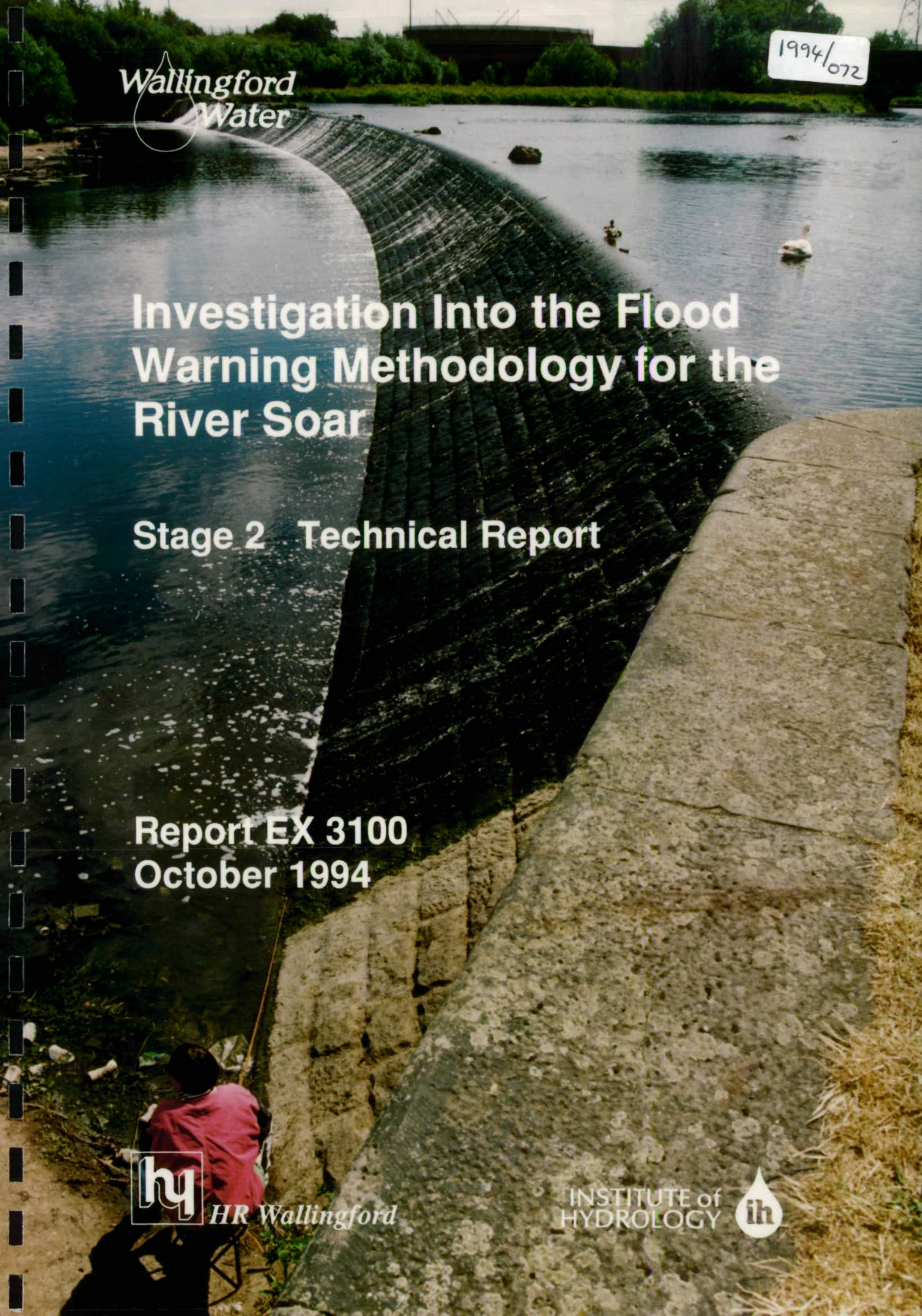

Wallingford Water

Investigation Into the Flood Warning Methodology for the River Soar

Stage 2 Technical Report

Report EX 3100
October 1994

HR Wallingford

INSTITUTE of HYDROLOGY

A FLOOD FORECASTING AND WARNING SYSTEM FOR THE RIVER SOAR

STAGE 2 REPORT

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. The Stage 1 report took a fresh approach to flood forecasting and warning for the Soar, not influenced by existing systems, by proposing a new hydrometric network and forecasting system under the idealised assumption that nothing exists. Recommendations were made 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. The purpose of the Stage 2 study is to identify shortcomings of the existing network and system and to compare them with the idealised design proposed under Stage 1. Definitive recommendations for action follow as a result of this assessment and comparison. The benefits of the proposed solution are also reviewed.

The main recommendations derive from an examination of the potential sources of unreliability in the current flood warning system and are as follows:

- Improved measurement of catchment average rainfall by installing two new raingauges, utilising data from five further gauges within NRA Anglian Region, obtaining better resolution by using smaller buckets, replacing the low resolution Type 1 radar data with much higher resolution Type 2 and employing the improved radar calibration and forecasting facilities available through HYRAD, including access to Frontiers forecasts.

- Improved and extended measurement of river stage and flow by installing new gauging stations at Freemans Weir and the Eye at Brentingby, enhancing the performance of existing stations at Kegworth, Pillings Lock, Littlethorpe, Syston and Eye Kettleby and utilising the control gates for flow estimation via extended telemetry and a current metering programme.

- Better resolution of all monitored data by employing a 15 minute data storage time step giving more accurate flood forecasts.

- Improved soil moisture accounting by upgrading the Brooksby climate station, leading to better rainfall-runoff modelling.

- Greater flexibility for rainfall-runoff modelling by gaining access to additional algorithms such as the PDM model which offers real-time state updating.

- Greater flexibility for channel flow routing by gaining access to the KW model.

- More scientific representation of flow phenomena such as backwater influences, inundation of floodplains and the operation of control structures by implementing the ISIS hydrodynamic model.

- More efficient and effective calibration of the hydrological and hydraulic model parameters via user friendly, visual calibration and optimisation tools.

- Improved updating scheme by employing a simpler, more stable error predictor.

- Greater flexibility in forecast construction, with the system providing for extension to new catchments, models and forecast variables, such as water quality.

The Consultants believe that these recommendations will lead to a significant improvement in the reliability of the flood warning service for the River Soar Catchment and restore the confidence of the Flood Duty Officers in the system.

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 under the project management of T.Parkinson, Wallingford Water. Additional support has come from V.A. Bell at IH on the hydrometric network assessment and from P. Hollingrake, HR, on field investigations and gauging method selection. Dr P G Samuels at HR undertook the water level forecast uncertainy analysis presented in Appendix 6.

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. Richard Cross is thanked for his help in understanding the forecasting software in use by NRA-ST. Les South and Simon Wills provided information on the control structures and river gauging network respectively. Jim Waters is thanked for thoughtful discussions on the hydrometric network.

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1. Introduction

This document reports work under Stage 2 of a study concerning 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 Stage 1 study ignored the existence of existing systems so that the flood forecasting system and hydrometric network currently in use did not exert any influence on the proposed solution. A new hydrometric design and forecasting system was proposed tailored specifically to best meet the requirements for flood warning. In this Stage 2 report these recommendations are reviewed against the suitability of the actual systems in place. Section 2 considers each component of the hydrometric network including the measurement of rainfall, river flow and level, weather and soil moisture variables. The models in use for forecasting on the Soar are reviewed in Section 3 and their suitability compared with those proposed in the Stage 1 report. This review and comparison extends to the methods used for real-time updating of model forecasts using the most recent observations of river flow and level. Other topics considered are the techniques used for model calibration, for rainfall forecasting, for assessing forecast accuracy and for making decisions to issue flood warnings. An operational assessment of the current forecasting system, based on the analysis of forecasts made over ten flood events, is reported in Section 6. The system environment within which forecasts are constructed and inspected by users is reviewed in Section 5 and compared to that recommended in Stage 1. Consideration extends to the telemetry management and Graphical User Interface software currently used. Section 6 presents a set of recommendations for improving the existing system along with an implementation plan. Finally, Section 7 reviews the benefits of the proposed solution.

2. Hydrometric Network for Flood Forecasting

2.1 INTRODUCTION

A specific requirement of the Stage 1 Study was to arrive at a fresh approach to flood forecasting for the Soar through not being influenced by the existing forecasting system, referred to here as the ST-FFS, or the associated hydrometric network used to support it. The latter requirement implied the need to undertake a completely new hydrometric design tailored specifically to best support the flood warning requirements in the Soar catchment. This section compares the idealised network design proposed under Stage 1 with the actual network in place in the Soar catchment. The measurement of rainfall, river level and flow, climatic variables and soil water are each considered in turn in Sections 2.2 to 2.5.

2.2 RAINFALL MEASUREMENT NETWORK

2.2.1 Raingauge network

The Stage 1 report recommended a network of between 8 and 10 tipping bucket raingauges configured on a regular lattice over the Soar catchment, subject to variation according to local siting details. Ideally at least one gauge should be sited within each of the major tributary catchments. Figure 2.2.1 shows the actual configuration of telemetry raingauges in the vicinity of the Soar catchment and Table 2.2.1 provides a summary of information relating to them, including the period of record. The total number of gauges in the immediate vicinity is 7 which is close to that recommended in Stage 1 for the idealised design. A further 6 are located beyond the eastern edge of the catchment, with Stanford in the Trent basin and the remainder in the Anglian Region. In terms of configuration, the 7-gauge network is arranged roughly in two east-west lines, 4 gauges along a line through the centre of the catchment and the other 3 across the headwater streams of the Upper Sence and Soar to the south. The latter three gauges are reasonably well placed to support rainfall-runoff modelling of these two upstream catchments. Also Brooksby and Whissendine are well located for modelling the Wreake, upstream of Syston and Melton Mowbray respectively. However, the nearest gauges serving the Rothley Brook catchment are Wanlip near its confluence with the Soar and at Mount St. Bernards to the north-west in the Black Brook catchment. It is recommended that an eighth gauge be located in the middle/upper Rothley Brook catchment at circa SK 480 070. A ninth gauge, on roughly the same northing but to the east of the middle Soar, might prove useful in estimating the ungauged lateral inflows entering on the opposite bank (circa SK 660 070). There doesn't appear to be a strong case to strengthen the network in the north, for example in the Kingston Brook catchment, on account of the flood warning sites being upstream of the Brook's confluence with the Soar.

A further recommendation of the Stage 1 report was to use 0.2 mm (or 0.1 mm) tipping buckets in the telemetry raingauges. In practice 0.5 mm buckets are used, and whilst this may be satisfactory for supporting models run at an hourly time-step, it is considered these will be deficient for a 15-minute time-step model and for radar raingauge calibration purposes. A recent NRA Research and Development Note (Moore *et al.*, 1993) illustrates the benefits of a 15-minute time step for rainfall-runoff modelling, particularly with respect to forecast updating. Independent of rainfall resolution, a 15-minute model time-step is preferred particularly to represent the operation of control structures. As a consequence the Stage 1

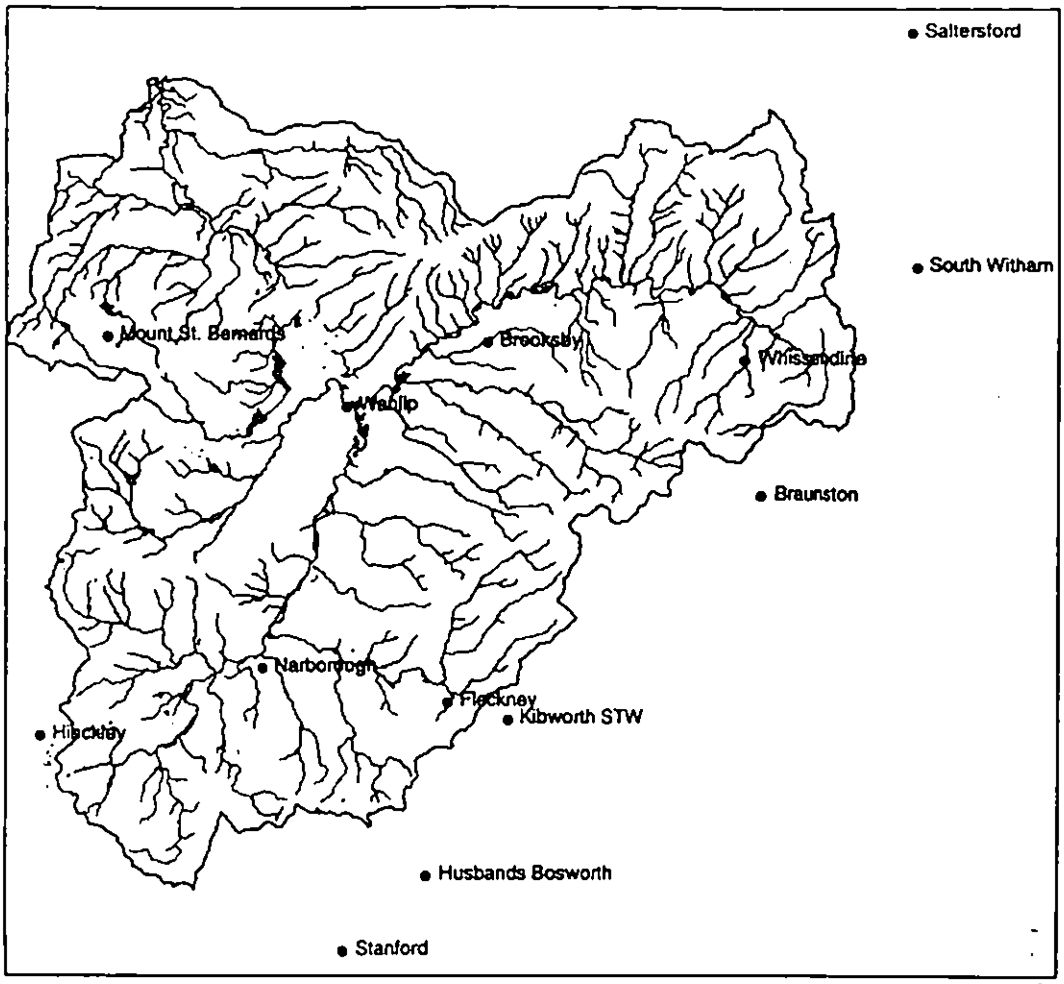


Figure 2.2.1 Location of telemetry raingauges in the vicinity of the Soar catchment

Table 2.2.1 Telemetry raingauge network in the vicinity of the Soar catchment

Station name	NRA Ref	Met Office No.	Grid Ref	Altitude (m)	SAAR (mm)	Start of record
Hinckley	3198	98210	SP420927	99	640	9/1962
Narborough	3605	111398	SP549966	74	614	2/1971
Mount St. Bernards	3641	115296	SK459158	186	751	10/1985[1]
Brooksby	3680	113774	SK679154	70	611	7/1964
Wanlip	3683	112545	SK598117	52	600	10/1985[2]
Fleckney	3686	111729	SP656946	99	635	12/1985[3]
Whissendine	3687	112771	SK829144	104	624	12/1985[4]
Stanford	1155	447787	SP596804	112	651	5/1964
Husbands Bosworth	Anglian		SP644847			Proposed
Kibworth STW	"		SP691936			1987
Braunston	"		SK838065			1985
South Witham	"		SK929198			1977
Saltersford	"		SK926335			1987

[1] Earlier records are available from a former AWS at this site
[2] Earlier records exist
[3] Site relocated from Wistow, for which earlier records exist
[4] Site relocated from Wymondham, for which earlier records exist

recommendation is reinforced here, implying either replacement of the buckets of existing gauges by 0.1 mm buckets or the use of a counterweight and recalibration to operate as 0.2 mm buckets (the cheaper option). The gauges record time-of-tip which allows 15 minute totals to be readily derived, as well as allowing data to be resolved to a finer time interval if needed. No change to the method of recording is therefore required.

2.2.2 Weather radar

Within the Severn-Trent Region use is made of the Type 1 (single site) weather radar data from Clee Hill and Lincoln, along with the Network picture. Both types of data are of low resolution, picture quality giving values for 5 km square pixels in 7 intensity classes plus zero. The additional information included in the Type 1 data includes 5 minute images, instead of the 15 minute interval Network pictures, and one hour totals of rainfall for selected subcatchments; 15 minute totals are not supplied for the Severn-Trent subcatchments. In contrast, the Stage 1 recommendation was to use the higher resolution, quantitative images provided by the Type 2 data for modelling purposes, from Clee and Lincoln. These provide 2 km data out to 76 km radius of the radar, and 5 km data to 210 km, both at 208 intensity levels and a 5 minute interval. This recommendation is reinforced here, with these data being used instead of the Type 1 data. Use of the Network data should be maintained to provide a broader national picture of incoming storm systems. Whilst the Type 2 data also provides subcatchment rainfall totals, it is recommended that a move towards a strategy of local processing of the Type 2 data be adopted. This would include calibration with telemetry raingauges, radar rainfall forecasting and derivation of subcatchment rainfalls for these processed radar images. It is recommended that HYRAD be used to accomplish this local processing as well as providing an interface to pass processed subcatchment rainfall to the flood forecasting system. A brochure for HYRAD is included here as Appendix 1.

The display of radar images in the Severn-Trent Region relies on either rather crude displays of Type 1 data supported by the REMUS system, with images downloaded from the VAX, or by The Computer Department's MicroRadar system. The latter was an excellent system at its time of development. It supports both the acquisition and display of the standard set of Met. Office radar products, including Type 1 and Network data currently displayed by NRA-ST, along with Type 2 and Frontiers data. However, it predates Windows 3.1 and in this sense is out-of-date and also supports none of the processing functions available in HYRAD (which incorporates a Windows 3.1 display system).

Finally, no use is yet made of the Met. Office's Frontiers forecasts, initially trialled in the Northwest and Thames regions of the NRA, and only released generally over the last few months. Whilst the quality of these forecasts leave room for improvement, the recommendation of Stage 1 to adopt Frontiers for rainfall forecasting from 2 to 6 hours ahead is reinforced here. An ongoing programme of research and development at the Met. Office, under the Nimrod banner, aims to provide an improvement on Frontiers next year. Frontiers forecasts can be displayed within HYRAD, and are seen as complementing HYRAD's own higher resolution, more accurate, forecasts which focus on the shorter lead-times from 15 minutes to 2 hours ahead.

During Stage 2 of the project a draft copy of the Long Range Calibration Study (LORCS) Final Report was made available. This reports work undertaken by the NRA and the Met. Office, as part of the Lincoln Weather Radar Consortium, and concentrates on the accuracy of the Lincoln radar at long range. It was noted in the Stage 1 report that the Soar catchment was not well located with respect to the network radar, about two-thirds being outside the 76 km range circle for Ingham, defining crudely the "quantitative" limit for the radar. At 80 km range the radar beam exceeds 1 km in height and can overshoot shallow rain-forming clouds. Attenuation of the beam and decreasing sensitivity as the 1° width of the beam expands with range also reduces accuracy. Of particular relevance in the LORCS study is the inclusion of "Leicester Laterals" as one of the 42 subcatchments for which radar rainfall totals are examined in detail. This subcatchment lies at 89 km range from Ingham and is encompassed by seven 5 km radar squares. The performance assessment criteria used are somewhat varied and the detail of these will not be given here. Suffice it to say that radar subcatchment estimates for the Leicester Laterals (catchment 27) were judged acceptable, and indeed performed generally no worse than the 11 subcatchments lying within the 76 km range circles. For 75% of the time when rainfall exceeded 2 mm/hr the radar to gauge ratios fell within a range 0.62 to 1.6, calculated over the period May 1989 to April 1991. There was little evidence of anaprop (anomalous propogation) degrading the radar data over the Soar catchment. These results are more encouraging, in terms of the value of radar data to support flood forecasting in the Soar, than might originally have been expected. It is likely that application of a local calibration technique making use of telemetry gauges in the Soar catchment would make these results even better. HYRAD would provide this functionality as an off-the-shelf proven technique requiring very little effort to implement for the Soar. Details of the method used by HYRAD is reported in a paper included here as Appendix 2, and a paper outlining the approach used for rainfall forecasting forms Appendix 3.

2.3 RIVER GAUGING STATION NETWORK

2.3.1 Assessment of actual and design networks

Figure 2.3.1 shows the location of the 11 river level and flow station that currently operate within the Soar catchment. This is complemented by Table 2.3.1 which presents information on each station, including the gauge datum, catchment area, available record, type of gauging equipment and whether on telemetry. The second part of this table provides information on 13 stations which are now closed, and is important from the viewpoint that records may be useful to support modelling and some may be candidates for re-opening to support the flood forecasting system.

Figure 2.3.2, reproduced from the Stage 1 report, presents potential gauging sites inferred from a digital terrain model (DTM) analysis to avoid backwater-influenced sites. The specific recommendation for gauging stations made in the Stage 1 study was as follows:

Station 1: the Lower Soar upstream of SK 4920 2785;

Station 2: the middle Soar in the vicinity of Loughborough where the canal and river share the same channel and bypassing is minimised;

Station 3: the upper Soar in Leicester at Freemans Weir;

Station 4: the Soar above the Sence confluence upstream of SP 553 987;

Station 5: the Sence upstream of SP 554 987;

Station 6: the Wreake upstream of SK 603 118;

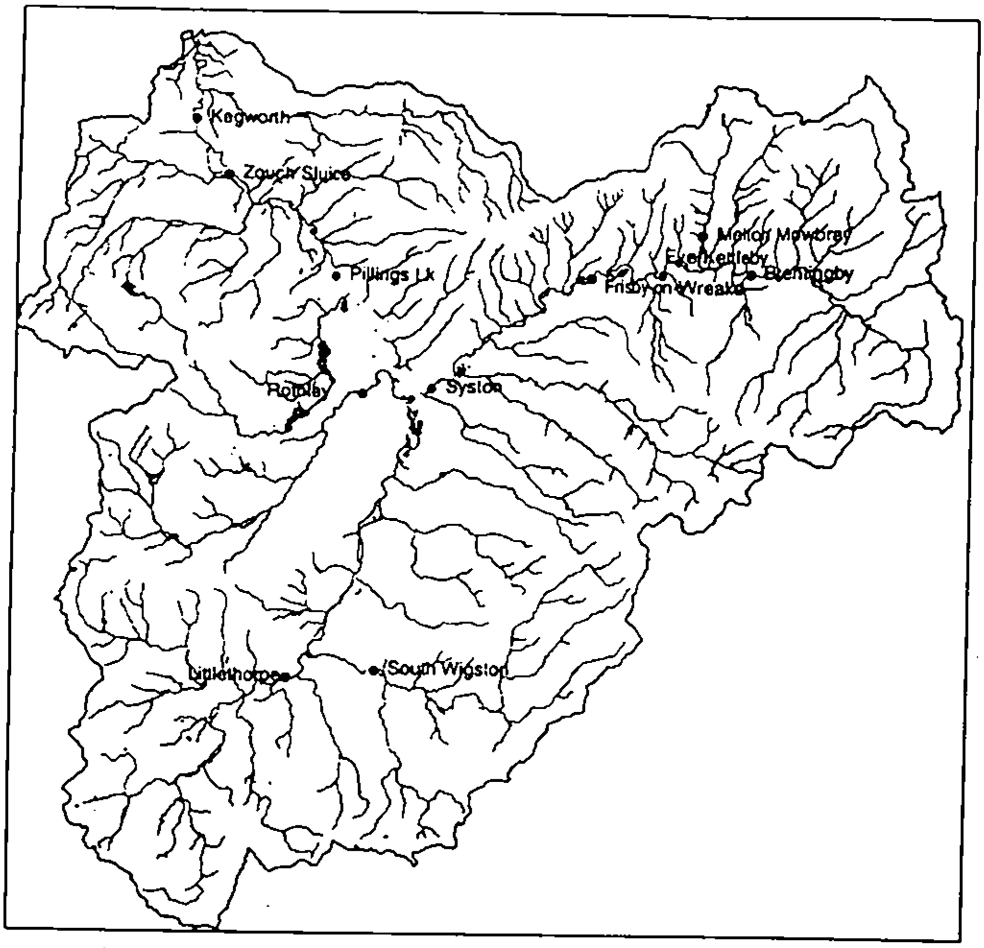


Figure 2.3.1 Location of river level and flow gauging stations operating in the Soar catchment

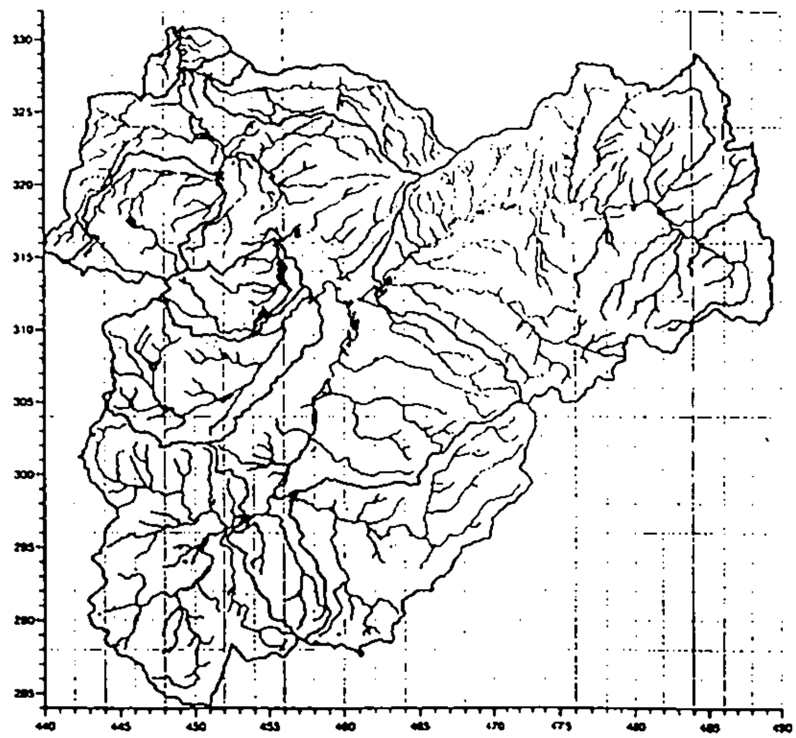


Figure 2.3.2 Location map of lowest potential gauging sites not affected by backwater

Table 2.3.1 River level and flow stations in the Soar basin

(a) Open stations

River	Station	NRA ref	Grid ref	Datum mAOD		Area km²	Level record	Flow record	Type & Equipment	Telemetry
Soar	Littlethorpe	4082	SP542973	61.693	(22/10/81)	183.9	11/1981-	5/1983-	EM TG CH	Yes
Sence	South Wigston	4086 (4505)	SP588977	66.460	(1/1/84)	113.0	9/1983-	12/1983-	EM TG CH	Yes
Eye	Brentingby	4845	SK784185	?		158.3	1/1979-		OC CH	
Scalford Bk.	Melton Mowbray d/s	42729	SK758205	79.624	(1/10/91)	22.3	10/1991-		TG	Yes
Scalford Bk.	Melton Mowbray u/s	4729	SK758205	81.647	(1/10/91)	22.3	10/1991-		RE TG	Yes
Wreake	Frisby-on-Wreake	4873	SK697182	?		271.3	3/1988-		RS TG	Yes
Wreake	Syston	4024 (4503)	SK615124	46.000	(1/1/82)	414.0	7/1967-	8/1967-	EM TG CH	Yes
Rothley Bk.	Rothley	4056	SK580121	47.375	(1/5/73)	94.0	5/1973-	5/1973-	FT TG CH	Yes
Soar	Pillings Lk	4093 (4506)	SK565182	38.000	(1/7/85)	1105.0	2/1985-	8/1986-	US TG	Yes
Soar	Zouch Sluice Gate	4109	SK509234	?					BC TG	Yes
Soar	Kegworth	4074 (4513)	SK492263	32.000		1292.0	12/1978-	12/1978-*	US TG CH	Yes

* Pre-1990 records, from a single path ultrasonic, are less reliable and often missing

Table 2.3.1 cont. River level and flow stations in the Soar basin

(b) Closed stations

River	Station	NRA Ref	Grid Ref	Datum mAOD		Area km²	Level Record	Flow Record	Type & Equipment
Soar	Belgrave	4844	SK592076	?			5/1976-1/1986		OC CH
Sence	Blaby[1]	4054	SP566985	62.542	(1/8/71)	133.0	8/1971-1/1986	8/1971-4/1984	FT CH PT
Kingston Bk.	Kingston d/s[2]	4229	SK503227	?		57.0	-12/1985		OC DS CH
Kingston Bk.	Kingston Hall[2]	4029	SK503277	31.044		57.0	11/1965-12/1985	5/1966-2/1984	CC CH PT
Wreake	Eye Kettleby	4889	SK738184	?			1/1990-?/1994		CH OC
Wreake	Kirby Bellars	4846	SK718181	64.250			12/1978-4/1989		OC CH
Soar	Leicester PS u/s	4847	SK577025	?			7/1975-7/1984		CH
Soar	Mountsorrel	4848	SK582153	?			10/1976-1/1986		CH
Soar	Narborough[3]	4051	SP551985	60.777	(1/8/71)	202.0	8/1971-7/1986	8/1971-4/1984	FV CH PT
Black Bk.	Onebarrow	4030	SK466171	111.191	(1/4/67)	8.0	4/1967-12/1985	4/1967-2/1984	RS CH PT
Soar	Ratcliffe on Soar	4849	SK496293	?			-12/1985		OC CH
Wreake	Syston u/s[4]	4854	SK615125	47.710		414.0	-2/1983		OC CH
Soar	Wanlip d/s[5]	4228	SK603109	?		480.0	3/1970-3/1985		DC CH
Soar	Wanlip u/s[5]	4028	SK603109	46.025	(25/1/81)	480.0	3/1970-1/1986	9/1972-2/1981	CC CH PT
Soar	Zouch	4013	SK498240	31.394		1289.0	7/1961-9/1980		OC CH

[1] Informal low flow structure, drowned out due to weed growth, replaced by South Wigston
[2] Demolished, compound crump which suffered frequent blocking-up of divide piers
[3] Demolished, flat-vee weir located too close to confluence with Sence, experiencing variable backwater at high flows, replaced by Littlethorpe
[4] Replaced by electromagnetic gauge
[5] Badly bypassed

Station 7: the Frisby control structure on the Wreake;

Station 8: the Wreake in the vicinity of Melton Mowbray;

Station 9: Rothley Brook upstream of SK 594 01305.

