if data are to be resolved to at least a 15 minute time interval. The main argument for a 0.2 mm bucket is that greater timing sensitivity can be achieved. Whilst the requirement will be less for a river modelling system making use of hourly data, it is recommended here that improved model performance will result through the use of a 15 minute data and model time-step. Advantages will accrue particularly for the hydrodynamic model in situations where gate controls are dominant. In general, the ability to update forecasts more frequently, at a 15 minute rather than hourly frequency, is also known to bring benefits in forecast accuracy. A complicating issue is the accuracy of the raingauge when used with different buckets. For example, the Didcot gauge uses the same mass of bucket for 0.2 and 0.5 mm gauges, with a counterbalance for the 0.2 mm version. This means that its accuracy is lower due to loss of water during the tipping process, which occurs more frequently for the smaller bucket. However, the 0.1 mm bucket design uses a low mass bucket, moves faster and therefore provides greater accuracy than the 0.2 and 0.5 versions, but with a range limit of 200 mm h^{-1}. A new design based on the 0.1 mm gauge modified to record 0.2 mm tips will be even more accurate, given the same mass but lower frequency of tip. If a raingauge calibration error correction algorithm is used then the gauge accuracy for all three instruments is about the same. The cost of converting an existing .5 mm gauge to .2 mm is about £35 (counterweight and recalibration), whilst that based on installing new buckets (0.1 or 0.2 mm) is about £120. Consideration might even be given to using a 0.1 mm bucket, since very extreme rainfalls rarely exceed 12 tips per minute (144 mm h^{-1}), although this size has yet to gain adoption within other regions of the NRA where a 0.2 mm bucket is the norm. A final application favouring use of a smaller bucket is that of radar raingauge calibration. Here the quantisation error may significantly affect the calibration factor (ratio of gauge to coincident radar value) calculated for a 15 minute period.

The review of the Soar catchment has revealed that the catchment can be regarded as reasonably homogeneous from a rainfall siting point of view, possibly with the exception of the Charnwood Forest area. A raingauge configuration can therefore be chosen which is essentially uniform, provided the density is such as to include at least one gauge in the Charnwood Forest area. An arrangement on a regular lattice would be the idealised design, and local factors such as ease of access and land ownership would lead to deviations from this ideal. An informal means of arriving at a gauge density is to first provide one gauge in each of the major tributary catchments and then include additional ones to achieve a reasonably spread over the Soar catchment as a whole. This has the merit for rainfall-runoff modelling, the main use of rainfall in the proposed forecasting system, that each model is associated with one gauge.

A much more formal approach is needed to achieve an objective design meeting prescribed accuracy requirements. Surprisingly, there have been relatively few detailed studies of the accuracy of rainfall measuring networks of different density, and of these most are concerned with daily or monthly amounts. For example, Seed and Austin (1990) provide results based on radar data for 8-30 August 1987 from Florida, USA and for an entire summer of convective rainfall over Neisprut, South Africa in terms of the estimation error associated with areal average rainfall for different "gauge" network densities and areas. Figure 3.3.1 shows for a 45,000 km^2 area the errors associated with mean areal daily rainfall extracted from gauge networks of different density, for Florida and Neisprut conditions. The large variation in estimation error between sites highlights the sensitivity of the errors to the relative variability of the rainfall at each site. Accuracy, for a given gauge density, was found to be also significantly affected by the size of the raining fraction of the area. Huff (1971) provides results for shorter time-intervals obtained for 6 hour storms over a 1040 km^2 area of Illinois and for showers and thunderstorms over a 570 km^2 area of Florida (Figure 3.3.2). Again local conditions exert a strong influence with much larger errors for Florida being accounted for by larger rainfall gradients and smaller storms than experienced over Illinois. Huff also highlights the great variability that exists about the average curves presented in the figure, making estimates of error for a given storm difficult to predict.

Whilst the above studies provide some insight into the accuracy of areal rainfall estimates as a function of gauge density for different size areas and storm conditions they fail to give the accuracy expected in the end application, that is flood forecasting. Eagleson (1967) performed an interesting theoretical study of this problem, using a simple 1-D "open book" representation of a catchment and a storm centred at the catchment outlet with an assumed correlation-distance function He derived errors for peak discharges associated with different network densities. Table 3.3.1 summarises the number of gauges required for a 1400 km^2 under conditions likely to be experienced in an Australian basin experiencing a cyclonic storm. The results are dependent on a measure quantifying the ratio of basin to storm dimension, with partial coverage occurring for values greater than 2. Whilst the catchment area is similar to that of the Soar, in other respects the simulation conditions are not; in particular, historical floods on the Soar have primarily been associated with more uniform depression systems.

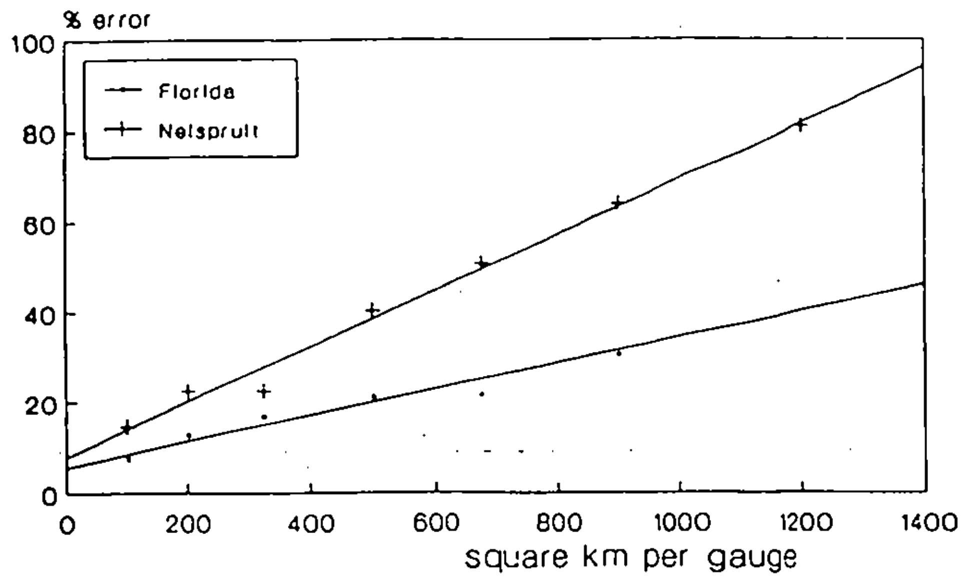


Figure 3.3.1 Errors in the estimation of mean areal daily rainfall using distance-weighted interpolation, for gauge networks of different density over a 45,000 km² area (after Seed and Austin, 1990)

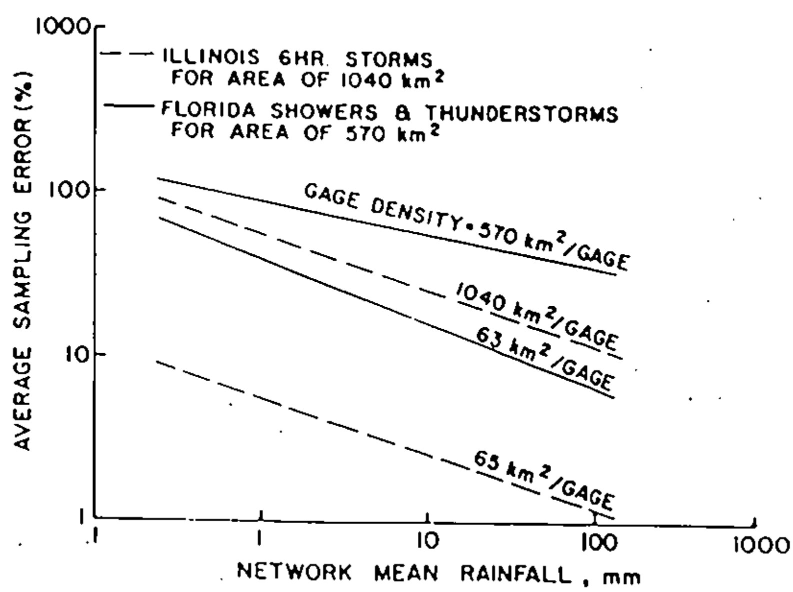


Figure 3.3.2 Average rainfall depth sampling error versus network mean rainfall and gauge density for Illinois and Florida summer storms (after Huff, 1971)

Table 3.3.1 Number of raingauges required for flood forecasting to achieve a given error in peak discharge; conditions simulate a 1400 km² basin in Australia experiencing cyclonic storms (after Eagleson, 1967)

% error in peak discharge	Ratio measure of basin to storm dimension			
	1	2	4	10
5	4	7	24	46
10	2	4	10	14
15	1	2	5	7

In practice the design of a raingauge network for the Soar should not be considered independently of weather radar. Studies performed by IH, this time for UK conditions, are described in the next section which provide important insights into the difficulty of prescribing a raingauge network density, both with and without the support of weather radar, for flood forecasting purposes.

3.3.2 Weather Radar

The Soar catchment is unfortunately not well served by the UK Weather Radar Network. Figure 3.3.3 indicates that a little over half the catchment lies outside the "quantitative" area of coverage, delineated approximately by the 76 km range "circles". The Ingham radar, near Lincoln, provides quantitative coverage for the north-east part of the catchment. Within the range of 76 km, data are available on a 2 km grid and resolved to 208 intensity levels. Outside this range, data on a 5 km grid are available. Whilst the 76 km limit for transition from so-called quantitative to qualitative data is somewhat arbitrary, it reflects the deterioration of radar performance to estimate ground level rainfall at increasing range. A principal factor causing the drop in performance is that the radar beam is sensing a volume of the atmosphere whose size and height above the ground increases with range. This means that sensitivity (resolving power) is lost as the beam width expands and more importantly rain in the sampled volume is more unlikely to be a good representation of that near ground level. Figure 3.3.4 illustrates the radar beam variation with range (the lowest, zero, beam is that use operationally over the Soar) and it can be seen that at about 80 km range the beam is at a height of 1 km, which can be above shallow rain-forming clouds.

Table 3.3.2 summarises the radar data products supplied or used by UK Meteorological Office. In the Severn-Trent region use is made of Type 1 and Network data, which are referred to as "picture" data because of their low quantisation of rainfall intensity (7 levels, plus 0) and spatial resolution (5 km at all ranges out to 210 km). Such data products were primarily designed for picture display purposes on the old Jasmine display units, but the data also include 15 minute integrated catchment area totals for pre-defined catchments. Whilst there is a strong argument for making use of the higher resolution Type 2 data in other parts of the Severn-Trent Region the case is probably weakest for the Soar catchment on account of its range. However, on regional grounds we would argue for greater use of Type 2 data for quantitative applications, such as flood forecasting, and local processing of these data to remove anomalies, to form catchment average rainfall, to perform local calibration using telemetered raingauge data and to generate short-term rainfall forecasts. IH's HYRAD

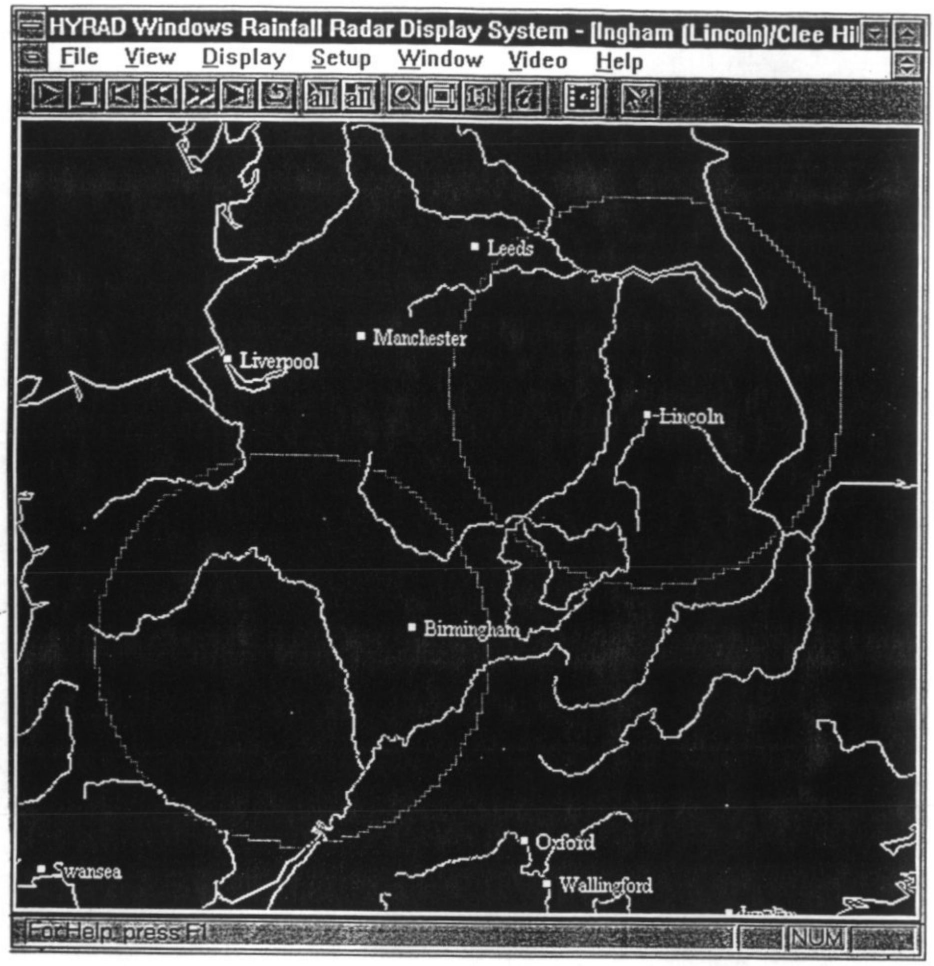


Figure 3.3.3 *Radar coverage over the Soar catchment provided by the Ingham (Lincoln) and new Clee radars (76 km range "circles" for "quantitative" coverage are indicated)*

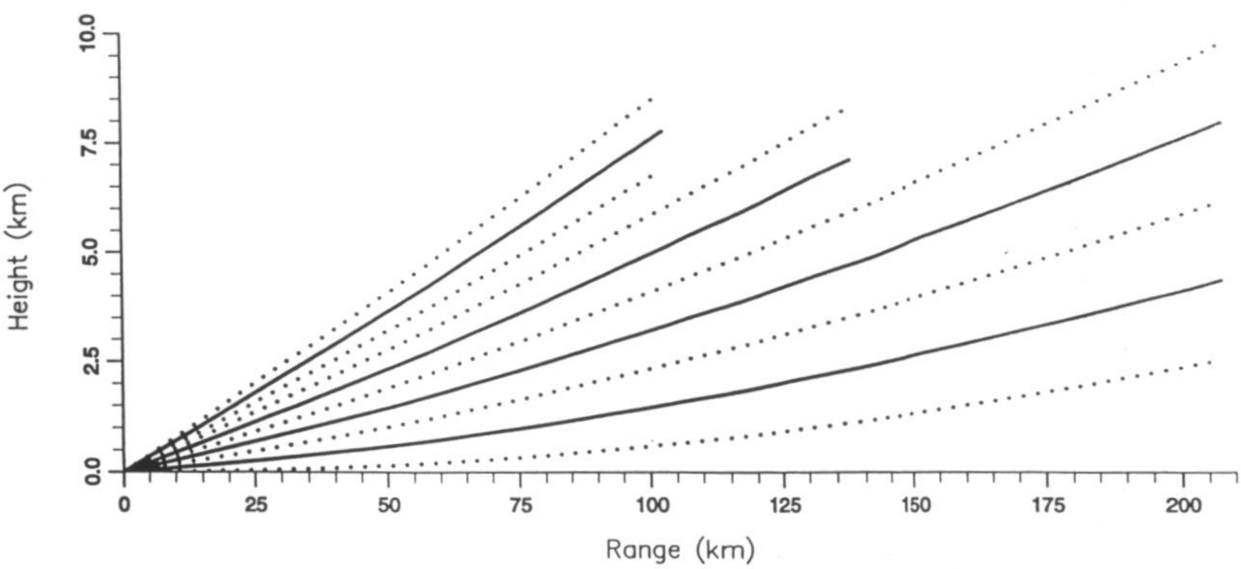


Figure 3.3.4 *Increasing height and width of the radar beam with range from radar; four beam angles are used in a 5 minute scan but only Beam 0 is disseminated to users at present.*

(HYdrological RADar) System is specifically design to provide this functionality and to interface to a River Flow Forecasting System. Appendix 1 provides a HYRAD brochure summarising the functionality this system provides, which includes display of Type 2, Network, COST-73 and Frontiers actual and forecast products. The display capability is particularly relevant when using weather radar as an initialising step in the flood warning process, particularly as a guide to monitoring and scanning requirements. At present the REMUS system (see Section 5.3.2) is used as a radar display user interface by NRA-ST and is liked by users, especially on account of its simplicity of use. However, we understand that the system is being considered for upgrading and suggest that incorporation of HYRAD might be considered as one option, particularly if the new design is to be Windows 3.1 based.

It should be noted that Frontiers forecasts are now, at least in principal, available to the NRA-ST Region and the six hour forecasts this product provides will prove useful to the Soar Flood Forecasting System. A conclusion of the Frontiers evaluation study (Met. Office/NRA, 1994) is that for shorter-lead times up to two hours local rainfall forecasts, as provided by the HYRAD system, can provide improved accuracy over Frontiers and therefore serves as a valuable complement. However, at present HYRAD only provides forecasts within 76 km range of a radar. Development to provide the wider coverage, as required for the Soar catchment, is straightforward and already planned for a later release of HYRAD. The HYRAD Windows 3.1 GUI makes provision for animated display of Frontiers forecasts. It is recommended that the Soar Flood Forecasting System incorporates both Frontiers forecasts and the HYRAD system to obtain extended lead time flood forecasts.

The value of weather radar to provide a continuous estimate of the rainfall field over space is well appreciated in qualitative terms. However, when quantitative rainfall estimates are required as is the case for flood forecasting, the more accurate point estimates of rainfall from a network of recording raingauges can also be of great value. Clearly a combination of the spatial detail provided by radar and the point accuracy offered by raingauges provides a means of deriving better quantitative estimates of rainfall over a region. An investigation by IH, using the London Weather Radar, explored how rainfall estimation accuracy is affected by raingauge networks of differing density, thereby obtaining guidance on the optimal number of raingauges to combine with a weather radar to achieve a given level of accuracy.

A total of 13 events between June 1990 and April 1991 were selected for study, for which measurements were available from a common network of 44 gauges over an area of about 3600 km^2. So-called 'design networks' were created from this base network containing progressively fewer gauges. Gauges were selected for deletion to create a network at the next density level based on first identifying the pair of gauges with the smallest inter-gauge distance and deleting the one which is nearest to any of the others. The result is a set of 43 design networks containing from 44 to 2 gauges and varying in terms of mean distance between gauges from 6.64 to 78.6 km.

Figure 3.3.5 shows the results obtained when the root mean square estimate (rmse) criterion is pooled across the 13 events and plotted against the number of gauges in the design network. A similar multiquadratic surface fitting method was used to infer the rainfall field from the gauge network alone, this time fitting the surface directly to the point measurements of rainfall. The rmse resulting from this 'raingauge only' estimate as a function of number of gauges in each design network is shown on the same figure. Finally, the rmse, calculated using the 'radar-only' rainfall estimate and without using raingauges for calibration, is also displayed. The figure suggests that as many as 30 gauges are required before the accuracy of the uncalibrated radar can be achieved, equivalent to a spacing of 9.2 km between

Table 3.3.2 Types of radar data supplied or used by the UK Meteorological Office

Data Type	Resolution Space km	Resolution Time minutes	Resolution Intensity Levels	Range/coverage km	Transmission Interval minutes	Transmission Rate baud	Transmission Time	Other information transmitted and comments
Type 1	5	5	7, plus 0	210	15	1200	35 s	Calibration flags, synoptic type, 15 min subcatchment rainfall (updated every 1.5 min) plus 1 h and 1 day total
Type 2	2 5	5	208	75 210	5	1200	2 min	Calibration flags, synoptic type, height of bright band, subcatchment rainfall suitable for further processing by recipient
Type 3	5		208	210		2400	27 s	Used by MO to construct network components, calibration flags, synoptic type
Network	5	15	7, plus 0	640 x 640	15	1200	<2.5 min	Height of bright band, intensity colour-key for display
COST-73	20	60	7, plus 0					Composite of radar data from 13 European countries
Frontiers actuals	5	30	7, plus 0	1280 x 1280	30	1200		Decalibrated, quality controlled in near real-time, satellite data composite
Frontiers forecasts	5	15	208	1280 x 1280	30	1200	< 45 min	Forecasts up to 6 hours ahead (instantaneous and totals). On trial in NRA North West and Thames Regions

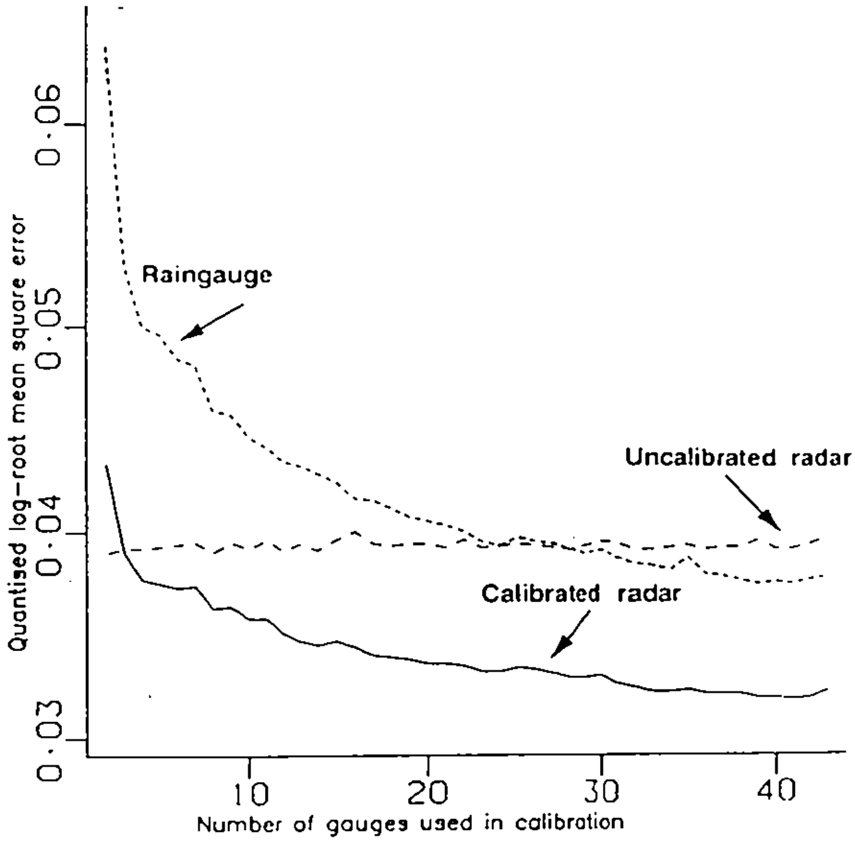


Figure 3.3.5 *The effect of the number of gauges on rainfall estimation accuracy results average over 13 events.*

raingauges. The accuracy of the calibrated radar continues to increase with increasing numbers of gauges but at a progressively diminishing rate. This information might be used to support a choice of raingauge network to be used in combination with a weather radar.

A more detailed analysis on an event by event basis reveals that there is considerable variation about the average results arrived at by pooling across the 13 events. As a result, any recommendation concerning an optimal number of raingauges to be used for radar calibration must be highly circumspect. Transient factors influencing the optimal number include the effect of bright-band due to melting precipitation and the problem of beam-infill (where the higher radar beam elevation is used in place of the lowest when this is blocked by local obstructions) associated with shallow rainfall-forming clouds. In such conditions the value of radar is least and the complementary role of raingauges greatest.

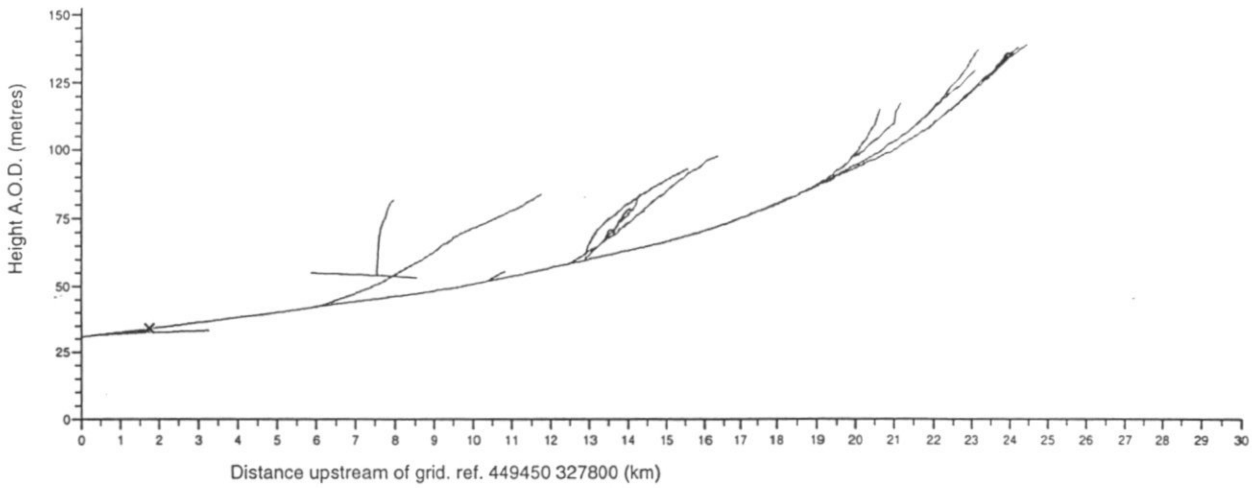
The results obtained also provide an indication of the number of raingauges needed when used in isolation from radar. Figure 3.3.5 indicates that there isn't a marked increase in accuracy beyond 20 to 25 gauges, roughly equivalent to one gauge every 180 to 150 km^2. This would suggest between 8 and 10 gauges are used within the Soar. This should be regarded as a recommendation, given the poorer quality of radar rainfall estimates over the Soar on account of its range from the Ingham and Clee Hill radars.

3.4 RIVER GAUGING STATION NETWORK

In designing a level and flow measurement network to support flood forecasting in the Soar catchment, consideration has to be given to the general configuration of stations, their localised siting and the type of gauging method. The general configuration must bear in mind the sites requiring a flood warning and the needs of flow forecasting models in constructing forecasts for critical sites used in the warning process. In order to provide forecasts along the main Soar it will be essential to have good measurements of the major tributaries contributing lateral inflows to the main channel. The basic principle in siting these "major tributary stations" is that they be located as near to the confluence of the main river, so as to gauge the majority of the lateral inflow, whilst being sufficiently far upstream not to be affected by backwater induced by flooding in the main Soar.

This principle of station siting has been investigated for the major Soar tributaries with the support of the IH Digital Terrain Model (DTM). The DTM provides elevations on a 50 metre grid as well as steepest gradient pathways inferred from these which are further classified into river and land paths. An algorithm has been developed to traverse the river paths, working upstream from a point on a chosen tributary just upstream of the confluence until a specified critical elevation is reached. The critical elevation chosen is an estimate of the 100 year flood level on the Soar at the tributary junction, as inferred from previous modelling studies, plus the depth of channel incision at the potential gauging site. This has been estimated from site visits as 2 metres, for the purposes of obtaining indicative locations. Thus the siting principle as applied here seeks to find the lowest point on the tributary not affected by the backwater profile of the 100 year flood, where the profile is approximated by a horizontal line from the confluence plus 2 metres to account for channel incision. The locations obtained for the seven major tributaries are displayed as crosses on longitudinal stream profiles inferred from the DTM in Figure 3.4.1. The details of the analysis and the resulting grid reference and distance upstream of the chosen points are summarised in Table 3.4.1. Figure 3.4.2 provides a map of the locations identified.The results should be treated with a degree of circumspection because the DTM elevations are inferred from contours from the 1:50000 Ordnance Survey maps rather than a surveyed longitudinal profile of the tributary bed; an incision depth of 2 metres has also been assumed for all tributaries. However, the locations obtained are indicative and demonstrate the application of the fundamental principle of design. The results indicate that all the stations may be located between about 1500 and 3500 m of their respective confluence with the Soar, provided other factors affecting gauge siting prove acceptable. There would be no requirement to gauge the Quorn Brook due to its control by Swithland Reservoir and lack of forecast points. The reservoir is used to mitigate flooding on the Quorn, releasing 15 Ml/d (.174 m^3/s) when the storage exceeds .3 m below top water level. At other times a flow of 0.2 Ml/d (.002 m^3/s) is maintained. Gauging of the two smaller tributaries, Kingston Brook and Black Brook, might also be viewed as not essential.

We can now turn to the problem of siting stations on the main Soar. The two main considerations in configuration are firstly to maximise the flow being measured, which suggests measurement downstream of major tributary junctions, and secondly to choose a site appropriate to the warning requirements, which suggests a nearby location suitable for gauging. Other factors suggest equispacing along the river, other things being equal, with a distance spacing chosen to give a required level of accuracy. Formal studies of this spacing problem have been undertaken, notably by van de Made (1987) in the Netherlands, using statistical methods and hydrodynamic models. In this case a network is chosen such that the standard error of interpolation of water level between stations will not exceed 2.5 cm. Clearly such design criteria can be modified to be more application specific, for example to meet a given forecast accuracy target rather than one based solely on interpolation. Application of such formal methods are beyond the scope of the present study and a more pragmatic approach is followed here. Whether to gauge upstream or downstream of the junction with *(a) Kingston Brook*



(b) Black Brook

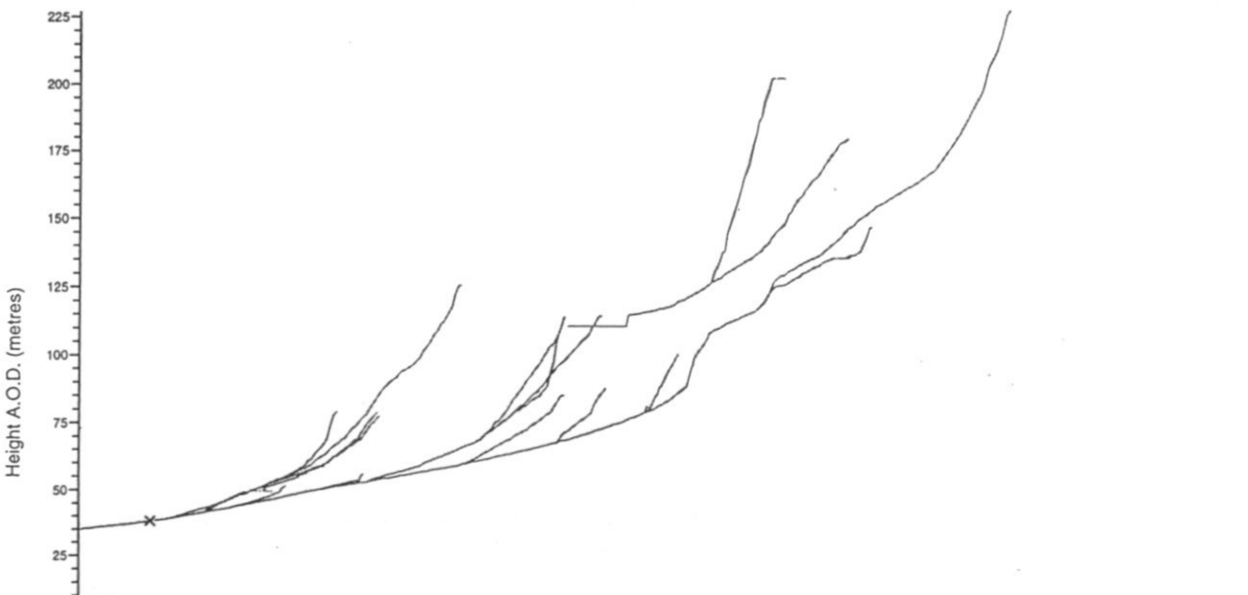
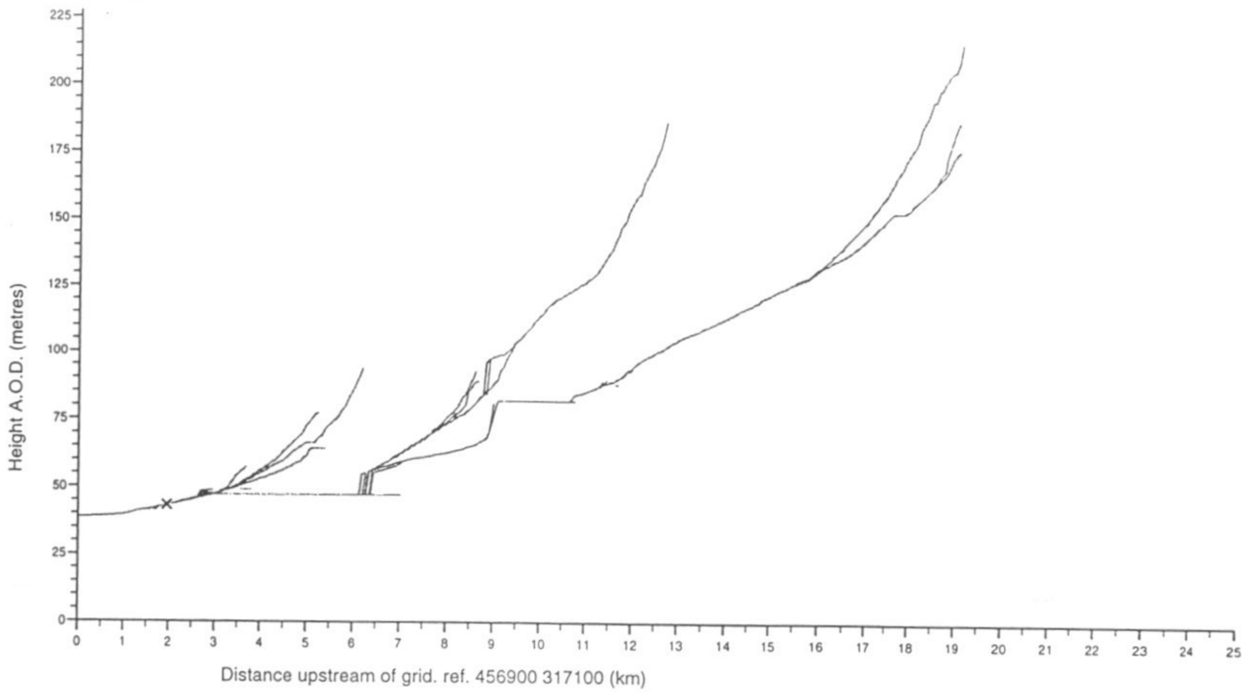


Figure 3.4.1 *Longitudinal river profiles for the main Soar tributaries; a cross marks the lowest potential gauging site on the tributary not affected by backwater from the 100 year flood on the main Soar*

(c) *Quorn*



(d) *Rothley Brook*

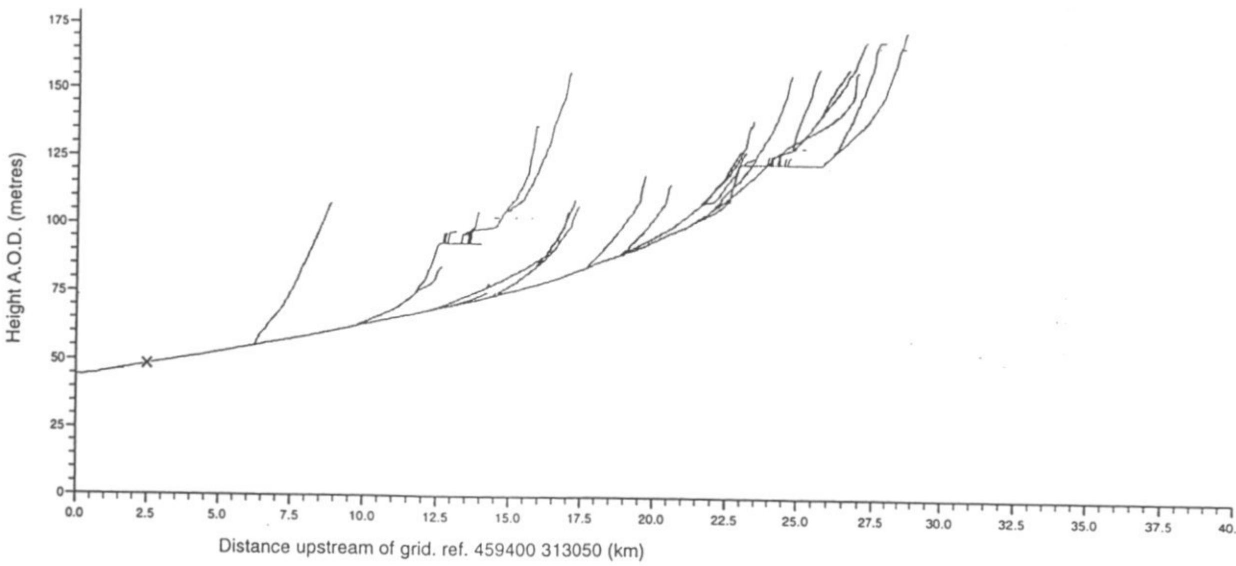
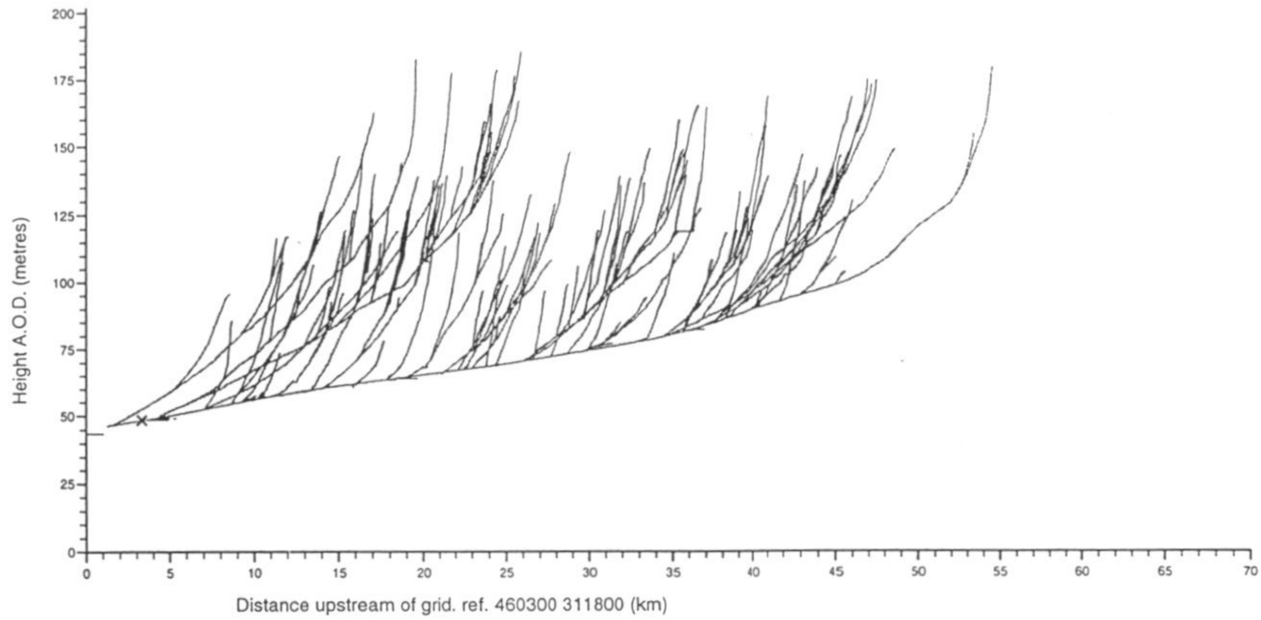


Figure 3.4.1 *cont. Longitudinal river profiles for the main Soar tributaries; a cross marks the lowest potential gauging site on the tributary not affected by backwater from the 100 year flood on the main Soar*

(e) *Wreake*



(f) *Upper Soar*

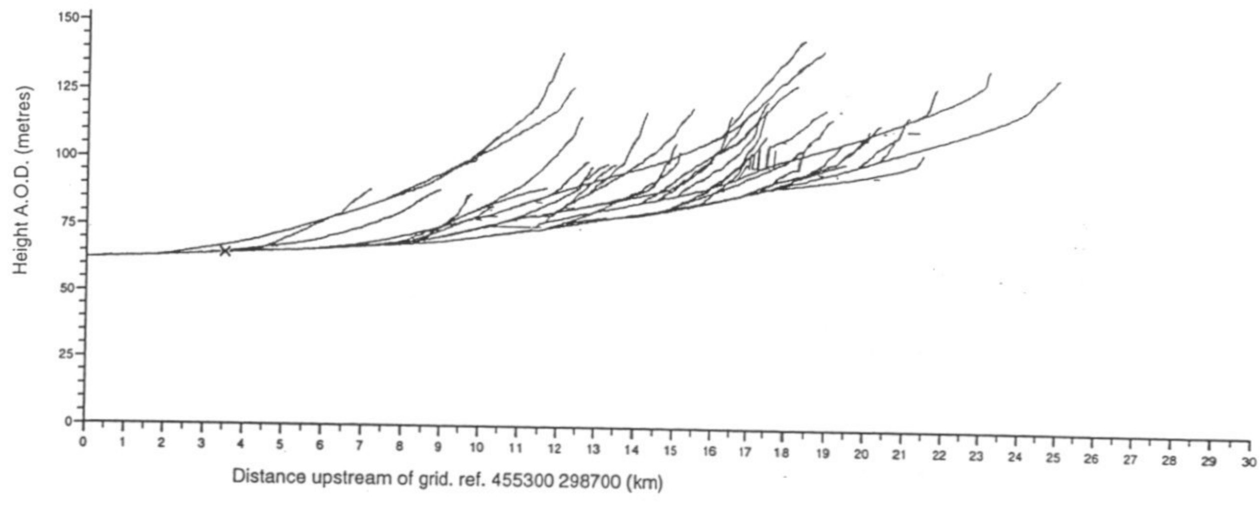
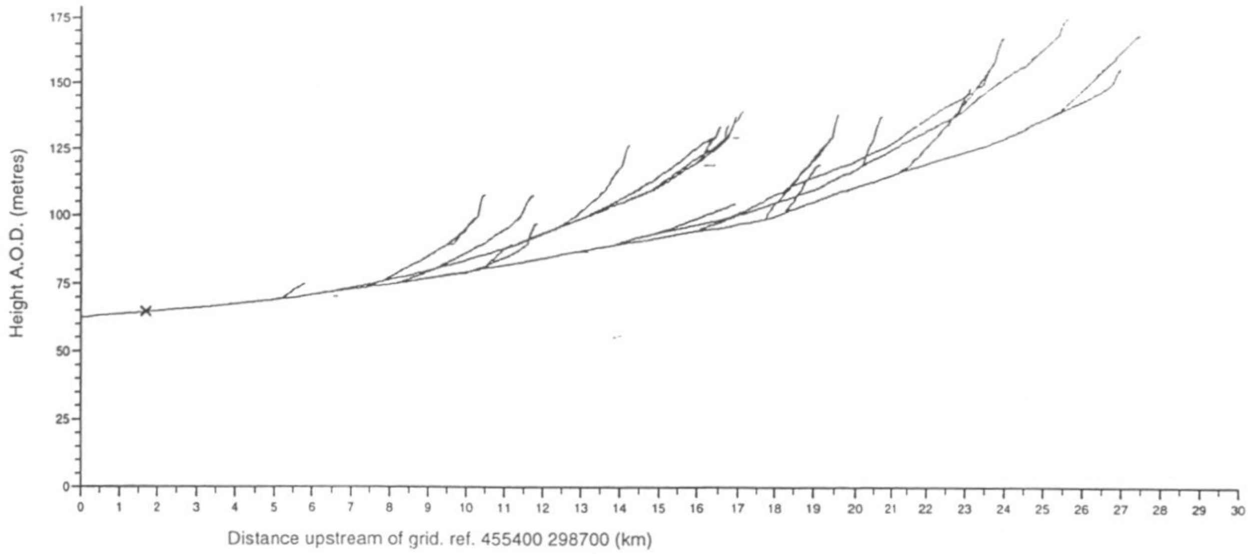