Those stations cited as upstream of specified grid references relate to catchments regarded as major from the set subject to DTM-assisted backwater analysis.

The aim here will be to compare this idealised gauging network design with the current network in operation, in order to make final recommendations for a modified network, if changes are necessary. There is a near-coincidence of Station 1 with the station on the lower Soar at Kegworth, giving some credibility to the DTM-supported analysis. Station 2 corresponds well to the existing station at Pillings Lock in the middle Soar near Loughborough. This station in the Stage 1 design served as a station on the middle Soar located within the stretch under backwater control. The recommended gauging method was therefore the multipath ultrasonic method; the Pillings Lock gauge is of this type. Whilst the station is susceptible to bypassing, it is generally difficult to avoid bypassing along this stretch of the Soar at higher flows when inundation of the flood plain occurs. Station 3 in the vicinity of Leicester, and chosen to make use of Freemans Weir, is not currently operational. Reference to the closed sites (Table 2.3.1 (b)) indicates that the nearest site is at Belgrave weir, which was considered a possible candidate, but Freemans Weir was preferred on account of no risk of flow bypassing and a higher step-up lessening the risk of drowning out. It is therefore recommended to make Freemans Weir a flow measuring site equipped with an accurate level sensor and maintained rigorously in summer against weed growth on the weir to achieve sensitive flow measurement over this long weir. Station 4 corresponds very well with the position of the existing station on the Upper Soar at Littlethorpe. Station 5 corresponds well with the station operating on the Sence at South Wigston. It is positioned somewhat higher up the Sence than appears necessary to avoid backwater effects from the confluence with the Soar, but is well-sited to receive the first significant tributary of the Sence. Turning now to gauging on the River Wreake, Station 6 corresponds very well indeed with the gauging station at Syston and Station 7, corresponding to the control structure at Frisby, is already a designated level site. A rating curve, based on levels downstream of the gate, was developed in 1993. The gate position, the water level immediately upstream of the gate, the upstream and downstream river levels and lake level are all available on telemetry. The requirement for Station 8 on the Wreake in the vicinity of Melton Mowbray is well met by the existing station on the Eye at Brentingby; Scalford Brook at Melton Mowbray appears less useful, as it monitors a flood retention facility for Melton Mowbray. The suitability of the Brentingby station is considered in the next sub-section. Finally, Station 9 on Rothley Brook corresponds very well to the existing station at Rothley.

2.3.2 Assessment of gauging stations and control structures operating in the Soar catchment

The gauging stations and control structures operating in the Soar catchment are reviewed in this section. Information has been gleaned from IH's Water Data Unit archive, from site visits carried out on 29 June to 1 July and 7 July 1994 and from discussions with Trent Area office staff on 2 August 1994.

Soar at Kegworth

The station is a mono-directional 4-path ultrasonic. Around 1990 it was upgraded from single-path to multi-path, but the cable was never replaced. This impairs the accuracy of low flow measurements and installation of a new cable in 1995 is being considered. Measurements at the high end are good. Gauging is done on the non-navigable channel, being too dangerous on the navigable reach. Ratcliffe ford is downstream and allowance is made for inputs between the gauge and the ford. Ultrasonic measurements have tied in well with gaugings. The NRA have considered installation of a cableway at Kegworth but have concluded that it is not practical.

It is estimated that the river/navigation channel and retaining wall on the right side of the right bank towpath will contain up to the 10 year return period flood. Higher events will by-pass the station on the right bank flood plain, and these are not monitored.

The station has been equipped with DTS TG1150 telemetry since ~ 1985, the start of digital records; Ott chart records are available back to December 1978. Prior to ~ 1990 there are large gaps in the flow record, although the level record is complete.

Soar at Zouch Sluice Gate

This continuously balanced radial gate commences opening at a water level of 34.82 mAOD, to maintain a fixed level upstream within 100 to 150 mm, closing again at this level. There are two non-standard side spill weirs from the river/navigation canal. Downstream on the left bank is a flood embankment designed to a 10 year standard.

The gate is equipped with a gate angle sensor but the values given cannot be interpreted at present in terms of gate angle. Lewin and Fryer were responsible for the gate. Some old records exist in printout form. The gate is equipped with a shaft encoder. Due to chambers becoming blocked there has been a change-over to ultrasonic level measurement. The gate has operated since 1993 and was installed by Anglian Engineering Services. DTS TG1150 telemetry is operated for the benefit of NRA Trent Area Operations.

The combination of control structures and road across the flood plain downstream of the site would make this the easiest of the lower Soar structures to calibrate accurately as a flow measurement site. A rating curve based on river levels downstream of the gate, was incorporated in the Flood Forecasting System around August 1994.

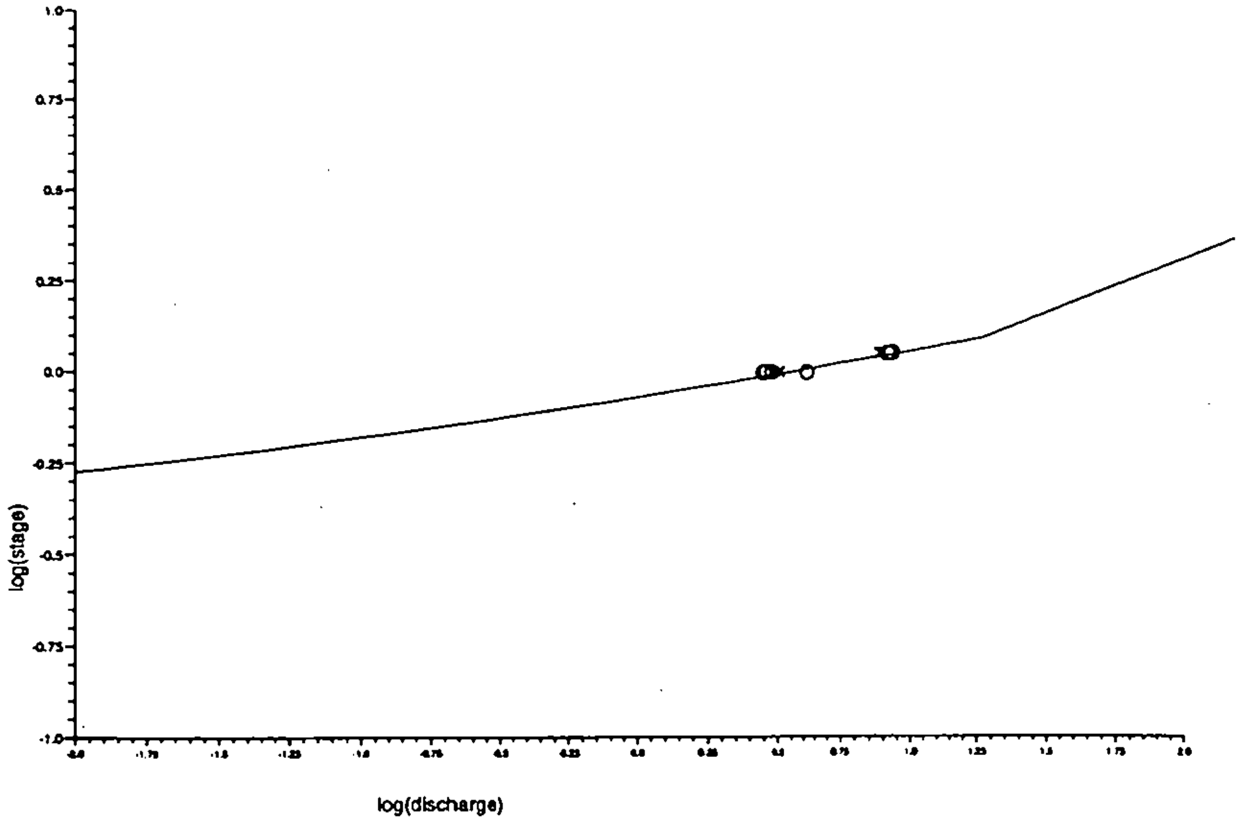
Soar at Pillings Lock

This site employs multi-path cross-path ultrasonic sensors within the channel and on the left-bank floodplain. At this location, upstream of Pilling's Lock, the main channel contains both the river and navigation canal. The choice of the multi-path cross-path ultrasonic at this site is sensible. It is tolerant of backwater effects, for example induced by navigation level controls and downstream weed growth (British Standard, 1993a). The multi-path design accommodates the effect of an unsteady velocity profile induced by backwater whilst the cross-path design can ameliorate effects of variations in flow path deviation. Since the ultrasonic method, unlike the electromagnetic method (British Standard, 1993b), is sensitive to weed growth (causing signal attenuation) it is important that the section be clear of weeds. This is not a major problem at this site although weed cutting is undertaken when necessary.

Of the 24 ultrasonic transducers (4 transducers at each of 6 levels) used in the main channel, the lowest four on the right bank at the lowest two levels are covered by silt. The cause is attributed to the original design assuming that the weir at Pillings Lock would be removed or lowered, with a regrading of the bed upstream lowering bed levels by ~ 1m. This did not occur in practice. The silting problem, as well as affecting velocity determination, will have an effect on the conversion of velocity to flow which depends on a stable relation between water depth and cross-sectional area. Assuming the bed has now stabilised, relocation of the sensors and resurvey of the gauged reach needs to be considered; in any case annual re-survey of the reach is standard practice. It is not thought that the new radial flood gate and bypass channel, under construction in the vicinity, will impact on current bed levels. The impact of silting on flow measurement accuracy will be greatest at low flows and is unlikely to be of concern at high flows.

An attempt has been made at Pillings to measure the bypass flows by installing ultrasonic sensors on the left-bank flood plain, the right bank being contained by a flood bank. The two groups of four transducers on the left-bank floodplain have been installed at 0.6 m above the ground, requiring a water depth of 0.2 m above this to start recording. Their location was based on siting one set below the 100 year flood level and the other between this and the 50 year level. Specifically, the NRA's estimate of the 100 year flood level is 40.2- 40.4 mAOD and the sensor paths are at 40.05 and 39.75 mAOD, recording with respect to a datum of 38 mAOD. Flood estimates obtained by HR from a Flucomp model gave values of 40.535 and 40.206 mAOD for return periods of 100 and 50 years and 40.191 and 40.109 under proposed flood protection scheme conditions (probably somewhat different to those implemented). Taking the lower sensor elevation of 39.75 and adding .2 m gives a minimum level of recording of 39.95 mAOD, which is .159 m below the 50 year level with the flood defence protection scheme in place. It is therefore not immediately obvious that the sensors have been set higher than planned, as has been suggested. However, a lower level setting would seem advisable to measure velocities of floodplain flows above the 10 year level used in the design of bank protection works for this stretch of river. In practice no records of the sensors operating under flood conditions exist but this does not necessarily imply that the sensors have never been submerged. A serial data logger with a barrel memory, which may only be visited as rarely as every 2 years, may have overwritten recorded data. Steps are being taken to improve the situation by downloading the path velocities using remote access software and an autopolling routine. There are still doubts as to whether the sensors have been installed too high and it is recommended that all aspects of the flood plain sensor installation be reviewed.

The ditch adjacent to the towpath on the left bank has been current metered and attempts to meter flows on the left flood plain have been made, although no substantial data exist. Flood Defence have plans to divert the ditch, which will make estimation of flood plain flows easier. Out-of-bank flow on the right bank is returned to the main channel upstream of the station by a transverse bank. Gauging is done by boat downstream of the weir structure, and the lock is ideally closed when gauging is in progress. There is a tendency for the ultrasonic to overestimate flows above 600 Ml/d by 60 or 70 Ml/d. The lock gates may leak, accounting for some error where water is lost to the gauged measurement. The Flood Forecasting System overestimates at Pillings generally. Figure 2.3.3 shows the rating curve for this station along with check current meter gaugings (cross) and the ultrasonic estimate (circle). This, and subsequent curves, are plotted using a $\log_{10}$ scale where -2, -1, 0, 1, 2 refer to .01, .1, 1, 10, 100 units of measurement; the units used are m^3s^{-1} for flow and m for stage.



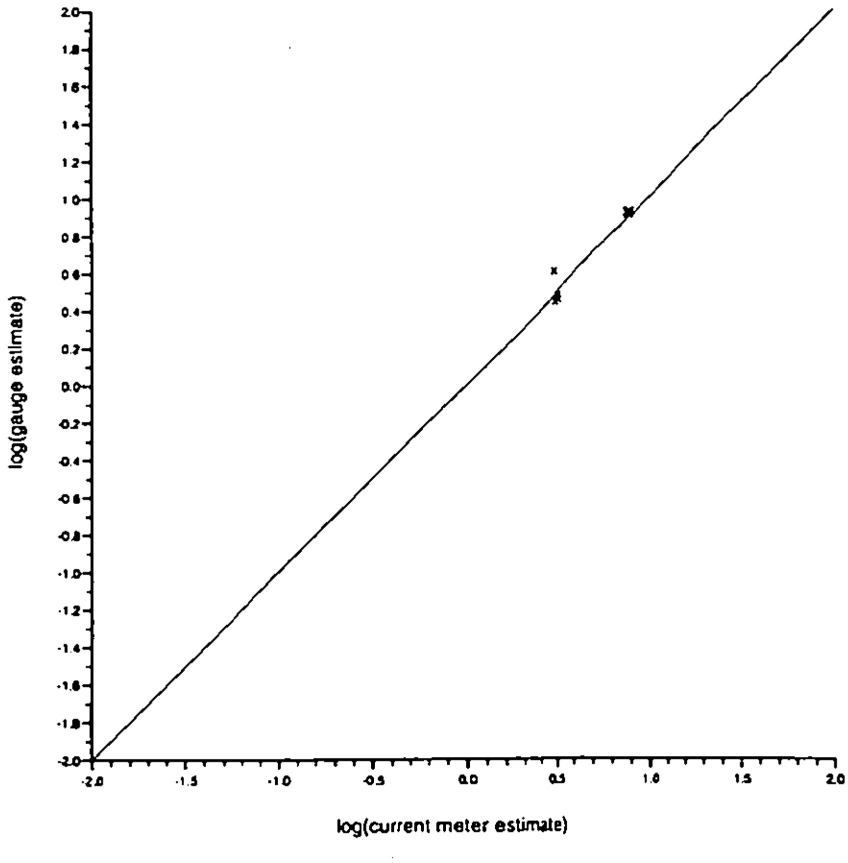


Figure 2.3.3 Stage-discharge curve for the Soar at Pillings along with current meter (crosses) and ultrasonic (circles) estimates

In general the site is not a good one with a slow bend upstream, although this will improve with the new works. A radial control gate is under construction on the right bank of the weir at Pilling's Lock, downstream of the gauging station. This gate, along with channel works upstream to Barrow-upon-Soar, will form the upstream limit of flood protection works for the Soar.

The station is equipped with DTS TG1150 telemetry and records began in February 1985.

Soar at Littlethorpe

This electromagnetic station in a straight reach suffers under high flows due to significant bypassing. Bypassing occurs even when flows are in-bank, leading to underestimation of flows. Flood flows are contained by the left bank but bypassing on the right bank occurs for medium return period floods, coming out-of-bank immediately downstream of the two bridges through the road embankment upstream of the station. One bridge opening is for the main river channel and the other for a flood relief channel which enters on the right bank just upstream of the station. Water backs up in an area of depressed land where this channel enters the main river, leading to standing water. The station is satisfactory other than at high flows when bypassing occurs. It is prone to weed growth, and occasional rubbish collected in the channel, but these have little impact on the performance of the em gauge. The em station, installed in 1982 to support flood forecasting, replaced the Soar at Narborough with which its records are combined. The Narborough records date back to May 1973 but high flows are affected by variable backwater from the Soar's confluence with the Sence. Figure 2.3.4 shows the stage-discharge curve along with current meter gaugings (crosses) and the electromagnetic gauge estimates (circles). There is a tendency for the electromagnetic measurement to overestimate at the highest flows.

The station is equipped with DTS TG1150 telemetry and an Ott chart recorder. Records from the em gauge began in November 1981.

There is clearly scope for improvement of flow measurement at high flows, when bypassing occurs, at this site. The NRA are considering extending the em insulating membrane up the right flood bank, and raising the bank level by .5 to 1 m over a length of 50-70 m, to increase the range over which em measurements are reliable. In addition, a current meter gauging programme from the bridge and in the bypass culverts is ongoing. This study recommends that the improvements under consideration be adopted. The cost of floodbank raising and membrane extension is estimated at £5-7K and £12K respectively.

Sence at South Wigston

This electromagnetic station is fully contained in 1:1 formalised banks, with high flood embankments on either side; only a little bypassing occurs on the left bank at extreme flows. The site is on a slight bend both immediately downstream and upstream where there is a mill stream confluence, causing skewed flows, but the electromagnetic sensor is designed to cope with such conditions. There is seasonal weed growth. Check current metering is carried out along the upstream face of the bridge, upstream of the station. The station replaces the Sence at Blaby (28054). Figure 2.3.5 presents the stage-discharge curve for this station along with current meter gaugings (crosses) and the corresponding electromagnetic (circles) estimates. The correspondence is encouraging.

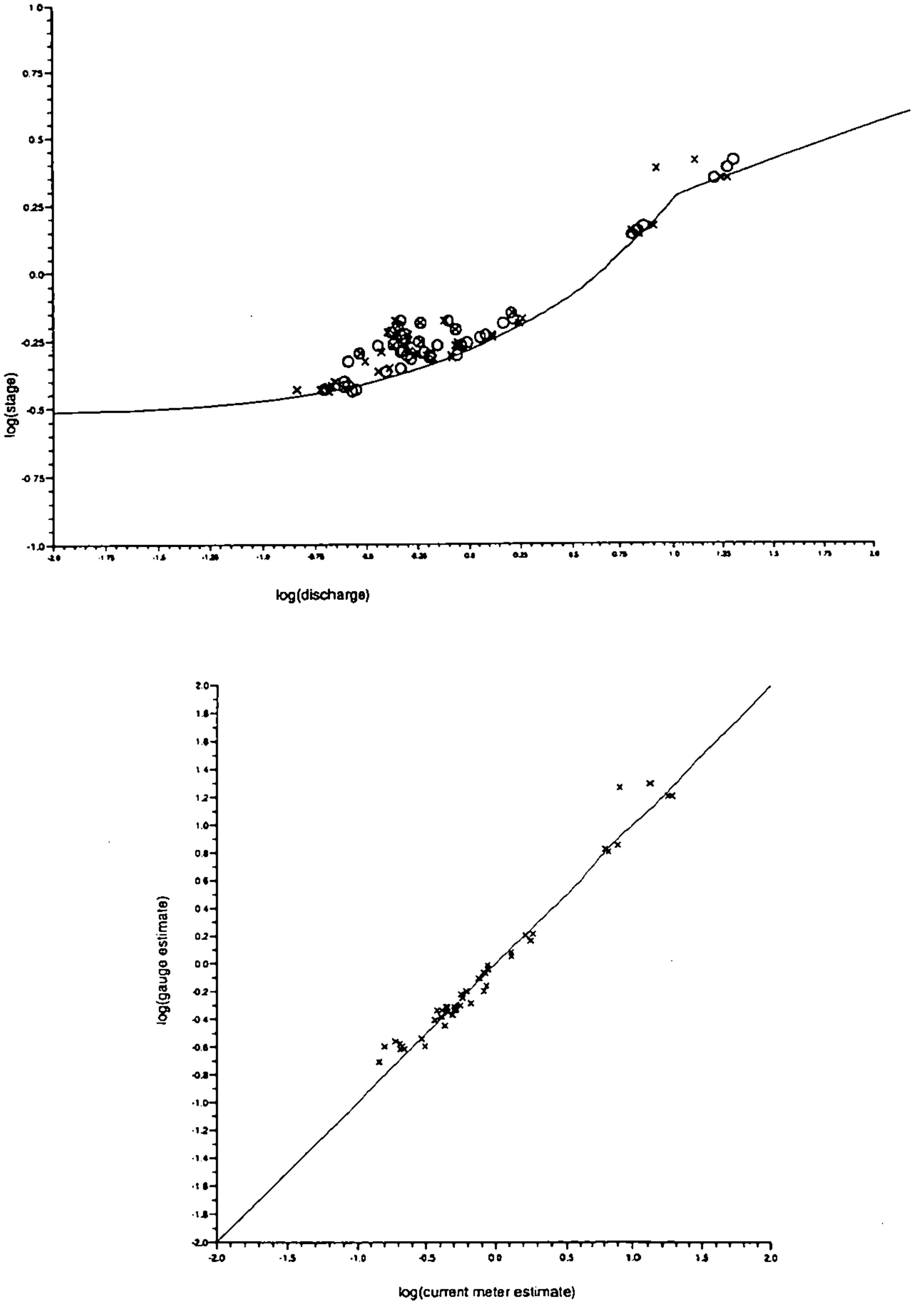
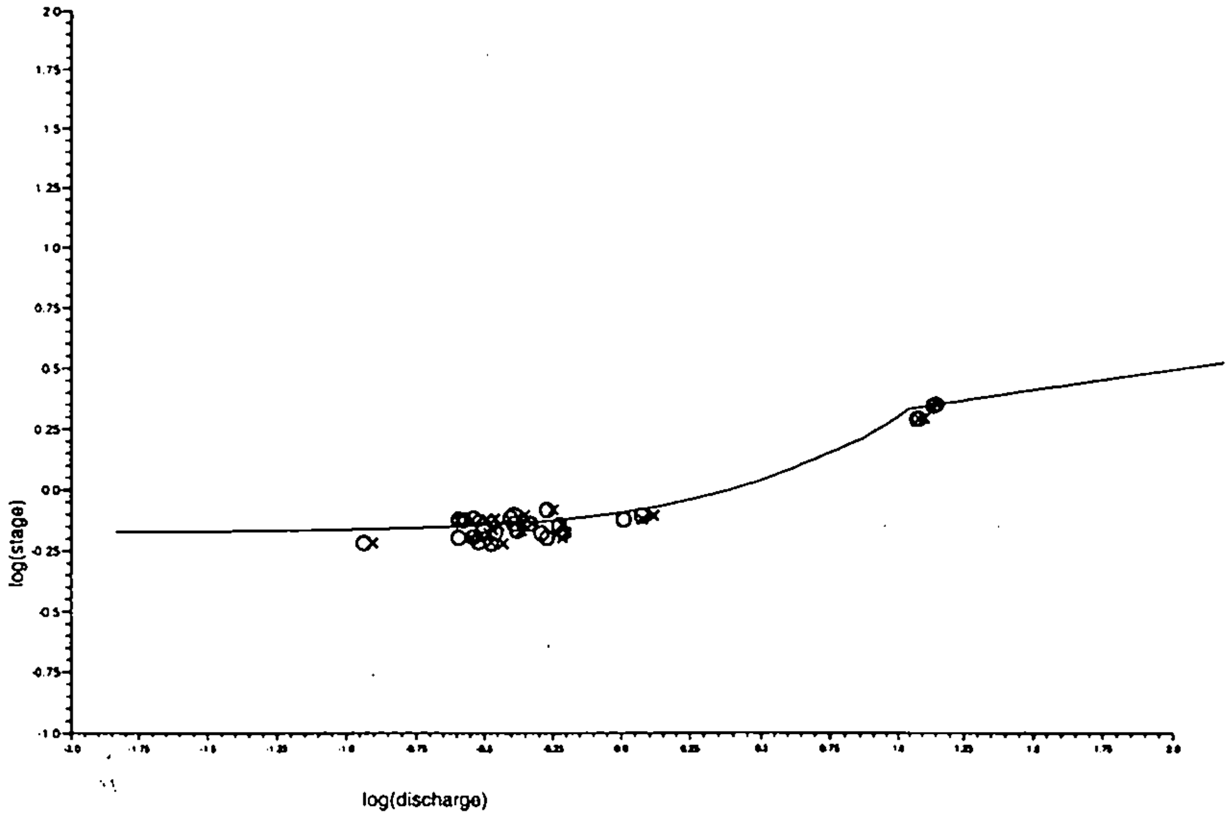


Figure 2.3.4 Stage-discharge curve for the Soar at Littlethorpe along with current meter (crosses) and electromagnetic (circles) estimates



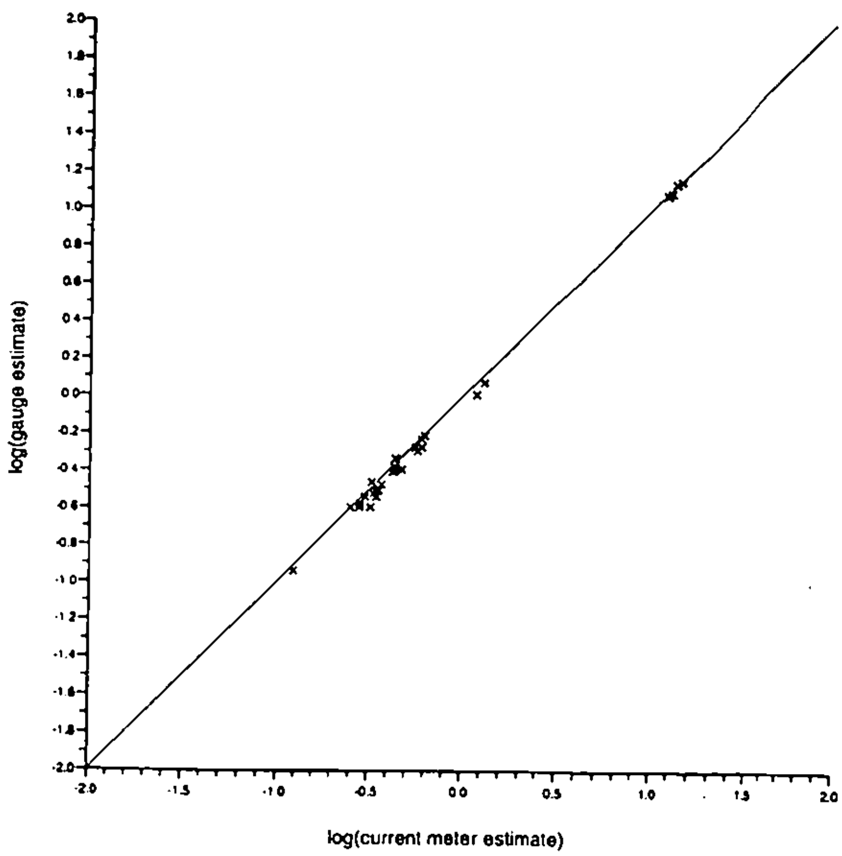


Figure 2.3.5 Stage-discharge curve for the Sence at South Wigston along with current meter (crosses) and electromagnetic (circles) estimates

The station is equipped with DTS TG1150 telemetry and an Ott chart recorder. Records began in September 1983.

Wreake at Syston

This is an electromagnetic station which suffers from flow reversals at all flows on the right bank, but the specially constructed section is very rarely bypassed. The right side of the channel is silted up, implying the channel section is too wide. NRA are considering redesigning the section to be a two-stage channel and may commission a physical modelling study to support this. The station is located at the backwater limit of influence of the Soar, Wreake and Grand Union Canal. Check current meterings have been taken from the footbridge at the upstream end of the metering section but a cableway upstream is also being considered. It is thought that the design of the bridge and flood openings for the Syston Bypass might have been adversely affected by the use of poor em gauge records. However, a gauged figure of 2903 Ml/d, including bypassed flows, might be seen to compare favourably with 2694-2567 Ml/d, without bypassed flows, measured by the electromagnetic.

The station has operated as an electromagnetic station since 1982. From July 1967 to 1982 a flume was used and this suffered from bypassing on the left bank with the flow coming through four flood openings in the railway embankment upstream. The station is equipped with DTS TG1150 telemetry and an Ott chart recorder.

Successful calibration of the hydrodynamic model of the lower Soar and the operation of the flow forecasting system will both need good knowledge of the flow from the River Wreake catchment into the Soar. The gauging station at Syston, as the lowest on the Wreake, is clearly very important in this regard. In order to confirm the design of the changes to the section geometry under consideration by the NRA, we recommend that a model investigation is carried out for the site to ensure that the revised section at the gauge produces the required minimum velocity under a range of flow and tailwater conditions. A 1-D model such as the ONDA or ISIS software is not really appropriate for this task since it cannot resolve the local detail of the flow. A better alternative to support the re-engineering of the gauging section will be to construct a natural scale physical model which can represent the true variation of velocity at the section. A further alternative might be to use a 3-D model such as Phoenics to represent the section. However, this approach would be more appropriate for a research demonstration exercise as the performance of the current generation of 3-D turbulence modelling software still requires validation.

Wreake at Frisby-on-Wreake

In normal conditions the flood control gate, hinged to the bed, lies flat. When the downstream level reaches 61.7 mAOD the gate is lifted off the bed by the action of hydraulic pistons and flow upstream is diverted into former gravel workings, which are now landscaped storage ponds used for recreation. When the level in the storage ponds reaches 63.5 mAOD the gate is lowered and the flow allowed to pass downstream freely, irrespective of the level downstream. The levels downstream and upstream of the structure and in the storage ponds are measured by downward pointing ultrasonic transducers. On recession the stored flow is released back to the river through a bank of four flap gates in the wall of the control structure upstream of the control gate. The control gate, when flush with the bed, has a crest level of 60.5 and 63.3 mAOD when fully raised. The electric powered gate is automatic but there is a manual system in the event of power failure: normal practice during an event is for two staff to be in attendance to support gate operation. Possibly as a result of using inaccurate flow measurements from Syston gauging station the gate/lake control may be underdesigned and only able to provide flood storage up to the 5 year event.

The gate at Frisby can be operated manually to higher levels to fill the lake, thereby protecting nearby vulnerable properties. It is very probable that the lake overfilled under manual control on 24-26 February 1994. An old canal feeder has been used to form a bypass channel around the gate. The gate movement is currently too slow, possibly being fixed on the maximum 30 minute delay: the timers have recently gone back for recalibration and reinstalled.

This flood control structure is on DTS TG1150 telemetry in support of the NRA Trent Area's operations responsibilities. In the past, use of pressure transducers for level measurement meant that levels were not recorded over their full operational range: historical records are therefore problematic to use. The stage-discharge relation has been developed from gaugings and is satisfactory for low flows mainly. Current metering in the downstream channel is being undertaken to establish the flow corresponding to the control level of 61.7 mAOD. Level records began in March 1988.