Figure 3.4.1 *cont. Longitudinal river profiles for the main Soar tributaries; a cross marks the lowest potential gauging site on the tributary not affected by backwater from the 100 year flood on the main Soar*

(g) Sence



(h) Soar confluence with Trent

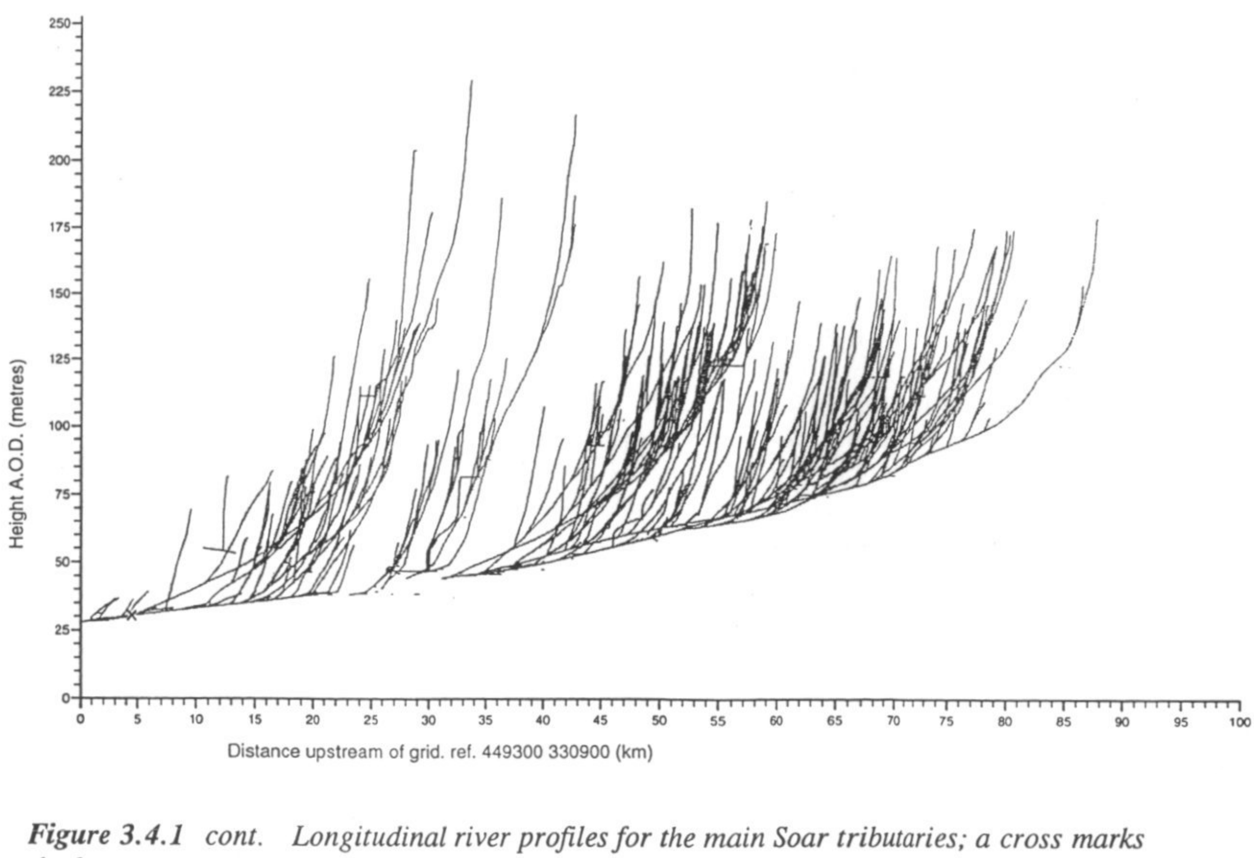


***Figure 3.4.1** cont. Longitudinal river profiles for the main Soar tributaries; a cross marks the lowest potential gauging site on the tributary not affected by backwater from the 100 year flood on the main Soar*

Table 3.4.1 Location of lowest potential gauging station on major tributaries of the Soar based on a DTM longitudinal river profile analysis of the 100 year return period flood elevation at the confluence plus 2 m channel incision

Tributary	Grid Reference of confluence	Elevation at confluence m AOD	Approx. 100 year flood level + 2m m AOD	Grid Reference on tributary where 100 year level + 2m is first reached m	Distance upstream m
Trent/Soar confluence	SK 4930 3090	27.6	30.4	SK 4920 2785	4480
Kingston Brook	SK 4945 2780	30.7	34.0	SK 5095 2740	1739
Black Brook	SK 5215 2190	34.9	38.0	SK 5170 2060	1531
Quorn Brook	SK 5690 1710	38.6	43.0	SK 3350 1605	1957
Rothley Brook	SK 5940 1305	44.5	48.5	SK 5800 1210	2499
Wreake	SK 6030 1180	43.5	48.5	SK 6235 1275	3317
Soar (upstream of Sence)	SP 5530 9870	62.3	64.6	SP 5335 9695	3546
Sence	SP 5540 9870	62.4	64.6	SP 5660 9845	1689

a gauged tributary is arguable and the choice should probably be taken with reference to the relative merits of the two locations from a warning standpoint; that is upstream if the warning requirement is nearer the upstream location. Specific recommendations for the main Soar are for a gauging station at the top, in the vicinity of Leicester, and in the middle around Loughborough. Freemans Weir and Belgrave Weir are possible sites for the Leicester location, and both could be calibrated accurately using physical models. Both structures will probably contain any flood flows, in particular Freemans Weir which has a long crest length and a high crest level which will preclude drowning of this non-standard weir profile. Belgrave Weir, near the downstream limit of the city, has the advantage of measuring the urban runoff contribution from Leicester but may have a small by-pass flow on its left side and its step-up is not as great as at Freemans Weir. Freemans Weir is the preferred option although its long crest length will demand use of an accurate ultrasonic level sensor and cleaning of the weir to achieve sensitive flow measurement. The middle Soar site in the vicinity of Loughborough should be chosen where the canal and river share the same channel and where bypassing is minimised.

Having outlined the considerations for specifying the general configuration of gauging stations the specific choice of location must bear in mind both the suitability for gauging and the specific requirement for warning. These may be conflicting requirements and in some cases may be reconciled through the use of a special method of gauging.

The factors affecting the choice of flow measurement method for a chosen site are varied. So many factors influence the choice of gauging method it is not possible to lay down a selection procedure which will lead positively to a single method as the optimum. The following notes aim to provide some guidelines for selection:

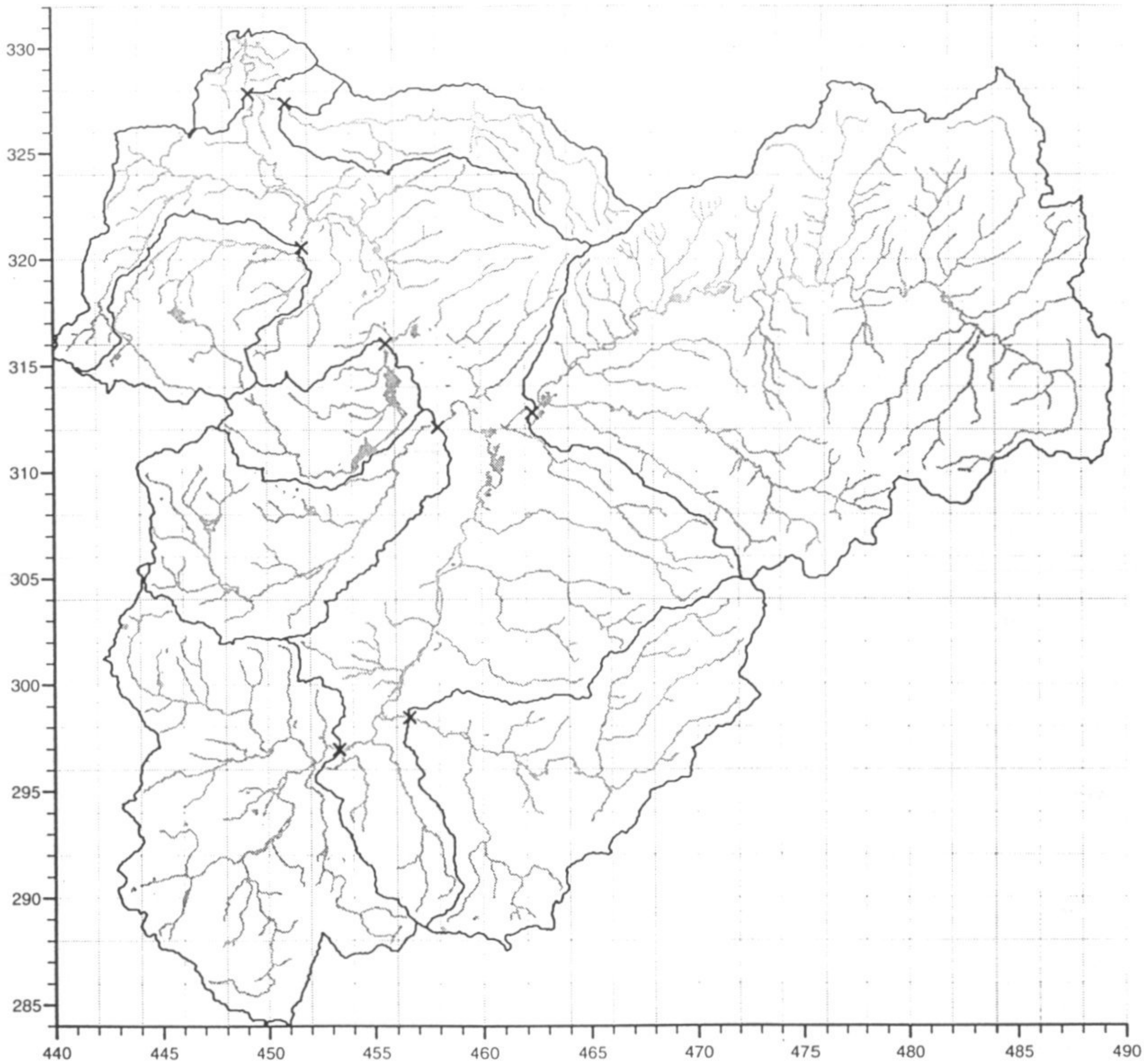


Figure 3.4.2 *Location map of lowest potential gauging sites not affected by backwater*

1. *Water quality*

- clear water : no restriction on choice.
- polluted water : chemical aspects may preclude structures with metal crest.
- water transporting sediments : may preclude some types of structure, ultrasonic and electro-magnetic methods.
- water with floating debris : avoid narrow flumes and thin plate weirs.

2. *Water quantity*

- very small discharges : V-notches with small vertex angle.
- small discharges : V-notches, V weirs, rectangular notches.
- medium discharges : Structures, velocity area, ultrasonic and electro-magnetic methods.
- large discharges : weirs, velocity area and ultrasonic method.

- very large discharges : velocity area and ultrasonic method.

3. *Ratio of maximum to minimum flow*

- small range : virtually any method.
- large range : V-shaped weirs, compound weirs.

4. *Gauging site*

- rivers with large width to depth ratio : avoid notches, V-shaped weirs and flumes.
- rectangular artificial channels : virtually any method.
- circular culverts and part full pipes : trapezoidal or U-shaped flumes.
- steep channels : avoid thin plate weirs, rectangular weirs, ultrasonic and electro-magnetic method.
- backwater influence : electro-magnetic method, avoid velocity area and ultrasonic methods.
- drainage problems : afflux, at a structure, may interfere with the flow system and cause drainage problems. Electro-magnetic and ultrasonic methods or structures with high coefficients of discharge are recommended, eg triangular profile and flat-V weirs.

Since much of the main Soar from Leicester to the confluence is under backwater influence (see Section 4.2) the above guidelines suggest that the electromagnetic method must be a serious contender for sites on the main river. There is also the prospect of using the control structures themselves, with upstream and downstream level and gate position measurements, as a method of flow gauging. The Frisby control structure would provide a useful flow measurement site for the middle Wreake catchment.

Specifically, the recommended river gauging station locations are: the lower Soar upstream of SK 4920 2785; the middle Soar in the vicinity of Loughborough where the canal and river share the same channel and bypassing is minimised; the upper Soar in Leicester at Freemans Weir; the Soar above the Sence confluence upstream of SP 553 987; the Sence upstream of SP 554 987; the Wreake upstream of SK 603 118; the Frisby control structure on the Wreake; the Wreake in the vicinity of Melton Mowbray; and Rothley Brook upstream of SK 594 1305.

3.5 WEATHER STATION NETWORK

The main use of weather station data in a Forecasting System is for estimation of Potential Evaporation for use within a rainfall-runoff catchment model of the soil moisture accounting type. Approximate standard evaporation profiles can be used for this purpose but derivation on a day-to-day basis using an AWS is preferred, and AWS data can be of value in other contexts. It is recommended that a single AWS be deployed in the Soar for this purpose; this should suffice given the fairly homogeneous weather and climate experienced over the catchment. The AWS should have at least the standard set of sensors required to determine evaporation using the Penman equation (wet and dry bulb air temperature, wind speed, net radiation) along with rainfall. Whilst not essential for this application, inclusion of wind direction and incoming solar radiation would conform to standard practice. These data should be transmitted by telemetry at a 15 minute data resolution and processed at the modelling computer to obtain aggregated daily values and Penman evaporation estimates. These data at a shorter time interval can be used to support snowmelt forecasting within the Forecasting System. At the request of the NRA further consideration of the requirements for snowmelt forecasting will not be dealt with here. The use of telemetry and computer automation is considered essential to the successful use of AWS data in the Forecasting System. Experience suggests that limited use of AWS data within the NRA stems from the lack of automated systems designed to process and use such data in the past. A further use may be in deriving local estimates of soil moisture deficit, which can be seen as an additional "Forecast Requirement" to be met by the System.

3.6 SOIL WATER MEASUREMENT NETWORK

At present there is no convincing evidence that a Flood Forecasting System can benefit from a soil water measurement network. Research is ongoing at IH on the use of a soil water station, incorporating a capacitance probe, for flood forecasting purposes. The need for a soil water station within the Soar catchment should be reviewed at a later date when the results of these research investigations become available.

4. Choice of Models for Flood Forecasting

4.1 INTRODUCTION

The choice of appropriate models to be used for flood forecasting on the River Soar is the concern of this section. First the specific modelling problems associated with the Soar are reviewed. Solutions are proposed placing emphasis on the choice of river model for different channel reaches of the Soar and its tributaries. Both hydrodynamic models and simpler, and less data demanding, hydrological flow routing approaches are considered along with the representation of structures and operating rules encountered in the catchment. Other issues addressed are the choice of rainfall-runoff and snowmelt model, model calibration, the choice of updating method, the need for rainfall forecasts to extend the lead time of forecasts and issues of forecast accuracy and when to warn.

4.2 MODELLING PROBLEMS ON THE RIVER SOAR

Real-time flood forecasting for the River Soar catchment will require some representation of the propagation of flood discharge along the river channels and associated flood plains. Earlier investigations and our own recent site visits have identified many physical features of the Soar system which influence flow conditions. These include:

- multiple channel flow paths
- the Grand Union Canal
- natural flood plains
- fixed water level control structures (weirs, bridges)
- movable-element control structures (gates)
- flood defence embankments
- flood plain crossings
- gravel workings (active and disused)
- significant in-stream vegetation
- variations in flood plain land-use
- gauged and ungauged inflows
- downstream influence from the River Trent.

It is important to identify which of these factors need to be considered in providing flood forecasts and how their influence is represented in the forecasting techniques. Since the above factors primarily affect the choice of river model to use this question will be addressed in some detail in the next section.

4.3 CHOICE OF RIVER MODEL

In general, several river model representations are possible including peak-to-peak correlation, kinematic wave flood routing and hydrodynamic simulation. For the Soar basin peak-to-peak correlation should be discounted because of the complexity of the system, lack of historical concurrent flow records and the recent development of the Soar valley and water courses. The method is also unable to forecast the complete hydrograph including the time at which flood inundation damage can first occur. The principal choice lies between flood routing methods and hydrodynamics simulations. In making a choice between these methods it is necessary to consider:

- the data required (fixed and time dependent)
- the speed of forecasting
- the physical factors flushing the flood movement.

Deterministic flood routing in a freely draining channel and flood plain system can be based either on the full St Venant equations:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{4.3.1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left[\frac{\beta Q^2}{A}\right] + gA\left[\frac{\partial h}{\partial x} + \frac{Q|Q|}{K^2}\right] \tag{4.3.2}$$

or the flood routing approximation provided by the convective diffusion equation

$$\frac{\partial Q}{\partial t} + c(Q)\frac{\partial Q}{\partial x} = Q\frac{\partial}{\partial x}\left[\alpha\frac{\partial Q}{\partial x}\right] + cq\,. \tag{4.3.3}$$

The notation used above is as follows:

A	flow area	m^2
c(Q)	flood wave speed	m/s
g	acceleration due to gravity	9.81 m/s^2
h	water surface elevation (stage)	mODN
K	conveyance of cross section	m^3/s
Q	river discharge	m^3/s
q	lateral inflow	m^2/s
t	time	s
x	distance along channel	m
α	attenuation parameter	m^{-1}
β	Boussinesq momentum coefficient	-

Equation (4.3.3) may be obtained from equations (4.3.1) and (4.3.2) by assuming that the first two terms in equations (4.3.2) are small and then eliminating all geometric parameters by combining the equations.

Although the St Venant equations form the main building block of all modern hydrodynamic river models, it is important to restate the assumptions (and hence limitations) of the method. These are:

(1) freely draining channel

(2) freely draining flood plain (laterally and longitudinally)

(3) lateral and vertical variations in flow not important

The flood routing approximation involves further assumptions:

(4) acceleration of flow not important

(5) river surface slope does not change in a flood.

The physical features of the Soar system noted at the start of this section would seem to put into question all of these assumptions. For example, assumptions (2) and (5) will be invalid close to moveable element control structures such as the new gates at Zouch. The looped rating wave at Belgrave illustrated in Figure 3.14 of the MacDonald report on the Soar capacity in Leicester, reproduced here as Figure 4.3.1, shows that at least in this area the acceleration of the flow can be important (contravening assumptions (4) and (5)).

Even in the River Soar and Sence upstream of their confluence the effects of floodplain storage is evident on the discharge hydrographs shown in Figure 4.3.2 (reproduced from Figures 3.5 and 3.7 of the MacDonald report). There are slight shoulders visible on the Sence discharge hydrograph at about $14m^3/s$ and $24m^3/s$ on the rising limb of the 1975 event and pronounced flattening of the hydrograph for the upper Soar starting at about $15m^3/s$. Although MacDonald simulated these events by adjusting parameters of the HEC1 hydrological model, the underlying process is likely to be storage and flow on the floodplain.

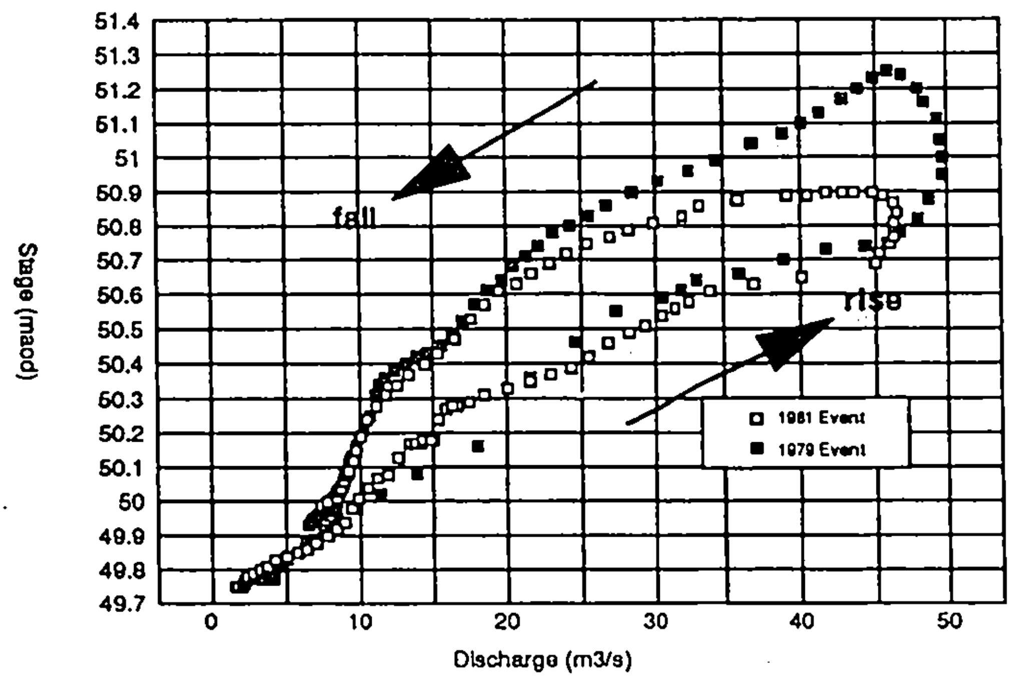
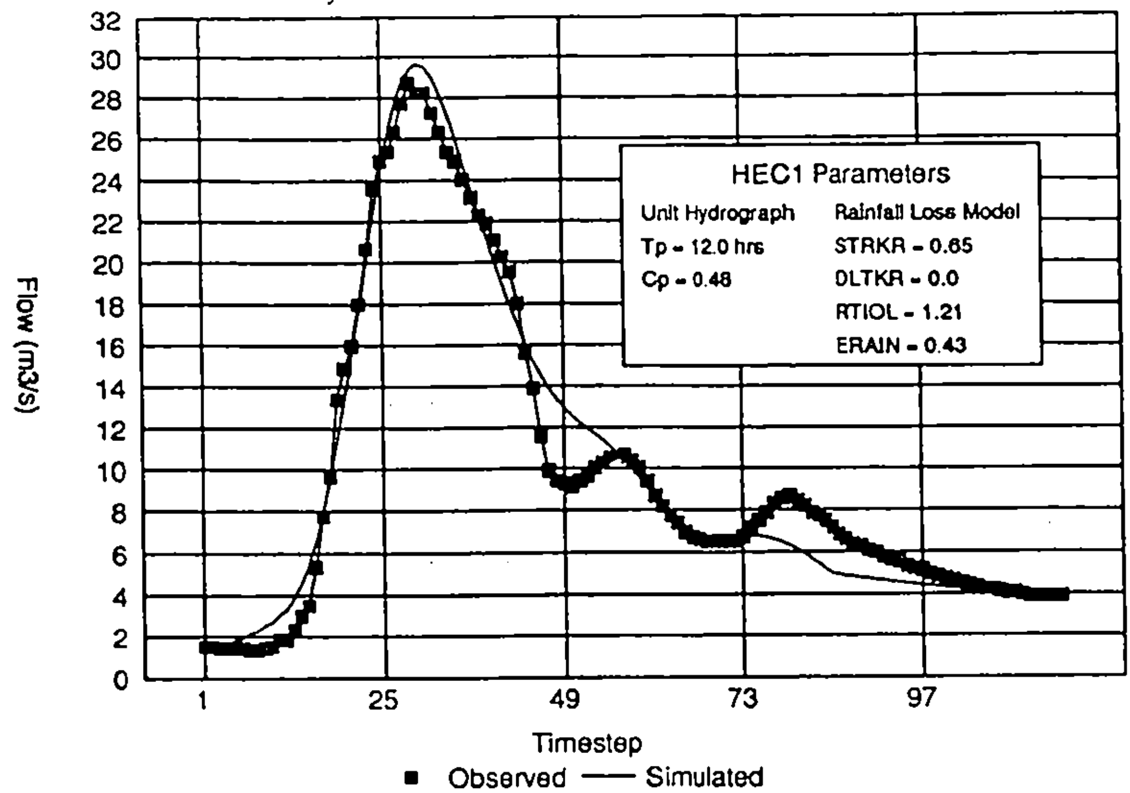