Wreake at Eye Kettleby

The gate/sluice/weir complex is operated to maintain water levels through the town of Melton Mowbray. A vertical lift gate flanked by concrete wall weirs discharging onto a masonry spillway forms the main control structure. Two sluice gate are located to the left of the gate, incorporated in the left bank concrete wall. A disused canal to the right of the river has twin sluice gates located on the upstream cill of the old lock chamber. The penstocks are never opened (they are seized up), but might be one day in a severe flood at Melton Mowbray. Operation of the gate is the responsibility of NRA (Operations). The NRA have proposed sensors on the gate to allow it to be used as a measuring structure. It should be satisfactory for low flows but difficult at high flows. The levels upstream and downstream of the gate have been on TG 1150 telemetry since 10 May 1994. It is recommended that the gate position is also put on telemetry in support of the forecasting system.

A gauging station, about 400 m downstream of the Eye Kettleby flood gate and just downstream of the outfall from Melton Mowbray sewage farm, was removed earlier this year (1994). Level records from an Ott chart recorder are available from January 1990.

Eye at Brentingby

This is a flood defence station equipped with an R16 Ott level (vertically mounted weekly chart) recorder but no rating. The site was installed in planning a new railway crossing in the vicinity of Melton Mowbray when data were needed to support modelling work. There are also some maximum level tubes in the vicinity. The site was first monitored from 1979 to the mid 1980's and then from 1990 to the present. Flows are mainly contained within the incised channel but NRA staff have observed shallow flood depths on the right flood plain. The recorder is sited on the outside of a bend in the channel, approximately 20 m upstream of a single span brick arch bridge.

The station is equipped with an Ott chart recorder only and records started in January 1979.

The station is under review and there is a danger that the recorder may be due for removal. This location has been identified in this study as of value to the flood forecasting system. The suitability of this site is in urgent need of investigation. It is recommended that this station be considered for upgrading and a programme of current metering instigated if the site proves suitable.

Scalford Brook at Melton Mowbray

This site is at Scalford Dam and reservoir and is equipped with pressure transducers upstream in the reservoir and in a pond downstream. The reservoir was constructed to counter flooding in Melton Mowbray by Scalford Brook and also to allow development of the catchment for residential purposes. The reservoir is impounded by an earthfill dam, called Scalford Dam, with two grasscrete spillways at each end of the dam crest, plus a grasscrete overspill at its centre, with a crest 0.3 to 0.6 m below the main crest level. Flow is normally through a 1.5-2 m concrete pipe at the foot of the dam, dropping into a forebay over a concrete surround wall. The downstream end of the pipe discharges into a small lake with an offset outlet, controlled by a concrete wall weir, passing water back into the brook downstream. During floods, flow through the pipe can be stopped by a manually operated penstock operated from the top of the dam. This acts as a throttle with water building up behind it. The penstock might be opened up during flood time.

The dam and reservoir is owned and operated by Melton Borough Council and is developed as a country park. The NRA maintain the DTS Telegen 1150 telemetry and the Borough Council would like them to take over responsibility for operation of the dam as well. This is likely to happen in the future. The upstream pressure transducer in the main reservoir has been offline for some time. There is no flow measurement.

Records began in October 1991.

Rothley Brook at Rothley

This is a rated structure of Crump profile flat-vee weir type in a trapezoidal channel. The site is quite good and although it suffers from weed is well maintained. Bypassing can occur at only very high flows, when water can overtop the right bank immediately upstream of station, ponding in a low lying area adjacent to the station. There is some backwater influence from the old twin-span arched bridge (a listed structure) about 20 m downstream. There is no crest tapping or downstream recorder but flows can become non-modular, drowning out when the head on the weir reaches about 0.4 m. Current metering of higher flood flows is undertaken from the clear span bridge approximately 100 m downstream of the station. Figure 2.3.6 presents the stage-discharge curve for this station along with the check gaugings which are well aligned except for some scatter at the higher flows. There are no flood warnings currently provided for Rothley Brook.

The station is equipped with DTS TG1150 telemetry and an Ott chart recorder. Records began in May 1973.

Potential gauging sites on the Soar near Leicester

(a) Freemans Weir

Whilst the Soar is in-bank at this site during floods the long length of the weir makes it insensitive as a gauging structure and is not currently used. However, the use of accurate level sensors might provide the necessary sensitivity and might be considered in the future.

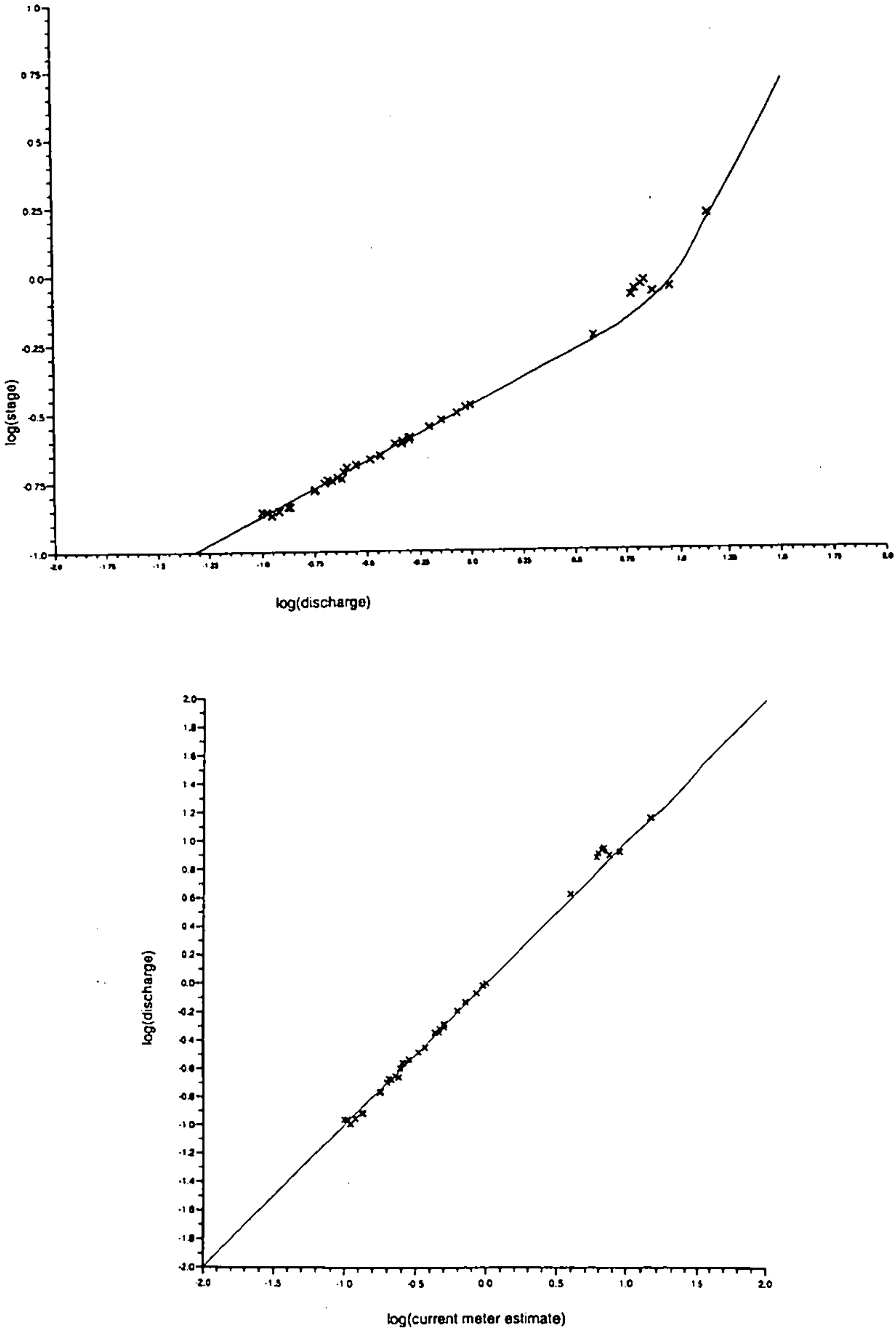


Figure 2.3.6 Stage-discharge curve for Rothley Brook along with current meter estimates

Its high crest level will preclude drowning of this non-standard weir profile.

(b) Belgrave Weir

This is located such as to pick up the urban runoff from Leicester, and this is its main advantage over Freemans Weir. However, it may possibly have a small bypass flow on its left side; also its high crest is not as high as Freemans Weir.

Theoretical ratings could be developed for either weir, provided accurate water levels can be obtained. It is possible that some work has already been undertaken for Freemans Weir.

Black Brook at Onebarrow

This station has been discontinued but there is a substantial weir structure existing. Because of its situation upstream of the reservoir it is of limited use for flood forecasting. It would also be costly to reinstate it as a gauging station. The bridge is dangerous. It was probably originally built to support drainage studies.

British Waterways Sluices

Whilst the sluices are operated normally by the BWB the NRA may close one at Zouch where it is adversely affecting retained (navigation) levels. Some sluices are not operated, but the NRA believe it might help if they were during times of flood.

2.4 WEATHER STATION NETWORK

There are two climate stations in the vicinity of the Soar catchment, one at Narborough (SP 549 966) at an elevation of 74 m and the other at Brooksby (SK 679 154) at an elevation of 70 m. Both stations record air temperature, wind run and rainfall and are on telemetry; records are not archived routinely. The Brooksby station is run by the Brooksby College of Agriculture at a cost of £1200 per annum. There are plans to close the site. The station has a good central location within the Soar basin and the existing telemetry outstation has the capacity to support 8 active analogue signals and 16 digital ones. It is recommended that Brooksby be used as the recommended site for the weather station proposed under Stage 1. The actual area occupied could be halved with the closure of the manually read instrumentation and additional sensors added to the existing telemetry installation. These sensors would measure wet bulb temperature, net radiation, incoming solar radiation and wind direction. An important advantage of using this existing site is that it will preserve continuity of historical records at a station previously destined for closure.

2.5 SOIL WATER MEASUREMENT NETWORK

There are no facilities to measure soil moisture in the Soar catchment. Use of the Met. Office's derived grid estimates of soil moisture deficit from the Morecs system is made as part of the reciprocal arrangement whereby NRA-ST provide data from selected raingauges. As indicated in this Stage 1 report the value of a soil water station, incorporating capacitance probes and tensiometers, should be assessed once the results of ongoing research at IH become available. Such data may be of use in correcting the soil moisture store contents of a catchment model, as part of a state updating procedure.

3. Models for Flood Forecasting

3.1 INTRODUCTION

This Section reviews the models in current use for forecasting in the Soar catchment and an assessment of their suitability compared with those proposed under Stage 1. Other issues addressed are techniques for model calibration, for forecast updating, for rainfall forecasting and for deciding when to warn.

3.2 RAINFALL-RUNOFF MODELStw

3.2.1 Introduction

The Stage 1 report recommended that 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. As one example of this type of model, the PDM was suggested which had the further advantages of being specifically tailored for real-time use and capable of representing a considerable variety of catchment response behaviours. In practice the catchment model used in the Severn-Trent Flow Forecasting System (ST-FFS) is of the type recommended and this model is first reviewed in the next section. It is then compared to the PDM model formulation in order to make a recommendation on the form of rainfall-runoff model to adopt for forecasting the flood response of the Soar sub-catchments.

3.2.2 The Severn Trent Catchment Runoff Model

The rainfall-runoff catchment model used in the ST-FFS is based on classical conceptual soil moisture accounting principles. An outline of the model is provided by Bailey & Dobson (1981) and a schematic of the model structure is shown in Figure 3.2.1. The model comprises three main stores: an interception store, a soil moisture store and a groundwater store. Rapid runoff is generated from the soil moisture store, the proportion of the input to the store becoming runoff increasing exponentially with decreasing soil moisture deficit. "Percolation" to the groundwater store occurs when the soil is supersaturated, increasing as a linear function of the negative deficit. When supersaturation exceeds a critical value "rapid drainage" also occurs as a power function of the negative deficit in excess of the critical value (the so-called excess water). This rapid drainage along with rapid runoff forms the soil store runoff. Evaporation occurs preferentially from the interception store at a rate which is a fixed proportion of the catchment potential evaporation. A proportion of any residual evaporation demand is then met by water in the soil store, the proportion varying as a function of the soil moisture deficit. Drainage of the groundwater store to baseflow varies as a power function of water in storage, the exponent being fixed at 1.5. The total output, made up of baseflow and soil store runoff, is then lagged and spread evenly over a specified duration to represent the effect of translation of water from the ground to the catchment outlet. Finally, the flow is smoothed using two non-linear storage functions, one for routing in-bank flow and the other out-of-bank flow, the two components being summed to give the catchment model outflow.

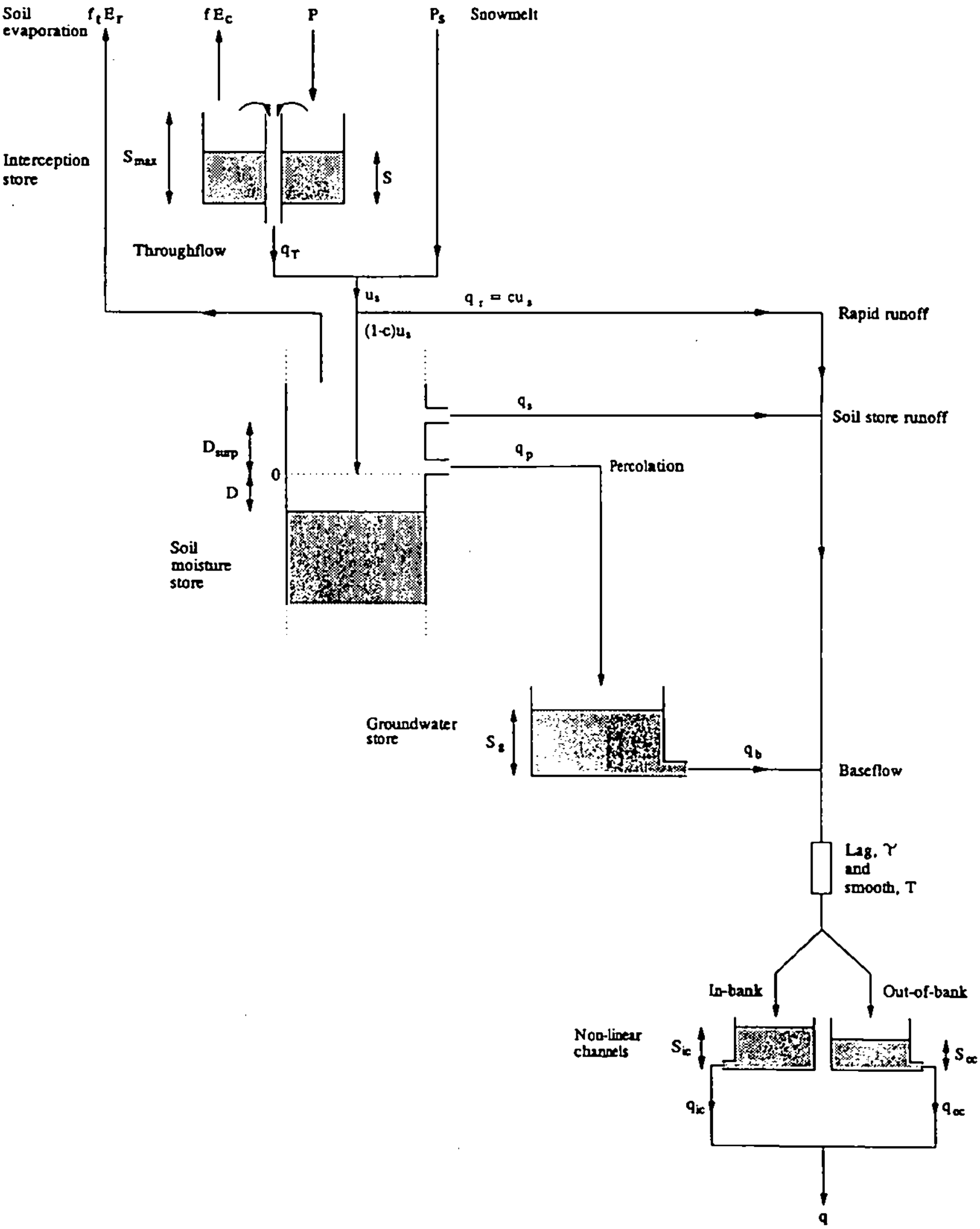


Figure 3.2.1 The Severn-Trent Catchment Runoff Model

The more detailed operation of each component of the Severn Trent Catchment Runoff Model will now be considered.

1. Interception store

The interception store operates as a simple bucket having a capacity, S_{max}, and with water in storage, S, increasing through the addition of rainwater, P, until full when overflows, q_T, enter the soil store as throughflow. A proportion, f, of the catchment atmospheric demand for evaporation, E_c referred to here as the catchment evaporation, is met by water in the interception store, or by a lesser amount if storage S is not sufficient. Thus we have the following sequential water balance operations for the interception store (dropping time suffixes for simplicity):

Interception Storage $$S = S + P \tag{3.2.1}$$

Throughflow

$$q_T = \begin{cases} S - S_{max} & S > S_{max} \\ 0 & \text{otherwise} \end{cases}$$

$$S = \begin{cases} S_{max} & S > S_{max} \\ S & \text{otherwise} \end{cases} \tag{3.2.2}$$

Potential interception evaporation $$E_p = fE_c \tag{3.2.3}$$

Residual evaporation demand

$$E_r = \begin{cases} E_p - \dfrac{S}{f} & E_p > S > 0 \\ 0 & E_p \le S \le 0 \\ E_c & S \le 0 \end{cases}$$

$$S = \begin{cases} 0 & E_p > S > 0 \\ S - E_p & E_p \le S; S > 0 \end{cases} \tag{3.2.4}$$

$$E_r = E_c \qquad S > 0$$

2. *Soil store*

The soil store has no defined capacity, calculations proceeding on the basis of the amount of water in deficit, D. Input to the soil store, u_s, is made up of throughflow, q_T, from the interception store plus any melt, P_s, from the snowmelt component, so that $u_s = q_t + P_s$. A proportion of the input, c, does not enter the store but forms rapid runoff. This proportion increases as an exponential function of the negative deficit, up to a maximum value c_{max}; thus

Rapid runoff proportion $\quad c = \min(c_{max}, c_o \exp(-c_o D))$ (3.2.5)

Rapid runoff $\quad q_r = c\, u_s$ (3.2.6)

Soil moisture deficit $\quad D = D - (1 - c)\, u_s.$ (3.2.7)

In practice the calculation is carried out incrementally, for each unit of input u_s, and the q_r values summed to account more accurately for the nonlinear dependence of the runoff proportion on the negative deficit.

Percolation to groundwater occurs only for negative deficits ($D < 0$) when it is governed by the equation.

$$q_p = \begin{cases} \dfrac{q_p^{max} D}{-D_{surp}} & q_p \leq q_p^{max} \\ q_p^{max} & \text{otherwise} \end{cases} \tag{3.2.8}$$

where q_p^{max} is the maximum percolation rate parameter and D_{surp} is the soil store moisture surplus parameter. The deficit is updated using

$$D = D + q_p. \tag{3.2.9}$$

Rapid drainage, q_d, which like rapid runoff bypasses the groundwater store, is generated when the negative deficit exceeds a critical value, D_{surp}, and gives rise to "excess water" conditions. Excess water is given by

$$W = -(D_{surp} + D) \qquad D < -D_{surp} \tag{3.2.10}$$

and rapid drainage is governed by the power function

$$q_d = \frac{W^{\gamma_d}}{k_d} \tag{3.2.11}$$

where γ_d is a soil function exponent and k_d is a soil function coefficient. The deficit is updated using

$$D = D + q_d\ . \tag{3.2.12}$$

Soil store runoff, q_s, is then

$$q_s = q_r + q_d. \tag{3.2.13}$$

Finally, the soil store is further depleted by any residual evaporation demand, E_r, according to the soil water evaporation function which gives soil evaporation as

$$E_s = f_t E_r \qquad (3.2.14)$$

where the transpiration factor, f_t, is given by

$$f_t = \begin{cases} T_p & D < E^D_{max} \\ T_m & D > E^D_{min} \\ T_p - \dfrac{(D - E^D_{max})(T_p - T_m)}{E^D_{min} - E^D_{max}} & \text{otherwise} \end{cases} \qquad (3.2.15)$$

with $T_m \leq f_t \leq T_p$. Here T_p and T_m are the potential and maximum transpiration parameters and E^D_{max} and E^D_{min} the corresponding deficit values at which these limiting conditions first apply.

Finally, the soil moisture deficit is updated using

$$D = D + E_s . \qquad (3.2.16)$$

3. Groundwater store

The groundwater store behaves as a non-linear storage with an exponent value of 1.5. It receives percolation, q_p, from the soil moisture store as input and output is baseflow, q_b. The groundwater storage is updated according to

$$S_g = S_g + q_p \qquad q_p > 0 \qquad (3.2.17)$$

and baseflow is given by the storage function

$$q_b = \frac{S_g^{1.5}}{1000\mathrm{k}_g} . \qquad (3.2.18)$$

Adjustment to the storage then follows as

$$S_g = \begin{cases} S_g - q_b & S_g > 0 \\ 0 & \text{otherwise.} \end{cases} \qquad (3.2.19)$$

4. Lag and spread of catchment runoff

The total runoff is the sum of baseflow and soil store runoff, $q_b + q_s$. This is lagged by a fixed time interval, τ, and spread evenly over a specified duration, T, in order to represent the translation of water from the ground to the catchment outlet.

5. Nonlinear smoothing of catchment runoff

The last operation in the Severn Trent Catchment Runoff Model is the application of a nonlinear smoothing function to produce a smooth catchment outflow hydrograph. Nonlinear storage functions are used for in-bank and out-of-bank flows, which are treated separately as follows. The out-of-bank component of the input and in-channel storage are calculated as

$$u_{oc} = \begin{cases} S_{ic} - S_{bf} & S_{ic} > S_{bf} \\ 0 & \text{otherwise} \end{cases} \tag{3.2.20}$$

$$S_{ic} = S_{bf} \qquad S_{ic} > S_{b} \ .$$

The in-channel outflow is given by the nonlinear storage function

$$q_{ic} = \begin{cases} k_{cr} S_{ic}^{\gamma_{cr}} & q_{ic} \leq .75 S_{ic} \\ .75 S_{ic} & \text{otherwise} \end{cases} \tag{3.2.21}$$

where k_{cr} and γ_{cr} are the in-channel routing coefficient and exponent. A similar expression is used to obtain the out-of-bank outflow, q_{oc}, from the out-of-bank storage, S_{oc}. Updating of the in-channel storage follows

$$S_{ic} = S_{ic} - q_{ic} \tag{3.2.22}$$

and for the out-of-channel store

$$S_{oc} = S_{oc} + u_{oc} \ . \tag{3.2.23}$$

Finally, the total catchment outflowe is calculated as

$$q = q_{ic} + q_{oc} \ . \tag{3.2.24}$$

3.2.3 Comparison with the PDM model

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 3.2.2 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.

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

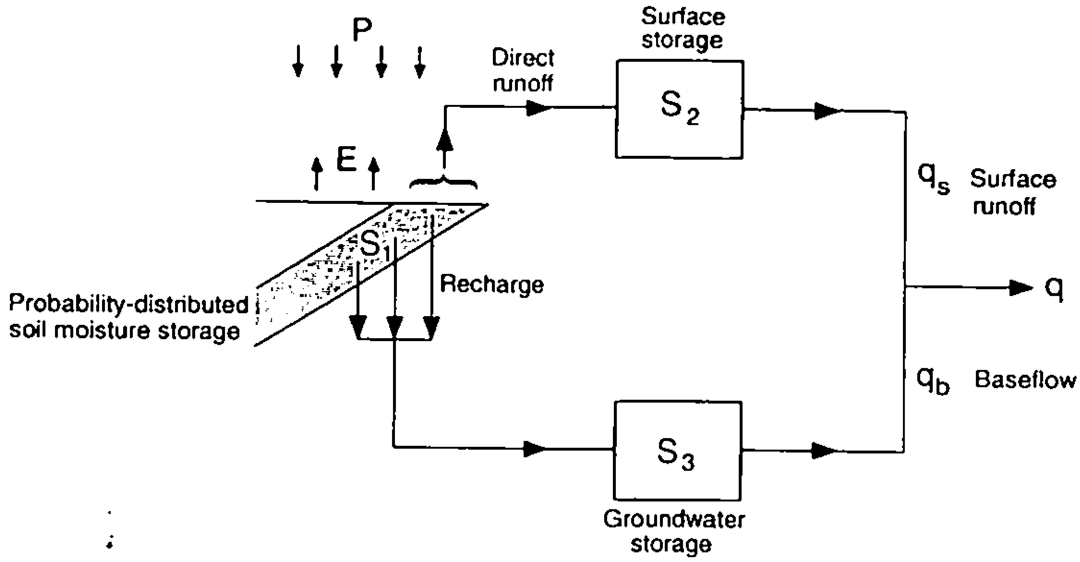


Figure 3.2.2 The PDM rainfall-runoff model

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 (1992a).

It is always difficult to assess the pros and cons of a particular conceptual rainfall-runoff without formal empirical evaluation, and even then the results are seldom clear-cut. The comparison of the Severn-Trent Catchment Runoff Model, or ST-CRM, with the PDM model recommended in Stage 1 is no exception. An analysis of 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. Indeed this commonality of model component has been exploited in the development of the PDM model. In common with the ST-CRM it conceptualises the catchment into a soil moisture store, a groundwater store and river channel stores. Rather than separate interception and soil moisture stores the PDM adopts a parsimonious representation in which the absorption capacity concept is used to unify these conceptual elements. An important extension offered by the PDM is the representation of moisture storage in distributed form, using the probability distributed concept. Through analytical integration simple algebraic expressions are obtained for the catchment response to runoff for a range of plausible distributions of absorption capacity over the basin.

In both models nonlinear storage elements are used to represent groundwater storage and the baseflow derived from it. In the case of the PDM a wide range of power functions of storage are permitted and the solutions used have been derived in continuous time assuming a constant input over the interval of integration. Simple analytical solutions to certain specific cases, such as linear, quadratic and exponential functions of storage, are employed. In contrast, the ST-CRM employs less rigorous discrete time updates without reference to the underlying continuity equation expressed as a differential equation. Use of the differential equation form for continuity ensures that proper account is taken of the difference between water volumes discharged over a specified interval and discharge rates at a specified instant. Also changing the time step of the model can be done in a rigorous way, allowing model parameters to remain unchanged in certain cases. This has allowed the PDM model to be implemented at 5 minute, 15 minute, hourly and daily time-steps for different applications. The PDM calibration code also allows 15-minute event data to be used in conjunction with continuous daily rainfall (and flow) data to allow a continuous water balance to be maintained between events, ensuring antecedent conditions prior to each event are properly initialised. Reference to daily flows also allows a sub-calibration on the parameters important to the long-term water balance of a catchment to be performed over several seasons. A second calibration step can then focus on the parameters dominating the short-term storm dynamics.

For channel routing the ST-CRM again employs nonlinear reservoirs, in conjunction with a lag and smooth function, equivalent to the classical time-area diagram operation. The PDM offers a range of functions including the nonlinear reservoirs described above together with a cascade of two linear reservoirs, expressed as a discrete-time equivalent transfer function formulation. The latter is most commonly used and is again formulated rigorously, starting with the underlying differential equation of continuity, before obtaining a simple close-formed solution which can be quickly computed at each time-step. The explicit modelling of in-bank and out-of-bank flows in the ST-CRM may be seen as an advantage, but may not be justified as a component in a catchment model due to the increased parameterisation and probable lack of parameter identifiability. However, an empirical assessment is needed to assess its true worth.

With the various thresholds operating in the ST-CRM interception and soil storages, and in the channel/flood plain component, it is likely that parameter optimisation will be more difficult than for the PDM. An advantage of the distributed moisture storage concept used in the PDM is that it often involves functions which are continuous and differentiable and therefore more amenable to parameter optimisation.

The PDM calibration facility employs a modified Simplex (polytope) procedure for parameter estimation whilst the Rosenbrock method is used with the ST-CRM. Both methods are suitable for parameter estimation of conceptual hydrological models and whilst the modified Simplex has been preferred for use with the PDM, use of either method is unlikely to be an important factor. Perhaps more important is the PDM's calibration visualisation aid which allows a selected parameter to be incremented and the resulting hydrographs displayed in rapid succession. The facility provides a dynamic image of the optimisation process and an important insight into the function of the chosen parameter. This can be particular important when, as is usually the case for conceptual rainfall-runoff models, there is parameter interdependence and lack of parameter identifiability confusing the optimisation process.

3.2.4 Application to the Soar

The ST-CRM is used as a catchment model for seven sub-catchments of the Soar basin. The model parameters employed are summarised in Table 3.2.1, which also includes those of the snowmelt component of the model which take on identical values across the Soar. Table 3.2.2 provides the catchment details used in combination with each catchment model, and includes information on the gauging station and raingauges used. Note that only four of the catchments relate to gauged stations. The other three relate to lateral inflows from ungauged catchments draining Leicester, the lower Wreake and Loughborough. The latter two catchments are seen as scaled versions of the Rothley Brook at Rothley flows, but forecasts are obtained from catchment models and using raingauges for rainfall input appropriate to each. The model parameters are appropriately modified: for example the runoff coefficient for Loughborough laterals is set at 0.55 compared to Rothley's 0.38 reflecting the urban/rural contrast of the two catchments.

3.3 HYDROLOGICAL CHANNEL FLOW ROUTING MODELS

3.3.1 Introduction

For river reaches not significantly affected by backwater, the Stage 1 report recommended the use of a hydrological channel flow routing model based on the convection diffusion equation, or an approximation to it. As one example of this type of model, the KW model was suggested. It had the further advantage of being tailored for use in real-time. In practice a hydrological channel flow routing is used to model all river reaches of the Soar, even where backwater influences are dominant, such as near control gates. The use of a hydrodynamic model in such situations is discussed later, in Section 3.4. Here, attention will focus on a review of the Severn-Trent reach model followed by an informal assessment of the model, along with the KW model proposed in Stage 1, for use in reaches not significantly affected by backwater.