Figure 4.3.1 Looped rating curve for Belgrave gauging station (after MacDonald, 1992)

(a) *River Sence at Shearsby*



(b) *Upper Soar at Narborough*

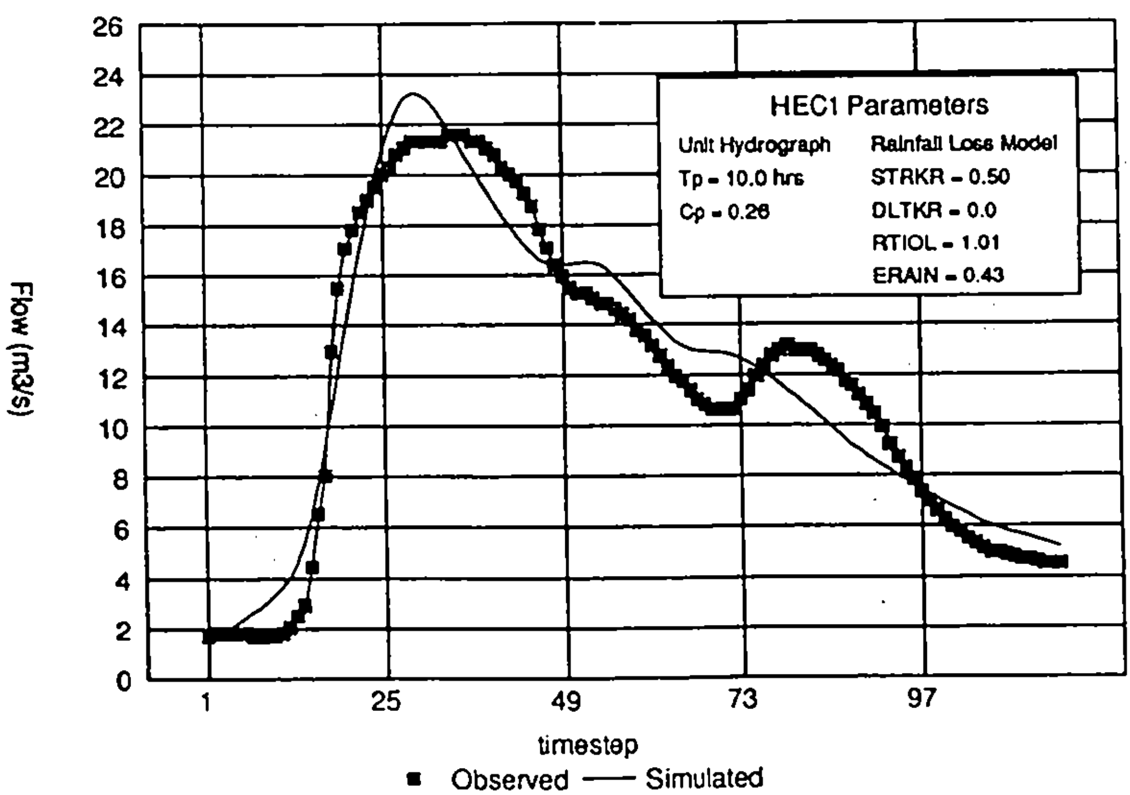


Figure 4.3.2 *Observed and HEC1 simulated hydrographs for the 8-13 March 1975 flood event (after MacDonald, 1992).*

The lower Soar valley has undergone extensive development in recent years with the obstruction of road bypasses and embankments for the Soar Valley improvement scheme. These new embankments, causeways and culverts will affect the movement of flood water along the valley, and their effects must be incorporated into any flow forecasting procedures for large floods.

For minor floods which just exceed the capacity of the flood defences the principal effect of the floodplain is to act as washland storage. This will cause attenuation of the peak flood discharge and increase the effective travel-time of the flood wave. At higher flows parts of the flood plain will act as floodway with significant volumes of water passing down the valley floor. The presence of raised walkways and culverts for flow under and over the roads in the neighbourhood of Zouch and Kegworth demonstrate that flow along the floodplain has occurred in the past.

In flood routing models based upon the convection diffusion equation (4.3.3), the flood wave speed c is given approximately by

$$c = \frac{1}{B}\frac{dQ}{dh}, \qquad (4.3.4)$$

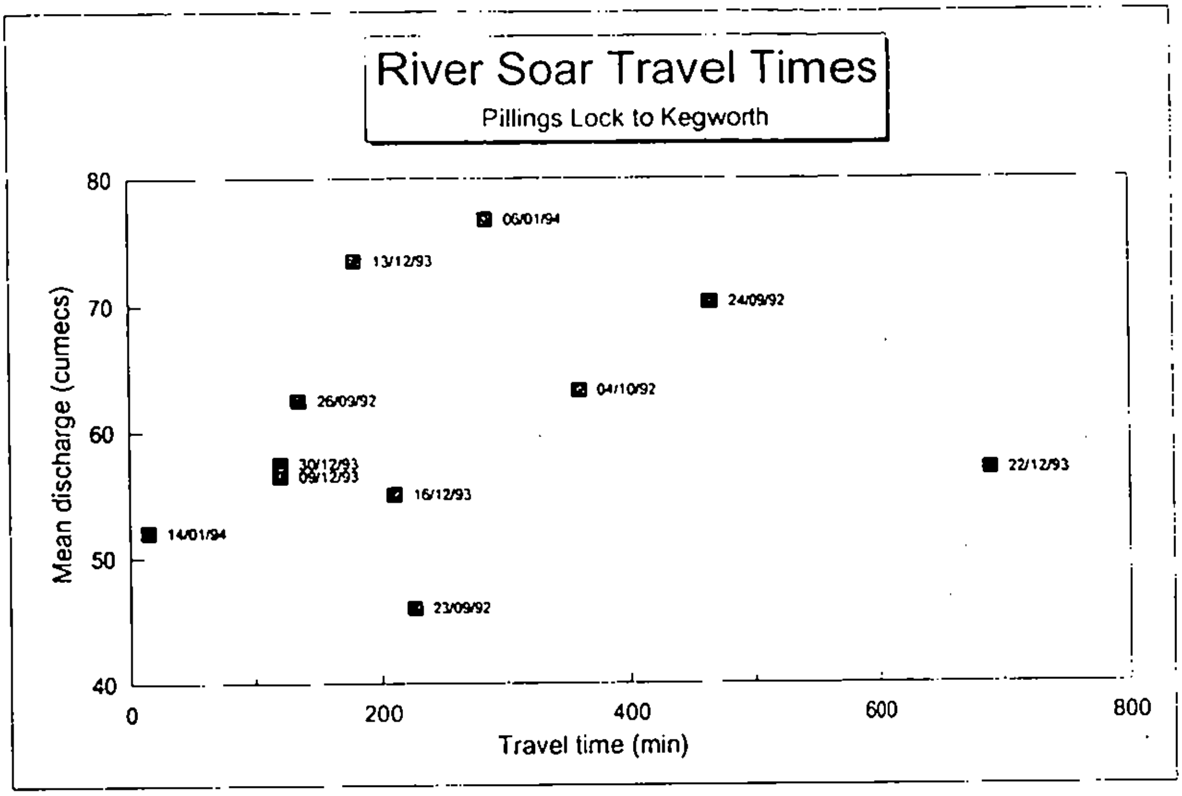
where B is the inundated width and dQ/dh represents the slope of the rating curve. Even for in bank flows on the Soar, the rating curve will not have a well defined slope due to the effects of the control structures.

The operation policy for the structures reflects the need to retain navigation depths for traffic on the Grand Union Canal and thus close to structures the flow is not well correlated to water level. The influence of any control structure affects the flow conditions over the backwater length of the river. This distance L is given approximately by

$$L = \frac{0.7D}{S_o} \qquad (4.3.5)$$

where D is the bankfull depth of the channel in metres and S_o is the channel bed slope.

Around Loughborough on the River Soar the backwater length is approximately 9.8 km (Samuels, 1989). Since the river was impounded for navigation it is unsurprising that in the lower Soar the distance between weirs and sluice complexes is less than the backwater length. This implies that the tail water at a structure is under the influence of the headwater of the next structure downstream. Although this situation is desirable for navigation, the effect on water velocity (and hence flood wave speed) is severe as is shown from the scatter of observed travel times and speeds between Pillings and Kegworth gauges shown in Figure 4.3.3. The values shown in these figures were extracted from the digital discharge record supplied for these sites by NRA. It should be noted that none of these flows exceed the mean annual flood for this reach of the Soar. These figures demonstrate that any method of flood routing which is based upon the assumption of a defined relationship between discharge and travel (or lag) time or wave speed will perform poorly on the lower reach of the River Soar. Clearly in this reach a sophisticated routing method, which recognizes the physics of the flow conditions, is needed. In such circumstances a full hydrodynamic model is indicated as it is capable of representing the effects of the control structures and flows over the flood plains.



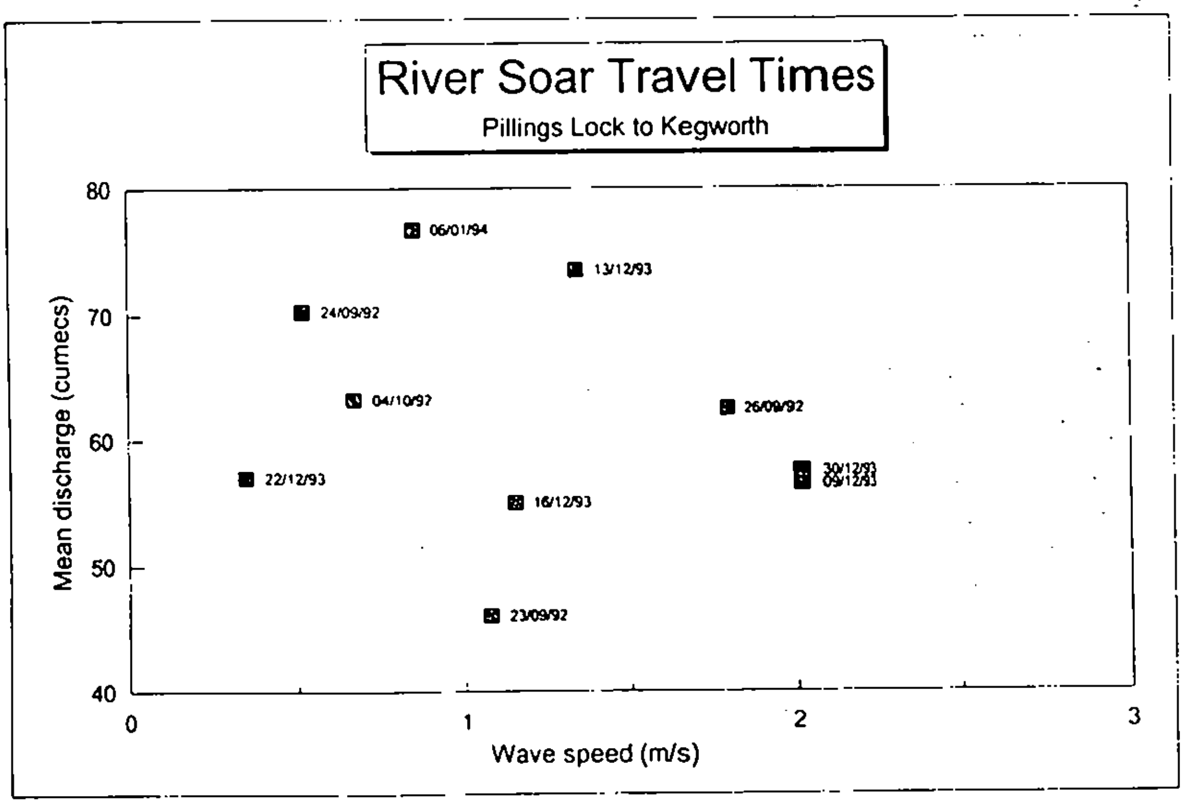


Figure 4.3.3 Observed travel times and speeds at Pillings and Kegworth

In the upper reaches of the River Soar, Sence and Wreake, where the water level is not controlled by a series of impounding structures, discharge routing procedures can be used to represent the propagation of flood flows where there is significant flood plain storage. Care will be needed in the use of these procedures where there are mineral works (active or disused) which may act as flood storage under high flow conditions. Some may have been over-filled in restoration and have the opposite effect. Any storage will act as flood washland attenuating the peak flood flows for a range of discharge.

In choosing the most appropriate river modelling procedure, the final consideration to make is the representation of the flood plain. The Soar valley flood plain is of three types:

- natural freely draining flood plain
- embanked flood plain which acts as washland
- embanked flood plain which acts as flood way.

In order to forecast flood conditions over the whole range of flows all of these types of flood plain flow must be incorporated in some way into the model. Modern full hydrodynamic models allow the floodplain to be represented by a network of flood cells which allow both storage and flow to be simulated. The water level gradients on the lower Soar and Wreake are sufficiently slack that the choice of flood cell size can be made on the spacing of important controls in the system and not on the need to resolve areas of steep slopes. A full hydrodynamic model will require the tail water condition from the outfall of the River Soar into the River Trent at Redhill. An error in the forecast level at this point from other parts of the NRA forecasting system will influence the level forecasts for the River Soar to about Kegworth, depending upon flow rate and condition of the control structures between Kegworth and Redhill.

From the above discussion of flow modelling for the river system, it will be clear that the most appropriate model algorithm will vary over the area. In the upper catchments rainfall-runoff techniques may be used. In some cases these may be used down to the confluence of a brook with the main river. An example, is the Black Brook at Loughborough where the Brook in its lower reaches has been excluded from the flood plain by an embanked two-stage channel. In the middle reaches where flood storage and flood way capacity are important but the flow is not constrained by embankments or channel structures, an approach based upon the convection diffusion flow routing equation (4.3.3), or a simplification of it, should be used. Finally where the river channel and flood plain have been affected by embankments, weirs, sluices etc, then a full hydrodynamic flow network model must be used. Thus the recommendations for the extent of the hydrodynamic model are as follows:

(a) The River Soar from the Trent confluence to upstream of any backwater influence from the Aylestone Causeway and Kingslock complex on the south west edge of Leicester. Using the channel bed and bank levels quoted in the River Soar Flood Capacity Appraisal (MacDonald, 1992), the backwater length may be estimated to be between 1 and 1.5 km. Therefore, the upstream limit of the hydrodynamic model of the River Soar should be 1.5 km upstream of the Aylestone Causeway (Grid Ref: SK 5635 0000). The final limit may be moved to accommodate the detailed siting of a gauging station and might be chosen to coincide with the proposed gauging stations on the Soar and Sence upstream of their confluence (see Section 3.4).

(b) The hydrodynamic model should extend to upstream of any backwater influence of Eye Kettleby Gate on the River Wreake. There is no channel survey data with which to estimate the backwater length. However, our judgement suggests that the model should extend into Melton Mowbray to Grid Ref SK 45050 18850.

The River Wreake, downstream of the Frisby Gate to Ratcliffe is uncomplicated by moveable gates and channel bifurcation. Therefore it may be possible to model this reach using a hydrological flow routing model. The advantage of this may be improved computational efficiency with little degradation of forecast accuracy. In adopting this approach consideration will need to be given to determining an accurate stage-discharge relationship to provide the downstream boundary condition for the Upper Wreake hydrodynamic model below the Frisby gate and its associated bypass channel (circa Grid Ref. SK 695 180).

c) The hydrodynamic model need not extend up the River Soar tributaries except where forecast points exist which are under backwater influences from the main river or are influenced by moveable gates. The one case of this is the Wreake which was addressed under b) above.

In establishing the full hydrodynamic model, a relatively coarse cross-section spacing can be used, more so than would be taken for engineering design purposes. The speed of operation of the forecasting model will decrease in proportion to the number of cells within the model and hence the need for short run times for forecasting requires the minimum number of cross-sections and flood cells to be used.

Existing River Models used in the Soar catchment

Since there is considerable effort involved in configuring and calibrating a hydrodynamic model to a given stretch of river and flood plain it is important to review work that has already been undertaken in the Soar catchment. Particularly important is the availability of survey data required to support model configuration, which can have an important bearing on the eventual cost of model implementation. No study has been undertaken in the Soar catchment that has involved the implementation of a hydrodynamic model in real-time. Indeed such applications are still a comparative rarity in the UK, notable exceptions being the Yorkshire RFFS modelling of the tidal Ouse and the Lincoln Washlands Operating System, both undertaken by members of the Wallingford Water consortium. The models reviewed below have all been undertaken as design studies, usually to assess the flood capacity of a river channel and to investigate whether additional flood protection works are required. Existence of a model constructed for design, along with its associated configuration data and calibrated parameters, can provide significant savings in implementation of a real-time hydrodynamic model. However, some simplification, use of a reduced number of cross-sections and possibly application over a more limited extent of river is generally advisable for real-time implementation of a hydrodynamic model.

The following provides a summary of relevant river model studies which have been completed or are ongoing in the Soar catchment.

(a) River Soar through Leicester Model.

Configured by Mott MacDonald (1992), under the River Soar Flood Capacity Appraisal, using the HYDRO model.

Calculation time-step: 1 hour

Upstream boundaries:	Station Road Bridge at Littlethorpe to south of Leicester (close to gauging station at Littlethorpe)
Downstream boundary:	Loughborough Road crossing downstream of Belgrave
Lateral inflows:	Sence at Blaby or South Wigstone Ungauged catchment around Leicester
Model configuration:	Looped network with floodplains
River control structures:	bridges (3), arched (7) and box (5) culverts, fixed weirs (12).
Survey data:	500 m cross sections (Land Development Services; 1986, 1990; MacDonald, 1991) supplemented by MacDonald topographic data survey where deficient for modelling.

The model covers an 18 km stretch of river through the city of Leicester and includes links with the Grand Union Canal. Downstream boundary is about halfway down the Soar, draining 440 km^2, about one-third of the total area of 1350 km^2 to the confluence with the Trent.

(b) River Trent Flood Plain Derwent to Colwick Model

Configured by Mott MacDonald (1992) using the HYDRO model.

Calculation time-step:	1 hour
Upstream boundaries:	Willington Bridge on the Trent Kegworth Bridge on the Soar Also Derwent, Erewash and Leen
Downstream boundary:	Colwick on the Trent (Holme Sluice)
Model configuration:	Looped river network including representation of flood storage areas as flood storage cells with stage-area/volume relationships (on the Soar) or extended cross-sections where there are no embankments.
River control structures:	On the Soar these are Ratcliffe Weirs, A648 Road Bridges over Ratcliffe Cut and the River Soar, and Ratcliffe Lock.
Survey data:	MacDonald (1992) floodplain topographic survey of lower Soar cross-section data at 200 and 500 m intervals. Four of the flood storage cells on the Soar are not covered by aerial survey: flood extent cannot be delineated due to lack of contour data.

The model was developed to investigate Nottingham flood defence levels and includes 4 km of the River Soar from Kegworth Bridge to its confluence with the Trent, which incorporates 6 flood storage cells. Holme Sluice at the downstream boundary operates automatically with a 3 minute reaction time: use of a 1 hour time-step forces approximation and overcompensation of level adjustment by the model.

(c) Syston Northern and Rearsby Bypass - Hydraulic Model of Wreake and Queniborough Brook Crossings

Physical model configured by HR Wallingford (1991,1992) to investigate design of 2 km long Syston bypass (plus Rearsby bypass) 10 km north-east of Leicester, and effect on flooding along the Wreake, Goddesby Brook and Queniborough Brook and associated floodplains.

Survey data at 100 m intervals (1988). Exposed electromagnetic gauging station on the Wreake at Syston Mills can underestimate flow by 25%. Model extent included 4 km of Wreake, 2.5 km of Queniborough Brook and about 1 km of Gaddenby Brook.

(d) Leicester to Trent Confluence Soar Model

Under construction by Halcrow based on ONDA. The following details are approximate due to lack of further information.

Upstream boundaries:	Soar at Leicester
	Wreake at Melton Mowbray
	Rothley Brook at Thornton Reservoir
Downstream boundary:	Trent Confluence

Two earlier models of the Soar - between Redhill and Leicester, undertaken by HR Wallingford in 1979 to 1981, using a flow routing model and from Zouch to Quorn, carried out by the NRA in 1989 using Flucomp - are not reviewed. These models are considered out-of-date and of little relevance to the current study.

4.4 RAINFALL-RUNOFF MODELS

There are many rainfall-runoff models available to represent the catchment flow response to rainfall. They range in complexity from physics-based models based on the Saint-Venant, Richards and Boussinesq equations of water movement through catchments, to simpler conceptual water storage descriptions and so-called black box or transfer function representations. It is generally acknowledged that the more complex physics-based representations are more appropriate to design applications, particularly impact assessments such as land use change, and that their greater complexity does not necessarily provide greater precision of forecasts in situations where flow data exists for model calibration and real-time updating. An analysis of the many brand-name conceptual models reveals that they are largely alternative configurations of a smaller set of more basic components which are common across a range of model types. Some components can be interpreted as deriving from simple transfer function models which leads to the conclusion that a transfer function model can be just one component within a more complete model conceptualisation of a catchment. They also can be interpreted conceptually in terms of storage routing, either through river channels or through the ground. This commonality of model component, and links between transfer function models and storage routing, has been exploited in the development of IH's PDM (Probability Distributed Moisture) model. This is the recommended model for application to the Soar in situations where a catchment rainfall-runoff model is required. It is described in outline below.

The Probability Distributed Model or PDM is a fairly general conceptual rainfall-runoff model which transforms rainfall and evaporation data to flow at the catchment outlet. Figure 4.4.1 illustrates the general form of the model. Runoff production at a point in the catchment is controlled by the absorption capacity of the soil to take up water: this can be conceptualised as a simple store with a given storage capacity. By considering that different points in a catchment have differing storage capacities and that the spatial variation of capacity can be described by a probability distribution, it is possible to formulate a simple runoff production model which integrates the point runoffs to yield the catchment runoff.

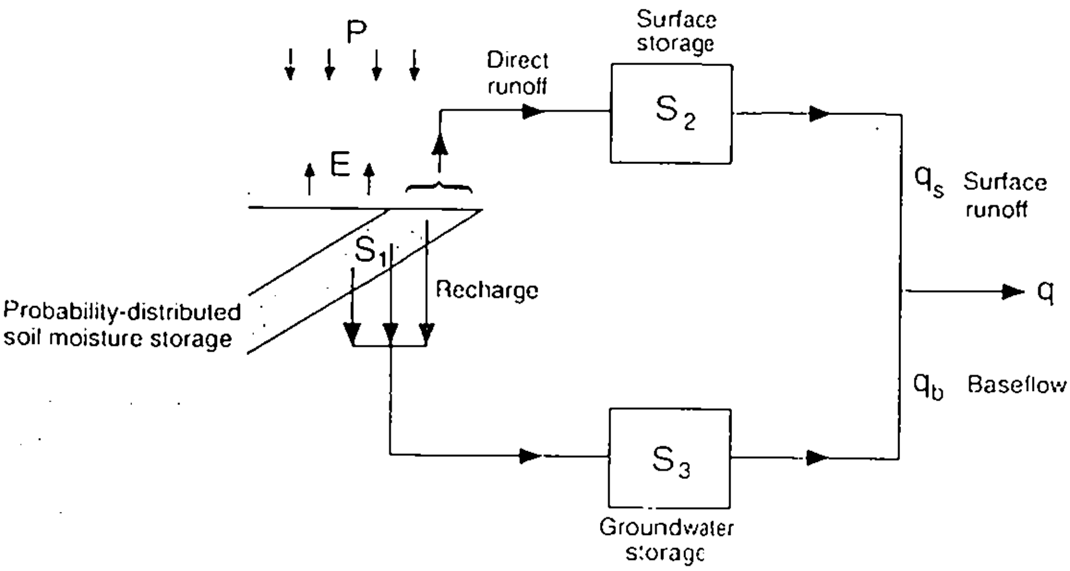


Figure 4.4.1 The PDM rainfall-runoff model

The probability-distributed store model is used to partition rainfall into direct runoff, groundwater recharge and soil moisture storage. Direct runoff is routed through a "fast response system", representing channel and other fast translation flow paths. Groundwater recharge from soil water drainage is routed through a "slow response system" representing groundwater and other slow flow paths. Both routing systems can be defined by a variety of nonlinear storage reservoirs or by a cascade of two linear reservoirs (expressed as an equivalent second order transfer function model constrained to preserve continuity). A variety of spatial distributions of store depth are available to define the probability-distributed store model. Alternatively the store model can be replaced by a simple proportional splitting rule for partitioning rainfall to follow surface and subsurface translation paths. A constant background flow can be included to represent compensation releases from reservoirs, or constant abstractions if negative.

The model is specifically tailored for real-time application. Facilities exist to correct the model forecasts in real-time, either by modifying the water contents of the conceptual stores or by augmenting the forecasts with an error predictor: these techniques are discussed later. Further details of the model structure deployed are contained in Moore (1985, 1986) and Institute of Hydrology (1992).

The Terms of Reference to this study indicated that consideration of snowmelt within a catchment rainfall-runoff model was not required. This was on account of an ongoing R&D investigation on this topic by IH. However, it is clear that since historical floods have had a snowmelt component that some reference to this problem should be made when dealing with catchment rainfall-runoff models. As an off-the-shelf solution to this problem it is proposed to use the PACK model available within IH's Flow Forecasting System, pending the outcome of the R&D study. This model was originally formulated under contract to the Severn Trent Water Authority (now the NRA Severn Trent Region) with additional support from the Ministry of Agriculture Fisheries and Food (Harding and Moore, 1988). The snowmelt process is represented in simplified terms using a snow store and a melt store to represent the snow pack storage. Melting of the snow store is controlled by a simple temperature index equation; this could be readily extended to incorporate turbulent heat exchange through the addition of a wind velocity term if required. The resulting melt enters the melt store where it is released slowly from its base. A second higher orifice allows release of water from the pack (snow and melt water) at a higher rate. The height of the orifice varies with the total water equivalent of the pack. This serves to represent the rapid break-up of the pack as a critical liquid water content is reached. A schematic of the structure of the PACK model is shown in Figure 4.4.2. An additional component is included to allow for incomplete spatial coverage of snow over a catchment for shallower, older packs. This employs an areal depletion curve to calculate the proportion of the catchment covered by snow, allowing some rain to fall on snow-free ground and effectively enter the rainfall-runoff model directly.

Two forms of the snowmelt algorithm exist within the proposed Forecasting System. The first is used in "point form" at snow survey sites and excludes the areal depletion curve. This is used to obtain errors between the model snowpack water equivalent and the surveyed amount. These errors are transferred to the "catchment form" of the model to adjust catchment snowpack water equivalents.

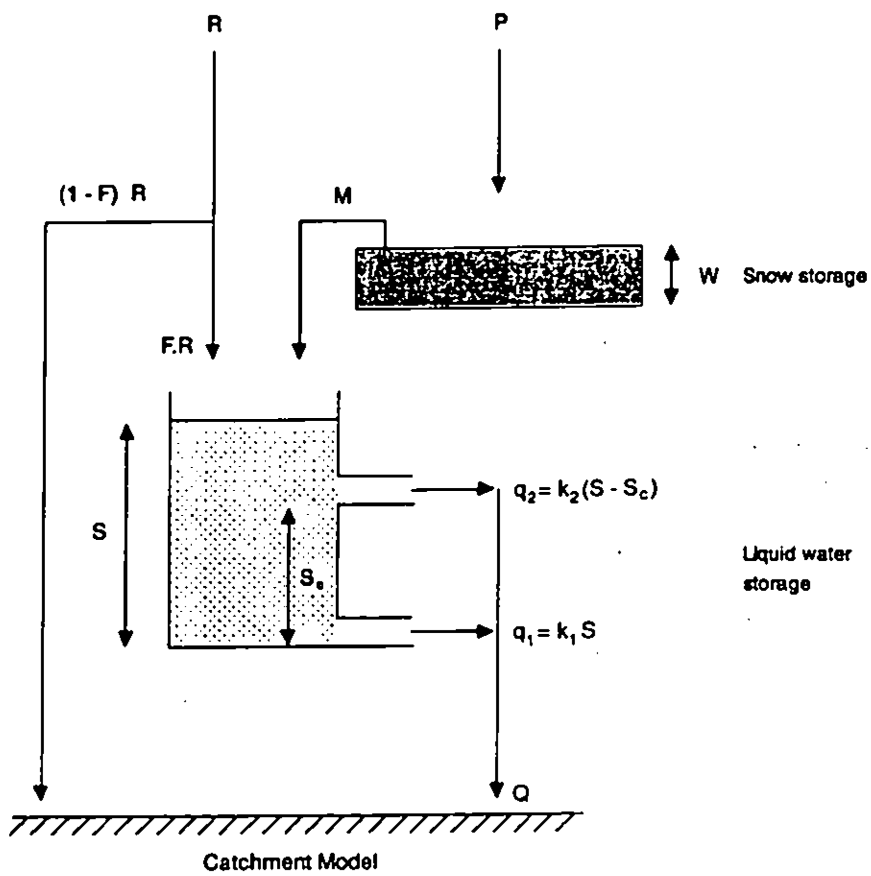


Figure 4.4.2 The PACK snowmelt model

4.5 HYDROLOGICAL CHANNEL FLOW ROUTING MODELS

Section 4.3 focussed on the requirement for a hydrodynamic representation of the translation of water through river channels in the Soar catchment. A simpler formulation based on the convection diffusion equation, or a simpler representation of it, was suggested for river reaches not significantly affected by backwater. A formulation based on the kinematic wave equation which, by virtue of its discrete formulation, accommodates both advection and diffusion effects on the flood wave is recommended for use in such cases. This provides an approximation to the convection diffusion equation, whilst being considerably faster to execute than the normal solutions used. Trials on the River Dee under the full range of flow conditions experienced suggests that the extended formulation, as well as being faster to run, can be at least as accurate due in part to the efficient model calibration possible with this simplified form of model. The formulation, called KW, is described in outline below.

The KW model is a generalised form of kinematic wave model which makes allowance for wave speeds to vary with discharge magnitude. In addition, storage functions are provided to represent flow into washlands to complement the modelling of in-bank flows. The basic form of the model is presented in Moore and Jones (1978) and Jones and Moore (1980). Water movement down a river channel is approximated by the kinematic wave equation with lateral inflow

$$\frac{\partial Q}{\partial t} + c\frac{\partial Q}{\partial x} = cq \qquad (4.5.1)$$

where Q is channel flow, q is the lateral inflow per unit length of the reach and c is the wave speed. This is expressed in finite difference form as

$$Q_t^k = (1-\theta)\, Q_{t-1}^k + \theta \left(Q_{t-1}^{k-1} + q_{t-1}^k\right) \qquad (4.5.2)$$

where Q_t^k is the flow at the k th node at time t and q_t^k is the lateral inflow into the k th section at time t-1. Node k is the downstream node of section k. The dimensionless wave speed $\theta = c\Delta t/\Delta x$, with Δt and Δx the time and space intervals of the discretisation. A time varying wave speed is allowed, changing as a function of the observed flow at a particular node K. The choice of functions available include a piecewise linear function over 3 or 4 segments as well as cubic and exponential parametric functions. An auxiliary threshold storage function can be applied, either at selected model nodes to represent overflow into washlands, or to observed lateral inflows to compensate for errors in the rating relationship, especially for out-of-bank flows. A number of forms of parameterised threshold functions are available.

The use of a variety of parametric functions to define the model form is particularly useful for real-time application to large, complex river basins where the use of survey data would be expensive in time or survey data may not be available. However, a tabular form of wave speed-discharge relationship can be used if survey data are available to infer the relation from hydraulic principles (Institute of Hydrology, 1989) and if this method is preferred. Calibration of the parametric model functions is accomplished using the Model Calibration Facilities discussed later in Section 4.9.

4.6 HYDRODYNAMIC MODELS

In Section 4.3 the need was identified for a hydrodynamic model to form part of the overall forecasting system for the River Soar and its tributaries. This section considers the options available to the NRA. An R&D project in progress on "Benchmarking for River Models" (Project Number 508) has identified several full hydrodynamic models which are in use or potentially available for use by the NRA (See the Interim Report submitted in June 1994). Rather than consider all these models here, attention will be restricted to:

- hydrodynamic models developed for real-time forecasting for use in the UK

- models in use by NRA-ST in the Soar and Trent catchments for flood defence purposes.

In the first of these categories are:

- EMBER developed by HR Wallingford and supplied to Severn Trent Water Authority for flow forecasting in the tidal reaches of the River Severn and Trent (1981 to 1985).

- LORIS developed by HR Wallingford and supplied to NRA Anglian Region under a Wallingford Water project for real-time advice on the operation of the Lincoln Washland gates.

- RFFS-HYDRO, originally based on the US National Weather Service DWOPER code but extensively revised and developed for real-time use by the Institute of Hydrology. It has been implemented on the tidal River Ouse as part of the Yorkshire River Flow Forecasting System (RFFS) and on the tidal Schenzhen River in Hong Kong, both real-time applications.

The EMBER model does not have the full functionality needed for this project (eg it lacks a full range of structures) and has been superseded by later software at HR Wallingford. Hence its use is not considered further for the River Soar.

The LORIS model forms the core of the HR Wallingford SALMON-F flood modelling package. It has the full functionality needed for the application to the River Soar. However, the software supplied for the Lincoln Washlands Operating System is a site specific adaptation of both the HR flood modelling and IH flow forecasting technologies. Application to the River Soar should start with the standard generic software now in use within the organisations.

RFFS-HYDRO has the important advantage that it is already tailored for real-time use and integrated as a model algorithm within IH's generic RFFS forecasting system (Section 5.2). However, flood way flows behind embanked flood plains cannot be represented explicitly. Also, there are no user-friendly procedures to aid in setting up and editing the data files required to represent the channels, flood plains, embankments and control structures in a new area of application. Whilst a modular program structure allows ready incorporation of control rules, such as those used for automatic gate operation (Section 4.6), only a limited set of control structure types are pre-programmed.

The hydraulic models currently in use in the Rivers Soar and Trent by NRA-ST are:

- HYDRO from Mott MacDonald and Partners
- ONDA from Sir William Halcrow and Partners.

Of these two models ONDA has the advantage that it is currently being applied to the target reach of the River Soar under a separate contract from NRA-ST to Halcrow. The HYDRO model has been applied for design to the Tidal Trent as well as in the flood capacity appraisal of the Soar through Leicester. Neither of these software packages has been linked to real-time flood forecasting algorithms in the UK to our knowledge and both would require substantial work to link to RFFS. Furthermore, it is our opinion that of these two models, the hydraulic description offered by ONDA is to be preferred.

Before stating two alternative approaches a further issue to consider is the current and planned development of the software available. First of all, IH are committed to maintaining and enhancing the technology in RFFS for all flow forecasting applications the Institute undertakes. Secondly HR Wallingford and Sir William Halcrow and Partners have recently entered into a joint venture arrangement for 1-D river modelling software to develop and promote a new product, ISIS. ISIS will replace ONDA, STYX, SALMON-F AND SALMON-Q the flow and water quality models from the two organisations in the Joint Venture. ISIS takes the best technology from these predecessor packages together with a state-of-the-art interface. We understand that all of the NRA regions are considering purchasing ISIS to upgrade their software from HR and Halcrow. Thus a further possibility to be considered is merging ISIS and RFFS. A brochure for ISIS is included as Appendix 2.

The two alternatives from the above which should be considered are:

(1) Enhancement of RFFS-HYDRO to include the necessary hydraulic functionality.

(2) Merging ISIS into RFFS.

The advantage for the first option is that RFFS-HYDRO is already integrated into the RFFS framework as a model algorithm. The main disadvantage is the need to code and test hydrodynamic enhancements. The advantages for the second option are that ISIS will read directly information from ONDA cutting down effort on the model building, the hydrodynamics have all the functionality needed and its modelling technology (in the guise of LORIS) has worked for real-time calculation in similar circumstances. The disadvantage of the option is that some effort will be required in the software integration. Both options would require fresh discretisation and calibration for the Soar system for real-time use, although this is likely to be easier for ISIS because of the availability of ONDA design configurations and calibrations. ISIS will be available to support design applications in December 1994.

Our preference and recommendation is for the second option, the integration of ISIS and RFFS, particularly as both packages have long-term development plans within the organisations involved.

4.7 REPRESENTATION OF STRUCTURES AND OPERATING RULES

The Rivers Soar, Wreake and their tributaries contain a large number of hydraulic structures, some modern, some old. In all cases the representation of these structures in the hydrodynamic model is through established head-discharge relationships (or estimated ones) for the type of structure. Inevitably there will be some discharge coefficients which will enable the performance of the model to be tuned to reproduce the hydraulic conditions at the structures. The most likely areas of difficulty are:

- labyrinth weirs where the discharge coefficient (or effective length) changes with head over the structure
- automatic operation policies for sluice (radial) gates,
- flows bypassing structures over the flood plain,
- flows through disused sluices, slackers etc
- leakage through lock gates,
- afflux at old bridges, and
- manually operated gates not under the control of the NRA.

HR Wallingford has developed a novel algorithm for tracking the movement of automatic gates. This was implemented first of all for Earith sluice over The Great Ouse Drainage System for Anglia Region of the NRA. The method is also available in the ISIS model. The crucial part of the control algorithm is that it decouples the polling time interval for the structure from the hydrodynamic model time step. Gate movements are assumed to be quantised (that is the gate moves a predetermined amount either opening or closing when needed). The automatic gates on the Soar appear to poll more frequently than once a minute and clearly this time interval is inappropriate to building forecasts of water level over many hours (or days). Thus several gate movements are possible in each time step. Thus the single control band implemented for the sluice gate on site is replaced by multiple bands requiring zero, one, two, three etc gate movements in a model time step. The actual separation of the bands is determined during the model calibration. A side effect of this implementation of the automatic control is that he model predictions are insensitive to uncertainties on the discharge coefficients for the structure until the gate is fully withdrawn from the flow. The discharge coefficient for a partly open gate could be calibrated from knowing the gate opening but, unless the exact gate opening is of crucial operational importance, this exercise is not necessary. However, it will be important to represent accurately the head-discharge relationship when the gates are fully withdrawn from the flow. Finally, calibration of the gate coefficients may be important if the flow forecasting model is started from a telemetered state where the actual gate openings at the start of the forecast period are supplied by the telemetry.

For forecasting levels at structures with manual gates, the standard operating schedule or policy adopted by the gatekeeper must be specified. This will then be implemented within the framework of the automatic sluice code.

A summary of the mode of operation of the three automatic gates operating in the Soar catchment follows. Suffice it to say that the automatic gate tracking algorithm outlined above will accommodate the types of operation required.

Eye Kettleby Gate Operation

The gate at Eye Kettleby on the River Wreake (Grid Ref: SK 7380 1830) is an automatic sluice gate responding to an upstream water level sensor, located near the railway bridge, so as to maintain a maximum upstream level within the range 68.77 m to 68.87 m. (level sensor scale range 68.50 to 69.75 m). Under normal operating conditions the gate is closed (down) maintaining a level of about 68.75 m. During a rising flood the gate is raised, at a trigger level of 68.87 m and after a delay of at least 30 seconds by 40 cm (increment scale range 0 to 60 cm). The delay setting is adjustable between 0 and 1 minute. Water level is checked every 10 minutes and if below the lower trigger level of 68.77 m for at least 30 seconds the gate is lowered. If between the trigger levels, no action is taken for 10 minutes when the level is checked again. If the upper trigger level is exceeded for the pre-set delay period the gate is raised a further 40 cm; this is repeated until the gate is fully open (1.5 m full gate travel; gate gauge range 66.5 to 69.00 m). On a falling flood the gate is lowered in 20 cm increments, subject to the preset delay period, until fully closed (at a gate gauge level of 66.87 m). Both the upstream water level sensor and the underside of the gate level are on telemetry. High and low level alarms are invoked when the levels 69.40 and 68.40 m respectively are transgressed.

Frisby Gate Operation

The Frisby gate is on the River Wreake at grid reference SK 6955 1805. Under normal flow conditions the gate operates in response to downstream river level. Following a preset delay of 0-10 seconds the gate rises initially up to a crest level of 61.30 m over a period of 7-8 minutes (0 to 15 minutes adjustable range), when water spills over the gate and the side weir into the lake (except at low flows). During this time water continues flowing through the bypass (old navigation) channel. The lake starts to fill at a discharge of 24 $m^3 s^{-1}$.

At a gate level of 61.30 m the downstream water level is checked again, gate movement being such as to maintain the downstream level between 61.50 and 61.60 m subject to the usual preset delay before the gate is moved. If the level falls below 61.50 m a timer (adjustable 0 to 5 minutes) is used to maintain the level for a continuous period. The gate moves in increments of up to about 8 cm. There is a choice of two timer delay settings: a scale of 1 to 30 minutes is used for a slow water level rise and 0.5 to 10 minutes for a fast rise.

When the lake level reaches 63.20 m control transfers to the upstream water level sensor. The gate is lowered and then raised in an attempt to maintain the upstream water level in the range 63.20 to 63.15 m. The sequence is repeated until the flood subsides, the downstream water level falls below 61.50 m when control reverts to the downstream water level sensor. The maximum range of the gate is 60.30 m (fully down) to 63.30 m (fully up).

An additional level sensor further upstream exists but is not used for control.

A summary of the water levels associated with the installation of gate and weirs is given in Table 4.7.1 and the sensor trigger levels are given in Table 4.7.2. The gate can be manually operated to higher levels to fill the lake, providing additional protection to vulnerable properties. The lake was overfilled during the event of 24-26 February 1994. In practice the time delay settings appear to be fixed at 30 minutes, irrespective of the rate of rise of water

Table 4.7.1 Frisby gate: levels of weir, spillway and embankment crests and of lake full and gate.

Feature	Crest level, m
Side weir (upstream of gate)	62.80
River weir	62.125
Lake weir	61.42
Lake full	63.20
Bypass channel weir	62.10
Primary Emergency Spillway	63.51
Secondary Emergency Spillway	63.60
Embankment	63.80
Gate: full down	60.96
Gate: full up	63.28

Table 4.7.2 Frisby gate: sensor trigger levels.

Sensor Trigger	Trigger level, m
Downstream level: gate trigger	61.60
Lake level: gate trigger	63.20
Lake level: lake full	63.51
Further upstream level: river weir (not used for control)	62.12

level: this problem is being addressed.

Zouch Radial Gate

This gate on the River Soar is located about 4 miles north-west of Loughborough town centre (Grid ref: SK 5095 2338). It is a radial underflow counter-balanced gate 10 metres wide and nominal height 3.7 m which automatically moves in response to changing upstream water levels so as to maintain a fixed level upstream to within 4 to 6 inches. The sluice gate was constructed to supplement the existing side weirs and sluices to provide a 1 in 10 year standard of protection. The gate opens at around 34.82 m and is equipped with three sensors: upstream river level (datum 34 m AOD), downstream river level (32 m AOD) and the angle of gate opening in degrees. It has operated since 1993.