3.3.2 The Severn Trent DODO model

The hydrological channel flow routing model used in the ST-FFS is called the DODO model (Douglas and Dobson, 1987). This is based on the Muskingum storage function

$$S = K(xu + (1-x)q) \tag{3.3.1a}$$

which relates the volume of water stored in a river reach at time t, $S \equiv S_t$, to the reach inflow, u, and reach outflow $q \equiv q_t$. Thus, channel storage is considered to be the sum of two components: the prism storage, Kq, and the wedge storage K(u-q), as shown in Figure 3.3.1. The effect of wedge storage is to increase the total storage on the rising limb and decrease it when falling, leading to a hysteresis loop in the relation between reach outflow and storage. In the DODO model the reach input u is the delayed input, $u \equiv u_{t-\tau}$, where τ is a pure time delay which is allowed to vary as a function of discharge. This extension to the basic Muskingum model along with a way of representing static storage and flow on floodplains are dealt with later. First, the relationship between the basic in-bank routing model used in the DODO model and the classical Muskingum routing procedure will be established along with its relation to transfer function models.

Table 3.2.1 Catchment model parameter values for the Soar basin (where two values are given, the first indicates the value used before date in brackets)

Parameter	Catchment: Upper Soar to Littlethorpe (28/6/93)	Sence to Sth. Wigston (28/6/93)	Leicester lat.	Upper Wreake to Frisby (6/7/93)	Lower Wreake lat. (6/7/93)	Rothley Bk at Rothley (28/6/93)	Loughborough lat.
Max. temp. snowfall	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Min. dens. snowfall	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Min. temp. snowmelt	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Snowmelt coeff.	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Snowmelt exp.	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Snowpack ripe	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Int. store cap.	0.8	1.1	0.7	1.0	1.0	1.0	1.0
Int. store evap. fac.	1.0	1.0	1.0	1.0	1.0	1.1	1.1
Pot. transp. fac.	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Max. SMD Pot. Evap.	80	90	110	110	110	110	90
SMD min. transp.	150	150	150	150	150	150	150
Min. transp. fac.	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Runoff coeff.	(0.45) 0.64	(0.45) 0.65	0.4	(0.5) 0.55	(0.5) 0.55	0.38	(0.38) 0.55
Runoff exp.	(0.023) 0.025	(0.015) 0.02	0.015	0.017	0.017	0.021	0.018
Max. runoff perc.	(0.7) 0.73	(0.9) 0.85	0.5	(0.6) 0.65	(0.6) 0.65	0.5	(0.56) 0.65
SSM surplus	7.5	10.0	10.0	10.0	10.0	18.0	10.0
S func. coeff.	19.0	20.7	20.0	20.0	20.0	40.0	30.0
S func. exp.	1.89	1.9	1.8	1.4	1.4	1.4	1.4
Max. percoln. rate	0.58	0.5	0.5	0.5	0.5	0.5	0.5
Baseflow coeff.	8.9	9.0	1.4	6.7	6.7	0.9	2.3
Lag time	(1.5) 1.0	(3.0) 2.0	1.5	(1.5) 1.0	(1.5) 1.0	1.5	1.5
Duration resp.	(16.0) 19.0	(17.0) 18.0	20.2	(16.0) 19.0	(16.0) 19.0	16.0	20.0
Chan. rout. coeff.	0.017	0.02	0.022	0.03	0.03	0.02	0.029
Chan. rout. exp.	1.9	1.9	1.9	1.9	1.9	1.9	1.9
FP rout. factor	0.023	0.03	0.025	0.026	0.026	0.03	0.02
FP rout. exp.	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Bankfull flow	(10.0) 7.0	10.0	10.0	15.0	10.0	(7.5) 9.0	10.0
Return flow	(10.0) 7.0	10.0	10.0	15.0	10.0	(7.5) 9.0	10.0
Stat. store cap.	0	0	0	0	0	0	0
Stat. evac. coeff.	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Stat. evac. exp.	1	1	1	1	1	1	1

Table 3.2.2 Catchment details for the Soar basin

Catchment name		U. Soar - Littlethorpe	Sence - Sth. Wigston	Leicester lat	Upper Wreake - Frisby
Forc. rain		Upper Soar	Upper Soar	Upper Soar	Upper Soar
AA Pot. Evap./Area/Altitude/AAR		527/187/100/600	527/124/119.2/620	527/172/75/650	527/256/100/630
Threshold: type/value	1	flow/9.0	flow/7.0		
	2				
	3		flow/7.5		level/2.5
	4	flow/14.0	flow/28.0		
	5				
	6				
Radar: block/point	1	5/35	5/36	5/37	5/38
	2	1/183	1/184	1/185	
Raingauge: id/chan/Wt/AAR	1	3198/1/4/640	3686/1/4/635	3605/1/4/614	3687/1/4/624
	2	3686/1/2/635	3605/1/4/614	3683/1/2/600	3680/1/2/611
	3	3605/1/4/614	115/1/1/651	3686/1/1/635	3683/1/1/600
	4	1155/1/2/651	3683/1/1/600	3680/1/1/611	3996/1/1/567
	5	3201/1/1/638	3198/1/1/640	3641/1/1/751	
	6			3198/1/1/640	
Temp Gge: id/chan/wt/alt	1	3605/1/2/74	3605/1/2/74	3605/1/2/74	3680/1/2/70
	2	3680/1/1/70	3680/1/1/70	3680/1/1/70	3605/1/1/74
	3	3100/1/1/43	3100/1/1/43		
Wind Gge: id/chan/wt/alt	1	3605/2/1	3605/2/1	3605/1/1	3605/2/1
	2	3100/2/1	3100/2/1	3100/2/1	3100/2/1
	3	3167/2/1	3167/2/1	3167/2/1	3167/2/1
Depr Gge: id/chan/wt/	1				
	2				
	3				
Riv Gge: id/chan/prop/type/qual/status		4082/1/100/level/low/OP	4086/1/100/level/low/OP		4873/2/100/level/low/OP
River rating: coeff/corr/exp/limit	1	6.934/-0.337/1.2492/2.007	58.58054/-0.61221/-2.31701/0.798		-12.53507/-0.05871/2.03261/0.287
	2	0.29405/0.3879/4.35305/2.75	9.21873/-0.70166/0.87652/2.205		-8.38566/-0.1/1.55076/1.01
	3		0.012/0.500/7.0375/2.4		8.38568/-0.1/1.55076/2.07
	4		0.012/0.500/7.0375/3.0		
Riv Gge: id/chan/prop/type/qual/status		4082/2/100/flow/high/OP	4086/2/100/flow/high/OP		
River rating: coeff/corr/exp/limit	1	1.0/0.0/1.0/15	1.0/0.0/1.0/999		
	2	-1.0/0.0/1.0/999			

Table 3.2.2 continued Catchment details for the Soar basin

Catchment name		Lower Wreake lat.	Rothley Bk - Rothley	Loughborough lat.
Forc. rain		Lower Soar	Lower Soar	Lower Soar
AA Pot. Evap./Area/Altitude/AAR		527/145/100/630	527/96/100/750	527/312/110/620
Threshold: type/value	1			
	2			
	3			
	4			
	5			
	6		level/1.908	
Radar: block/point	1	5/39	5/40	5/41
	2	1/186	1/187	1/188
Raingauge: id/chan/Wt/AAR	1	3680/1/4/611	3641/1/4/751	3641/1/3/751
	2	3687/1/2/624	3683/1/2/600	3683/1/4/600
	3	3683/1/2/600	3680/1/1/611	3680/1/2/611
	4	3996/1/1/567	3605/1/2/614	3057/1/1/625
	5	3605/1/1/614	3686/1/1/635	
	6			
Temp Gge: id/chan/wt/alt	1	3605/1/1/74	3605/1/1/74	3680/1/2/70
	2	3680/1/1/70	3680/1/1/70	3605/1/2/74
	3			3100/1/1/43
Wind Gge: id/chan/wt/alt	1	3605/2/1	3605/2/1	3605/2/1
	2	3100/2/1	3100/2/1	3100/2/1
	3	3167/2/1	3167/2/1	3167/2/1
Depr Gge: id/chan/wt/	1			
	2			
	3			
Riv Gge: id/chan/prop/type/qual/status		4056/1/66/level/high/OP	4056/1/100/level/high/OP	4056/1/31/level/high/OP
River rating: coeff/corr/exp/limit	1	15.987/0.001/2.5361/0.642	15.987/0.001/2.5361/0.642	15.987/0.001/2.5361/0.642
	2	13.931/-0.426/0.6391/1.04	13.931/-0.426/0.6391/1.04	13.931/-0.426/0.6391/1.04
	3	12.272/-0.293/0.6343/2.5	12.272/-0.293/0.6343/2.5	12.272/-0.293/0.6343/2.5
	4			
Riv Gge: id/chan/prop/type/qual/status				
River rating: coeff/corr/exp/limit	1			
	2			

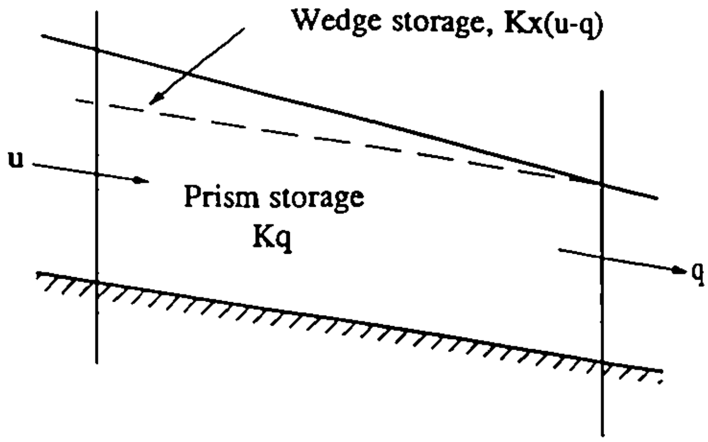


Figure 3.3.1 The Muskingum storage relation

The storage function of equation (3.3.1a) is expressed in the DODO model in terms of reach outflow as

$$q = f_1 u + f_2 S \tag{3.3.1b}$$

with $f_1 = x/(x - 1)$ and $f_2 = 1/K(1 - x)$. Note that the Muskingum storage function (3.3.1a) can be parameterised in terms of f_1 and f_2 as

$$S = -\frac{f_1}{f_2} u + \frac{1}{f_2} q . \tag{3.3.1c}$$

Continuity for the reach gives

$$\frac{dS}{dt} = u - q \tag{3.3.2}$$

which may be approximated, for a unit time interval, by the difference equation

$$S_{t+1} - S_t = u - q_t . \tag{3.3.3}$$

Eliminating q_t from (3.3.3) using (3.3.1b) yields the update equation used in the DODO model for the new reach storage at the end of the interval in terms of the reach input and initial reach storage; this is

$$S_{t+1} = (1 - f_1) u + (1 - f_2) S_t . \tag{3.3.4}$$

Finally equation (3.3.4) along with the storage equation (3.3.1c) can be used to obtain the predictive equation

$$q_{t+1} = (1-f_2)q_t + f_1 u_{t+1-\tau} + (f_2 - f_1) u_{t-\tau}. \tag{3.3.5}$$

Note that this is a transfer function model with dependence on the previous reach outflow and two delayed reach inputs. The recession behaviour provided by the model is therefore exponential.

Note that the conventional derivation of the Muskingum routing procedure (here extended to include an input delay) uses the following approximation to the continuity equation (3.3.2), for a time interval Δt, instead of (3.3.3):

$$\frac{S_{t+1} - S_t}{\Delta t} = \frac{u_{t-\tau} + u_{t+1-\tau}}{2} - \frac{q_{t+1} + q_t}{2}. \tag{3.3.6}$$

When combined with the Muskingum storage function this yields equation (3.3.5) but with

$$\begin{aligned} f_1 &= -\left[\frac{Kx - 0.5\Delta t}{K(1-x) + 0.5\Delta t}\right] \\ f_2 &= 1 - \left[\frac{K(1-x) - 0.5\Delta t}{K(1-x) + 0.5\Delta t}\right]. \end{aligned} \tag{3.3.7}$$

The two approaches to the solution therefore lead to an identical result, functionally speaking, but with different relations to the underlying storage function parameters.

Finally, solving (3.3.2) as before, using the approximation (3.3.3), but for a time step Δt instead of unity, gives the generalised forms of (3.3.4) and (3.3.5):

$$S_{t+1} = (1-f_1)\Delta t\, u + (1 - f_2 \Delta t) S_t \tag{3.3.8}$$

$$q_{t+1} = (1 - f_2\Delta t) q_t + f_1 u_{t+1-\tau} + (f_2 \Delta t - f_1) u_{t-\tau}. \tag{3.3.9}$$

Attention will now be turned to the two extensions of the Muskingum model used in DODO, the first to allow for a variable delayed reach input and the second to represent static storage and flow on floodplains. For in-bank flows the reach input, u, is the reach inflow delayed by a time period, τ, given by

$$\tau = \frac{L}{c} \tag{3.3.10}$$

where L is the reach length and c is the wave speed. The wave speed is assumed to increase as a power function of the reach inflow so

$$c = \alpha u^{\beta} \tag{3.3.11}$$

up to a maximum value c_{max}. This maximum velocity occurs usually between 75% and 100% of the bankfull discharge. The reach input u is defined as the sum of the upstream input, q^u, and half the lateral inflow to the reach, q^{lat}, so that

$$u = q^u + 0.5\, q^{lat} . \tag{3.3.12}$$

Instability can occur at low flows in certain reaches with small values of α or high values of β. Then small changes in discharge at low flows can produce large variations in the wave speed. For this reason the wave speed is constrained to have a minimum value of 0.5 m s^{-1}. If the units of τ, L and v are hr, km and m s^{-1} then a divisor of 3.6 is required on the right hand side of equation. The lag time is constrained to not exceed a prescribed global maximum lag time. It is planned to change the truncated power law function of equation (3.3.11) to one based on a sine function which rises from a value $0.5c_{max}$ at zero flow to a maximum value at $.67q_{bf}$ and falls to a value of $.25c_{max}$ at 1.5 q_{bf}. After this it rises linearly with a slope of $0.5c_{max}$ up to a value of c_{max} at three times the bankfull discharge, staying at this value for higher flows. The change has been coded but awaits calibration of c_{max} and testing.

For out-of-bank flows the reach inflow is split into an in-bank component and an out-of-bank component based on a bankfull discharge, q_{bf}, representing the average channel conveyance along the reach. This discharge is used as a threshold to define two upstream inputs, u^1 and u^2, as follows

$$
\begin{aligned}
u \le q_{bf} \qquad & u^1 = u \\
& u^2 = 0 \\
u > q_{bf} \qquad & u^1 = q_{bf} \\
& u^2 = u - q_{bf}.
\end{aligned}
\tag{3.3.12}
$$

Here, u^1 denotes the in-bank component and u^2 the out-of-bank component. In-bank routing is done as previously defined, but replacing u by u^1.

Routing of the out-of-bank component can assume an initial loss to static floodplain storage, S^s_{max}, representing the overbank storage capacity which typically exists behind embanked floodplains. The vacant static floodplain storage is filled if $u^2>0$ and $S^s<S^s_{max}$. Then the out-of-bank inflow volume is calculated as

$$S^u = u^2 \Delta t \tag{3.3.13}$$

where the time step, Δt, is 3600 if inflow is m s^{-1} and the time interval for calculation is 1 hour. The available static storage is

$$D^s = S_{max} - S^s . \tag{3.3.14}$$

If the available storage, D^s, equals or exceeds the inflow volume, S^u, then partial filling occurs and no floodplain flow is generated; thus

$$
\begin{aligned}
& S^s = S^s + S^u \qquad D^s \ge S^u \\
& u^2 = 0
\end{aligned}
\tag{3.3.15}
$$

Otherwise, the storage is filled and flow on the floodplain occurs as follows:

$$
\begin{aligned}
& S^s = S^s_{max} \\
& S^u = S^u - D^s \\
& u^2 = S^u / \Delta t .
\end{aligned}
\tag{3.3.16}
$$

Once static floodplain storage has been filled, residual inflows in excess of the bankfull discharge, u^2, are routed through a similar Muskingum storage to the in-bank one but having parameters appropriate to the floodplain. That is equations (3.3.3) and (3.3.4) are used along with the time delay equations (3.3.10) and (3.3.11) but with different parameters (f_3, f_4, γ, δ). Specifically for in-bank flows

$$\begin{aligned} q^1 &= f_1 u^1 + f_2 S^1 \\ S^1 &= (1-f_1)u^1 + (1-f_2)S^1 \end{aligned} \qquad (3.3.17)$$

and for significant out-of-bank flows ($u^2 > 0.05$ m^3 s^{-1}, $S > 0.05$ mm)

$$\begin{aligned} q^2 &= f_3 u^2 + f_4 S^2 \\ S^2 &= (1-f_3)u^2 + (1-f_4)S^2 \ . \end{aligned} \qquad (3.3.18)$$

The total outflow is then given by the sum of in-bank and out-of-bank outflows

$$q = q^1 + q^2 \ . \qquad (3.3.19)$$

This needs to be further updated under recession conditions.

During recession allowance is made for drainage from the static floodplain storage out of the reach. Whilst the reach outflow exceeds the return bankfull discharge, q_{rf} (which can be set lower than the bankfull discharge, q_{bf}) a limiting drainage function applies. Specifically the static storage is reduced by a seepage factor, f_s, so

$$S^s = f_s S^s \ ; \qquad (3.3.20)$$

a value of 0.998 is used for f_s. If there is significant static storage remaining ($S^s > 100$ mm) then further evacuation is considered. An excess outflow is defined as

$$q_e = q - q_{rf} \ . \qquad (3.3.21)$$

and a memory of the last peak in the excess outflow is held as q_{pk}. When q_e exceeds this value a renewed rise to a higher peak is registered and evacuation of the static storage stops. If the outflow rises by more than 5% of the last flow ($q_t > 1.05q_{t-1}$) then the proportional increase is calculated as

$$\Delta q = \frac{q_t - q_{t-1}}{q_{t-1}} \ . \qquad (3.3.22)$$

If the rise is more than 5% ($\Delta q > .05$) and there is excess outflow ($q_e > 0$) then evacuation of the static storage is stopped. If evacuation has ceased but there is a significant fall ($q_t < .95q_{t-1}$) then evacuation is started and q_{pk} reset to the previous peak in excess outflow. The return flow from static storage is therefore calculated on a falling or insignificantly rising, river.

Under evacuation conditions the potential return volume and flow from static storage are given by

$$S_r^* = \begin{cases} \gamma S^{s\delta} & S^s < S_r^* \\ S^s & \text{otherwise} \end{cases} \tag{3.3.23}$$

$$q_r^* = S_r^* / \Delta t \ .$$

If the reach outflow is below the reach return flow, q_{rr} ($q_e < 0$) then free drainage from the static storage occurs at the potential rate. The return flow is only limited to $|q_e|$ if necessary to prevent spurious outflow spikes occurring when return flows greatly exceed prior overbank peaks. Thus

$$q_r = \begin{cases} q_r^* & q_r^* \le |q_e| \\ |q_e| & \text{otherwise} \end{cases} \tag{3.3.24}$$

If the reach outflow is still above the reach return flow ($q_e \ge 0$) then the return flow is constrained by a factor, defined as the ratio of the excess outflow to the last independent peak in the excess outflow. Thus

$$f_c = \frac{q_e}{q_{pk}} \tag{3.3.25}$$

and

$$q_r = \begin{cases} (1 - f_c) q_r^* & q_r \le q_{pk} - q_e \\ q_{pk} - q_e & \text{otherwise .} \end{cases} \tag{3.3.26}$$

The static storage is reduced by the volume returned as return flow according to

$$S^s = S^s - q_r \Delta t \ . \tag{3.3.27}$$

When static storage becomes insignificant ($S^s <$ 100 mm) evacuation is stopped and S^s set to zero. Finally, the return flow is added to the reach outflow along with the downstream inflow, u^d, and half the lateral inflow to the reach to give the final reach outflow

$$q = q + q_r + u^d + 0.5 q^{lat} \ . \tag{3.3.28}$$

In summary, the DODO model is based on a Muskingum storage function with a lagged reach input where the lag decreases as a power function of the reach inflow, but limited to a minimum lag value. The component of reach inflow above the bankfull discharge is routed through a parallel, second Muskingum storage, after accounting for an initial contribution to static floodplain storage. On the recession water in static storage drains out of the reach, initially slowly, but then freely below a critical return bankfull storage as a power function of the volume of water in static floodplain storage. Lateral inflows to the reach are divided equally between the reach inflow and the reach outflow; a downstream input can also be added to the routed outflow to give the final reach outflow. The DODO model has a total of twelve parameters, six representing in-bank routing (f_1, f_2, α, β, c_{max}, q_{bf}) and six representing out-of-bank routing (f_3, f_4, γ, δ, S^{*}_{max}, q_{rf}).

3.3.3 Comparison with the KW model

The Stage 1 report recommended the use of a simple hydrological flow routing model based on the convection diffusion equation, or a simpler representation of it, for river reaches not significantly affected by backwater. Specifically 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 was recommended. 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

$$\frac{\partial Q}{\partial t} + c\frac{\partial Q}{\partial x} = cq \qquad (3.3.29)$$

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

$$Q_t^k = (1-\theta)\ Q_{t-1}^k + \theta\left(Q_{t-1}^{k-1} + q_{t-1}^k\right) \qquad (3.3.30)$$

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 the floodplain, 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 function 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 3.7. For a more extensive description of the KW model the reader is referred to the RFFS Course Notes for the KW model (Institute of Hydrology, 1992b).

Whilst a full description of the KW model has not been given, as in the case of the DODO model, it should be apparent that there are both similarities and differences between the two models. Firstly, it can be shown that the KW difference equation (3.3.20) can be derived as a special case of the discrete form of Muskingum model used by the DODO model. This special case was chosen deliberately to have a single parameter, θ, the kinematic wave speed which, for a given time and space step, controls both the speed and attenuation of the flood wave. This parsimonious form allows simple functions to be introduced relating wave speed to discharge, without recourse to a large number of model parameters. The KW model also avoids explicit representation of flood plain flows by a second channel, as is the case with the DODO model, preferring instead to use simple empirical threshold functions at model node points. These functions can be chosen to only allow a proportion of the inflow to a node, above a critical level, to pass downstream, the residual being lost to the flood plain or stored in it for subsequent return, depending on the option chosen. Again there are advantages in the efficiency of parameterisation but at the cost of a less explicit conceptualisation of the processes thought to operate. This is often justified in practice when there is limited information on the points of overflow to the flood plain, and of the nature of the storage and return processes. Inference of water transfers to a flood plain based solely on reach input and output data can often not justify a more explicit conceptualisation of channel and flood plain as separate entities. A more implicit approach, as used by the KW model, is often more practical provided the model is still capable of supporting warnings to critical flood prone sites. In general the KW model is likely to be easier to calibrate than the DODO model because of its more parsimonious parameterisation. A feature of the KW model used for model calibration is the ability to estimate the stage-discharge relation as an intrinsic part of the reach model. This has proved very useful in practice where only a river level station exists at the reach outlet, or reach inlet or lateral inflow location.

The above has provided an outline appraisal of the two models based on reasoning and experience. A stronger judgment would require model evaluation using flood event data for a variety of river reaches. Even then the outcome is unlikely to be clearcut with the possibility of either model performing best under different situations. The operational performance of the DODO model for forecasting on the river reaches of the Soar is assessed using past flood events in Section 4. As a consequence a recommendation on the preferred choice of reach model is deferred until then.

3.3.4 Application to the Soar

The DODO model is used to represent flows in 6 reaches of the Soar catchment. Table 3.3.1 summarises the model parameters used for each reach. Figure 3.3.2 provides a model schematic for the Soar showing the reach models (marked as rectangles) between stations (marked as hexagons) along with the rainfall-runoff models (marked as ovals) which provide upstream and lateral inflow inputs to the reach models. Table 3.3.2 provides details of how the reach models are configured with respect to the gauging stations and catchment and reach inflows, along with warning thresholds. Note that a majority of these reaches are considered to be under some form of backwater influence and for which a hydrodynamic modelling approach might be preferred.

Table 3.3.1 Reach model parameter values for the Soar basin (where two values are given, the first indicates the value used before date in brackets)

	Reach					
Parameter	**Freemans (Leics)**	**Belgrave**	**Syston**	**Pillings**	**Zouch**	**Kegworth**
	(6/8/93-4/10/93)	(6/8/93-4/10/93)	(30/7/93)	(6/8/93-4/10/93)	(31/10/94)	(9/8/93)
Bankfull flow	30.0	80.0	(20.0) 30.0	44.0	(80.0) 140.0	(80.0) 140.0
Return flow	30.0	80.0	(20.0) 30.0	44.0	(80.0) 140.0	(80.0) 140.0
Reach length	8.0	5.5	12.0	18.0	(12.0) 8.5	(2.5) 4.0
Wave speed coeff.	(0.6) 0.55	(0.6) 0.55	0.6	(0.6) 0.55	0.6	0.6
Wave speed exp.	0.48	0.48	0.5	0.48	0.4	0.4
Max. wave speed	2.5	2.5	2.5	2.5	3.0	3.0
Channel thro. flow	(0.2) 0.5	(0.2) 0.5	(0.02) 0.15	(0.2) 0.5	(0.69) 0.9	(0.69) 0.9
Flood P thro. flow	0.01	0.01	(0.23) 0.02	0.01	0.1	0.1
Chan. store outflow	0.2	0.2	(0.16) 0.05	0.2	0.75	0.75
Flood P store outflow	(0.04) 0.05	(0.04) 0.05	(0.2) 0.16	(0.04) 0.05	0.2	0.2
Stat. evac. coeff.	(0.01) 0.008	(0.011) 0.008	0.009	0.008	0.004	0.008
Stat. evac. exp.	1.2	1.2	1.23	1.2	1.2	1.2
Stat. store cap.	44.0	1.0	550	50	3500	500.0

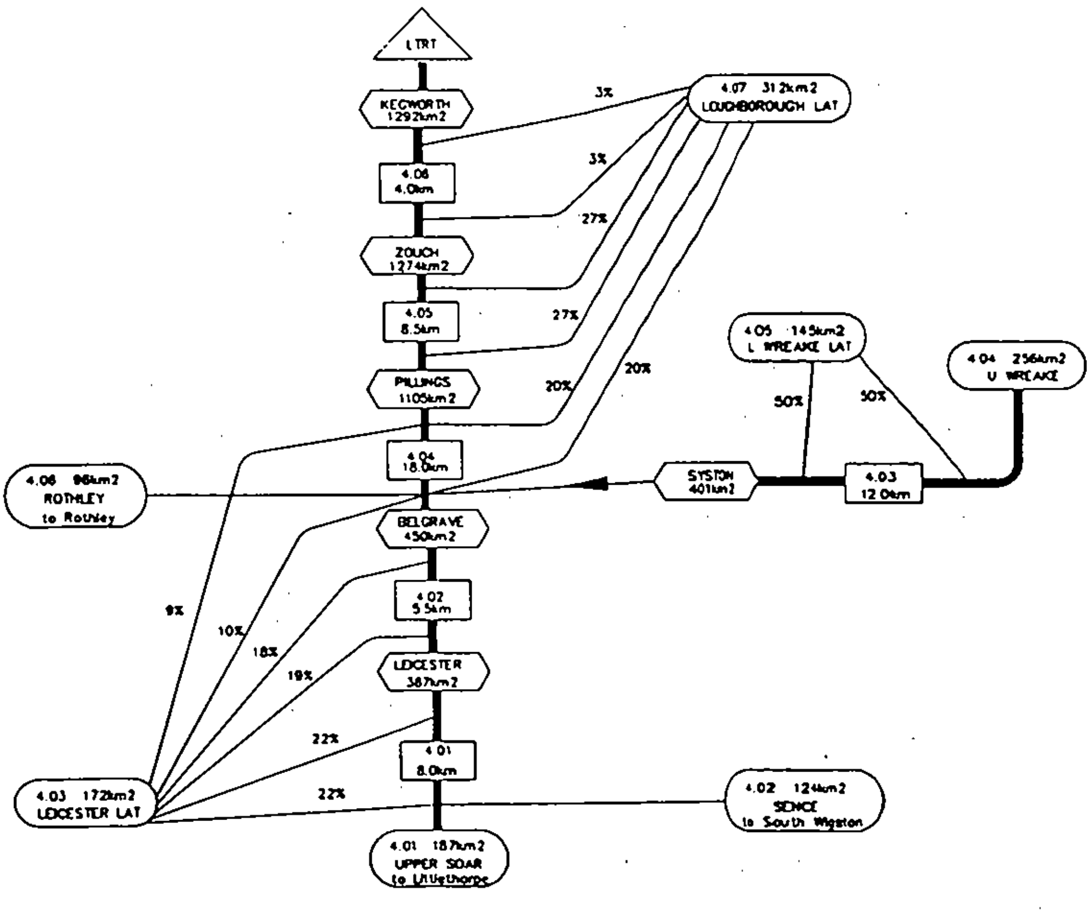


Figure 3.3.2 Model schematic for the Soar catchment

Table 3.3.2 Reach details for the Soar basin

Reach		Freemans (Leics)	Belgrave	Syston
Threshold: type/value	1	flow/20		flow/17.0
	2			
	3			flow/28.0
	4	flow/32		
	5	flow/130		
	6			level/3.199
Inflow: location/type/proportion/ sub-basin name/inflow name	1	upstream/catchment/100/Soar/U.Soar-Littlethorpe	upstream/reach/100/Soar/Freemans(Leics)	upstream/catchment/100/Soar/U.Wreake-Frisby
	2	upstream/catchment/100/Soar/Sence-Sth.Wigston	lateral/catchment/37/Soar/Leicester lat.	downstream/catchment/75/Soar/Lower Wreake lat.
	3	lateral/catchment/44/Soar/Leicester lat.		lateral/catchment/25/Soar/Lower Wreake lat.
	4			
	5			
	6			
Riv Gge: id/chan/prop/type/qual/status				4024/1/100/level/low/OP
River rating: coeff/corr/exp/limit	1	307.973/0.004/1.5899/0.5		1.0/0.0/1.0/40
	2			-1.0/0.0/1.0/999
	3			
Riv Gge: id/chan/prop/type/qual/status				
River rating: coeff/corr/exp/limit	1			
	2			

Table 3.3.2 continued Reach details for the Soar basin

Reach		Pillings	Zouch	Kegworth
Threshold: type/value	1	flow/20		flow/60
	2			
	3	flow/25		flow/85
	4	flow/55		flow/100
	5			flow/140
	6			
Inflow: location/type/proportion/ sub-basin name/inflow name	1	upstream/reach/100/Soar/Belgrave	upstream/reach/100/Soar/Pillings	upstream/reach/100/Soar/Zouch
	2	upstream/reach/100/Soar/Syston	lateral/catchment/54/Soar/Loughborough lat	lateral/catchment/6/Soar/Loughborough lat
	3	upstream/catchment/100/Soar/Rothley Bk-Rothley		
	4	lateral/catchment/19/Soar/Leicester		
	5	lateral/catchment/40/Soar/Loughborough lat		
	6			
Riv Gge: id/chan/prop/type/qual/status		4093/1/100/level/low/OP	4109/2/100/level/low/OP	4074/1/100/level/low/OP
River rating: coeff/corr/exp/limit	1	27.97/-0.280/5.7349/1.211	36.78738/-0.30958/1.09268/1.04	142.251/-0.347/1.6803/0.858
	2	8.5238/0.041/3.4441/3.0	19.60481/0.16546/1.52659/3.6	90.976/-0.038/3.4307/1.700
	3			
Riv Gge: id/chan/prop/type/qual/status		4093/2/100/flow/high/OP		4074/2/100/flow/high/OP
River rating: coeff/corr/exp/limit	1	1.0/0.0/1.0/120		1.0/0.0/1.0/120
	2	-1.0/0.0/1.0/999		-1.0/0.0/1.0/999

3.4 HYDRODYNAMIC MODELS

No use of hydrodynamic river models for operational flood forecasting is made at present in the Soar, or the Severn-Trent Region. There has been some work in the past, using the HR Ember model, to forecast the tidal Trent but this was only implemented for a brief period, due particularly to inadequate calibration and computer constraints at the time. The review and recommendations of Stage 1 are reinforced here, advocating that ISIS be adopted as the basis of this development and modified to Model Algorithm form for use with the RFFS-ICA. As a result of the review of river gauging stations the proposed extent of the model implementation has been revised to start in Leicester at Freemans Weir. Also its extent up the Wreake, defined as near Melton Mowbray, can now be more precisely located at Brentingby on the Eye. Both these amendments are subject to the two sites proving satisfactory as flow gauging sites.

Under Stage 2 it has been possible to inspect the ONDA model of the Soar, currently being constructed for design use by Halcrows. The model node maps provided by Halcrows may not represent the final model configuration but are at least an indication of the likely extent and form of the model configuration. Included in the model are the reaches of the River Soar between Leicester and the Trent confluence, the River Wreake from its confluence with the Soar to upstream of Brentingby, and the Rothley Brook from its confluences with the Soar to Thornton Reservoir. At present the model is split into two parts which are run independently. The first part is the River Soar and Rothley Brook model which comprises some 180 nodes representing the River Soar and a further 290 nodes representing the Rothley Brook. The second part represents the whole of the River Wreake using some 250 nodes. Currently both models take approximately five minutes to complete a simulation of 24 hours duration running on a PC 486 processor. The discrepancy between the number of nodes and run times for both parts of the model may be explained by the existence of a more complicated network of flow paths in the River Wreake model. As a result the more complicated matrix of model coefficients involved takes longer to solve at each time step of the simulation. This highlights the difficulty in predicting the computational speed of a hydrodynamic model where run times are a function of both the total number of nodes and the complexity of the flow paths.

It is apparent from the available node maps that the ONDA model will need to be extended in four areas to fulfil the requirements of the forecasting system. The upstream limit of the current ONDA model is near Birstall, some way downstream of Freemans Weir, and thus the model will need to be extended to Freemans Weir. Channel data should be available from the River Soar Flood Capacity Appraisal, but the out-of-bank representation may need to be reconsidered due to the enhanced modelling functionality offered by ISIS. The three remaining areas needing extension are the channels of the Kingston Brook, Black Brook and Quorn Brook where they cross the River Soar floodplain. The Stage 1 Report identified there was no need to extend the hydrodynamic model to tributaries for which there are no forecast requirements. However, the tributary channels crossing the floodplain need to be modelled to allow the tributary inflow to be entered at the edge of the floodplain rather than directly into the main channel. These tributary channels are not presented on the present ONDA model node maps and will need to be included in the forecasting model configuration.

3.5 REPRESENTATION OF CONTROL STRUCTURES AND OPERATING RULES

There is no explicit representation of control structures in the models currently employed to forecast the Soar. Conceptual catchment and reach models are used where such structures exist and the consequences of this are revealed later in Section 4. Suffice it to say that the recommendations made in Stage 1 are reinforced here. Specifically the major control structures should be explicitly accommodated within the hydrodynamic extent of the Soar forecasting model. The Stage 1 report reviewed the operating rules employed in the Soar and how these can be represented already within the ISIS code.

3.6 REAL-TIME UPDATING TECHNIQUES

3.6.1 Introduction

The choice of updating technique to use with the rainfall-runoff, hydrological channel routing and hydrodynamic river models will be considered in this section. The Stage 1 report recommended that an empirical state updating technique be used for the rainfall-runoff model, and an ARMA error predictor for the hydrological channel flow routing and hydrodynamic river models, in the latter case in multivariate form. Use of state correction for the river reach models might be considered in the future, but this was an area of ongoing research and proving trials. In the case of the Soar model, a single approach to updating has been adopted, based on a novel form of error prediction. This approach is reviewed next and then assessed along with the methods recommended under Stage 1.

3.6.2 The Severn-Trent approach

The Severn-Trent approach to forecast updating is referred to as the "Error Forecast Model". This examines the difference between observed and simulated outflows over the last m (set to 6) hours of the hindcast period. A judgement is made on how predictable future errors are and forecast outflows are adjusted accordingly. The approach is described in greater detail below.

First the observed errors over the last m hours are isolated to form the set $\{\eta_{-m+1}, \ldots, \eta_0\}$ where η_0 is the most recent observed error and

$$\eta_i = Q_i - q_i \tag{3.6.1}$$

where Q_i and q_i are the observed and simulated flows at instant i. The error differences are then calculated as

$$\delta_i = \eta_i - \eta_{i-1} \qquad i = -m+2, -m+3, \ldots, -1, 0 \tag{3.6.2}$$

and from this set $\{\delta_i\}$ the maximum error difference is calculated as

$$\delta_{max} = \max\{|\delta_i|\}. \tag{3.6.3}$$

The mean observed discharge is calculated as

$$\bar{Q} = \frac{\sum_{i=0}^{-m+1} |Q_i|}{m} . \tag{3.6.4}$$

Using $\bar{Q}$ and δ_{max} the duration in the forecast period over which "normal" updating will be undertaken is defined as

$$\tau = \frac{\bar{Q}}{2\delta_{max}} . \tag{3.6.5}$$

Thus, the duration for normal updating is shortened with larger errors, when judged in proportion to the mean observed discharge.

Consider now the forecast period of duration τ. An autoregressive model for the error differences is used to provide estimates of the next error change, $\hat{\delta}_i$. This takes the form

$$\hat{\delta}_i = \phi_1 \delta_{i-1} + \phi_2 \delta_{i-2} + \ldots + \phi_{m-1} \delta_{i-m+1} \qquad i=1,2,\ldots,\tau \tag{3.6.6}$$

which is computed recursively, substituting $\hat{\delta}_i$ on the right-hand side when actual δ_i values are unavailable for future times. The autoregressive coefficients $\{\phi_j, j=1,2,\ldots,m-1\}$ are interpreted as a set of error reduction factors. In practice m = 6 and $\{\phi_j\}$ = (.36, .21, .12, .07, .04), which implies $\phi_j = .36(.583)^{j-1}, j=1,2,..,m-1$. That is the factors decrease exponentially into the past.

This allows the following error predictor to be formulated as the sum of the previous error and the predicted error change

$$\hat{\eta}_i = \eta_{i-1} + \hat{\delta}_i, \qquad i=1,2,\ldots,\tau \tag{3.6.7}$$

which is again computed recursively with $\eta_o = Q_o - q_o$ and thereafter substituting $\hat{\eta}_{i-1}$ for η_{i-1} on the right hand side.

The updated flow forecast is then simply given by the sum of the simulation forecast and the prediced error:

$$\hat{q}_i = q_i + \hat{\eta}_i, \qquad i=1,2,\ldots,\tau . \tag{3.6.8}$$

In practice if the updated forecast is negative, the forecast is reset to the forecast at the previous time step.

This updating scheme is therefore based on forecasting the error differences, using an exponentially-fading weighted average of $m-1$ (here, equal to 5) past observed and/or forecast error differences. The forecast error is then the old error plus the forecast error difference. Adding this to the simulation model forecast gives the required updated forecast.

The updating procedure for the period $\tau+1$ to 2τ, asymptotes the updated forecasts back to the raw forecast at a lead time of 2τ. A "final error divider" is defined as $\Delta = \eta_\tau/\tau$. This is used in the following recursions for $i=\tau+1, \tau+2, \ldots, 2\tau$ to obtain the future forecast errors and updated flow forecasts:

$$\hat{\eta}_i = \hat{\eta}_{i-1} - \Delta \qquad (3.6.9)$$

$$\hat{q}_i = q_i + \hat{\eta}_i . \qquad (3.6.10)$$

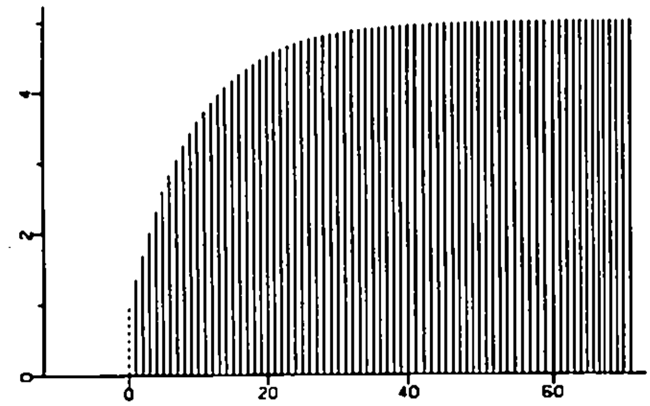
Again if the updated forecast is negative the forecast reverts to that at the previous time-step. In the event that missing data occur in the hindcast period no updating is attempted and the simulated flows are used over the whole forecast period.

3.6.3 Comparison with the proposed methods

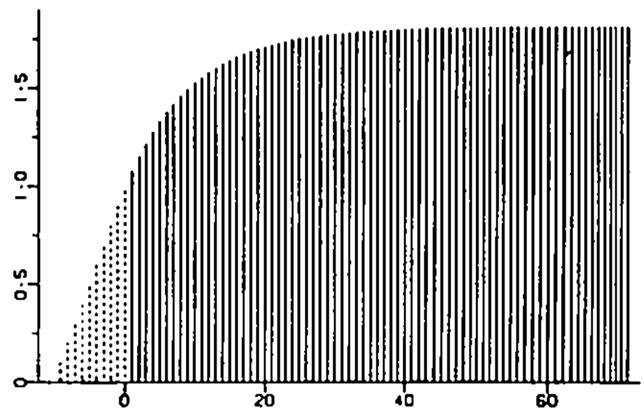
Since the Error Forecast Model, EFM, is a form of error predictor it will be first assessed along with more conventional ARMA error predictor approach recommended for river reach modelling in Stage 1. The basic approach is to predict error differences from one time step to the next using an exponentially weighted average of five past error differences. This is equivalent to an autoregressive model structure, of order five, operating on the error differences, and using predefined autoregressive coefficients equal to .36, .21, .12, .07 and .04. Whilst the error model is stationary in the error differences it is nonstationary in the errors themselves. The model is referred to as a nonstationary autoregressive model within the so-called ARIMA class of models (Box and Jenkins, 1970). Its use in the present context stems from its ability to project forward a trend. Forecasts with increasing lead time asymptote to a level determined by the autoregressive coefficients and the 5 previous error differences. Therefore the nonstationary autoregressive model produces forecasts which are stable, asymptoting to a level. (Only when used for simulation does the integration, or summation process, characteristic of this model become unstable.) Figure 3.6.1 illustrates the behaviour of the predictor for a unit pulse model error at time zero, for a linear increasing set of 10 past errors and a constant past error. The asymptotic approach to a level, of variable magnitude, is clearly seen.

The recommended ARMA error prediction approach operates directly on the simulation model errors and not their differences from one step to another; the option is also provided to work with the proportional errors, $\log(Q_i/q_i)$. The more general form offered by the ARMA model structure and the off-line estimation of the model coefficients, by optimisation using the model simulation errors for several flood events, are seen as clear advantages. The off-line estimation procedure ensures that a model is identified such that the updated forecasts are assured of asymptoting to the simulation model forecast with increasing lead time. This is not generally the case for the integrated form of AR model, which asymptotes to a variable level rather than to zero. Return to the simulation forecast is imposed in the EFM by switching to a second updating scheme after a duration τ, which assures a linear approach to the simulation model forecast, meeting it a time 2τ. This is likely to create a discontinuity in the updating scheme leading to unrealistic forecast hydrographs.

A straightforward application of ARMA models can sometimes lead to error predictors which exhibit unsatisfactory behaviour, for example having a unit response function that rises abruptly followed by a long tail. This might arise particularly when there are abrupt changes in the observations themselves, due to observation error. The effect of the sharp rise can lead to unrealistic forecasts. IH have developed a method based on using an autoregressive model with equal roots which incorporates allowance for errors in the observations. The resulting model unit response function has a lower peak whilst retaining a long-tailed decay to zero. Parameterisation of the model includes the autoregressive parameter and the ratio of the *(a) Unit error*



(b) Linearly increasing past errors



(c) Constant past errors

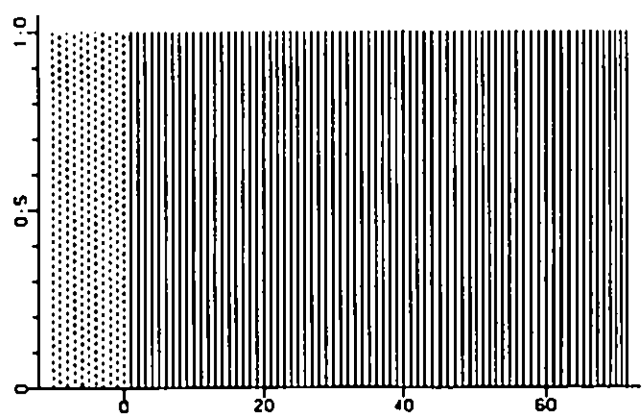


Figure 3.6.1 Forecasting different forms of past errors using the nonstationary lag-5 autoregressive model

variances of the observation error and the model error, the variance ratio controlling the deflation of the peak. It is possible that the motivation for developing the EFM method, rather than adopting a more standard ARMA model approach, may have arisen from similar problems to those discussed above. The equal root AR model with observation error may provide an attractive alternative error predictor form in such situations.

The performance of the EFM is investigated under operational conditions for ten flood events in Section 4 and a final judgement on the scheme will be deferred until then. In closing this commentary on error prediction schemes it should be highlighted that their success depends on the persistence in the model errors, which is usually weakest in the vicinity of the rising limb and peak of the flood hydrograph where good forecasts are most needed. Nonetheless, assessments indicate that the use of error prediction is of benefit overall in such situations and the scheme is easy to apply.

The empirical state updating scheme is not currently a feature of the Soar model although it is understood that Severn-Trent hydrologists have been considering the use of this approach. Currently it is used in conjunction with the PDM for rainfall-runoff modelling in the RFFS. The approach was reviewed in the Stage 1 report and further details will not be given here. Suffice it to say that the approach requires to be tailored to a particular model and this would imply a scheme being specifically developed for the Severn-Trent Catchment Runoff Model. In contrast, application of the ARMA error predictor is model independent and would not require further development for model error prediction in the Soar catchment. Further details of the ARMA error predictor approach are provided in the RFFS Developers' Training Course Notes (Institute of Hydrology, 1992c).

3.7 MODEL CALIBRATION

Calibration of the catchment and reach models is done using the CALIB and CALDIS suite of programs (NRA-ST, 1993). The CALIB programs are used to carry out model optimisation on the MicroVAX 3100. Results are decanted to a PC, using the Reflections 2 software, where the CALDIS software is used to display the results graphically. The software design is therefore similar to the FFS and REMUS programs used for operational forecasting, the former generating forecasts on a VAX and the latter displaying them on client PCs (see Section 5). State variable sets required to initialise model calibration runs are those automatically extracted from the 7 am routine daily run of the FFS. CALIB is comprised of three suites of programs, the first "SVA" dealing with the State Variable Archive, the second "ESD" dealing with Extraction of Sensor Data used for calibration and the third "CSM", or Calibration System Manager, being responsible for the actual model calibration.

The Rosenbrock technique is used for parameter optimisation and up to 10 model parameters can be estimated at any one time; optimising 6 or less is more practical since CALDIS only displays the first 6 parameters. A choice of 5 objective functions are given: absolute difference, sum of squares, sum of cubes, percentage efficiency and least squares. Optimisation is carried out on a maximum of 15 days worth of data so that essentially single events are optimised at a time. A compromise "average" set of parameters are obtained informally having first obtained optimal sets for each "calibration event". The software can be configured to submit batches of optimisation runs for several events, catchments and reaches and the results decanted to the PC for interpretation using the CALDIS display software. This can be quite efficient but has the disadvantage of not allowing visually interactive calibration.

An important feature of the reach model calibration is that it allows catchment models of ungauged lateral inflows to be incorporated. However, it does not allow the model parameters of these "nested" catchment models to be optimised as part of the reach model calibration procedure. Rather, informal manual adjustments of the lateral inflow catchment models are performed in response to observed deficiencies in the reach model optimisation. Several connected reaches can be treated as a single entity, referred to here as a "group reach", allowing reach models for reaches with ungauged outlets to be optimised with respect to gauged flows for a reach further downstream. It is often advantageous with Muskingum-type models to have cascades of identical reaches in order to achieve an efficient parameterisation of the speed and attenuation of the flood wave through a stretch of river. This can be achieved for the reach parameters in the group reach selected for optimisation. Initial parameter values for use in the optimisation are taken from the reach detail file for the downstream gauged reach and used for all reaches in the group. Those parameters not selected for optimisation take on the values in the reach detail file and therefore can differ from one reach to the next in the group of reaches.

There is no optimisation of a parameterised updating technique routinely employed in CALIB at present, although a prototype empirical state updating technique can be invoked on request. It is understood that this does not support the fixed origin, variable lead time and fixed lead time, variable time origin modes of operation that are usually provided to test an updating technique at the calibration stage.

Having outlined the key functions of the calibration facilities attention will now be turned to more detailed aspects. Since 1990 the RECS/FFS sensor data have been saved on monthly backup tapes for use in model calibration. Also, since early 1992, the model state sets used to provide initial conditions have been stored. A program within the SVA suite automatically extracts the states at 7 am from the FFS Dynamic Hydrological data files for the Severn and Trent basins, produced by the two routine daily model runs following the 7 am telemetry poll. More informal setting of the state variable set is possible within the SVA facilities, for example for use with storms prior to 1992. Then, Morecs SMD values and the baseflow before the event can help in specifying the initial state set for a given event. Provision is made within the SVA programs to enter states through a blank pro-forma or to correct an existing state set. The set created is converted to binary form for actual use in calibration. Transition states ("flows in transit") cannot be seen or edited. Each state set file is named according to basin, date and hour. Extension would be needed for a 15 minute time-step and a decision to use GMT/BST and not GMT as standard could introduce further complications in providing greater generalisation. Monthly archiving of these files to tape occurs, with facilities provided for archiving and retrieval.

A sensor data archive file comprises 35 days worth of telemetry data at an hourly interval for the entire Severn-Trent Region. The ESD program extracts from a sensor data archive file a period of data, not exceeding 15 days, for use in calibration.

Running of the CSM, or Calibration System Manager, involves three control parameter files and nine FFS parameter files (in addition to the sensor data and state files previously discussed). The control files contain run description text and general calibration parameters, definition of the catchment calibration and definition of the reach calibration. Copies of the FFS parameter files used operationally are used to provide further details, and can be changed if required but generally are not. These contain the catchment and reach details and parameters for each basin along with the hydrological names for both basins. Running of CSM reports progress on the screen and produces a log file and a text output file which are used primarily to report whether the calibration has been set up and run correctly. The main output is the binary output produced for inspection on the PC using the CALDIS program.

Display of the calibration results using CALDIS follows the style of display of operational forecasts through REMUS. The calibration output files available for display are presented and, for the one currently highlighted (selected), the reach and catchment calibration results available for selection are given. This leads to a Catchment Selection or Reach and Support Catchment Selection screen providing a further level of site selection. The latter is split into reaches with calibrated output to the left and supporting reaches and catchments to the right. Selecting a catchment yields a graphical display, including a table of parameter values, and a plot of rainfall, observed and simulated flow hydrographs, at different iterations of the optimisation if invoked, and of the simulated soil moisture index (SMI). The plot for a reach is similar, but omitting rainfall and SMI. Selecting a supporting catchment leads to the Supporting Catchment Display which displays the inflows to the model, either observed or model simulated (but not optimised) as appropriate.

The practical steps involved in model calibration will now be outlined, commenting when appropriate on the difference with the IH Model Calibration approach recommended in Stage 1. The calibration software can optimise up to 10 parameters at a time, although a more step-wise approach, choosing different sub-sets to optimise is used in practise. The calibration is restricted to calibration for single events, up to a maximum of 15 days duration. Typically about 6 events are used for calibration, and a further 2 for independent evaluation, events being chosen which are at or above the yellow warning level. Because of the single event calibration, a different set of parameters are obtained for each event and from these a single compromise set are derived which gives reasonable predictions across all events. In contrast, the IH Calibration Facility employs an approach based on analysing the events as a single optimisation process, with a switch from a 15 minute to a daily time step between events in order to maintain a water balance between events to provide initial water storage states for each event. A single objective function incorporating errors pooled over the entire set of events is used to achieve a single optimisation and one set of model parameters. The approach reduces the importance of the initial state set and readily allows for a "warm-up" of the state variables. The state set is clearly parameter dependent and thus the CALIB approach of using past sets associated with different model parameter values is somewhat inconsistent.

In the sequential procedure for optimising the Catchment Runoff Model parameters first priority is given to improving the runoff coefficient to get the flood peaks about right. Only later are lag time and duration parameters explored. A similar procedure is used for the reach model. In the sequential optimisation, priority is first given to the wave speed parameters (channel, outflow, throughflow), floodplain storage, and sometimes the static evacuation coefficient depending on whether events are out-of-bank. Prior to calibration a baseline schematic is established defining the reach length and bankfull discharge. This task is supported by RIMS (River Information Management System), a Flood Defence database which includes reach lengths and left/right bank bankfull discharges. Typically about 6 RIMS reaches would make up a single FFS reach and the reach model bankfull discharges are obtained so as to represent an average for the reach.

The relative merits of the Model Calibration Facility proposed in Stage 1 and that used in the Severn-Trent Region has already been considered to some extent at the end of Section 3.2.3. The use of the Rosenbrock optimisation procedure for model parameter estimation within the Severn-Trent model calibration software, rather than modified Simplex as used in IH's Model Calibration Facility, is not seen as a source of concern. However, use of calibration visualisation aids to support calibration of conceptual hydrological models have been found by IH to be of significant benefit. The provision of facilities to calibrate embedded models, such as a hybrid model comprising a channel flow routing model and rainfall-runoff models for the lateral inflows, is seen as a further desirable requirement. Such a system has been specified at IH and is currently being coded as a development of the existing RFFS Model Calibration Facility.

3.8 RAINFALL FORECASTS

Currently only rather informal weather forecasts are received by Severn-Trent in support of flood warning. They are received at 4 pm from the Weather Department, Birmingham via telex straight into the VAX. These can be viewed in the RECS/FFS system but are not made automatically available to be used in the model forecast runs. No use is yet made of Frontiers forecasts or Numerical Weather Prediction (NWP) Model forecasts for longer lead times to support flow forecasting. The recommendation to employ HYRAD for forecasts within two hours and Frontiers out to 6 hours ahead is reinforced here, as is the suggestion to explore with the Met. Office the availability and value of NWP model precipitation and temperature forecasts for longer lead times. The latter may prove the best source of longer term forecasts, available in numerical form, and be preferred to upgrading the Weather Forecast products to a form suitable for entry as values into the modelling system. Special consideration will need to be taken of their coarse spatial resolution (circa 16 km squares) prior to entry into forecasting models. Such considerations are in a research phase at present.

3.9 FORECAST ACCURACY AND FLOOD WARNING

No estimates of forecast accuracy are provided within the forecasting system used on the Soar. The recommendations made in Stage 1 are merely reinforced here. Provision of Decision Support System functionality to explore a range of possible outcomes to alternative future scenarios, for example of rainfall, would form the cornerstone of a recommended approach to assisting with when to issue warnings, given forecast uncertainty. A formalisation of this approach based on ensemble forecasting is to be investigated in a research context at IH.

4. Analysis of flood forecasts

4.1 INTRODUCTION

The aim of this section is to analyse a set of past flood events in the Soar catchment in order to assess the operational performance of the Severn-Trent Flood Forecasting System for this area. This will be undertaken against the background understanding of the forecasting techniques employed, gained through the review reported in the preceding section. In this way it is hoped to identify any shortcomings in the existing forecasting techniques and use this information to support any recommendations for change.

A set of 10 flood events were selected by the NRA for analysis and these are listed in Table 4.1.1. The majority of events were supplied in the form of REMUS data files on disc, which allowed their visualisation via the REMUS package on a PC. These files contained the actual operational telemetry data and forecasts output from the RECS/FFS system for a given forecast run time. This allowed an exact evaluation of the performance of past forecast runs. For most events, files for more than one model run were provided so it was possible to assess the performance of forecasts made at different times within the same event. In particular, for event 9 covering the five day period 24-28 February 1994 forecasts made at nine time origins were available. For two of the events only hard copy plots of the forecast results were supplied. The large number of forecast hydrograph plots analysed are included as Appendix 5. These will need to be referred to in order to fully appreciate the assessment of the forecasts for each event presented in Section 4.3

Complicating factors in the analysis of the ten events are the changes made to the model parameters and to the methods of gauge measurement at various times since the first event in November 1992. It is important to understand these changes as background in analysing the events. The next section aims to provide this background prior to proceeding with the analysis of events in Section 4.3.

4.2 CHANGES TO MODEL PARAMETERS AND DISCHARGE MEASUREMENTS

A review of the Soar model configuration calibration was undertaken over the period June to October 1993. This first revealed basic configuration errors such as reach length and catchment/reach areas which required revision of the lateral inflow proportions indicated in Figure 3.3.2. Specifically the reach lengths of Zouch - Kegworth and Pillings - Zouch were changed to 4 and 8.5 km from 2.5 and 12 km. The areas draining to Pillings, Belgrave and Leicester were changed to 1105, 450 and 387 km^2 from 1036, 460 and 390 km^2. This led to the lateral inflow proportions for Loughborough Laterals into the Belgrave to Kegworth reaches changing to 20, 20, 27, 27, 3 and 3% from 9, 9, 38, 38, 3 and 3%. The Leicester lateral inflow proportion to the reaches between the Upper Soar to Pillings were changed to 22, 22, 19, 18, 10 and 9% from 23, 23, 21, 20, 7 and 6%. Configuration and calibration changes to Rothley, Littlethorpe and South Wigston catchment models were made on 28 June 1993 and those to the Freemans, Belgrave and Pillings reach models on 6 August 1993, and revised on 4 October 1993. The catchment models for the Lower and Upper Wreake laterals were changed on 6 July 1993 and the reach models for Syston and Kegworth on 30 July 1993 and 9 August 1993. The changed model parameter values have been summarised previously

Table 4.1.1 Flood forecast events available for analysis

Event/forecast run	Date	Forecast run time
1	12 Nov 1992	07.00
2	24 Nov 1992	07.00
3	04 Dec 1992	16.00
4-1	11 Jan 1993	16.00
4-2	13 Jan 1993	18.00
4-3	14 Jan 1993	15.00
4-4	15 Jan 1993	07.00
4-5	"	09.00
5-1	11 Jun 1993	15.00
5-2	12 Jun 1993	19.00
5-3	13 Jun 1993	07.00
6-1	7 Oct 1993	15.00*
6-2	8 Oct 1993	11.00*
7	15 Nov 1993	09.00
8-1	8 Dec 1993	13.00*
8-2	"	21.00*
8-3	9 Dec 1993	03.00*
8-4	"	09.00*
9-1	24 Feb 1994	16.00
9-2	25 Feb 1994	15.00
9-3	"	23.00
9-4	26 Feb 1994	00.00
9-5	"	11.00
9-6	"	19.00
9-7	27 Feb 1994	07.00
9-8	"	19.00
9-9	28 Feb 1994	13.00
10-1	18 Mar 1994	23.00
10-2	19 Mar 1994	03.00
10-3	"	10.00

* not on disc: hard copy plots only

in Tables 3.2.1 and 3.3.1. The overall impact of these configuration and model parameter changes on the analysis of forecast performance is that events 1 to 5 essentially relate to old conditions and events 6 to 10 relate to the new ones. We would therefore hope to see some improvement over the second half of the events arising from these changes.

Two river gauging station ratings are given in the catchment and reach detail files of the FFS (previously summarised as Tables 3.2.2 and 3.3.2) for so-called "New technology sites" providing first "rated flow" and secondly "direct flow". The rated flows are stage-discharge relations whilst the direct flow is the electromagnetic or ultrasonic flow measurement. Quality flags on the overall rating and individual components of it are used to define which rating takes priority, and if both are high quality then the first takes priority. The low quality is indicated for individual components by a minus in front of the coefficient value. The effect of this priority means that for some stations, particularly in the past, there have been switches between ratings, for example first using an em gauge estimate, then a stage-discharge estimate and then revoking to the em gauge estimate again causing abrupt changes to the profile of the inferred hydrograph. More recently there has been a change towards maintaining a given estimate, rather than switching between estimation methods, but it is possible this has been overdone in some cases. An example, is Littlethorpe where the em gauge estimate takes priority over the full flow range even when there is known to be bypassing above flows of 15 m^3/s.