River levels are relatively critical upstream of the gate with some riverside chalet gardens submerged when the gate starts to open at around 34.82 m AOD. The High Water Alarm, triggered above 35 m AOD, is associated with more gardens being flooded. The Low Water Alarm, triggered below 34.45 m AOD is associated with only 50 mm depth of water over the main side weir. The radial gate lifts after flow at Pillings gauging station exceeds 26 m^3/s; forecasting of this flow is made to allow time to man the gate for checking and adjustment as the critical water level of 34.82 m is exceeded. Manning at the time of gate closure is also required. Remote monitoring of this gate is also possible, although their have been problems with this in the past.

There has also been revisions of the setting of the outlet penstock (V4) from 50% open to 36% open to anticipate flooding of riverside gardens prior to the gate being opened at its trigger level.

4.8 REAL-TIME UPDATING TECHNIQUES

4.8.1 Introduction

Two forms of updating of model forecasts to incorporate information from the most recently telemetered values of river level and flow are available. The first is state correction which has been briefly discussed in the context of the PDM rainfall-runoff model; at present this form of updating is only available for this model. It is proposed to use an ARMA (AutoRegressive Moving Average) model as the basis of updating for hydrological and hydrodynamic flow routing models. This technique exploits the dependence seen in model errors, with runs of overprediction and underprediction being common. The ARMA model structure characterises this dependence through a weighted combination of past model simulation errors and one-step ahead updated forecast errors. The result is a prediction of the future errors which are added to the model simulation forecasts to form updated forecasts for different lead-times. Two variants on the normal form of ARMA error predictor are available. The first is a logarithmic form of ARMA model, in which proportional errors are treated rather than the normal additive ones. The second is a multiple ARMA model which would be applied to the error series from the hydrodynamic models for the several level recording sites along tidal rivers in the Anglian Region.

4.8.2 State updating

The term "state" is used to describe a variable of a model which mediates between inputs to the model and the model output (Szollosi-Nagy, 1976). In the case of the PDM rainfall-runoff model the main input is rainfall and basin flow is the model output. Typical state variables are the water contents of the soil, surface (channel) and groundwater stores. The flow rates out of the conceptual stores can also be regarded as state variables: examples are q_s, the flow out of the surface storage, and q_b, the flow out of the groundwater storage.

When an error, $\epsilon = Q-q = Q-(q_s+q_b)$, occurs between the model prediction, q, and the observed value of basin runoff, Q, it would seem sensible to "attribute the blame" to mis-specification of the state variables and attempt to "correct" the state values to achieve concordance between observed and model predicted flow. Mis-specification may, for example, have arisen through errors in rainfall measurement which, as a result of the model water accounting procedure, are manifested through the values of the store water contents, or equivalently the flow rates out of the stores. A formal approach to "state correction" is provided by the Kalman filter algorithm (Jazwinski, 1970; Gelb, 1974; Moore and Weiss, 1980). This provides an optimal adjustment scheme for incorporating observations, through a set of linear operations, for linear dynamic systems subject to random variations which may not necessarily be Gaussian in form. For nonlinear dynamic models, such as the PDM model, an extended form of Kalman filter based on a linearisation approximation is required which is no longer optimal in the adjustment it provides. The implication of this is that simpler, intuitive adjustment schemes can be devised which potentially provide better adjustments than the more complex and formal extensions of the Kalman filter which accommodate nonlinear dynamics through approximations. We will call such schemes which make physically sensible adjustments "empirical state adjustment schemes".

A simple example is the apportioning of the error, ϵ, between the surface and groundwater flow routing components of the PDM rainfall-runoff model in proportion to their contribution to the total flow. Mathematically this may be expressed as

$$q_b^* = q_b + \alpha g_b \epsilon \quad (4.8.1a)$$

$$q_s^* = q_s + (1-\alpha) g_s \epsilon \quad (4.8.1b)$$

where

$$\alpha = q_b/(q_s + q_b) \quad (4.8.2)$$

and the superscript * indicates the value after adjustment. The "gain" coefficients, g_b and g_s, when equal to unity yield the result that $q_b^* + q_s^*$ equals the observed flow, Q, thus achieving exact correction of the model flow to equal the observed value. Values of the coefficients other than unity allow for different adjustments to be made, and g_b and g_s can be regarded as model parameters whose values are established through optimisation to achieve the "best" fit between state-adjusted forecasts and observed flows.

A generalisation of the above is to define α to be

$$\alpha = \frac{q_b}{\beta_1 q_s + \beta_2 q_b} \quad (4.8.3)$$

and to choose the incidental parameters β_1 and β_2 to weight the apportionment towards or away from one of the flow components; in practice β_1 and β_2 are assigned values of 10 and 1.1 to apportion more of the error adjustment to the surface store. Note that the adjustment is carried out at every time step and the time subscripts have been omitted for notational simplicity. The scheme with α defined by (4.8.2) is referred to as the proportional adjustment scheme and that defined by (4.8.3) is the super-proportional adjustment scheme. Replacing α and $(1-\alpha)$ in (4.8.1) by unity yields the simplest non-proportional adjustment scheme.

An extension of the empirical state updating method has been recently developed at IH apopropriate for making adjustments to the storage contents of routing reaches in a hydrological channel flow routing model.

4.8.3 Error prediction

State correction techniques have been developed based on adjustment of the water content of conceptual storage elements in the belief that the main cause of the discrepancy between observed and modelled runoff will arise from errors in estimating basin average rainfall, which in turn accumulate as errors in water storage content. Rather than attribute the cause directly and devise empirical adjustment procedures we can analyse the structure of the errors and develop predictors of future errors based on this structure which can then be used to obtain improved flow forecasts. A feature of errors from a conceptual rainfall-runoff model is that there is a tendency for errors to persist so that sequences of positive errors (underestimation) or negative errors (overestimation) are common. This dependence structure in the error sequence may be exploited by developing error predictors which incorporate this structure and allow future errors to be predicted. Error prediction is now a well established technique for forecast updating in real-time (Box and Jenkins, 1970; Moore, 1982). Predictions of the error are added to the deterministic model prediction to obtain the updated model forecast of flows. In contrast to the state correction scheme, which internally adjusts values within the model, the error prediction scheme is wholly external to the deterministic model operation. The importance of this is that error prediction may be used in combination with any model.

The Transfer Function (TFN) Modelling Package, referred to later in Section 4.9.2, provides tools to identify the form of error predictor and to estimate its parameter values. Model Algorithm forms of ARMA error predictor are available within the RFFS for real-time implementation of the method, both for single error series and for multiple ones which arise when applying the technique to errors from a hydrodynamic river model. Model Algorithms are discussed further in Section 5.2.

4.9 MODEL CALIBRATION

4.9.1 Calibration Shell Models

A comprehensive range of facilities are available to calibrate the above models using observed data. Calibration facilities for the PDM rainfall-runoff model, the KW channel flow routing model and the PACK snowmelt model share a common Calibration Shell Program. This shell essentially provides a framework within which any time series model may be optimised (ie. parameters of the model are estimated to minimise a prescribed objective function which makes the modelled time series approximate the observed) and model performance assessed. The shell can also be used to incorporate new models to allow model development to proceed in an efficient manner. A modified form of the Nelder and Mead simplex, or polytope, method is used for optimisation (Nelder and Mead, 1965; Gill, Murray and Wright, 1981). The program may be used in the normal optimisation mode, or to generate plots and statistics to assess the performance of a given model or to generate a response surface plot showing how a pair of parameters affects the value of the objective function. The latter is used to reveal any interdependence between model parameters which may degrade the search for an optimal parameter set. An example of a plot used for performance assessment is shown in Figure 4.9.1.

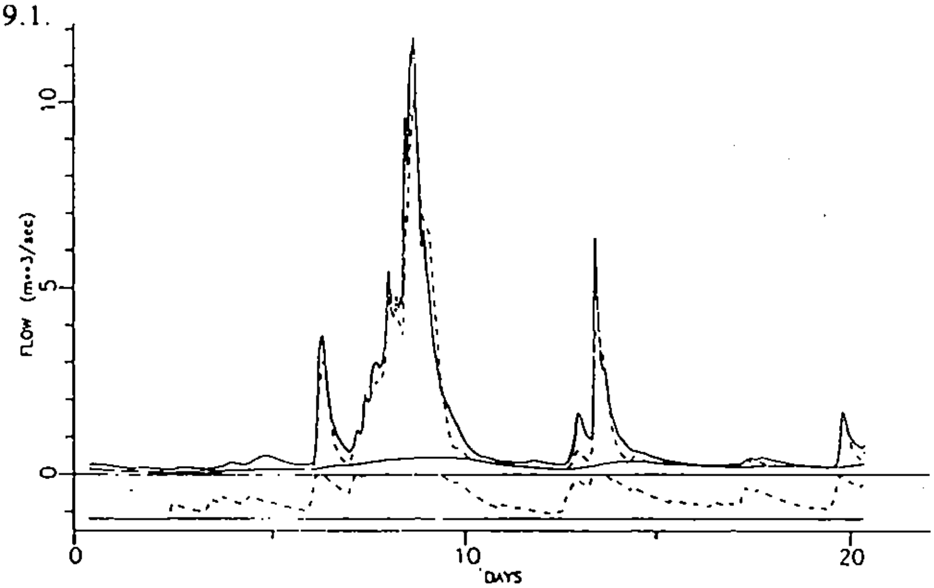


Figure 4.9.1 Calibration result for the PDM rainfall-runoff model (Upper dashed line: total forecast flow; Lower continuous line : baseflow forecast; Lower dashed line: soil moisture deficit)

4.9.2 Transfer Function Noise (TFN) Modelling System

A separate Transfer Function Noise (TFN) Modelling System is provided to support general exploratory data analysis prior to formal modelling. It is also used to identify the "pure time delay" between rainfall and the first significant response at a flow gauging station needed as a parameter within the PDM rainfall-runoff model. The TFN Modelling System incorporates modules for correlation function analysis and fitting of transfer function and ARMA models (Box and Jenkins, 1970). The latter are used to construct error predictors for the KW channel flow routing model forecasts to achieve improved performance in real-time, through the incorporation of the most recently telemetered values of flow.

4.9.3 Hydrodynamic Model Calibration

The Salmon-F hydrodynamic model calibration software is available as a separate system from HR Wallingford Ltd, and is already in use in the Severn-Trent Region to support design studies. A new development to unify Salmon-F and Halcrow's ONDA model under the name of ISIS has previously been discussed in Section 4.3.

Whatever hydrodynamic model is applied to the River Soar several factors will complicate model building and calibration. These factors include:

- variation of effective roughness with velocity, depth and season
- discharge coefficients for the hydraulic structures particularly the site weirs, labyrinth weirs and locks
- the unevenness of the natural river banks
- the flows through culverts in causeways across the flood plain
- the afflux at old road bridges, particularly where the approach conditions are irregular such as at Zouch and Kegworth.

The fact that these problems are due to be addressed by Halcrow in their current commission from the NRA for the lower Soar makes particularly attractive the recommended alternative for the forecasting model development. The discretisation adopted for flood forecasting however may be coarser than that used for the current contract by Halcrow. The minimum topographic description compatible with the forecast accuracy should be developed in the model building phase of the implementation.

4.10 RAINFALL FORECASTS

In order to extend the lead time of forecasts it will be necessary to supply the forecasting system with rainfall forecasts. Weather Centres can usually be contracted to supply prescribed quantitative precipitation forecasts for catchments such as the Soar. These might take the form of 3 hour totals over the next 24 hours and 6 hour totals for days two and three. Construction of these forecasts commonly utilises a local interpretation of the numerical weather prediction model result alongside a synoptic analysis. There would be much merit in considering an automated system which receives directly appropriate numerical output from the numerical weather prediction model run twice a day at Bracknell. This would provide an automated product of more consistent quality and, in theory, at lower cost.

Shorter term forecasts at a higher temporal and spatial resolution are available from the UK Met. Office's Frontiers forecasts, made for 15 minute intervals on a 5 km grid over lead times of up to 6 hours, updated every half hour but with a transmission delay of some 40 minutes. To complement these forecasts, IH's HYRAD system can provide local forecasts on a 2 km grid out to a range of 76 km, updated every 15 minutes which are immediately available. Forecasts beyond the 76 km range on a 5 km grid are planned for a later release of HYRAD. The NRA/Met. Office assessment of Frontiers highlighted the complementarity of these national and regional systems for rainfall forecasting.

A combination of forecasts from the numerical weather prediction model, from Frontier and from HYRAD is recommended for use on the Soar.

4.11 FORECAST ACCURACY AND FLOOD WARNING

Forecast accuracy is a difficult area because of the variety of sources of uncertainty involved and the complexity of the error structure associated with flood forecasts at different lead times. An empirical approach to defining forecast uncertainty is likely to prove the most reliable but this must be underpinned by a substantial historical database, relating to conditions that have remained largely unchanged. This is not possible at present for the Soar on account of the recent spate of flood improvement schemes along the Soar. Forecast accuracy for the present should be built up through operational experience and ex post analyses of significant flood events.

The question of whether, when and where to warn, given uncertain forecasts is a thorny issue, and for the time being on the Soar must rely strongly on the judgement of the hydrologist. This judgement will be based on a understanding of any deficiencies in the hydrometric network, such as the failure of radar under bright band conditions, and his past experience of model performance at different locations, acquired through model calibration results and ex post assesssments of past flood events. In the longer term there is a need for more fundamental research on forecast accuracy and decision-making concerning the issue of flood warnings. The main support to this process, which can be made available under the proposed system, is the provision of Decision Support System (DSS) facilities designed to answer "what if?" type questions. The DSS could be used, in real-time, to determine the sensitivity of flood forecasts to, for example, uncertainties in input varables likely to affect the forecasts such as rainfall forecasts. This will provide valuable support to decision-making on the issuing of flood warnings.

5. System Environment

5.1 INTRODUCTION

It is often too easy to focus on the choice of models to be used within a Forecasting System and not to give proper attention to the system environment within which the models are to operate. The system environment is particularly important for real-time applications in order to properly manage the incoming data from telemetry and other sources, to efficiently construct the forecasts needed, to display the forecasts to users of the System and to produce and disseminate the flood warning messages so that effective action can be taken. In addition, decision support facilities are required to support "what if?" questions concerning, for example, alternative gate control operations and alternative input forecasts of rainfall.

Figure 5.1.1 illustrates a design which is typically required of a system environment for flow forecasting. It comprises a shell and kernel. The kernel is responsible for managing forecast construction in real-time, and supporting model calibration off-line. The shell supports a database managing both observed and forecast data, and has external interfaces to the telemetry, weather radars and weather forecasts (possibly from a numerical weather prediction model). The shell also provides a graphical user interface and reporting/warning dissemination facilities to users of the system. Consideration of the system environment also extends to the choice of computer platform to use. These system environment issues are dealt with in this Section. Section 5.2 describes how the Information Control Algorithm of IH's RFFS performs the task of forecast construction within the shell. Section 5.3 considers the shell and the external interfaces required to support flood warning in the Soar Catchment. Finally, Section 5.4 makes recommendations on the computer configuration required to run the Forecasting System.

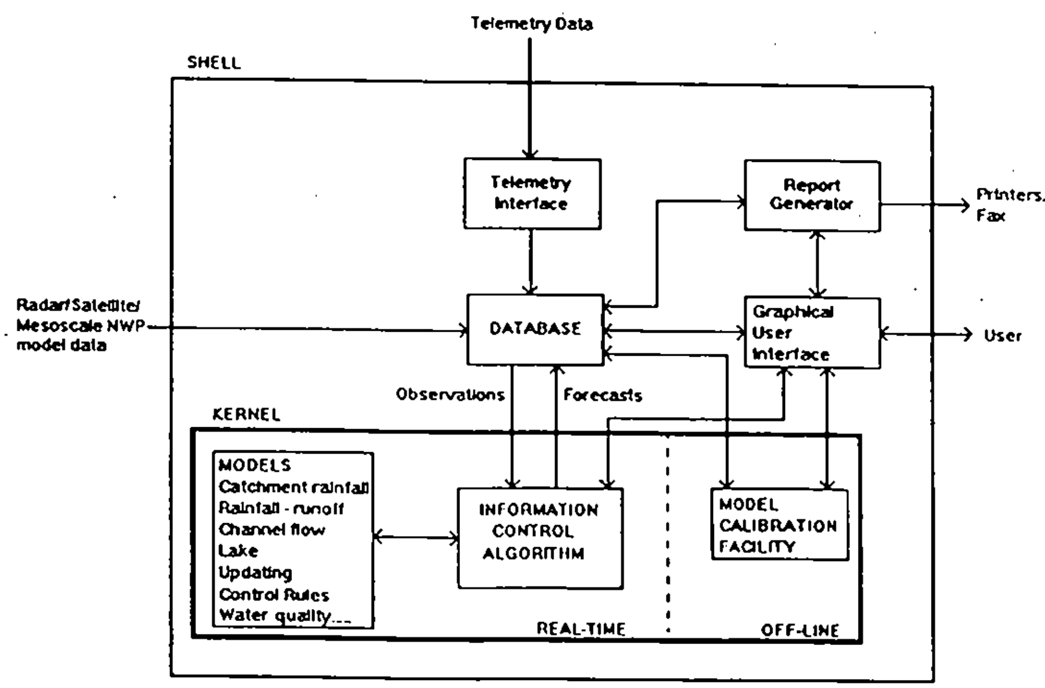


Figure 5.1.1 System environment of a Flow Forecasting System

5.2 INFORMATION CONTROL AND FORECAST CONSTRUCTION IN REAL-TIME

5.2.1 Introduction

Since 1988 the Institute of Hydrology has been engaged in the design and development of a generic River Flow Forecasting System (RFFS) kernel which is now in operational use throughout Yorkshire and in the White Cart Water in the vicinity of Glasgow. The design of the kernel allows configuration to any river network or set of networks without recoding. This makes it a particularly good foundation from which to develop a flow forecasting system for the Soar. In addition, a modular and generic design allows use of a wide choice of hydrological and hydrodynamic forecasting models and river control algorithms. It is the purpose of this Section to review the general functionality of the proposed Forecast System kernel and how it constructs forecasts in real-time.

5.2.2 The Information Control Algorithm

At the heart of the Forecasting System is an algorithm which controls the flow of data required to make forecasts and which selects the model algorithms to be used in their construction. This is the Information Control Algorithm or ICA. The ICA tackles a possibly complex overall forecasting problem through division into a number of simpler sub-problems, or "Model Components". The results of one or more model components are fed as input series into a subsequent Model Component. These input series will in practice be made up of observed values in the past, model infilled values in the past where observations are missing and model forecast values in the future. The infilled or forecast values will usually be constructed using preceding Model Components. At the extremities of the information network, beyond the river network, are special model components which can provide missing values for their input series through the use of backup profiles. Rainfall series completion is a typical example. Thus a particular forecasting problem may be viewed as a node and link network in which each node is associated with a forecast requirement (e.g. to forecast flow at site x) and each link to a Model Component which contains a set of Model Algorithms used to construct the forecasts.

A particular configuration of forecast points within a river system is described within the ICA by a set of description files. These files take two main forms:

(i) a Model Component file which defines the form of model structure, through the specification of Model Algorithms to be employed, and the data inputs to be used to make forecasts for a particular location or set of locations; and

(ii) a Forecast Requirement file which defines for each forecast point the Model Component to be used to construct the forecast for that point, the type of forecast (eg. river level, flow, snowmelt) and the connectivity with other model components.

A Model Component is typically made up of a number of Model Algorithms, for example for snowmelt modelling, rainfall-runoff modelling and real-time updating. Model Algorithms comprise forecasting procedures which can be used to create forecasts for several sites in the region, a particular procedure typically only differing from site to site through the model parameters used. The model algorithms to be used are defined within the Model Component file description, together with the parameter values appropriate to the site(s) for which the

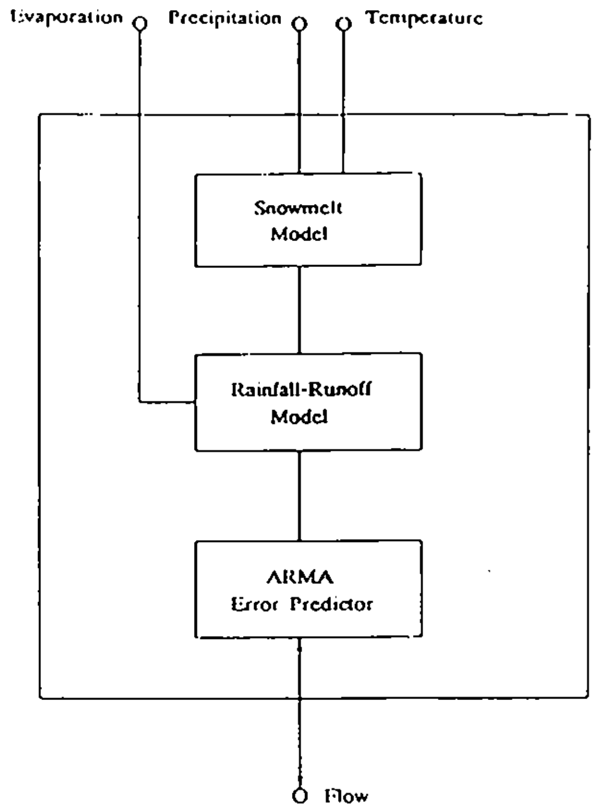


Figure 5.2.1 A model component and its associated model algorithms

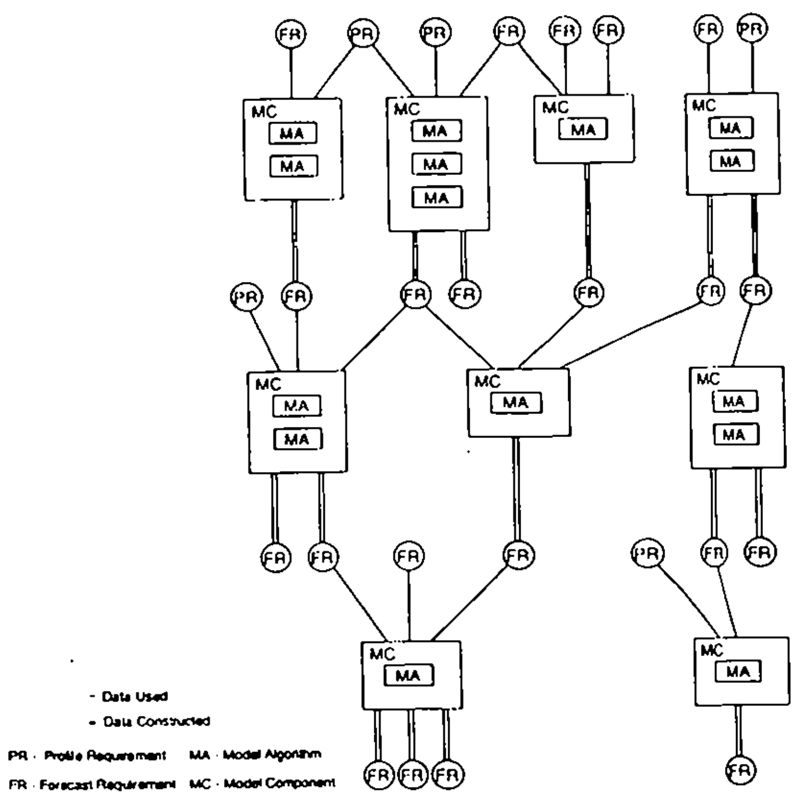


Figure 5.2.2 Connectivity between model components

component is to provide a forecast. Figure 5.2.1 illustrates a typical Model Component and its associated Model Algorithms and Figure 5.2.2 illustrates the connectivity between model components. This connectivity allows the ICA to represent river systems with complex dendritic structures including bifurcations. The specifications for a Model Component can be replaced with those for a modified version without disturbing the specification of the rest of the Model Component network and, essentially, without having even to consider more than the local part of the rest of the network. This provides for flexibility and ease of modification of an existing configuration.