A summary of the changes made to these so-called "switch flows" over the period of the 10 events for the three electromagnetic stations is given below to aid interpretation of the flood forecast performance.

Syston: Before 10 December 1993 the em gauge estimate was replaced by a rating curve estimate above a flow of 35 $m^3 s^{-1}$ (or possibly less). The "switch flow" was raised to 38 $m^3 s^{-1}$ on 10 December 1993 and to 40 $m^3 s^{-1}$ on 11 January 1994. On 24 January 1994 a higher level switch was introduced back to the em gauge estimate.

South Wigston: The original method switched to the rating curve estimate above 15 m^3/s, until this became low quality, when the low quality em gauge estimate was used again. After 15 November 1993 the quality flag on the rating curve was removed, allowing the curve to be used always above 15 m^3/s. After 24 January 1994 the em gauge estimate has been used over the whole range.

Littlethorpe: Probably from before 4 June 1993 the em gauge estimate was used up to 15 $m^3 s^{-1}$, then the rating curve, and above 21.5 $m^3 s^{-1}$ the em gauge estimate again. On 24 January 1994 the upper switch at 21.5 $m^3 s^{-1}$ was removed, using the rating curve estimate at all flows above 15 $m^3 s^{-1}$. Probably during the winter of 1994 a change was made to use the em gauge estimate over the whole flow range.

The main impact of these changes to the switch flows on forecast performance should therefore be primarily evident in the last two events, events 9 and 10.

The following summarises changes made to the gate flow measurements over the period.

Frisby: A rating curve for the Wreake at Frisby, downstream of the gate, was added to the FFS in 1993 but was only used in the routing model from 17 January 1994.

Zouch: A rating curve for the section downstream of the Zouch radial gate was added in August 1994 but has only just been incorporated in the model (October 1994).

The potential of these rating curve estimates of flow to calibrate the catchment reach models has not yet been exploited.

4.3 ANALYSIS OF EVENTS

The 10 events are discussed in turn. By way of background the synoptic conditions prevailing at the time of each storm are summarised first. Information has been gleaned from the weather log published monthly in Weather and the British weather summary for each month given in the Journal of Meteorology. This background is followed by a general summary of the forecast runs available for the event, indicating particularly which run is used to assess the simulation model performance and which set of runs are used to assess the updating technique. For a few events supplementary information on the quality of gauged flows is given. The performance of the catchment models is first analysed followed by that of the reach models.

Event 1: 12 November 1992

A vigorous westerly outflow across the North Atlantic brought rain for most of November 1992, giving nearly twice the normal monthly rainfall in parts of Britain. On the 11th a vigorous wave depression gave a lot of rain to the south as it moved east across southern Britain. The rain was associated with hail and thunder in places.

Only one forecast run is available for this event, made at 07.00 12 November 19 hours after the peak for Rothley Brook at Rothley (also used in scaled form to estimate Loughborough lateral inflows). This run therefore provides a good indication of the simulation forecasts obtained from the model, but cannot be used to assess the performance of the updating technique.

Lateral inflows: The Loughborough lateral inflow model simulation is poor compared to the "observed" hydrograph with significant underestimation of flood volumes and peaks. A late peak of ~12 is predicted at 00.00 2 November, compared to the "observed value" of ~21 some 12 hours before. However, the "observed flow" in this case is simply a scaling of the Rothley observed flows by a factor of about 3 (actually 1/.31 = 312/96 the ratio of the two catchment areas in km^2) whilst the forecast flow is obtained from a catchment model. The model gives a very similar forecast profile to that for Rothley Brook, but scaled by a factor of 3/2. Scaling of the Rothley forecast by 3 to get an estimate of the lateral inflows would give a peak estimate of 24, much better than the model-derived forecast of only 12, given the scaled "observed" peak is 21. This merely serves to highlight the futility of using the scaled observed flows at Rothley to assess model forecast performance, which naturally favours a scaling approach over a catchment model approach to estimating flows for ungauged catchments. It is of interest to note that the low model forecast may at first appear to be at odds with the main difference in the two catchment models, with a higher runoff coefficient of 0.55 being used for Loughborough laterals compared to .38 for the rural Rothley Brook (Table 3.2.1). The lower forecasts in fact appear to result from somewhat lower catchment average rainfall estimated for the Loughborough lateral inflow catchment, than for Rothley Brook, and probably more importantly from the lower initial flow predicted by the lateral inflow catchment model. It is also worth noting that the Leicester lateral inflows are not available on disks downloaded at the Trent area office. This has revealed use of an old version of the REMUS program and the need to update it. In the case of the Lower Wreake lateral inflows a scaling of 145/96 = 1/.66 = 1.5 is used. These scaled lateral inflows will not be considered further in subsequent events.

Rothley Brook at Rothley: The simulated flow overpredicts with a peak of 8 compared to the observed value of ~6.5, and as with Loughborough lateral inflows is shifted by 24 hours.

Sence at South Wigston: The simulation forecast is quite good, particularly in forecasting the peak at ~10, although somewhat late and with volume underestimation on the rising limb.

Upper Soar at Littlethorpe: Again the simulation forecast is reasonable with a good hydrograph shape but with some overestimation of the peak: ~11 compared to ~9.

Wreake at Syston: The simulation is poor in shape, predicting a false early peak on the 10 November and then predicting a second peak of the wrong shape too late. However the peak magnitude is well predicted (29 rather than 30) but 6 hours late.

Pillings: The reach model forecast for Pillings lags the observed hydrograph by some 6 hours and underestimates the flat peak level of ~48, predicting ~45.

Kegworth: The reach model simulation predicts the rising limb very well indeed, but overshoots the observed peak at ~48, predicting ~58. The updated forecast beyond the run time origin looks reasonable in form, but the observed hydrograph is not available to make an absolute assessment.

Event 2: 24 November 1992

The last 10 days of November brought the most disturbed weather in what was a very wet month (see Event 1). On the 21st and 22nd Nantmor near Snowdon experienced 75 mm in 48 hours and on the 24, 25, 28-30 November much of south-west England and South Wales experienced more than 25 mm each day. The rain was associated with a very mild airflow with temperatures of 15°C.

Only one run is available for this event, made at 07.00 24 November after the peak has passed, so only the simulation forecast will be commented upon.

Rothley Brook at Rothley: The catchment model simulation forecast badly overestimates the volume of the flood hydrograph. It predicts an early peak followed by a lower later peak whilst in practice it appears rain is absorbed initially and then a later higher peak formed. The peak forecast is ~5 compared to ~3.5 observed, with a time difference of ~18 hours.

Sence at South Wigston: The catchment model simulation forecast underestimates the volume of the flood hydrograph badly and is too damped. The forecast peak at ~3.5 compares with an observed value of ~6.5.

Upper Soar at Littlethorpe: The catchment model simulates the initial rise quite well but underestimates the peak (~5 compared to 6 observed) and the volume of water on the recession, falling too quickly.

Pillings: Although the initial rise of the hydrograph is underestimated the forecast in the vicinity of the peak is excellent (exact peak prediction of ~36), as is the decay from the peak.

Kegworth: The volume of the rising flood hydrograph is overestimated a little. The observed peak has a broad flat top at ~41 whilst the predicted peak is more rounded and reaches ~45. This may be control gate and/or floodplain storage induced.

Event 3: 4 December 1992

Vigorous troughs gave copious rainfall on 1-2 December, especially in the west and north of Britain. It was also very mild. Around 250 mm of rain fell in the 10 days to the 3rd in the hills of South Wales. There was severe flooding in the first week of December over South Wales, the West Country, the West Midlands and the Thames Valley.

Only one run is available for this event, made at 16.00 4 December 1992 after the peak has past so only the model simulation performance will be investigated.

Rothley Brook at Rothley: The flood peak volume is badly underestimated and the recession volume overestimated. The peak prediction of nearly 8 compares with an observed value of nearly 10, a 20% underestimation.

Sence at South Wigston: The catchment model badly underestimates the flood volume and a forecast peak of ~8 compares with an observed peak of ~12.5. Flattening of the observed peak at this discharge seems to occur.

Upper Soar at Littlethorpe: The catchment model badly underestimates the flood volume. A forecast peak of ~11 compares with an observed value of ~15, about 25% underestimating.

Wreake at Syston: The reach model forecast follows the general trend of the observed hydrograph, both underestimating and overestimating. The peak forecast is 25 compared to an observed value of ~28, with no timing error.

Pillings: Whilst the forecast follows the general trend of the observed hydrograph it consistently underestimates it by ~5. The peak forecast at ~60 compares with an observed value of ~65 some 6 hours earlier.

Kegworth: The reach model forecast hydrograph, whilst having the right trend, overestimates the flow consistently. The peak forecast of ~76 compares with a flatter observed peak of ~71.

Event 4: 11-15 January 1993

Milder weather reached all parts by the 5th, remaining mild but unsettled for the rest of the month with very disturbed west to south-westerlies prevailing. Gales and storms were common. On the 10th a new Atlantic depression centred over north-west Scotland set a new record of 916 mbar for Northern Hemisphere temperate latitudes. A cold, unstable westerly flow followed in the wake of this depression giving heavy wet snow and high winds and causing widespread disruption to transport and power over the next few days. The south was badly hit by damaging gales on the 13th as a front, centred over the Midlands swept across the country. Another frontal system crossed the country on the 15th.

The following rainfalls were recorded for 13 January: Narborough - 25 mm in 6 hrs, 3 year return; Mt.St. Bernards - 20.5 mm in 6 hrs, 0.5 year return; Hinckley - 23.5 mm in 6 hrs, 1 to 2 year return.

At Littlethorpe a peak of 19.8 m^3s^{-1} from the electromagnetic gauge disagreed with a flow of 28 m^3s^{-1} calculated from the rating curve at 02.00 14 January. An estimated return period of 5 to 10 years was calculated for this event, given the poor quality of records at Narborough and Littlethorpe. Bypassing around the electromagnetic gauge was known to have occurred.

At Rothley Brook on the 14th 12.6 m^3s^{-1} was recorded, with an estimated return of 2.3 years (the mean annual flood). At Pillings the flood return period was estimated at 5 years.

An analysis of the flood peak at South Wigston (the Sence) by the NRA suggested a return period of 5 to 10 years. The electromagnetic gauge recorded a value of 39.6 m^3s^{-1}, but a lower figure of 20 to 25 estimated from a stage-discharge curve was considered more realistic. If this is true then the implication is that the electromagnetic gauge may overestimate flows by as much as a factor of 2! The peak level of 2.703 m was similar to that in September 1992 when a flow of 26.3 m^3s^{-1} was recorded; however, the flow for this January event is likely to be greater on account of weed growth increasing the September level. The highest current meter measurement at 2.411 m , made on 15 December 1989, gave a flow of 20.9 m^3s^{-1}, suggesting a best estimate of 28 m^3s^{-1} for the 13 January 1993 event peak. In general the South Wigston station is not ideal for high flow gauging and there is likely to be appreciable uncertainty associated with the rating relation.

It is of concern that a 3 year old culvert in the Sence catchment designed to a 100 year standard surcharged and flooded a number of properties with serious consequences during this flood. The design used an impermeability factor of 15% which may be too low for this clay catchment, especially with saturated antecedent conditions. Model studies carried out by NRA-ST suggest impermeability factors of 0.25 to 0.5 for rural catchments when antecedent soil moisture deficits are 0 to 20 mm; responses equivalent to a 50% urban catchment can be obtained from rural catchments. The previous practice of using 0.2 to 0.3 for impermeability factors in rural catchments is likely to underestimate runoff significantly, leading to underdesign of culverts in the past.

The following peak flows have been estimated for the 13 January event: Croft- 11.6, Sharnford- 3.6, Littlethorpe- 28.4, Great Glen (Sence/Burton Brook)- 9.8, South Wigston (Sence)- 28.

Rothley Brook at Rothley: The simulation forecast (Run 5) is not too bad for a catchment model and yields a peak forecast of 11 compared to the observed value of ~12.5.

The updated forecast for Run 2 is poor, only projecting the past observed flows upwards for a short time and then dipping quickly back to the lower simulated forecast, producing a sawtooth forecast. Subsequent runs start after the peak has past and are of little interest.

Sence at South Wigston: The simulation forecast from this catchment model is very poor (see Run 5), badly underestimating the peak flow as ~13 compared to ~40 from the electromagnetic gauge. Even the preferred rating curve estimate of 20 to 25 implies significant model underestimation. The lower recession is well predicted at the start and end of the event. The underestimation again results in a short-lived sawtooth adjustment, dropping quickly back to the simulation forecast.

Upper Soar at Littlethorpe: The simulation prediction (see Run 5) is very good with a more or less exact forecast of the peak. Note, however, that the observed peak according to these telemetry data is ~17.5, whilst the electromagnetic (em) gauge value was 19.8 and the "best estimate" from the rating curve was 28. The discrepancy of 2 from the same em gauge should be investigated. The suggestion is that bypassing of the gauge is the cause of the rounded, flat topped observed hydrograph and that the model is underestimating the true flow by as much as 10 m^3s^{-1}. If the model is calibrated to the em gauge, without correction for bypassing at high flows, then the model may not be the source of the problem. Given the "good" simulation forecast the updated forecast is also good with Run 2 showing a slight, but short-lived, improvement.

Wreake at Syston: The simulation forecast (Run 5) of the peak, although 12 hours late and the wrong shape, is about right in magnitude (about 34). The very flat top to the observed hydrograph presumably reflects the operation of the Frisby and Eye Kettleby gates upstream. The updated forecast for Run 2 made before the peak again shows a sawtooth, short-lived adjustment. Use of a persistence forecast based on an ARMA model is likely to be better in such a situation of consistent past underestimation.

Pillings: The simulation forecast ((Run 5) for this routing reach is poor, badly underestimating most of the flood hydrograph and predicting a peak of ~60 compared to the observed value of ~110. Since inflows come from Belgrave (Soar), Syston (Wreake) and Rothley (Rothley Brook) upstream, and from Leicester and Loughborough lateral inflows, the sources of error are difficult to identify. The forecast adjustment for Run 2, before the peak, is short-lived, sawtoothed and not very effective.

Kegworth: The simulation forecast (Run 5) badly underestimates the observed flat-topped peak of ~105, flattening out at ~80. Possible sources of error include those associated with model inflows from Zouch upstream (which propagates errors from Pillings), and use of 6% of the Loughborough lateral inflow. The updated forecast for Run 2 made near the bottom of the rise is too short-lived to be useful, and sawtooths again to the simulation forecast, forecasting a peak of ~70 and not 100.

Lateral inflows: The Loughborough lateral inflows are badly underestimated in simulation mode (see Run 5), and the peak forecast is ~20 compared to ~40 observed. Updating on Run 2 is ineffective and quickly sawtooths to the simulation forecast.

In contrast the Lower Wreake lateral inflows are reasonably well estimated. For Run 2 the initial underestimation on the rising limb causes an ineffective, short-lived sawtooth adjustment.

Event 5: 11-13 June 1993

June 1993 was a mostly quiet and dry month except from 9-16 it became very cyclonic and disturbed with some remarkable rainfalls. Thundery low pressure drifted from France on the 9th, the low deepening steadily over England over the next couple of days. Thundery outbreaks were widespread from 9-11 with heavy falls of rain: 92 mm in 2 hrs and 123 mm in 12 hrs on the 9th at Culdrose in Cornwall; 121 mm in 2 hrs at North Weald in Essex and 140 mm in 4 hrs at Llandudno on the 10th. Very cool air came around the south-west flank of the depression giving south-west Britain 48 hrs of prolonged heavy rain, centred on the 11th, along with strong winds and very low temperatures. At Aberporth 151 mm fell in 48 hours, with higher falls over the Cornish moors, and flooding was severe over Cornwall and parts of Wales. On the 13th the area of low pressure eased away eastwards, giving a dryer day, but more depressions and rain followed from 14-16 June, after which the rain stopped, for 24 days in the south.

Rothley Brook at Rothley: The catchment model simulation (Run 3) significantly underestimates the flood volume. A simulated peak of ~8 compares with the observed value of ~17, underestimating by more than a factor of 2. Run 1 made at 15.00 11 June five hours before the observed peak at 20.00 is useful for assessing the updated forecast performance. The adjustment is reasonable for up to 2 hours ahead, reaching a peak of ~12, but then sawtooths back down to the low simulation forecast.

Sence at South Wigston: The catchment model simulation (Run 3) again significantly underestimates the flood volume, and peaks at ~14 rather than the observed value of ~37. Updating (Run 1) is of little use and quickly approaches the low simulation forecast in a sawtooth manner.

Upper Soar at Littlethorpe: The catchment model simulation in this case is better with both overestimation and underestimation. The observed peak of ~12.5 at ~18.00 is well forecast but the simulated hydrograph continues rising for 9 hours to attain a peak of ~16. The updated forecast (Run 1) in this case modifies the shape of the rise to the observed peak very well, but like the simulation forecast continues to rise to overpredict the peak by ~25%.

Wreake at Syston: The overall volume of the simulated flood at Syston is correct but the double peak that is observed is forecast as a single higher peak (29 compared to 22 observed). The updating (Run 1) is quite effective over the first two hours after which it shares the problems of the simulation forecast.

Pillings: The reach model simulation (Run 3) consistently underestimates the observed hydrograph, and at the peak attains a value of 60 compared to ~78 observed, an underestimate of nearly 25%. However, the forecast crossing of the amber warning level is very good indeed. The updated forecast (Run 1) is not successful and quickly reverts in a sawtooth manner to the simulated forecast.

Kegworth: The reach model simulation (Run 3) provides a reasonable forecast of the peak, giving ~62 rather than the observed ~64. It fails to predict the humped nature of the hydrograph, rather giving a smooth rise and fall. The updated forecast (Run 1) is not very useful, increasing the prediction on the underpredicted rising limb but quickly sawtoothing back to the low simulated hydrograph.

Event 6: 7-8 October 1993

This event caused property flooding at Croft and at Rothley. For the 96 hour period ending at 15.00 7 October there were three main pulses of rain centred on 00.00 4 October, 15.00 5 October and 16.00 6 October. The rainfall at Narborough reached 30.5 mm in 43 hours and 20.5 mm in 13 hours, with an estimated return period of only between 1 and .5 years; similar low return period rainfalls were estimated for Hinkley (24.5 mm in 10 hrs, .5 year return) and Mt. St. Bernards (37.5 mm in 11 hrs, 1 year return).

The rain falling on an already saturated catchment produced near record levels of flooding at Littlethorpe with a rating-curve derived flow peak of 31.9 m^3s^{-1} at 09.00 7 October, checked by current meter at the peak as 35 m^3s^{-1}. An estimate of its return period, based on a 12 year record, gave 10 to 15 years. The electromagnetic gauge recorded only 20 m^3s^{-1}, due at least in part to observed bypassing.

At Rothley Brook flow peaked at 15.3 m^3s^{-1} at 12.00 7 October, with an estimated return of ~5 years.

An earlier high level at Littlethorpe of 2.559 m was recorded at 22.00 on 11 June 1993, whilst the gauged flow was only 12 m^3s^{-1} and no property flooding occurred. Weed growth affecting this summer event would only enhance the levels by up to 60 cm so backing up effects downstream of the gauge is a more likely factor.

Rothley Brook at Rothley: Only plot for 15:00 7 October. Poorly underestimates peak of

~15 at 12.00 7 October, predicting only ~7 a little earlier. Adjustment recedes at same rate as past observed for ~6 hours, and then ramps down linearly over ~6 hours to simulation forecast. No observed to assess the quality of this adjustment but the two segment forecast looks unrealistic.

Sence at South Wigston: The simulation forecast badly overpredicts the true peak of ~4 at 12.00 7 October, forecasting ~7. The updated forecast for the first run is initially good when it is based on persistence but unrealistically climbs to meet the simulation forecast over the period 6 to 12 hours ahead.

Upper Soar at Littlethorpe: Discontinuities in the observed hydrograph are evident at ~10, 14 and 20. Two of these relate to the em "switch" flows at 15 and 21.5 $m^3 s^{-1}$. The simulation forecast grossly underestimates the peak: ~8 compared with ~32. The persistence updating for the first run predicts a concave recession and not the actual convex, steeper recession. The correction on the second run is more satisfactory in appearance.

Wreake at Syston: Odd blip on the observed hydrograph at ~15.00 6 October. Forecast peak is well defined at ~18 (12.00 7 October), just above standby level, whilst actual peak remains quite flat at ~11 from 15.00 7 to 00.00 8 October. Adjustment for later run again is a sensible persistence error forecast on the recession. The earlier update starts from the last observed value as a persistence correction for ~12 hours, followed by a taper for ~12 hours to meet the simulation forecast. It is reasonably successful.

Pillings: The simulation forecast is reasonable, underestimating up to 0600 7 October and then overestimating to 06.00 8 October. Updating on the first run is satisfactory, and the persistence followed by tapering scheme seems intuitively reasonable for the second run.

Kegworth: Underestimation of peak at ~58 (01.00 7 October), with ~42 forecast. Sensible persistence adjustment for run at 11.00 8 October. For the run made at 15.00 7 October a persistence forecast continues the trend of the observed hydrograph well (in recession) but is unrealistically tapered upwards to meet the simulation forecast, which is too broad and flat, over the lead time period 12 to 24 hours.

Event 7: 15 November 1993

A sluggish airflow across the Atlantic towards Britain persisted for most of November, allowing a strong anticyclone to develop over the former Soviet Union. Between the 9th and 14th a much more unsettled westerly regime took over, bringing alternating rain and sunshine. On 9-10 a large area of rain moved slowly east, followed by two sunny days, and then a deep, vigorous depression crossed southern and central districts on 13-14 bringing widespread heavy rain. A 24 hr fall of 70 mm was recorded at Fylingdales, North Yorkshire. Gales followed in the wake of the depression. Conditions from the 15th were dominated by a strong anticyclone to the east, with cold dry weather.

There is only on run available for this event, after the main peak has passed and so attention will focus on the simulation forecast performance, and not updating.

Rothley Brook at Rothley: The catchment simulation model underestimates the flood volume somewhat but is not too bad for a rainfall-runoff model. At the peak the model predicts ~12 compared to ~14 observed and the timing is also quite good.

Upper Wreake at Frisby: The catchment model simulation produces a reasonable forecast, unlike the observed hydrograph which is serrated, and artificial looking. This presumably reflects control of the gate at Frisby. The simulated peak of ~32 compares with an observed value of ~41.

Sence at South Wigston: Again the catchment model simulation looks reasonable whilst the observed hydrograph has a vertical rise at a flow of ~ 15, corresponding to the switch from the em to the rating curve estimate, and spikes at ~ 18. The forecast peak is ~ 18 whilst the observed value is ~22.

Upper Soar at Littlethorpe: The catchment model again looks reasonable whilst the observed flow exhibits changes in shape. At a flow of ~13 the hydrograph rises vertically and at ~20 it rounds off to a peak of ~25. These correspond to switch flows at 15 and 21.5 $m^3 s^{-1}$. The forecast peak attains a value of ~22.

Wreake at Syston: Although the forecast rise is poorly underestimated by the reach model simulation the peak forecast is almost exact at ~37. However, the observed peak reaches this level one day earlier and stays there for ~2 days!

Pillings: The reach model simulation is excellent. Flows peak at ~90.

Kegworth: The reach model simulates the initial hydrograph rise very well but continues rising to peak at ~ 100 whilst the observed flows rise slowly from 80 to 90.

Event 8: 8-9 December 1993

December 1993 was a very unsettled month with a steady stream of easterly moving depressions. Most places were very wet with twice the normal rainfall in parts of the west and south. A mild start to the month, and much rain in the north and west, gave way to a cold front and clearer air on the 4th. Heavy rain in the north and west occurred on the 6th, followed by showers on the 7th, and wet and very windy weather spreading to all districts on the 8th. Damaging winds occurred at night. More rain occurred on the 10th, winds veering northerly and bringing snow showers to the north. Snow preceded the next rain area on the 12th, especially in hilly central regions. Cold air and frosts followed.

A continued period of heavy rain occurred from 05.00 8 December to 04.00 9 December, being particularly intense around 07.00 8 December. Rainfall for the 96 hours ending 09.00 9 December was typically 20 mm over the Soar.

Four forecast runs were available in hard copy form for this event: Run 1 - 13.00 8 December, Run 2 - 21.00 8 December, Run 3 - 03.00 9 December, Run 4 - 09.00 9 December. The last run, Run 4, is used to assess the simulation performance of the model.

Rothley Brook at Rothley: The catchment model predicts the rising hydrograph very well but turns over too soon at ~8 at 00.00 9 December, whilst the observed hydrograph continues up to ~9.5 over a further 9 hours.

The updated forecasts of the observed peak at ~9.5 are ~6.5, ~9.5 and ~9.5 for runs 1, 2 and 3 which are 16, 8 and 2 hrs before the peak. The updating is satisfactory, even the saw-tooth form of the peak forecast tapering to the simulation forecast for Run 2.

Sence at South Wigston: The observed hydrograph looks suspect with a saw-tooth profile instead of the more realistic smooth forecast peak. The rise of the hydrograph is very well forecast.

In updating mode the (suspect) observed peak at ~8 is forecast as follows for runs 1 to 3: ~8, ~10, ~10. Only the adjustment on Run 3 is unnatural with a saw-tooth produced by the persistence forecast being followed by a an upward taper to the simulation forecast. Given the odd shape of the observed hydrograph the performance of updating could be said to be very satisfactory.

Upper Soar at Littlethorpe: The rainfall-runoff model for Littlethorpe predicts the flood hydrograph shape and peak quite well, with a forecast peak of ~9.5 overestimating the observed peak of ~8.5 and with no timing error. The overall forecast volume is worse with the forecast hydrograph being both fatter and higher.

In updating mode the forecast peaks are excellent for Run 1 (~8), poorer for Run 2 (~9) but again excellent for Run 3 (~8 again). The performance overall is very good.

Wreake at Syston: The routing model performance is poor in simulation mode, badly underestimating the peak (21 compared to ~30) and failing to forecast the actual yellow alert.

The effect of the update is to initially adjust for the underestimation for Run 2 but quickly to taper downwards to the low simulation forecast after about 5 hours, failing to improve the prediction of the peak. For Run 3, made at the peak, the effect of updating is very bad predicting a continued rise to ~38 and then a fast taper back down to the low simulation hydrograph. This is a difficult situation for any updating procedure to work well in, and highlights the need for an improved model structure (if hydrometric data are not the cause).

Pillings: The shape of the rise is well predicted although consistently underestimated until the observed hydrograph flattens out at ~48 at 02.00 9 December. However, the observed flow hydrograph doesn't continue for long enough to comment on the peak forecast and whether the amber level was actually exceeded as forecast.

The effect of updating correctly compensates for the consistent underestimation on the rising limb, although no comment on the adjusted peak forecast can be made due to unavailability of the peak observation. Of concern is the form of adjustment for Run 1 where the two-stage adjustment creates a saw-tooth forecast, Continuing with a persistence forecast but with diminishing effect would be better than use of a taper to the simulation forecast. Certainly an ARMA error predictor is likely to have performed better in this situation, tapering smoothly to the simulation forecast with increasing lead time.

Kegworth: The simulation forecasts badly overestimate the observed flows (60 compared to ~42).

The adjustment for runs 2 and 3 are sensible but not sufficient to correct for the simulation model's overestimation. Run 1 produces a saw-tooth forecast, reverting to a better simulation forecast (~55 compared to ~42) than is the case for Run 4. The simulation forecast is even worse for Run 3 (~73). This presumably reflects higher inputs (Zouch and/or Loughborough lateral inflows) coming into this routing model for these runs, particularly Run 3.

Event 9: 24-28 February 1994

From the 11th south-westerlies brought a drop in temperature and light snow on the 13th, followed by very cold weather and further widespread snow. Heavier snow spread northwards on the 15th (4-10 cm depth) followed by a thaw in the south and further snow in the north on the 16th. Milder weather returned to the south from 16-19, but very cold east European air returned by the 20th giving widespread moderate snowfalls. Milder air on the 22nd brought prolonged rain and fog in southern counties, but there was further snow over the next few days from the Midlands northwards. Renewed warm southerlies on the 25th brought a thaw over England and mild showery weather.

A total of 9 forecast runs are available for this event. Run 8, made after the flood peak has passed, is the most useful for assessing the simulation model performance. The earlier runs 3 to 7 provide a valuable indication of how the updating technique performs on the rising limb of the flood hydrographs.

Rothley Brook at Rothley: The catchment model simulation predicts the initial rise well but fails badly to predict the later volume of flood runoff, which includes the observed peak at ~12. The simulation flattens off at around 9 and starts to recede about 6 hours before the observed peak occurs. The updated forecasts are reasonable in not having a sawtooth form but fail to predict the broader observed peak, not surprisingly. Run 6 is the critical failure in not continuing the still rising observed hydrograph, instead falling almost linearly to the simulation forecast over an ~36 hour period.

Upper Wreake at Frisby: The catchment simulation model badly underestimates the volume of flood runoff after a reasonable early start. The observed hydrograph is rather jagged, presumably indicating the effects of gate control. The predicted peak of ~23 compares badly with the observed peak of ~36, although the timing is good. The updated forecasts also underestimate the peak badly. The peak forecasts increase slowly within the event and only at Run 6 does it exceed 30, but the forward extrapolation upwards is short-lived (~2 hours), quickly sawtoothing down to the simulation forecast.

Sence at South Wigston: The catchment model simulation is excellent, both in terms of volume and peak prediction (both about 14). The updated forecasts are well behaved and in general provide a marginal improvement.

Upper Soar at Littlethorpe: The catchment model simulation is reasonable but generally consistently overestimates by ~2, with a resulting higher volume and peak (~17 compared to 14). The earlier updated forecasts are very good indeed (Run 3) but progressively start to overestimate. The adjustment is well behaved until Run 5, 13 hours before the peak, when the simulation starts to overpredict. This results in the adjusted forecast being turned down over a period of 12 hours, instead of continuing to rise, and then flattening for 12 hours when it meets the simulated forecast and falls again. The result is a too low, unrealistic looking forecast.