The Model Algorithms are formulated within a generic subroutine structure which allows new algorithms to be coded and accessed by the ICA without recoding of the ICA itself. The generic structure is sufficiently general to allow algorithms of varying complexity to be coded. For example, algorithms can be as simple as calculating catchment average rainfall as a weighted average of raingauge data or may be as complex as ones which incorporate control rules for river gate settings as part of a hydraulic river model. The generic features of the algorithm interface are made specific to a particular model algorithm through a third type of description file. This Model Algorithm file defines an identifier, the name and number of the parameters, states, types of input/output and other features which are specific to a particular algorithm. The values given to a particular model algorithm parameter set in its application to a specific site is given in the Model Component file.

It is worth emphasising the importance of Model Component construction in the effective configuration of the ICA to a forecasting problem. One option is to equate Model Component and Model Algorithm and to have many Model Components. A more effective construction is to identify model algorithms which commonly occur together and use these as Model Component building blocks. This preserves flexibility whilst simplifying configuration and understanding of the resulting system. It is clearly easier to build a house from large bricks than small ones, provided the bricks are not too large to handle or too varied.

Having constructed a set of Model Component and Forecast Requirement description files to define a structure for the particular forecasting problem, the ICA initially employs these to construct a file used to order the sequence of Model Component executions. This "order-of-execution" list need only be constructed once for a given forecast network configuration. Operational running of the ICA deploys this list to get the data it requires to make the forecast run and then to execute each Model Component. The ICA works down the tree network of the river system, in the order dictated by the list, so that forecasts of flow or level are used as input to the next Model Component downstream. At run time the lead time of the forecasts can be changed as well as various settings controlling the input used by the Model Components.

The ICA allows the user to dynamically define "subnetworks" within the overall model network configuration. These can be defined, for example, to exclude the hydrodynamic model and to execute only a selected set of rapidly-responding catchments requiring a flash-flood warning, updated at frequent intervals. In the Severn-Trent Region the subnetwork concept could be used for each Area, to separate particular river networks, to separate each hydrometric area or to correspond to chosen "Catchment Areas", such as selected tributary catchments of the Soar.

On completion of a forecast run the "states" of the models required to initialise a subsequent run are stored; the time selected for storing the states is usually 30 minutes before the present time to allow for delays in receiving telemetry data. The states will be typically the water contents of conceptual stores within snowmelt and rainfall-runoff models or the river levels and flows of channel flow routing models. A subsequent run at a later forecast time origin will start forecasting forwards from the time of storing the states from a previous run. The set of model states for an algorithm, for a particular time point, contains a sufficient summary of all data previous to that time point to allow the algorithm to continue executing as if it had been run over a warm-up period up to that time point.

Operationally in non-flood conditions the system would be run automatically once a day, say at 7 am following routine data gathering by the Severn-Trent Regional Telemetry System. This means that the model states are available to provide good initial conditions from which to run the model for a flood event occurring later the same day, thus avoiding the need for a long "warm-up" period for model initialisation. During flood events the system would be run frequently under the control of the Forecasting System operator.

5.2.3 Model Algorithms

The model algorithms available for use within the ICA fulfil a range of functions. Some serve as simple utilities to set flows to a constant value, for example to represent a fixed compensation release from a reservoir, or to merge data from different sources according to a priority hierarchy to ensure that a data series required for forecasting is complete. The more conventional forms of model algorithm perform some specific hydrological function such as rainfall-runoff modelling, channel flow routing, snowmelt modelling or hydraulic river modelling of the tidal river. The main hydrological modelling algorithms currently available for use are:

(i) PDM: a rainfall-runoff model

(2) KW: a channel flow routing model

(3) PACK: a snowmelt model

(4) RFFS-HYDRO: a hydrodynamic model

(5) ARMA: an error predictor for forecast updating

The hydrodynamic model presently available for use within the ICA is based on the United States National Weather Service's DWOPER/NETWORK program (Fread, 1985) which employs a four-point implicit scheme to solve the Saint Venant equations. Substantial changes of the code were made to conform with the generic structure required of an ICA model algorithm, to operate in a real-time environment and to extend its functionality (Moore and Jones, 1991). It is proposed to substitute the use of this algorithm with the Isis code. The previous experience of conversion of a hydrodynamic model to the generic structure required by the ICA should prove a great help in completing this task.

5.2.4 System resilience, merging algorithms and profile data

The ICA has been designed so that the generation of flow forecasts can be resilient to data loss. This is accomplished for a point "internal" to the network by ensuring that the model component which constructs forecasts for the point will also infill missing values in the past data. For "external" points, typically rainfall and other forms of climate data, model algorithms are used to merge data time series from a variety of sources. In the event of no data being available provision is made to supply a backup profile. A hierarchy of priority of data source can be imposed in the case of data being available for a given time from more than one source. For example, in the case of rainfall the priority for a given catchment rainfall might be radar data from Ingham (the Lincoln radar), raingauge data from n raingauges and then any combination of less than n (allowing for raingauge system malfunction), and a backup rainfall profile. For future times when no observation data are available the priority might be a Local Radar Rainfall Forecast from HYRAD, a FRONTIERS forecast and a Numerical Prediction Model or synoptic forecast (provided automatically to the modelling computer by a computer/telex facility from the Met. Office or Weather Centre) and finally a backup rainfall profile. The rainfall profiles can be selected to be seasonally dependent and categorised into light, moderate and heavy with the option of invoking a selection at run time. They may also be subdivided into different synoptic regions over the Severn-Trent Region. Other uses for profiles are for potential evaporation and temperature to support rainfall-runoff and snowmelt modelling.

5.2.5 Forecast construction using the ICA

A forecasting problem for a typical region will be divided into a number of model components, of which the majority will have one of two tasks: sub-catchment modelling using a rainfall-runoff model, and channel flow routing using a simple hydrological rather than hydrodynamic modelling approach. An overview of the types of operations the ICA is doing when it creates forecasts for a region may be gleaned from the following description of what these two types of model component do. To simplify a hydrological channel flow routing model is assumed.

(A) For each sub-catchment:

i) calculate areal average rainfalls up to the present time;

ii) construct a complete series of areal average rainfalls into the future including any external forecasts of rainfall;

iii) retrieve values for the internal states of the rainfall-runoff model, and of the updating technique, for the beginning of the forecast run;

iv) access any available observations of flow for the downstream point of the sub-catchment;

v) use the rainfall-runoff model up to the present time, applying an appropriate forecast updating technique;

vi) save values of the model states for the present time;

vii) continue use of the rainfall-runoff model into the future to create forecasts of flows.

The outcome of this is a complete series of flows for the downstream point of the sub-catchment, consisting of any observations of flow that are available, with any missing values up to the present infilled and, similarly, the missing values in the future replaced by forecasts.

(B) *For each reach to be treated using a channel flow routing model:*

(i) access the completed data-series for flows at upstream points on the reach and tributaries of the reach;

ii) retrieve values for the internal states of the channel flow routing model, and of the updating technique, for the beginning of the forecast run;

iii) access any available observations of flow for the downstream point of the reach;

iv) use the flow routing model up to the present time, applying an appropriate forecast updating technique;

vi) save values of the model states for the present time;

vii) continue use of the flow routing model into the future to create forecasts of flows for the downstream point.

Once again the outcome of this is a complete series of observed and forecasted flows for the downstream point of the reach.

It will be seen from this description that the generic functionality of the two types of model component is essentially the same. This functionality is reflected throughout the ICA. In practice, the ICA controls the supply of input data and initial states to the model components, arranges to save a copy of the states after running the modelling algorithms up to the present time, and arranges the safekeeping of the completed output series generated: these output series may be required as input series by other model components and they will usually be required to be permanently stored for later examination since they represent the primary product of the forecast run. The ICA executes the model components and algorithms in an order that ensures that complete series are available for all the input series of a component before trying to generate forecasts from that component.

5.2.6 Types of Model Component

The problem of constructing forecasts throughout a region is undertaken by dividing the whole task into a number of sub-tasks or model components. Each model component represents the task of constructing forecasts for a particular subset of the overall collection of forecast requirements : here a "forecast requirement" relates to a particular site and a particular data-series for that site. Because groups of model components perform similar tasks for different collections of forecast requirements, there will be relatively few distinct types of model component. These classes of model component will be described next.

A general model component uses a number of input series and a number of output series, where values from the input series "cause", or at least are used to calculate forecasts and infilled values for the output series. In order to simplify the task of designing the overall configuration of a forecasting network, the approach taken is that most model components will not need to handle missing values among the data-values for their input series: it is expected that other model components will fill in any missing values among the observations and provide forecasts for these series and such series will be known as "complete" or "completed" data series. Thus there are certain special types of model component whose primary task is to construct such complete data series from incomplete input data.

Series-completion Model Components

An evaporation Series-completion Model Component is used for a particular Climate Station to produce a complete series of evaporation for use by the Catchment Flow Model Components. The data series produced is scaled to have a mean evaporation rate of 1 mm per day: when used by other model components the required evaporation rate for the catchment is obtained by scaling the input data-series for the component with the rate required in units of mm per day.

Catchment Runoff Model Components

Catchment Runoff Model Components are used for all catchments for which the calibration of rainfall-runoff models has proved possible. Each such model component consists formally of separate models: a snowpack model for the catchment as a whole, and a rainfall-runoff model of the PDM type. The rainfall-runoff model uses a state-updating procedure to make use of any observations of flow from the catchment.

The snowpack modelling section of the component exactly parallels that within the Snow Observation Site Model Components and makes use of the same types of input data, together with the modelling error series transferred from one these components. The rainfall-runoff modelling section uses an effective catchment rainfall input derived from the snowpack modelling section, together with a completed evaporation data-series produced by one of the Evaporation Series-completion Model Components.

Hydrological Channel Flow Routing Model Components

Channel Flow Routing Model Components are used to forecast the flow and river level at a site from similar information at a site immediately upstream on the same river channel and on any tributaries entering the intermediate reach. They are also used in some cases to derive a forecast of flow at a site within the modelled reach.

The ordinary Channel Flow Routing Model Components within the forecasting network make use of a simple hydrological routing algorithm which can make some allowance for out-of-bank storage. This algorithm is used to provide the initial modelled values and then the error-prediction approach is applied to make use of any observations of flow to construct the final set of forecast flows. Several of the model components of this general type make use of an additional modelling facility which allows use of a model-calibrated stage-discharge relation in those cases where there is no formally established relation.

Hydraulic Model Component

The Hydraulic Model Component uses a "4-point" numerical modelling scheme to provide initial modelled values for flows and river levels throughout a stretch of river to be modelled hydodynamically. In order to improve forecast accuracy, the component includes error-prediction schemes which make use of observations within the data-series for those forecast requirements which may be telemetered.

A feature of the Hydraulic Model Component is that it may include a representation for the Control Rules for operating structures, and for the effects of these. Account would be taken of any observed values for the structure-settings, telemetered or manually entered; otherwise, the model incorporates settings derived from modelled water-levels in accordance with the control rules.

Snow Observation Site Model Components

There will be Snow Observation Site Model Components corresponding to each of the established snow observation sites. Each component maintains an internal representation of the snowpack at the site and uses any observations of the snowpack depth and density to construct data series to represent corrections for modelling errors: these data series are passed to the Catchment Flow Model Components which contain their own snowpack models representing the whole catchment. Additionally, each of the Snow Observation Site Model Components will produce a completed series of temperatures, again for use by the Catchment Flow Model Components.

Snow Observation Site Model Components will make use of data from raingauges, radars, Meteorological Office Forecasts and from backup rainfall profiles to assess precipitation. They will also use data of temperature from Climate Stations, from the Meteorological Office Forecasts and from backup temperature profiles.

Fixed-flow Model Components

Fixed-flow Model Components may be used where there is insufficient data to allow calibration of a rainfall-runoff model. In particular, there may be no flow data available for some sites or no raingauge data that can reasonably be used to provide the catchment rainfall for events for which flow data exist.

The Fixed-flow Model Components are constructed in such a way as to generate a constant flow value (set to the mean annual flood where known) as an initial modelled value and then an error-prediction approach used to incorporate any observations of flow for the site in constructing the final set of forecast flows.

Dummy Model Components

The simplest type of model component used are the "dummy" components. These are always used in conjunction with dummy forecast requirements. The Forecast System does not expect values to be constructed for dummy forecast requirements and the corresponding forecast series are not saved. Thus a dummy component does not actually construct any forecast values.

The reason for the existence of dummy model components is to provide a simple way in which the nomination of a single (dummy) forecast requirement can force the construction of forecasts for a collection of real forecast requirements which are not otherwise formally on the same model network tree. For example, the dummy forecast requirement "1-REGION" might use a dummy model component to force the construction of forecasts for the entire modelled region. Similarly, the dummy forecast requirement "1-NONHYDRO" would provide a simple way of ensuring that forecasts are constructed for the sites not involving the running of a hydraulic river model. This would avoid the relatively time-consuming computation involved in constructing and saving forecasts for the sites on the reaches produced using the hydrodynamic model.

A specific example of sets of algorithms used in Model Components for catchment modelling and channel flow routing will now be given. The following combination of model algorithms is most often used within a Catchment Modelling Model Component:

(a) TMERGE : this takes rainfall information from a number of sources (raingauge, radar, synoptic forecasts and backup profile) and merges these sources together in a way which depends on a temperature series. The algorithm constructs data series for two dummy requirements which represent the amounts of precipitation falling as rain and as snow.

(b) SNOW : this takes the output series from TMERGE and uses them, together with a temperature series and model-correction information passed from the snow-observation site model, with a snowpack modelling algorithm to construct a further dummy forecast requirement representing the amount of liquid water entering the catchment.

(c) FA_PDM2 : this is a rainfall-runoff modelling algorithm, incorporating state updating. This uses, as input data, the dummy forecast requirement for "received" rainfall and a completed-series for evaporation constructed by another model component. Forecasts for the output series, the flows at the required site, are constructed within the algorithm having taken account of any observations of the flow by using the state-updating technique.

The following combination of model algorithms is frequently used as a Channel Flow Routing Model Component for sites not influenced by significant backwater:

(a) FA_KW : this routes flows from the upstream point(s) to the downstream point for which a forecast s required, and possibly to an intermediate point or points. The modelled flows are put into a dummy forecast requirement so that the later algorithm, ARMA, can make use of these as simulation mode forecasts. The algorithm may include allowances for abstractions and/or ungauged lateral inflows.

(b) ARMA : this combines the simulation mode forecasts constructed from the upstream flows with any observations which are available for the forecast point, using an error prediction technique.

5.2.7 The Operational System

The Operational System will be made up of a configured set of Forecast Requirement and Model Component files operating on a selected set of model algorithms, profiles and observation data. Figure 5.2.1 shows a typical forecast operated in a mode which mirrors how the system will be operated in real-time: the lower forecast is based on observed data only up to the forecast time-origin and backup profile data beyond this, whereas the upper forecast assumes perfect knowledge of future rainfall. This points to the importance of rainfall forecasts for headwater catchment rainfall-runoff modelling for extended lead-time forecasts; however, this importance diminishes further down the river network when the natural lag time in the river system, observations of river level and the relatively good accuracy of channel flow routing models make forecasts more accurate and resilient.

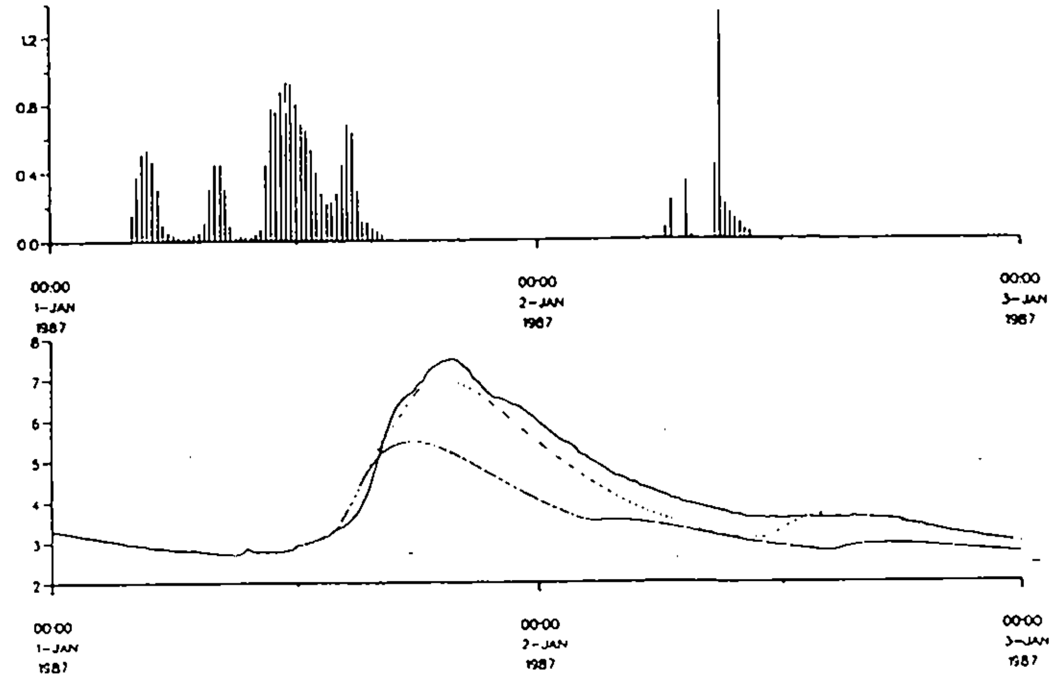


Figure 5.2.1 Operational flow forecast: the upper forecast assumes perfect foreknowledge of rainfall whereas the lower forecast is based only on observed rainfall up to 12:00 1 January 1987 and a backup rainfall profile after this.

At a broader level, outward from the ICA real-time forecast execution process, Figure 5.2.2 provides a decomposition of processes and their associated data flow interactions associated with the proposed Forecasting System. This Data Flow Diagram divides into an upper half depicting the data transfers involved in off-line model calibration and network configuration and a lower half relating to the real-time system. It serves to clarify how the products (model parameter values, details on channel geometry, etc.) of the IH model calibration and the ISIS calibration environments are integrated as ISIS and ICA information files for use by the real-time ICA. The latter accesses its dynamic data via a real-time database receptive to incoming radar, possibly via HYRAD, and telemetered hydrometric data and returns forecasts to it for subsequent access for display and other decision support activities.

5.3 THE SYSTEM SHELL AND EXTERNAL INTERFACES

5.3.1 Introduction

This section deals with the three main functions of the shell environment, namely support of external interfaces (principally telemetry, radar and weather forecasts), the graphical user interface (GUI) and reporting and dissemination facilities.