Wreake at Syston: The reach model simulation underpredicts the volume of the flood and underestimates the peak, giving 32 instead of 40. The observed hydrograph has a very jagged top indicating the effect of control gates. Because of the underestimation of the simulation model on the rising limb, updating gives the characteristic sawtooth adjustment which is both unrealistic and not very effective at improving forecast accuracy. Updating after the first observed peak has the effect of suppressing a further rise in the forecast, failing to predict later peaks. Updating during gate control is clearly problematic without an explicit model of the gate operation.

Pillings: The reach model forecast at Pillings is excellent over the entire hydrograph. A peak approaching 80 is attained and correctly simulated. Runs 3 to 7 on the rising limb underestimate the peak but get progressively better over the 32 hour period: 59, 63, 66, 79 and 79 respectively. The excellent forecast from Run 6 is made 17 hours before the observed peak. Underestimation by the simulated flows causes the usual sawtooth forecast, rising more steeply but then falling back abruptly to the simulated hydrograph.

Kegworth: Initially the reach model predicted rise is good but the observed hydrograph starts to flatten at ~70, whilst the simulation continues to rise to peak at ~96 (compared to a later observed peak of 80). The forecast is a yellow alert which does not occur in practice. Overestimation on the rising limb causes a zizag adjustment which does not look realistic. The updated peak forecast is initially too low but begins to overestimate between runs 4 and 5. At Run 6, after the observed hydrograph has flattened off, the updated adjustment is excellent predicting the continuing flat peak at just below 80, although not quite rising high enough.

Event 10: 18-19 March 1994

The month was dominated by vigorous westerly airflows bringing frequent bands of rain interspersed with sunshine, showers and windy conditions. An active cold front progressed slowly and erratically southwards across the country on the 14th and 15th, all areas experiencing heavy rain and a sharp drop in temperature. Cold weather continued to the 21st when mainly north-westerly winds brought squally wintry showers and sunny intervals. Secondary depressions crossed southern Britain on 18,20 and 21 March bringing prolonged rain.

Three runs are available for analysis for this event, and Run 3 is used to assess the simulation performance of the model.

Rothley Brook at Rothley: The simulated peak forecast for this event is very good, predicting the observed value a little above 8 almost exactly. However, the overall shape is shifted forward, underestimating on the rising limb; the observed recession is not available to judge the recession performance. The updated forecasts show the usual sawtooth adjustment when underpredicting on the rising limb, and are of little benefit. The so-called expected peak forecast is difficult to improve upon, and for Run 1 gives an excellent 13 hour ahead forecast of the peak.

Upper Wreake at Frisby: The observed hydrograph is very jagged reflecting control of the gates. The rise of the catchment model simulation is excellent but clearly does not predict the erratic changes of flow due to the gates. More by good fortune, the updated forecast at Run 2 predicts the rise following the initial drop in flows but thereafter fails to predict further rises and falls.

Sence at South Wigston: The rise of the hydrograph is well simulated by the catchment model but Run 3 is not late enough to record the observed peak, and comment on the model's ability to forecast it. However, it is likely to be good. Updating does little to improve this already good forecast.

Upper Soar at Littlethorpe: The catchment model simulation of the rising hydrograph is very good, but above 4 starts to overpredict. The observed hydrograph flattens out at about 6 whilst the forecast continues rising to above 8. Because the simulation is so good on the rising limb updating is not too important. However, as the simulation overshoots updating effectively stops this but since the later part of the observed hydrograph is unavailable it is difficult to assess the later performance.

Wreake at Syston: The reach model simulation rises initially quite well but at ~ 15 flattens off markedly to produce a late forecast peak of only ~22. In contrast the observed peak reaches ~35 about 14 hours earlier. Updating on the rising limb for runs 1 and 2, is ineffective, producing the usual unrealistic sawtooth adjustment, dropping abruptly down to the simulation prediction after a short initial rise.

Pillings: The reach model simulation is very good, although the observed peak is not quite available at the time Run 3 is made. There is consistent underestimation of only a few m^3/s. The use of the first phase updating, based on a weighted average of past errors, is not applied for long enough given the very persistent underestimation. Instead it reverts quickly down to the somewhat lower simulated hydrograph after a period of about 4 hours for Run 1. This makes the updating of little value.

Kegworth: The observed peak is not yet available at the time Run 3 is made making an assessment of the reach model simulation difficult. The recession and early rise of the simulation is excellent but above ~30 overestimation begins. At the time of the forecast run 3 a simulated value of ~67 compares poorly with an observation of only ~50. Updating for runs 1 and 2 is largely ineffective, with the usual jagged adjustment having no effect on the forecast peak estimate. However, for Run 3 updating does pull the peak down but in the absence of the observed peak it is difficult to comment on the overall success.

4.4 CONCLUSIONS

The following general conclusions can be drawn from the analysis of the forecasts made for the ten flood events:

(1) Lateral inflow models:

It is difficult to assess the success of the lateral inflow simulations on account of the lack of observations. Clearly using a scaling of the observed flows at Rothley provides an inadequate basis for assessment. If this was indeed adequate then a forecast approach based on scaling would be preferred to one based on a rainfall-runoff model. The advantage of using a rainfall-runoff model is that actual rainfall for the catchment can be used. However, the success of this approach may depend strongly on how the model parameters have been estimated. This would ideally be done by embedding the lateral inflow catchment model within the reach model it forms an inflow to, and estimating the parameters of both models as a single entity. A scheme for updating could also be developed for this combined configuration of models. The relative merits of a model-based approach, versus scaling flows from a neighbouring catchment, for estimating ungauged lateral inflows needs to be investigated through empirical studies, along with the use of embedded model calibration as discussed above. Peculiarities noted in the Loughborough lateral inflow model simulations and "observations" deserve further investigation.

(2) Catchment model simulation performance:

Rothley Brook at Rothley: Four of the 10 events are simulated acceptably, the first two are overestimated and the remaining 4 underestimated. There is an overall tendency to underestimate (7 of the 10 events).

Wreake at Frisby: Performance has only been assessed for three events and these exhibit underestimation of the gate-influenced observations. Improvements in forecasting are unlikely to derive from a hydrological reach model approach, a hydrodynamic model representation being recommended.

Sence at South Wigston: The model has performed well over the last three events, but there was a tendency to underpredict on five earlier events. Performance overall may be judged satisfactory.

Upper Soar at Littlethorpe: Four of the 10 events were satisfactorily forecast (events 1, 4, 5, 8) and the remainder gave both overestimation and underestimation. There is nothing consistently wrong with the model in terms of its ability to predict the gauged flows (see (4) below).

(3) Reach model simulation performance:

Wreake at Syston: Three events could be said to be forecast adequately (events 3, 4, 7), whilst there is an overall tendency towards underestimation. Given the influence of gate control for this reach a hydrodynamic model approach is recommended to gain improvement.

Pillings: The reach model performed much better for this site with 4 good forecasts and 2 excellent ones, whilst the remaining four tended to underestimate (events 1, 3, 4, 5). Performance is good given observed inflows and therefore simulation forecasts after the peak has past look good. However, at the initiation of the flood, forecasts of the Pillings peak are uncertain due to the uncertainty of the forecasted inflows. Thus, the reach model appears good whilst the blame for poor forecasts early on stem from forecasting problems upstream. The truth of this depends on the adequacy of gauged flows at Pillings which is satisfactory until flows are generated on the floodplain. Then the interpretation becomes complex. Some of the uncertainty in forecasting the inflows may be helped by establishing a gauging station at Freemans Weir, as proposed in Stage 1 and reinforced here.

Kegworth: The performance at Kegworth was not good overall with a strong tendency to overpredict, except on two occasions when underestimation occurred.

(4) Updating:

The updating technique was generally ineffective and its two-phase form tends to produce unrealistic looking forecast hydrographs.

(5) Gauging problems:

Upper Soar at Littlethorpe: There is some evidence that the gauge may be underestimating flows by as much as 10 m^3s^{-1}, when the true flow approaches 30 m^3s^{-1}, due to bypassing. The observed hydrograph has a rounded, flat-topped form. Thus whilst the model may provide apparently acceptable results, having been calibrated to gauged flows, it may significantly underestimate the true flow. This will have water balance implications for the reach models downstream.

It is important to note that between events 8 and 9 a change in the method of calculating flows at Littlethorpe was invoked. Prior to 24 January 1994 there was a switch from the em gauge estimate to a rating curve estimate above a flow of 15 $m^3 s^{-1}$, at which bypassing was judged to first occur. At around 21.5 $m^3 s^{-1}$, above which the rating curve is classed as low quality, reversion back to the em gauge estimate occured. The effect of this switch is clearly apparent with the observed hydrograph rising steeply. Since 24 January 1994 the upper switch back to the em gauge estimate has been removed and the model recalibrated. Most recently (probably winter 1994) the em gauge estimate has been used for all flows, despite bypassing at higher flows. The main advantage is a more realistic looking observed hydrograph whilst the drawback is that model updating at higher flows may not properly take into account the bypassed flow component. This will be a source of volume errors for reach models downstream.

Sence at South Wigston: This electromagnetic gauge may overestimate a true flood flow of 20 m^3s^{-1} by as much as a factor of 1.5 to 2. Thus whilst the model fitted to em-derived flows may perform satisfactorily, it may overestimate the true flood flow considerably with water balance implications to reach models downstream.

Overall the changes made to model configuration, model parameters and electromagnetic gauge switch flows have not led to any consistent improvement in model performance across the Soar. One exception is possibly at Pillings where the performance has been generally more satisfactory for the last 5 events, following model reconfiguration and calibration. However, the general conclusion is that there is clearly scope for improvements in both gauging flows and in modelling and calibration.

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 reviews how the ST-FFS performs the task of forecast construction within the shell and how this compares with the approach used in IH's RFFS Information Control Algorithm. Section 5.3 reviews the shell and the external interfaces used to support flood warning in the Soar Catchment. Finally, Section 5.4 reviews the computer configuration used to run the Flow Forecasting System. In reviewing each issue the existing system is compared with that recommended under Stage 1 and recommendations for improvement made.

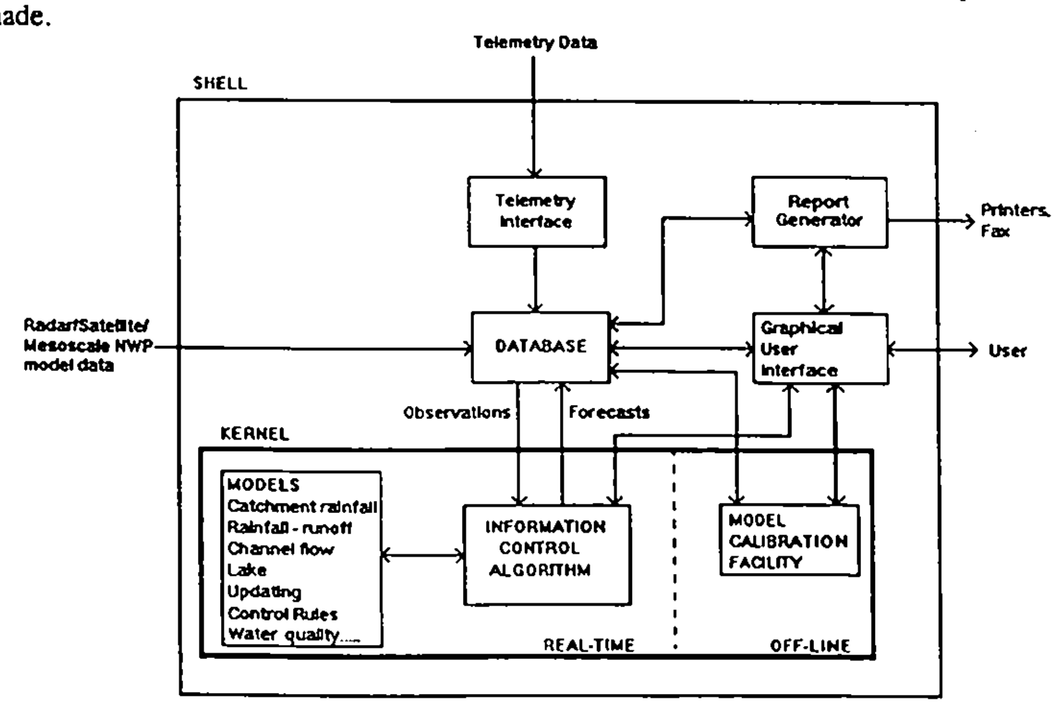


Figure 5.1.1 System environment of a Flow Forecasting System

5.2 INFORMATION CONTROL AND FORECAST CONSTRUCTION IN REAL-TIME

The NRA Severn-Trent Flow Forecasting System, ST-FFS, comprises two main parts: RECS REgional Communication System) which operates on a VAX at Solihull and supports telemetry and forecasting functions, and REMUS (REMote USer interface) which it serves as a GUI on client PCs and functions primarily to display observed and forecast results decanted from the VAX. The two systems communicate using the Reflections 2 software (Version 4.3). The flow forecasting system within RECS is FFS II (Version 4.0). RECS and FFS II really form a single system with RECS largely an enhancement of ODH, the Outstation Data Handling interface. Other components are RDH (Radar Data Handling), USS (User SubSystem), FCS (ForeCasting Subsystem), GNM (Global elements), and RTI (Remote Terminal Interface). As a fall-back to the FFS there is a level-to-level correlation based forecasting system called ELFS, which runs independently of FFS, and is invoked through a menu option in a new version of REMUS. This is discussed further in Section 5.3.4.

In the Severn-Trent forecasting system the control of incoming telemetry data along with forecast construction is the task of the RECS System and the FFS (Flow Forecasting System). The "System data design specification" for the FFS describes the high level data design for the FFS (Software Sciences, 1993). This document provides a useful point of reference to understand the internal structure of the FFS, including its access of telemetry data and running of models. For this reason it will be reviewed here and used to identify any problems and shortcomings which might affect forecasting on the Soar. Its suitability, relative to the RFFS-ICA system for information control and forecast construction recommended in Stage 1, will be considered at the end of the section.

The specification document defines the Data Structures accessed by the FFS. Data are either stored in the shared memory global sections (virtual memory sections), accessed by include files and linker options, or as disk files. The virtual memory sections incorporate the following: dynamic sensor data, sensor binary details, raw weather radar data, sensor polling table, current alarms, new alarms, status data, hydrological names and dynamic hydrological data.

The Dynamic Sensor Data (DSD) section contains dynamic data collected from the fixed-period and event-logged outstations. Specifically, for example, 15 minute level data and time-of-tip raingauge data are collected but are stored as hourly instantaneous and total values respectively in the DSD section. A rolling memory of 35 days worth of hourly values are held. Sensor details include such information as the identifier, name and telephone number of an outstation. The Raw weather radar section accommodates only the two radars accessed by NRA-ST: data are only held temporarily in support of the radar processing modules concerned with radar subcatchment and image data. Polling and alarm sections support the normal telemetry functions such as the number of poll attempts made so far, sensors currently in alarm and new stations in alarm which are still to be acknowledged by the RECS operator. The latest recorded value or status of a sensor is held in the status data section. The Hydrological Names (HNM) section holds basin, subbasin and catchment/reach names. There are two basin records, one for the Trent and the other for Severn, each comprising records for 6 sub-basins which in turn can accommodate its name and up to 15 catchment names and 15 reach names. The Dynamic Hydrological Data (DHD) is separated into two global sections, one for the Severn and one for the Trent (DHS and DHT). These contain the hindcast flow data (up to 240 hrs worth) and forecast flow data (up to 120 hrs worth) and model state variable set. Also contained are up to 240 hrs hindcast climate input data and 30 hrs forecast weather input data. Information on alarm exceedences is also held.

The disk files contain the following: dynamic sensor data, radar subcatchment and image data, sensor details, alarm telephone numbers, bulletin boards, activity logs, system common data, alarms log, current and new alarms, status data, hydrological names, dynamic and offline hydrological data, catchment and reach details and parameters, and quantitative precipitation forecast data. The Dynamic Sensor Data (DSD) file contains a copy of the DSD section, as last stored on disk, and is used to restart the system without incurring loss of data. There are two radar subcatchment files, for Clee Hill and Lincoln, containing the last 35 days of hourly radar subcatchment data. Up to 300 radar images are held for each radar, each file containing one image. The sensor binary details are disk copies of those held in virtual memory whilst the sensor details file contains static information such as outstation telephone numbers. Bulletin Boards exist separately for the Severn and Trent, and include exceedence memos and alarm messages. The System Common contains dynamic information used to control data collection and modelling functions, such as the polling frequency and the time of the next model run for each of the 12 sub-basins. The Hydrological Names file is a user-editable file used to construct a binary equivalent. The Dynamic Hydrological Data file is a copy of that held in virtual memory. There are two sets, for the Trent and Severn, and 5 versions of each can be held on disk concurrently to support model comparisons and re-runs. These files are used for the display of forecasts and of state variables. Only one version of the off-line form of this file is held. The Catchment details contains parameters used to pre-process sensor data to form catchment hindcast data, such as the catchment name and area and weighting factors applied to raingauges to derive catchment rainfall. Part of the contents of this file for the Soar catchment is displayed in Table 3.2.2. The Reach Details file contains parameters used to pre-process sensor data to form observed reach hindcast data, such as the reach name and length and river rating equations. Table 3.3.2 summarises part of the contents of this file for the Soar. The Catchment parameters file contains the catchment model parameters, which through the catchment model allow observed catchment hindcast input data to be transformed to produce simulated hindcast and forecast flows. The Reach parameters file is the equivalent for the reach model. The information contained in these files for the Soar have been summarised in Tables 3.2.1 and 3.3.1. Lastly, the Quantitative Precipitation Forecast file is not yet available within the FFS. Its planned use is to store default rainfall forecasts for each sub-basin sub-area, probably derived from Met. Office forecasts, with unavailable data filled with zeros. With 6 sub-basins each containing 3 sub-areas there will be 18 rainfall forecast sequences in each of the two user basins, making 36 sequences in all.

This review of FFS's high level data design allows the following observations to be made:

(1) Whilst telemetry data are initially accessed as 15 minute values they are only stored within FFS at an hourly interval. This has serious implications if the forecasting models are to be run at a shorter time-step, such as the 15 minute period recommended in Stage 1.

(2) In other respects the telemetry functionality provided, such as polling and alarm handling, appears to be sound.

(3) Radar access is limited to Type 1 data (5 km, 15 minute, 7 plus zero intensity level) from two radars, Clee Hill and Lincoln. Support of Type 2 data (2 km, 5 minute, 208 intensity level together with 5 km data) and Frontiers forecast data, recommended in Stage 1 for input to forecasting models, is not provided.

(4) The basic geographical sub-division into basin, subbasin and catchment/reach seems useful but, as implemented in the data structure design, may restrict the definition of future subnetworks. A user-configured subnetwork concept used by the RFFS-ICA allows freer definition of sub-units of a forecasting system. Indeed new subnetworks can be created in real-time by users if desired. Creation of a hierarchical structure might be implemented at a higher level as part of a GUI. The restricted number at each level of sub-division (2 basins, 6 sub-basins, 15 catchments and 15 reaches) is, however, soft-coded in the FFS providing for some flexibility.

(5) The split between two networks, for the Severn and the Trent, along with associated bulletin boards for each could be configured more generically providing for more generality and avoiding duplicity. The Main Network concept within the RFFS-ICA allows for any number of named networks. Alternatively they might be configured as separate RFFS-ICA implementations. Both options allow for concurrent runs on the same computer.

(6) The FFS's use of state variable initialisation to create seamless forecasts from one run to the next and of storing dynamic and state variable data to allow re-runs is good. The RFFS-ICA also works in this way.

(7) The data structures holding the catchment and reach model parameters are specific to the two models currently used in the Severn-Trent region. This inhibits experimentation with different models and new models cannot be readily configured into the existing design. The RFFS-ICA design employs a generic model algorithm interface. This provides the capability of adding or substituting models of any type without having to re-code the ICA itself or formulating a new data structure to hold model parameters.

(8) The pre-processing of sensor data, for example to derive subcatchment rainfall, may be better structured as a model algorithm supporting the merging of data according to priority and availability. Such a design becomes more important when both radar and raingauge measurements and rainfall forecasts, from one or more sources, are available to derive catchment average rainfalls.

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. A preliminary review of how some of these functions are met in the Severn-Trent Region, by RECS and REMUS, were included in the Stage 1 Report at the request of the NRA. Further details are provided here in order to provide a basis for recommending how these functions should be met in the proposed system shell.

5.3.2 Telemetry and other data interfaces

The present telemetry system operates to support 80 to 100 telemetry raingauges in the

Severn-Trent region. These are event-recording and use a 0.5 mm tip. Many are heated sufficiently to melt any snow falling in their funnels. There are some 200 river level and flow stations on telemetry in the Severn-Trent region.

The telemetry system is telephone based and employs TG1150 outstations with a 35 day rolling memory and incorporating a dial-out facility. A data interval of 15 minutes is used but data are "aggregated" to hourly values for input to the FFS. The basic 15 minute data are not stored by the telemetry system and only hourly data can be recovered from the FFS/RECS system.

A routine poll of all outstations is done at 7 am each morning and takes about 20 minutes. Once completed the system automatically invokes model runs for the Severn and Trent basins. Polling is based on a 4 try maximum and 98-99% data capture is usual during flood events. Data from a 10 am poll on selected raingauges are given to the Met. Office in exchange for Morecs data for squares covering the Severn-Trent region. These are sometimes used to reset the catchment model state variables relating to soil moisture when these get out of line, possibly due to rogue raingauge data being used as model input.

The master menu of RECS on the VAX has the following options: Polling and Model Control, Data and utilities suite, Bulletin board display, Weather forecasts, FFS newsletter, Alarm telephone numbers, Menus on/off toggle, Show menu structure, Log off FFS II system. The menus provided by RECS are simple Fortran read/write created menus with responses made at the command line prompt. The weather forecasts are received at 4 pm from the Weather Department, Birmingham via telex straight into the VAX.

The Severn and the Trent basins are each broken up within the FFS into 6 sub-basins, with the sixth being tidal. The Bulletin board display provides notification of exceedences, both in the hindcast period (before time now) and in the forecast period. It also provides information on outstation alarms. Forecast information provided by RECS/FFS is only available in tabulated form: there are no graphical displays. These are provided by the REMUS PC GUI. All the information on both observed and forecast data are restricted to an hourly interval; there is no access to the event logged or 15 minute data. The system supports a 35 day (840 hr) memory of hourly sensor data. Access to the model state variable values is gained through the Data and utilities suite, where values can be modified. Four state sets plus the latest set are stored along with their time.

Within RECS radar support is limited to 5 km and subcatchment Type 1 single site data from Clee Hill and Lincoln and depends on REMUS for display. MicroRadar, developed by the Computer Department, Malvern, is the main software for supporting the display of radar data. This is used to support the display of Type 1 single site data (5 km, 15 minute, 7 plus zero intensity levels) from Clee Hill and Ingham (Lincoln) together with network and sferics data. No use is made of Type 2 data which includes 2 km, 5 minute data at 208 intensity levels more suitable for input to forecasting models.

The Data Archiving System is totally separate from RECS, and indeed duplicates it even to the extent of polling independently. Scanning of the outstations is done on a daily midnight dial-around using the Hydrolog system on a PC. Data are transferred to a file server on the Local Area Network for general access. Only one telephone line is used (compared with 13 for RECS operational polling) and the daily scan gathering 15 minute data takes 6 hours. Polling includes gate settings at Zouch.

This review of how RECS currently supports the telemetry and other data interface functions serves to primarily reinforce the observations reported at the end of Section 5.2. The following additional observations can be made:

(1) The use of a telemetry-based Data Archiving System which operates totally independently of the real-time RECS system implies a significant level of duplication. It is recommended that this approach be re-appraised, particularly following on from the recommendation that RECS be modified to handle the 15 minute values it currently receives, but processes to an hourly interval before storing.

(2) The master menu of RECS, based on simple Fortran read/write created menus activated at the command line prompt, is a candidate for upgrading. This should be done using a Windows environment, as an integral part of the GUI, supported by a client-server link to the RECS telemetry interface on the VAX. This might be viewed as a second-stage upgrade, with the existing RECS system supporting the telemetry functions, and other non-forecast model functions, in its present form initially. The feasibility of this may depend on the detailed solution of extending RECS to handle 15 minute data.

(3) The radar functionality within RECS should be replaced by HYRAD, bringing significant additional functionality as previously discussed.

5.3.3 User interface

The master menu for REMUS gives the following options: Connect to FFS, Radar display suite, Hydrograph display suite, Sensor data suite, Retrieve TG1150 data (ROMULUS), Mail boxes and session logs, Remus utilities, Display the help tree, Exit REMUS. Figure 5.3.1 presents a table of REMUS functions by way of summary. Connect to FFS is used to collect data from the VAX using VT340 emulation. Line speeds are 9600 baud for a direct line and 14,400 baud maximum for a home phone connected via a digital exchange (2,400 baud otherwise). A total of 96 hours past flow and raingauge data can be decanted and 120 hours of radar data. There are plans to upgrade REMUS to be window-based. The main practical feature of REMUS is the ability to select forecasts for plotting from a table of sites. There is a basic sub-division between catchment and reach sites, depending on whether forecasts derive from rainfall-runoff or reach models. Also level forecasts for groups of up to four stations can be displayed. Plotting is fast and user friendly once data have been decanted to the PC from the VAX. The groupings used are hard coded and therefore not sufficiently generic.

The following observations can be made as a result of this review of REMUS:

(1) REMUS is simple and easy-to-use and forecast results can be displayed rapidly and with a minimum of fuss.

(2) The functionality of REMUS is quite restrictive in the way forecasts can be viewed. As one, important, example it is not possible to display several previous runs on the same graph, providing an indication of the manner in which past forecasts have performed in order to anticipate how the current forecast will perform.

- CONNECT TO FFS
  - COLLECT DATA AND UPDATE RATINGS
  - COLLECT DATA FROM FFS
  - ROAM AROUND FFS
  - ROAM AND THEN COLLECT DATA
  - COLLECT THE LATEST WEATHER FORECAST
  - UPDATE THE RATINGS AND THRESHOLDS
- RADAR DISPLAY
  - CLEE HILL RADAR DISPLAY
  - LINCOLN RADAR DISPLAY
  - CLEE HILL SUBCATCHMENT DATA
  - LINCOLN SUBCATCHMENT DATA
- HYDROGRAPH DISPLAYS
  - LEVELS FORECAST HYDROGRAPHS
  - CATCHMENT FORECAST HYDROGRAPHS
  - REACH FORECAST HYDROGRAPHS
- SENSOR DATA DISPLAYS
  - RAINFALL DISPLAY
  - LEVELS DISPLAY
- DIAL TG1150s
  - ROMULUS
- MAILBOXES
  - WEATHER FORECAST LOG
  - ROAM SESSION LOG
  - BULLETIN BOARD LOG
  - NEWSLETTER LOG
  - DECANT LOG
- UTILITIES
  - STAGE/DISCHARGE TABLES
  - UPDATE THE ROMULUS TELEPHONE LIST
  - SWITCH BASIN (where appropriate)
  - INITIALISE DATABASES
  - SAVE AND LOAD DATABASES FROM DISK
  - CLOCK CHECK AND SET
- QUIT

Figure 5.3.1 Table of REMUS functions

(3) The lack of Windows 3.1 functionality is a restriction, and it is understood NRA are considering upgrading to support this. It should be noted that IH is currently undertaking an RFFS shell development under Windows 3.1 which is scheduled for a first release at the end of 1995. This will meet many of the existing functions of REMUS, and more.

(4) The radar display functionality in REMUS is limited and should be replaced by HYRAD operating under Windows 3.1.

5.3.4 A back-up forecasting system: ELFS

A new version of REMUS, still under development, provides a back-up forecasting system in the event that the FFS is unavailable, for example because the VAX computer fails. At the heart of ELFS is a database of peak-to-peak levels which is used to establish a relationship between upstream and downstream water levels for a selected pair of sites, one being the forecast site of interest and the other the supporting site (usually an upstream station). Inclusion of the time and date of each peak level in the database allows peaks from two stations to be "matched", using a specified "cut-off-time" and an estimate of the travel time made. The relationship between peak levels at two stations, can follow either a straight line or a quadratic curve, and is recomputed as a least squares fit to data in the database whenever a level-level plot is requested. The system is totally independent of the VAX used by the RFFS, depending solely on the REMUS software on the local PC and the connection to the

TG1150 telemetry outstations it supports.

Operation of ELFS in real-time involves first using REMUS to dial-out to sites of interest and then selecting the ELFS option to invoke the peak-to-peak level relationship of interest. It automatically registers the dial-out value of the support site and gives the value at the forecast point, along with an estimate of the travel time. User interaction is necessary to choose, or estimate, the peak value (with the aid of present and past dial-out values) at the support site in order to better estimate the peak at the forecast point, and its time of occurrence. An extension is envisaged to allow more than one support site to be used to extimate the peak at the forecast site, through a multiple regression relation. The system seems to provide a sensible and simple fall-back forecasting system in the event that the FFS fails, or is unavailable, for some reason.

5.3.5 Dissemination of warnings

Section 2.2 of the Stage 1 report reviewed the locations that are warned. The main means of communication is by fax to the Police, confirmed by telephone. Telephone is also used to notify key individuals, some acting as flood wardens with the responsibility to warn others. No computer-assisted warning dissemination system is in place, as recommended in the Stage 1 report. It is considered that warning messages, whose creation is computer-supported would be of value in some cases. Communication would be via telex/fax using standard warning templates and clusters of fax/telephone numbers held on the computer. The technology now exists, also, to send a telephone message simultaneously to many individuals, offering an improvement on the flood warden system in some cases. The two systems should be seen as complementary, one being more appropriate than another in certain situations and both being needed in others.

5.4 COMPUTING PROVISION

The hardware supporting the FFS/RECS system includes a Dynamic Logic Alarm Out Transmission Unit plus 20 modems, 13 for polling and 7 supporting the input/output for modem users and others. A Microvax II, running VMS V5.3 and supporting Fortran V5.5 and CMS (Code Management System) V3.4, is used as the main computer. There are two disks: an RD53 of 75 Mbyte and an RD54 of 150 Mbyte. This computer is becoming unsupportable and is due for replacement this year. The replacement is likely to be a VAX 3100/Model 95. DEC provide a 4 hour call out on this operational machine. A newer VAX 3100/Model 20 is used as an off-line machine, supporting model calibration work and water resource planning tasks. This is not used for operational work because it doesn't support a hot start. It supports two 104 Mbyte disks. There are 3 terminal servers: two Dec server 200/MC and one DEC server 300. The system also supports TK50 tape drives. Disks on both computers are more than two-thirds full most of the time. Daily, weekly and monthly backups are made.