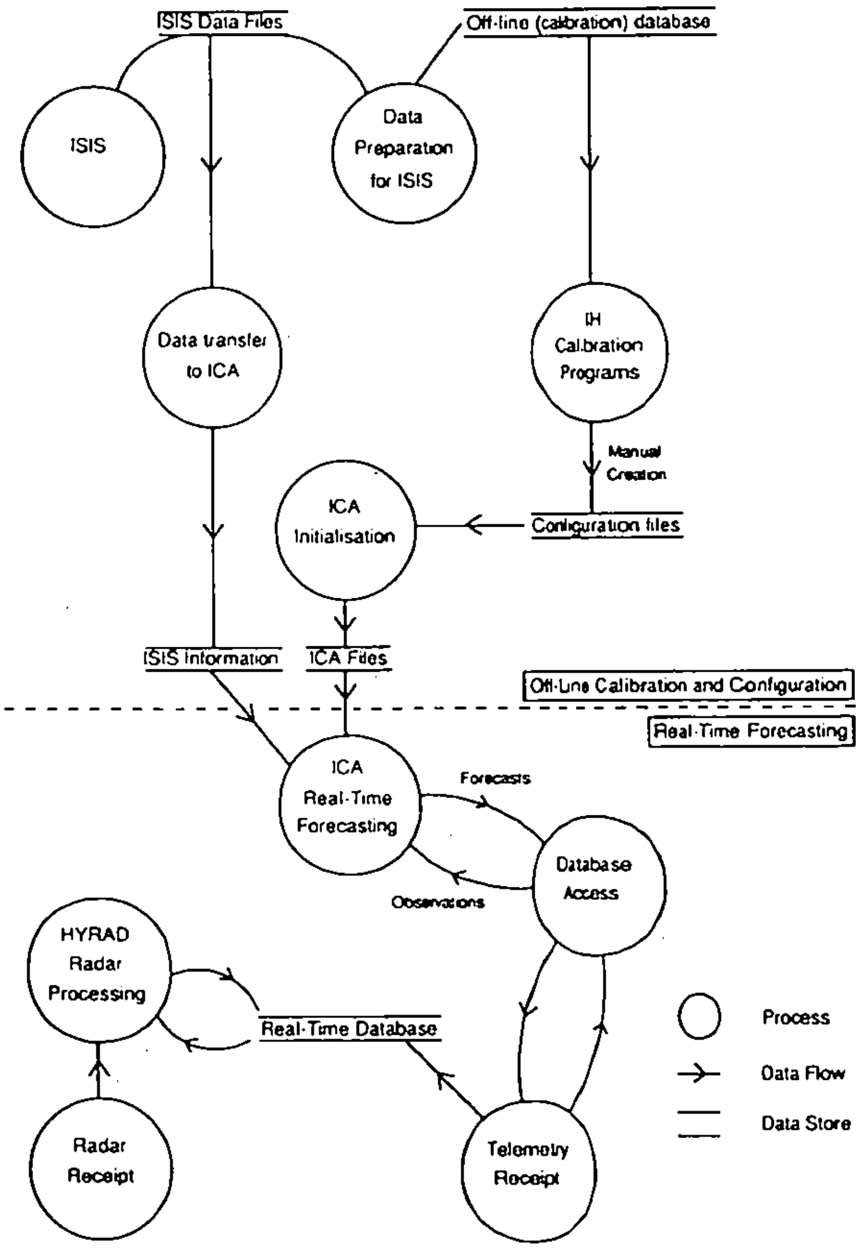


Figure 5.2.2 Level 0 Data Flow Diagram for the Soar Flow Forecasting System

5.3.2 Telemetry and other data interfaces

The shell will require to support incoming data from the NRA-ST telemetry system. Telemetry management is the function of the RECS system which runs on the VAX computer which also supports the Flow Forecasting System. RECS maintains a database of telemetry data on the VAX. Much of the existing investment that relates to the telemetry system, RECS and the database need not be affected by the proposed modelling system. Replacing the existing FFS by a new system based on the RFFS kernel technology will have some implications on the functionality the database will have to support. A more detailed investigation of RECS and its associated database structure will feature in Stage 2 of this investigation.

5.3.3 User interface

The NRA-ST Region currently employs the REMUS (REMote USer interface) as the Graphical User Interface (GUI) to its Flow Forecasting System. As well as providing a GUI it also contains a file-based database, an interface to the telemetry system and display facilities for radar data. Wallingford Water were specifically asked by the NRA to consider the use of REMUS as a possible GUI for the shell environment to any proposed Flow Forecasting System kernel. First, a review will be made of the functionality offered by REMUS and then consideration will be given to its suitability as a GUI for the shell.

REMUS is a menu driven system, for remote MS-DOS PCs, displaying observed data and forecasts produced by the forecasting computer of the ST-FFS (Severn-Trent Flow Forecasting System). Copies of the data from the forecasting computer allow the following to be displayed or printed out: radar images, raingauge maps, lists of subcatchment data, level and flow hydrographs of historical and forecast data. REMUS also supports interrogation of outstations and access to weather forecasts. Further details are provided in the REMUS Version 6.10 User Manual (NRA Severn Trent Region, 1993). It's primary function is as a Graphical User Interface (GUI) to the ST-FFS and, through its dependence on simple file transfer, can be utilised as a GUI to other forecasting systems. This means that it has the functionality to support the display of data series constructed using the IH RFFS ICA forecast construction kernel (Section 5.2). Data transfers are achieved via a direct connection (fastest), via a dedicated telephone line (e.g. home telephone, external offices) or via a switchboard (slowest). Communication with the forecasting computer is achieved using the REFLECTIONS 2 package, which utilises the WRQ transmission protocol: a 14,400 baud modem is used as standard. It takes about 4 minutes to fill an empty database and one minute for decanting data to the database is typical. Radar displays are limited to 5 km data.

REMUS is not windows-based and thus while users find it simple and friendly to use, is somewhat limited in its flexibility. However, the NRA-ST Region are considering upgrading the user interface, and an upgrade to Windows 3.1 is a likely prospect. This upgrade would fit well with the proposed use of HYRAD to support the radar processing and display functionality required. Indeed, elements of the HYRAD Windows 3.1 System design could prove a useful foundation to provide for display of time series graphs of observed and forecast flood hydrographs.

Any database and GUI design must be generic to allow storage and plotting of a variety of quantities of interest in an expandable way. These would include, in addition to multi-plots of flow and level hydrographs, also gate settings, hyetographs from raingauges and radar, and possibly for the future water quality variables.

5.3.4 Dissemination of warnings

It is envisaged that a computer-supported fax system be used to support the dissemination of warnings to interested parties. This would include functionality to support flood warning templates to help in the preparation of warning reports. It would also have configurable destination groups that allow one warning to be sent to a set of parties requiring a common warning. Standard reporting utilities would allow the flood situation to be assessed on say a day-to-day as well as an hour-to-hour basis.

5.4 COMPUTING REQUIREMENTS

The type of Flow Forecasting System envisaged would typically run on a workstation, such as a Sun Sparc 2, VAX station 3100 or similar, and be accessed by user PC's running on 486 processors or better. The RFFS kernel software is largely machine independent and current implementations run on VAX, Data General and Sun workstations.

5.5 SUMMARY AND RECOMMENDATIONS

(i) The flexible system design of the forecasting system, realised through the Information Control Algorithm or ICA, makes it ideally suited for application to the Soar catchment. Configuration to the Soar's river network can be achieved externally to the program code through a set of system description files. Configuration without the need for code modifications ensures both lower implementation costs and higher reliability.

(ii) The generality of the models already provided with the System should prove applicable to the Soar. If this proves not to be the case, or other models are preferred, then the generic model algorithm structure will readily accommodate new models or control algorithms. The following extensions or additions to the current set of Model Algorithms might be envisaged for the Soar implementation:

(a) Replacement of the existing Hydrodynamic Model Algorithm by one based on ISIS.

(b) Possible development of a hydrological routing model for use in reaches affected by backwater and river controls as an alternative to a more complete hydrodynamic approach.

(c) Consideration might be given to formulating and evaluating a state-correction methodology for a hydrological channel flow routing model which incorporates the ability to make corrections in both upstream and downstream directions of a gauging station, using telemetered observations at this station.

(d) Development of a set of generic control Model Algorithms for representing river control rules.

(iii) Emphasis should be placed on first achieving good forecast performance within the constraints of data availability. It is recommended that provision of confidence limits associated with the forecasts should be regarded as only of secondary importance, at least initially. Once the system is fully configured and calibrated and some experience has been acquired in the performance of the system then fuller consideration should be given to the provision of confidence limits. An approach based on deriving confidence limits based on the empirical forecast errors from model calibration runs might be one approach to consider. As an interim measure some indication of uncertainty could be provided through suitably constructed 'what if?' decision support runs. For example, forecast runs could be compared using a 'best estimate' rainfall forecast, a zero rainfall forecast and a worst-case rainfall forecast. Markov chain conditional rainfall forecasts, constructed for different risk levels, could be provided as another alternative, although the predictive performance of such a model is generally poor.

(iv) The adaptability in the design of the System is expected to prolong the life of the Forecasting System well beyond the year 2000.

6. System Implementation

6.1 INTRODUCTION

The previous sections have investigated the requirements for flood forecasts in the Soar, the design of a hydrometric network to support these forecasts, the choice of models to use and the nature of the system environment within which to construct forecasts and to make and disseminate flood warnings. As a consequence it is now possible to present some conclusions regarding an appropriate flood forecasting and warning system for implementation to the Soar catchment. These conclusions also serve as a summary of recommendations made in the body of the report. An implementation plan follows the outline of the recommended system design.

6.2 THE RIVER SOAR FLOOD WARNING SYSTEM

6.2.1 Hydrometric Network

(i) Raingauge network: The network should comprise between 8 and 10 tipping bucket raingauges (0.2 or 0.1 mm buckets) recording the time of tip. These should be configured on a regular lattice as a guiding principle, although issues of reprentativeness, ease of access and land ownership should influence the detailed local siting. The configuration should aim to ensure that at least one gauge is located within each of the major tributary catchments.

(ii) Radar network: The Soar is poorly served by the UK radar network, with over half the catchment lying beyond a range of 76 km from the Clee Hill and Ingham radars. Nonetheless, radar will prove invaluable in a qualitative way in portraying moving storms as they approach the Soar. Also, through local calibration there is some prospect for improved rainfall estimation, although the height of the radar beam above the Soar means that low, shallow rain-bearing cloud will not be detected. It is recommended that the processing and display features of IH's HYRAD Windows 3.1 system be adopted for use with the Flood Forecasting System. This provides both calibrated and forecast rainfall fields and catchment averages with an interface to the Flood Forecasting System, as well as animated images of real-time radar data displays. The Met. Office Frontiers forecasts should be utilised to provide longer term rainfall forecasts, say from 2 to 6 hours ahead.

(iii) River gauging network: The major tributaries should be gauged near to the confluence with the main Soar, but sufficiently upstream not to be affected by backwater. A detailed site survey is required to select appropriate locations, ideally having a fixed control, high sensitivity and unique stage-discharge relationship. Additional sites on tributaries should be chosen for their usefulness for flood warning requirements in the vicinity. Stations on the main Soar should be located either upstream or downstream of confluence points, depending on their usefulness for flood warning. Since much of the Soar downstream of Leicester is under backwater influence it is likely that the electromagnetic gauging method will be an appropriate choice of gauging method on the main Soar. Control structures, along with their associated level and gate position measurements, should be utilised as another means of gauging.

Specifically, the recommended river gauging station locations are: the lower Soar upstream of SK 4920 2785; the middle Soar in the vicinity of Loughborough where the canal and river share the same channel and bypassing is minimised; the upper Soar in Leicester at Freemans Weir; the Soar above the Sence confluence upstream of SP 553 987; the Sence upstream of SP 554 987; the Wreake upstream of SK 603 118; the Frisby control structure on the Wreake; the Wreake in the vicinity of Melton Mowbray; and Rothley Brook upstream of SK 594 1305.

(iv) Weather station: A single AWS should be installed in the Soar catchment monitoring the standard set of variables required to calculate Penman evaporation (wet and dry bulb air temperature, wind speed, net radiation) along with rainfall. Inclusion of wind direction and incoming solar radiation, whilst not essential for this application, would conform to standard practice. Data should be recorded at 15 minute intervals and telemetered to the forecasting computer, where they can be automatically processed to estimate daily PE values for input to rainfall-runoff models and used to support snowmelt forecasting at a finer time resolution. Whilst this study assumes no existing climate stations, in the event that a station exists, use should be made of it to capitalise on existing equipment and historical records where practical. This might imply addition of sensors rather than installation of a complete AWS.

(v) Soil moisture station: A decision on the installation of a soil moisture station in the Soar catchment should be deferred pending the outcome of ongoing research at IH.

6.2.2 Flood Forecasting and Warning System

(i) A hydrodynamic model, such as ISIS, should be used for the main Soar from the confluence with the River Trent to upstream of Aylestone Causeway (on the south west edge of Leicester) and for the River Wreake to Melton Mowbray, with the possible omission of the stretch from Ratcliffe to Frisby.

(ii) The convection diffusion equation, or an approximation to it, should be used for channel flow routing on reaches not significantly affected by backwater. The KW model provides an appropriate approximation tailored for use in real-time.

(iii) A conceptual rainfall-runoff model based on continuous soil moisture accounting principles should be used to model the tributary catchments draining to the channel routing reaches. An appropriate choice is the PDM model specifically tailored for real-time use and having considerable variety in the behaviours it is able to represent. For snowmelt conditions again a conceptual water equivalent accounting model is recommended. The PACK model would be an appropriate choice at present pending the outcome of ongoing research sponsored by the NRA and MAFF.

(iv) It is recommended that empirical state updating be used as the updating technique for the rainfall-runoff model and ARMA error prediction for the hydrological and hydrodynamic channel flow routing models. Some investigation of a newly developed state updating method for hydrological channel flow routing models is needed before this approach can be commented upon.

(v) Model calibration facilities should be incorporated in the supplied system and these should support both automatic optimisation procedures and visually interactive calibration aids.

(vi) The kernel to the forecasting system should be generic and configurable to new forecast requirements and new model algorithms. It should also employ state variables as a means of efficiently constructing seamless forecasts when forecasts are made at infrequent intervals during non-storm periods. It should also support the concept of subnetworks which allows only parts of the modelling system to be run in response to real needs. Such functionality is provided by the ICA within IH's RFFS system.

(vii) The forecast system environment should have a generic design configurable to new requirements. It should have interfaces to external systems, such as telemetry, weather radars and weather forecasts as well as a graphical user interface and reporting and dissemination facilities. The role of RECS and REMUS deserves further investigation under Stage 2 of this study before definitive recommendations on the shell environment and associated interfaces can be made.

(viii) The type of flow forecasting system envisaged typically would run on a workstation, such as a Sun Sparc 2, VAX station 3100 or similar, although the system kernel is largely machine independent. The workstation would function as a server to client PC's running on 486 processors or better.

6.3 IMPLEMENTATION PLAN

The following is a broad outline of the implementation plan:

(i) Installation of hydrometric network

(ii) Development and testing of ISIS Model Algorithm

(iii) Shell interface development

(iv) Data take-on for model calibration

(v) Model calibration of rainfall-runoff and hydrological channel flow routing models models

(vi) Configuration of the ISIS hydrodynamic model to the Soar

(vii) Calibration and proving trials of the ISIS model

(viii) Configuration of the ICA to the Soar catchment

(ix) Factory acceptance tests

(x) Site acceptance tests

(xi) Training

(xii) Maintenance and support

The implementation plan is expected to run over an 18 month period, given model calibration data exist. The idealised assumption of a totally new hydrometric network and no historical data might require this period to be extended, for example to allow one year of data to be collected before model calibration tasks are begun.

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Appendix 1

HYRAD BROCHURE

Institute of Hydrology

HYRAD

A Radar rainfall preprocessing, calibration, forecasting, catchment averaging and display system for hydrological use

IH has recently integrated its radar rainfall preprocessing, calibration, forecasting and catchment averaging procedures into a single software package. HYRAD employs these procedures as the Radar Hydrology Kernel of a Windows 3.1 based radar data reception, processing and display system.

The system supports the following functions:

- Radar preprocessing to correct for static anomalies and transient clutter.
- Radar calibration by raingauges.
- Radar rainfall forecasting, using either calibrated or uncalibrated fields.
- Calculation of rainfall fields from raingauge network data alone.
- Calculation of catchment average rainfalls from uncalibrated, calibrated or forecast radar rainfall or raingauge network data.
- Static and rapid replay of radar images (uncalibrated, calibrated or forecast) along with overlay information on raingauge location, river networks, catchment boundaries, coastlines and other feature data.
- Real-time reception of 2 km, 5 km network and other radar data types.
- A radar data archiving facility.
- An interface to the RFFS (River Flow Forecasting System).

For VAX (or UNIX) applications a client-server architecture is used in which the Radar Hydrology Kernel and data reception and archiving software run on the VAX (or UNIX) computer. A PC (desktop or portable, colour or monochrome) running under Windows 3.1 provides a menu-driven management and visualisation interface.

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Appendix 2

ISIS BROCHURE

ISIS - Advance Information

Overview

ISIS is a system for simulating flow and water quality in canals, rivers and estuaries. ISIS has been developed to provide engineers and managers with tools to assist in the design of cost-effective engineering schemes and the development of river basin management strategies. Developed as a joint venture between HR Wallingford and Sir William Halcrow & Partners, ISIS combines the skills and experience of these two organisations to offer proven hydraulic and water quality modelling capabilities within a state-of-the-art user environment.

Pedigree

ISIS derives from the SALMON and ONDA hydraulic and water quality engines and benefits from three decades of development and application in simple and complex systems in the UK and overseas. Running under Windows and Motif, the best features of SALMON and ONDA are incorporated into the ISIS system.

ISIS Flow

At the heart of ISIS is the hydraulic simulation engine ISIS Flow. Developed from well proven computational models, ISIS Flow has all the features needed to model a system, including:

- Robust solver of full unsteady equations
- Fast steady state solver
- Object orientated design
- Looped and branched systems
- Flood plain modelling
- Extensive range of structures
- Full range of boundary conditions

ISIS Workbench

Workbench improves productivity of the modelling process with tools to assist in building models, editing data, presenting results and organising files. A fully object orientated network visualiser enables complex systems to be built graphically by selecting units that represent a channel, junction, flood plain or structure. Entry of text and numerical data is made simple through the data editor while cross sections, long sections and time-series plots of data are provided by the graph manager. The organisation of project files is undertaken by ISIS Workbench.

ISIS Quality

Comprehensive simulation of water quality is provided by the optional module ISIS Quality using water movements from ISIS Flow. The pollutants represented are:

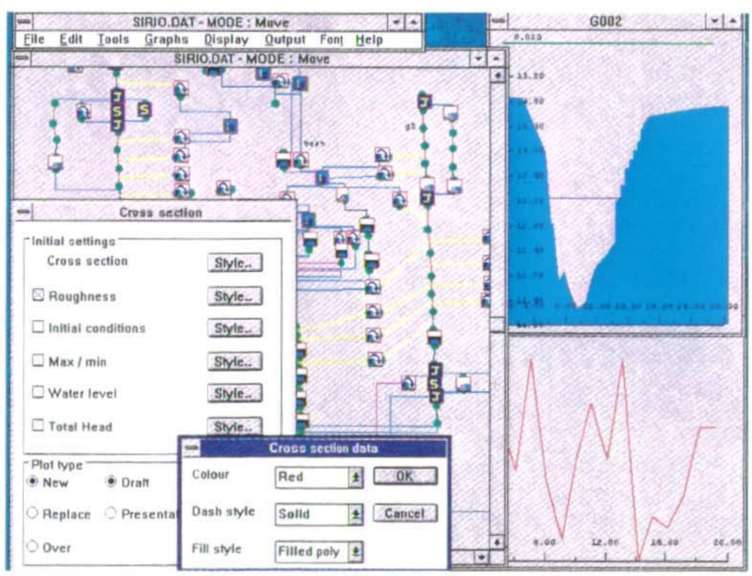
- Salt, temperature and sediment
- Four BOD fractions
- Fast and slow organic nitrogen
- Ammoniacal nitrogen and nitrate
- Algal carbon, phosphate and silicate
- Detrital material, macrophytes, benthic algae

ISIS Hydrology

The optional module ISIS Hydrology calculates design flows for input into ISIS Flow. It includes the Flood Studies Report method, the US Soil Conservation Service method and any user defined unit hydrograph and rainfall sequence.

ISIS Sediment

Full mobile bed sediment transport is provided in the optional module ISIS Sediment driven by the results from ISIS Flow. ISIS Sediment has various options for updating the bed geometry.



ISIS is a joint venture of HR and Halcrow. The names and registered offices of the joint owners are: HR Wallingford Ltd, Howbery Park, Wallingford, Oxfordshire OX10 8BA, UK Registered in England No. 2562099 and Sir William Halcrow & Partners Ltd, Vineyard House, 44 Brook Green, London W6 7BY Registered in England No. 1722541

Appendix 3

DOCUMENT INVENTORY

Document Inventory

Hydraulics Research (1991) Syston Northern Bypass: hydraulic model of River Wreake Crossing. Report EX 2253, June 1991, 44pp plus Tables, Figures and Plates, Hydraulics Research, Wallingford.

Hydraulics Research (1992) Rearsby Bypass: Hydraulic model of Queniborough Brook Crossing. Addendum. Report EX 2253, December 1992, 7pp plus Tables, Figures and Plates.

Mott MacDonald (1992) River Soar Flood Capacity Appraisal. Final Report, May 1992, Contract report to National Rivers Authority Severn-Trent Region.

Mott MacDonald (1992) River Trent Flood Plain Derwent to Colwick Model. Final Report, October 1992. Contract Report to Severn-Trent Region.

National Rivers Authority Severn-Trent Region (1993) Hydrometric report and catalogue 1992, 68pp plus 31pp Catalogue. NRA Severn-Trent Region, Solihull.

National Rivers Authority Severn-Trent Region (1994) Flood Event 3 December 1993 - 17 December 1994, 20pp plus Appendices. Operations & Data Section, and Flood Defence, April 1994.

Simpson, C.M. (1981) Report on the floods of April 1981, with particular reference to the Soar and Devon catchments. June 1981. Available from NRA Severn-Trent Region, 19pp.

Pirt, J. (1977) Hydrology of the River Soar catchment 16 December 1976 to 28 February 1977 with particular reference to February 18-28. Trent Area Unit, available from NRA Severn-Trent Region, 18pp.

Severn-Trent Water Authority (1979) Soar Valley Flood Alleviation Scheme. Severn-Trent Water Authority, Soar Division, 6pp plus Figure.

NRA Severn-Trent Region (undated) Charnwood Reservoirs, Section 10 of unknown report, 76-79.

NRA Severn-Trent gate operation reports:

(i) D. Harwood (1986) Eye Kettleby Gate Operation, SDRH Rep 173 D4, 2pp.
(ii) Zouch Gate, NTT2704, 3pp; plus letter 12 January 1993 from Les South.
(iii) Fricky Gate Operation, FLD/30, Appendix S5 to S10

Severn-Trent Water Authority (undated) First Survey of Water Services: River Soar Basin, Corporate Planning Dept., 76pp.

NRA Severn-Trent Region (1993) REMUS Version 6.10 User Manual, June 1993, 46pp.

Drawings:

Soar Valley Improvement Scheme Cotes to Quorn improvements, Lewin, Fryer and Partners, January 1991. Cross section survey drawings:

395-398
411-416a
417-420
445-450
358-360

(Drawing numbers 687/02/20,31,35,36,42).

Soar Valley Improvement Scheme Phase 2, Pillings Gauging Station, General Arrangement, West Bank Flood Plain, Drg. No. 504/2211E, 1983.

Stage-discharge rating curves:

Soar at Pillings Lock
Sence at South Wigston
Wreake at Syston

Tables of check gauges for electromagnetic gauging station at South Wigston (Sence) 7/1/92 - 8/6/9 and ultrasonic gauging station at Pillings Lock (Soar) 5/8/93 - 15/9/93.