This study supports the proposed purchase of a VAX3100/Model 95, along with additional disk capacity. It is seen as providing a suitable platform to support the RECS telemetry functions, the HYRAD radar reception and processing kernel and the RFFS forecasting kernel. As clients to this server computer, the NRA already widely employ 486 PCs, in line with the Stage 1 recommendations.

6. Summary, recommendations and implementation plan

6.1 INTRODUCTION

The previous sections have assessed the existing hydrometric network to support flood forecasting, the models used and the nature of the system environment employed to construct forecasts and to make and disseminate flood warnings. This assessment has been undertaken against the background of the idealised design proposed under the Stage 1 study. As a consequence it is now possible to present the final conclusions regarding an appropriate flood forecasting and warning system for implementation to the Soar catchment. These conclusions are presented first as a summary of the findings of the study and then as a set of recommendations for action. The section ends with an outline plan for implementing the recommendations.

6.2 SUMMARY

6.2.1 Hydrometric Network

(i) **Raingauge network**: A recommendation of the Stage 1 report was that the raingauge 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 representativeness, 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. In practice, the actual network in the immediate vicinity of the Soar comprises 7 gauges configured approximately on two east-west lines through the middle and southern part of the catchment. The gauges record time-of-tip, but employ a .5 mm bucket size.

It is recommended that two further gauges be installed, one located in the middle/upper Rothley Brook catchment at circa SK 480 070 for use in the Rothley catchment model and the other to the east of the Middle Soar, for estimating the ungauged lateral inflows entering along the right bank, located at circa SK 660 070. The buckets of the existing gauges should either be counterbalanced and recalibrated to record a tip for every 0.2 mm of rain, or new 0.1 mm buckets installed (the more expensive option).

Any further model calibration should investigate the value of records from the 5 raingauges along the eastern edge of the catchment, located in the NRA Anglian Region. If these prove useful then a telemetry connection to the Severn-Trent Region will be needed in order to make use of these stations in real-time. These gauges are likely to be useful for a local radar recalibration system for the Soar based on HYRAD.

(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. Results reported in a draft copy of the Long Range Calibration Study Final Report for the Leicester Laterals subcatchment suggest that radar estimates are of acceptable quantitative accuracy over the Soar. Through local calibration using HYRAD 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.

The Stage 1 report highlighted the benefit of the Type 2 radar data for use in modelling, providing data quantised at 208 intensity levels, and at 2 km resolution within a range of 76 km of the radar. In practice only Type 1 data from the Clee and Ingham radars are received, along with the Network product providing the broader national picture. Both provide intensities at only 7 levels plus zero and are at 5 km resolution. They are not suitable for regional processing, including local calibration, rainfall forecasting and calculation of catchment average rainfall. Whilst the advantages of Type 2 data are arguably not so strong for locations beyond 76 km, it is recommended that Type 1 data be replaced by Type 2 data for quantitative use as a strategy for the Severn-Trent Region. Existing investment in the MicroRadar system can be protected, through its use for qualitative display purposes in the many offices of the NRA Severn-Trent Region. However, in the longer term, migration to standardise on Type 2 data and higher quality displays should be borne in mind.

(iii) **River gauging network**: The nine stations proposed under the Stage 1 study are largely already supported by the existing network and the recommendations relate primarily to how existing sites can be improved. One exception is the recommendation for a gauging site in Leicester at Freemans Weir, to be equipped with an accurate level sensor and with the weir maintained rigorously in summer against weed growth. Such measures should achieve more sensitive flow measurement over this long weir. The other eight recommended sites are met by the following existing stations: the lower Soar at Kegworth, the middle Soar at Pillings Lock, the upper Soar at Littlethorpe, the Sence at South Wigston, the lower Wreake at Syston, the middle Wreake at Frisby, the Eye at Brentingby (meeting the upper Wreake near Melton Mowbray requirement) and the Rothley Brook at Rothley.

Since much of the Soar downstream of Leicester is under backwater influence it was considered likely that the multi-path ultrasonic gauging method would be an appropriate choice for the main Soar. The site recommended for the middle Soar near Loughborough corresponds well to the Pillings Lock gauging site, being located in a section of the river which is also the navigation canal. Gauging is by the multi-path cross-path ultrasonic method and therefore conforms with the recommendation. Silting of the lower sensors has occurred. It is recommended that the sensors be relocated and the cross-section re-surveyed. The implementation of sensors to measure flood plain flows, which otherwise bypass the station, has not proved successful. It is recommended that all aspects of the flood plain sensor installation be subject to review. Whether or not the sensors have ever been submerged is uncertain because of the use of a barrel memory, infrequently downloaded, and lack of telemetry access. Planned improvements to logging and remote access of the sensor values should help, and are supported. Diversion of the ditch adjacent to the towpath on the left bank is also planned and supported here. The review should expose the need, or not, of lowering the sensors, although this seems a likely prospect. Regular grass cutting, to a level below the sensor path, may be needed if this proves to be the case.

The Stage 1 report also recommended more use of the control structures, along with their associated level and gate position measurements, as another means of gauging. Inclusion of all gates (including Zouch and Eye Kettleby) in the hydrodynamic modelling of the Soar will achieve this objective, although a current metering programme would provide valuable support and validation to the modelling work. In practice the NRA have recently established provisional rating curves for Frisby and Zouch, based on levels downstream of their respective gates and flows from a current meter programme. Further work, supported by current metering and modelling, is recommended to estimate flows over the full flow range through these gates.

Some further investigation of the suitability of the station on the Eye at Brentingby is required. If found suitable the station should be upgraded, a current meter programme initiated to establish a rating and telemetry installed.

The following needs, or plans, for improvement to existing gauging stations have been identified in consultation with the NRA:

(a) Soar at Kegworth: Replacement of old ultrasonic cable in order to improve accuracy, especially at low flows.

(b) Soar at Zouch Sluice Gate: There is a requirement to interpret the gate angle sensor records in terms of angle in degrees, as intended in the original design.

(c) Soar at Littlethorpe: Extension of electromagnetic gauge insulating membrane up the right flood bank and raising of bank level by 0.5-1.0 m over a length of 50-70 m in order to extend the range of flow estimation by the gauge. Establish a rating curve above this based on a continuation of the existing current metering programme, with main channel metering from the bridge and floodplain metering across the bypass culverts. These measures will improve the station's performance at high flows, when underestimation occurs due to bypassing.

(d) Wreake at Syston: Silting up of the right side of the channel suggests that the present constructed section has been designed with too large a width. A physical model study of the section used by this electromagnetic gauge should be commissioned. It is probable that a two-stage channel form will prove appropriate. The gauging section should be engineered to the new design and the electromagnetic gauge recalibrated.

(e) Wreake at Frisby-on-Wreake: Recalibration and installation of timers controlling gate movements, which are possibly stuck on the maximum 30 minute delay (this is in hand).

(f) Wreake at Eye Kettleby: The gate position should be put on telemetry.

(g) Eye at Brentingby: Review suitability of station for upgrading, and if satisfactory install telemetry and initiate current meter programme.

(h) Scalford Brook at Melton Mowbray: Service upstream pressure transducer installation, which has been offline for some time.

(iv) **Weather station**: The Stage 1 report recommended that a single AWS 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 the Stage 1 study assumed no existing climate stations, it pointed out that 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.

In practice two climate stations exist in the catchment at two of the telemetry raingauge sites: Narborough and Brooksby (see Figure 2.2.1). The climate station at Brooksby, due for closure, would make an ideal site for enhancement to a full AWS. It currently records air temperature, wind run and rainfall on telemetry. It is recommended that this station be upgraded to include wet bulb temperature, net radiation, wind direction and incoming solar radiation on telemetry. The existing telemetry outstation has the capacity to support these additional sensors.

(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) **Hydrodynamic river model**: The Stage 1 report recommended that 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. Since the existing Flood Forecasting System does not employ a hydrodynamic model, making exclusive use of a conceptual hydrological channel flow routing model, the Stage 1 recommendation is reinforced here. One exception is that consideration be given to shortening the extent of the hydrodynamic model through Leicester, with Freemans Weir being used as the upstream boundary. The acceptability of this change depends particularly on the success in gauging Freemans Weir. The upstream boundary on the Wreake, in the vicinity of Melton Mowbray, should be taken as the station on the Eye at Brentingby, provided this proves a satisfactory flow gauging site.

It was anticipated in the Stage 1 report that the ONDA model configuration for the Soar, currently being undertaken by Halcrow, could be used to support an initial configuration of ISIS for real-time use. However, access to node maps of the model during Stage 2 has served to identify four areas where the model configuration will require extension. These are: from Birstall (the ONDA model upstream boundary) to Freemans Weir and the channels of the Kingston Brook, Black Brook and Quorn Brook where they cross the Soar floodplain. The three brooks need to be entered into the model on the edge of the floodplain and not directly into the main channel of the Soar.

(ii) **Hydrological channel flow routing model**: Stage 1 recommended that 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 was suggested as one choice in providing an appropriate approximation tailored for use in real-time. The NRA-ST's own DODO model is currently used as the reach model in the forecasting system for the Soar. This model falls into the class of model recommended. It is based on the Muskingum storage concept, which has been shown by Cunge to provide an approximation to the convection-diffusion equation. The way it handles floodplain flows has a stronger conceptual basis than the IH KW model, but the latter arguably has greater flexibility to accommodate a range of behaviours. This is achieved through the use of a variety of speed-discharge functions and threshold storage functions able to represent the transfer of channel flows to the floodplain. A detailed empirical intercomparison, using flood events for several reaches, would be needed to support any recommendation for change. Therefore, given the widespread use of the DODO model in both the Soar and elsewhere in the Severn-Trent Region, it is recommended that this model be supported by the proposed Flood Forecasting System. The implication of incorporating the DODO model into the RFFS is to recommend that it be coded as an RFFS Model Algorithm, capitalising on the RFFS's generic model algorithm interface to ease this task. Use of the RFFS has the added advantage of giving immediate access to the KW model to support any evaluation study. Indeed the two models may be configured alongside each other for operational trials if required.

(iii) **Rainfall-runoff catchment model**: Stage 1 recommended that 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 was suggested to be 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 was recommended. The PACK model was suggested as an appropriate choice at present pending the outcome of ongoing research sponsored by the NRA and MAFF.

In practice the catchment model used for modelling the Soar tributaries employs a conceptual model of the type recommended, both for rainfall-runoff and snowmelt. In this case the PDM has certain advantages in the way it represents soil moisture variability over the catchment, the use of a mathematical formulation which originates in continuous time, and the incorporation of inbuilt empirical state correction procedures for real-time updating. However, because of the widespread application of the Severn-Trent catchment model in the Soar and elsewhere across the region, there would be a need to perform a model intercomparison before recommending a change to existing practice. The recommendation is to develop a Model Algorithm form of the catchment model for use in the RFFS. Again the option to trial or use the PDM model, or other models, is provided in this integrated approach.

(iv) **Forecast updating**: In the Stage 1 report it was 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 was needed before this approach could be commented upon. In practice the method of updating used in the Soar model, for both reach and catchment components, is a form of error prediction. A careful analysis of the performance of the approach used suggests that it's two-phase form can lead to rather odd behaviours and is often not very helpful. A simpler approach is recommended based on ARMA error prediction, in which a constant parameter ARMA model fitted off-line can be guaranteed to produce a stable adjustment which asymptotes to the simulation forecast with increasing lead-time. If necessary, a special form of ARMA model based on an AR model with equal roots and allowing for errors in the observations could be used. In the absence of a state updating scheme for the catchment model the most straightforward implementation would make use of the ARMA error predictor for catchment, reach and hydrodynamic models.

(v) **Model Calibration Facility**: Stage 1 recommended that model calibration facilities should be incorporated in the supplied system and these should support both automatic optimisation procedures and visually interactive calibration aids. Facilities are available in the system in use to calibrate the reach and catchment models using the Rosenbrock automatic optimisation procedure. The recommended RFFS calibration facilities employ a Simplex method, but there is little to choose between this and the Rosenbrock method. More important is the visually interactive calibration aids now supported by the RFFS, which ease the task of estimating parameters of conceptual catchment models which invariably lack uniqueness and independence. This is seen as the major shortcoming in the calibration facilities in current use by NRA-ST. Other features that are lacking include: (a) pooled calibration across a set of events; (b) continuous soil moisture accounting between events for catchment models, through a switch to daily rainfall data, removing the need for event state initialisation sets; (c) long-term (many-season) optimisation of water balance parameters using a switch to a daily time interval and using daily observed flow values; (d) embedded optimisation of stage-discharge curves, useful for extending the range of existing relations or for establishing new ones; (d) embedded optimisation of ARMA error predictor parameters; and (e) assessment of updated model forecasts using fixed-origin variable lead-time plots, fixed lead-time variable time-origin plots and associated performance statistics. These are features available in the RFFS Calibration Facility. A further feature of value is the calibration of nested models. The most useful example of this is where rainfall-runoff catchment models of ungauged lateral inflows are nested within a reach model, with the parameters optimised with reference to the observed outflow from the modelled reach. A specification for the optimisation of general configurations of models has been prepared at IH, and coding is ongoing.

(vi) **Forecast construction**: Stage 1 recommended that 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. The ST-FFS in use in the Soar catchment, and elsewhere in the Severn-Trent region, has some of these features but not all. The system is configurable to new forecast requirements but cannot readily accommodate new model algorithms through a generic model algorithm interface. This is particularly important with regard to the ease with which a hydrodynamic model might be accommodated within the existing system, which is judged to be quite difficult. The FFS is well designed in its use of state variables but does not support the subnetwork run concept, other than supporting a Trent model and a Severn model. The recommendation is therefore to adopt the RFFS ICA system, whilst capitalising on the telemetry functionality provided by RECS.

(vii) **System environment**: Stage 1 recommended that 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. Definitive recommendations on the shell environment and associated interfaces were deferred pending a review of RECS and REMUS under Stage 2. This has now been undertaken and the following recommendations can now be made. The RECS/FFS system should be retained to provide the telemetry interface to the RFFS system but the FFS component should be replaced by the RFFS ICA for forecast construction. RECS should be modified to accommodate 15 minute telemetry data.

REMUS is due to be revamped as a Windows 3.1 system in the NRA's work programme. The radar functionality of REMUS should be provided by HYRAD, a Windows 3.1 implementation. IH is also developing a Windows 3.1 (and Chicago) shell for RFFS, with an interface to HYRAD, and this is likely to meet most of NRA-ST's requirements for a shell environment. A useable system is scheduled for completion towards the end of 1995.

(viii) **Computing provision**: The type of flow forecasting system envisaged in the Stage 1 recommendations typically would run on a workstation, such as a Sun Sparc 2, VAX station 3100 or similar, although the system kernel proposed is largely machine independent. The workstation would function as a server to client PC's running on 486 processors or better. In practice the ST-FFS runs on a MicroVax II, although an upgrade to a VAX 3100/Model 95 is planned, which acts as a server to client PCs running REMUS. There is a clear advantage to NRA-ST in staying with Digital, through the support of existing VMS applications needed to meet operational responsibilities, particularly flood warning. The recommendations of Stage 2 support the upgrade to the processor and the need for more disk capacity, which is often more than two-thirds full.

6.3 RECOMMENDATIONS

6.3.1 Hydrometric Network

(i) **Raingauge network:**

(a) It is recommended that two further gauges be installed, one located in the middle/upper Rothley Brook catchment at circa SK 480 070 for use in the Rothley catchment model and the other to the east of the Middle Soar, for estimating the ungauged lateral inflows entering along the right bank, located at circa SK 660 070.

(b) The buckets of the existing gauges should either be counterbalanced and recalibrated to record a tip for every 0.2 mm of rain, or new 0.1 mm buckets installed (the more expensive option).

(c) Any further model calibration should investigate the value of records from the 5 raingauges along the eastern edge of the catchment, located in the NRA Anglian Region. If these prove useful then a telemetry connection to the Severn-Trent Region will be needed in order to make use of these stations in real-time. These gauges are likely to be useful for a local radar recalibration system for the Soar based on HYRAD.

(ii) **Radar network**:

(a) 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.

(b) The Met. Office Frontiers forecasts should be utilised to provide longer term rainfall forecasts, say from 2 to 6 hours ahead, as a complement to the HYRAD forecasts.

(c) It is recommended that Type 1 weather radar data be replaced by Type 2 data for quantitative use as a strategy for the Severn-Trent Region. Existing investment in the MicroRadar system can be protected, through its use for qualitative display purposes in the many offices of the NRA Severn-Trent Region. However, in the longer term, migration to standardise on Type 2 data and higher quality displays should be borne in mind.

(iii) **River gauging network**:

(a) **Soar at Freemans weir**: It is recommended that a new gauging station be established in Leicester at Freemans Weir. The station should be equipped with an accurate level sensor and with the weir maintained rigorously in summer against weed growth so as to achieve more sensitive flow measurement over this long weir. The other eight recommended sites are met by the following existing stations: the lower Soar at Kegworth, the middle Soar at Pillings Lock, the upper Soar at Littlethorpe, the Sence at South Wigston, the lower Wreake at Syston, the middle Wreake at Frisby, the Eye at Brentingby (meeting the upper Wreake near Melton Mowbray requirement) and the Rothley Brook at Rothley.

(b) **Soar at Pillings Lock**:

- It is recommended that the silted-up sensors on the left bank of the main channel be relocated and the cross-section re-surveyed.

- It is recommended that all aspects of the flood plain sensor installation be subject to review. Planned improvements to logging and remote access of the sensor values are supported. Diversion of the ditch adjacent to the towpath on the left bank is also planned and supported here. The review should expose the need, or not, for lowering the sensors, although this seems a likely prospect. Regular grass cutting, to a level below the sensor path, may be needed if this proves to be the case.

(c) **Frisby and Zouch gates**: Further work, supported by current metering and modelling, is recommended to estimate flows over the full flow range through these gates.

(d) **Soar at Kegworth**: Replacement of old ultrasonic cable in order to improve accuracy, especially at low flows.

(e) **Soar at Zouch Sluice Gate**: There is a requirement to interpret the gate angle sensor records in terms of angle in degrees, as intended in the original design.

(f) **Soar at Littlethorpe**: Extension of electromagnetic gauge insulating membrane up the right flood bank and raising of bank level by 0.5-1.0 m over a length of 50-70 m in order to extend the range of flow estimation by the gauge. Establish a rating curve above this based on a continuation of the existing current metering programme, with main channel metering from the bridge and floodplain metering across the bypass culverts. These measures will improve the station's performance at high flows, when underestimation occurs due to bypassing.

(g) **Wreake at Syston**: Commission a physical model study of the section used by this electromagnetic gauge, to include consideration of a two-stage channel form. Engineer the section to have the new design and recalibrate the em gauge.

(h) **Wreake at Frisby-on-Wreake**: Recalibration and installation of timers controlling gate movements, which are possibly stuck on the maximum 30 minute delay (this is in hand).

(i) **Wreake at Eye Kettleby**: The gate position should be put on telemetry.

(j) **Eye at Brentingby**: Review suitability of station for upgrading, and if satisfactory install telemetry and initiate current meter programme.

(k) **Scalford Brook at Melton Mowbray**: Service upstream pressure transducer installation, which has been offline for some time.

(iv) **Weather station**: The climate station at Brooksby currently records air temperature, wind run and rainfall on telemetry. It is recommended that this station be upgraded to include wet bulb temperature, net radiation, wind direction and incoming solar radiation on telemetry. The existing telemetry outstation has the capacity to support these additional sensors. 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.

(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.

6.3.2 Flood Forecasting and Warning System

(i) **Hydrodynamic river model:** It is recommended that the ISIS hydrodynamic model, a new integrated version of the Salmon and Onda models, should be used for the main Soar from the confluence with the River Trent upstream to Leicester, probably at Freemans Weir, and for the River Wreake to Melton Mowbray, probably as far as the Eye at Brentingby, with the possible omission of the stretch from Ratcliffe to Frisby.

The ONDA model configuration for the Soar, currently being undertaken by Halcrow, should be used to support an initial configuration of ISIS for real-time use. Four areas where the model configuration will require extension are: from Birstall (the ONDA model upstream boundary) to Freemans Weir and the channels of the Kingston Brook, Black Brook and Quorn Brook where they cross the Soar floodplain. The three brooks need to be entered into the model on the edge of the floodplain and not directly into the main channel of the Soar.

(ii) **Hydrological channel flow routing model:**

(a) It is recommended that the existing DODO reach model be supported by the proposed Flood Forecasting System.

(b) The implication of incorporating the DODO model into the RFFS-ICA kernel is to recommend that it be coded as an RFFS Model Algorithm, capitalising on the RFFS's generic model algorithm interface to ease this task.

(c) It is recommended that a formal off-line evaluation of the performance of the DODO and RFFS-KW reach models be carried out, possibly as a joint investigation with the NRA.

(iii) **Rainfall-runoff catchment model:**

(a) It is recommended that a Model Algorithm form of the CRM (Catchment Runoff Model) is developed for use with the RFFS-ICA kernel software.

(b) It is recommended that a formal off-line evaluation of the performance of the CRM and RFFS-PDM rainfall-runoff models be carried out, possibly as a joint investigation with the NRA.

(iv) **Updating procedures:**

(a) It is recommended that the ERM method of error prediction be replaced by the ARMA error prediction approach. A constant parameter ARMA model fitted off-line can be guaranteed to produce a stable adjustment which asymptotes to the simulation forecast with increasing lead-time.

(b) If necessary, a special form of ARMA model based on an AR model with equal roots and allowing for errors in the observations could be used.

(c) It is recommended that, at least initially, a straightforward implementation is made where ARMA error predictors are used for catchment, reach and hydrodynamic models.

(d) An approach based on state updating may be considered at a later stage, initially through an off-line evaluation study.

(v) **Model Calibration Facilities:**

(a) The NRA-ST's Calibration Facilities lack the following important features which are present in the RFFS Calibration Facilities:

- visually interactive calibration aids which ease the task of estimating parameters of conceptual catchment models which invariably lack uniqueness and independence

- pooled calibration across a set of events

- continuous soil moisture accounting between events for catchment models, through a switch to daily rainfall data, removing the need for event state initialisation sets

- long-term (many-season) optimisation of water balance parameters using a switch to a daily time interval and using daily observed flow values

- embedded optimisation of stage-discharge curves, useful for extending the range of existing relations or for establishing new ones

- embedded optimisation of ARMA error predictor parameters

- assessment of updated model forecasts using fixed-origin variable lead-time plots, fixed lead-time variable time-origin plots and associated performance statistics.

It is recommended that a strategy be developed to provide some, or all, of this functionality. This might be achieved by either extending the present NRA facilities or adopting the RFFS Calibration Facilities and incorporating the DODO and CRM models within the RFFS calibration shell environment. An enhanced form of the latter, specified and undergoing coding at present, will provide for nesting of models. This is seen as particularly important for calibrating reach models with significant ungauged lateral inflows, allowing the parameters of rainfall-runoff models of the ungauged tributaries to be estimated along with those of the reach model.

(vi) **System environment**:

(a) **Forecast construction**: It is recommended that the RFFS Information Control Algorithm, or ICA, be used as the environment to construct forecasts in real-time, with an interface to the telemetry data provided by RECS.

(b) **Telemetry interface**: The RECS/FFS system should be retained to provide the telemetry interface to the RFFS system but the FFS component should be replaced by the RFFS ICA for forecast construction. RECS should be modified to accommodate 15 minute telemetry data.

(c) **Graphical User Interface:**

- The radar functionality of REMUS should be provided by HYRAD.

- IH is developing a Windows 3.1 (and Chicago) shell for RFFS, with an interface to HYRAD, and this is likely to meet most of NRA-ST's requirements for a shell environment. A useable system is scheduled for completion towards the end of 1995. It is recommended that the NRA consider adoption of this shell as a replacement for REMUS. This might be scheduled as a second phase system enhancement.

(d) **Computing provision:** The planned upgrade of the modelling computer to a VAX 3100/Model 95, together with an increase in disk capacity, is supported.

6.4 IMPLEMENTATION PLAN

The following is a broad outline of the implementation plan:

Stage I: Hydrometric improvements and software development

(i) Improvements to the hydrometric network

(ii) Development and testing of ISIS Model Algorithm

(iii) Development and testing of reach and catchment Model Algorithms

(iv) Interface development from RECS to ICA and REMUS

Stage II: Soar implementation

(i) Data take-on for model calibration

(ii) Calibration of rainfall-runoff, hydrological channel flow routing and error predictor models to operate at a 15 minute time step.

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

(iv) Calibration and proving trials of the ISIS model

(v) Configuration of the RFFS ICA to the Soar catchment

(vi) Configuration of HYRAD to the Soar catchment

(vii) Development and implementation of RFFS shell to replace REMUS

(viii) Factory acceptance tests

(ix) Site acceptance tests

(x) Training

(xi) Maintenance and support

Stage III: Region-wide Implementation

(a) Systems Analysis Study
(b) Implementation

Stage I is expected to run over a 9 month period, Stage II a further 9 months and Stage III a further 12 months.

7. Benefits of the proposed solution

7.1 INTRODUCTION

The forecasting of flows and river levels in natural river networks is a complex task associated with many sources of uncertainty. This uncertainty arises from the natural variability in the forcing inputs to the system, primarily in the form of rainfall, and to a lesser extent climate forcing variables which affect evaporation loss to the catchment system. In addition to the natural variability of rainfall in space and time there is the uncertainty associated with the measurement of rainfall fields, either by raingauges or radar or a combination of both. In order to extend the lead time of flow and level forecasts the need arises to forecast rainfall fields: this is associated with even greater uncertainty, particularly as the lead time increases.

Within the river network, errors associated with the measurement of river level and flow provide another source of uncertainty, which is likely to be greatest during overbank flood conditions. Lastly, there is the uncertainty associated with modelling the complexity of the propagation of water through natural river systems. Such systems are characterised by complex networks of flow paths and storages, both underground and at the surface, including the concentrated flow paths we recognise as river channels. Paradoxically, when complexity is greatest, such as in the land phase of runoff production, an appropriate model representation is often relatively simple. For the case of catchment rainfall-runoff models, simple conceptual formulations which employ configurations of storage elements are the norm. However, whilst such models are appropriate for representing the complexity of runoff production at the catchment scale they can be an important source of uncertainty in flow forecasts. Where the pathway is better defined, principally in the river channel, a more detailed modelling of the process can often reduce uncertainty. This is particularly true when additional information is available in the form of land surveys and bed roughness estimates derived from field data. However, in simpler river channel situations the more complex hydrodynamic model formulation naturally reduces to simpler forms, such as those based on kinematic flow routing which can be represented by quite simple hydrological storage formulations. In such situations, and with accurate measurements of inflows to the river channel reach, uncertainty in flow forecasts can be least. Where the flow dynamics are more complex, such as where backwater from flood gate and navigation level controls exert an influence, then the greater complexity of a full hydrodynamic model becomes justified. In such situations the uncertainty in flow and level forecasts may not be great, provided the system is well defined in terms of survey data and measurements of lateral inflows and of river levels and settings at the controls.

Accuracy becomes a more complex issue still when the ability to update model forecasts with reference to observed flows and levels is considered. In general updating techniques can greatly reduce the uncertainty of forecasts for short lead times, but will be largely ineffective at longer lead times when the adequacy of the deterministic model formulation becomes paramount, along with the uncertainty of the possibly forecast input variables.

The above review of uncertainty in flood forecasting systems serves to highlight the considerable variability in uncertainty due to

- the natural variability in rainfall and other climatic forcing inputs

- the forecasting of model inputs, especially rainfall
- the sampling and measurement errors associated with rainfall along with river level and flow
- the modelling approximations employed, and
- the forecast updating schemes used.

Any proposal for improvement should address each of these sources of uncertainty, and this proposal has followed this route. However, it must be clear from the above review that forecast uncertainty is complex and highly variable in time, in space and in context. For this reason the benefits of proposed improvements to an existing forecasting system cannot generally be forwarded in a quantitative manner, such as proposal X will lead to a Y% reduction in forecast uncertainty at site Z, leading to C% reduction in flood damage costs at the set of sites R at risk.

The aim of the recommendations is to tighten up the existing system where uncertainty and error exist: in the hydrometric network and in the modelling system. However, the benefits go beyond reducing uncertainty of flood forecasts to providing a modelling environment that allows more to be done, notably in decision-support for flood warning and control, and which can evolve over time as new developments in modelling and measurements arise and as new requirements for forecasts emerge. Some of these benefits are identified in the following sections with reference to specific recommendations.

7.2 HYDROMETRIC NETWORK

River gauging stations

The main shortcoming in the existing hydrometric measurement network is the failure of some river gauging stations to measure flood flows, particularly when incursion on the flood plain occurs. This leads to volume errors in models downstream of the gauging station. A complicating factor is that models fitted using data which fail to accommodate flood plain flows can take on model parameter values which implicitly compensate for this fact. This leads to essentially equivalent models, which in some cases can provide adequate forecasts, but sometimes for the wrong reason. The source of uncertainty becomes progressively obscure as one progresses down the river system, as measurement errors mix with model errors, including those associated with model calibration to error-prone flow measurements as well as those associated with inadequacies in model formulation. As a consequence, the flood duty officer loses confidence in the forecasting system as it fails to provide a reliable tool to support flood warning. The proposed improvements to the river gauging stations aim to address the problem at source, which will mean that subsequent model calibration will be more robust and not a source of error propagation down the model river network. Forecast updating in real-time will be more assured of improving the accuracy of forecasts downstream if the measurements of flow used for updating are reliable.

Whilst the extent of the river gauging station network is broadly adequate the study has identified the need for one new station at Freemans Weir on the main Soar at Leicester. This is needed to provide the upper boundary condition to the proposed hydrodynamic model for the main Soar. A second station at Eye Brentingby on the River Eye, in the upper Wreake catchment, needs to be upgraded to provide an upstream boundary condition for the proposed hydrodynamic model encompassing the Eye Kettleby flood gate control. Other hydrometric improvements required, that relate to the hydrodynamic river models, concern the logging of gate movements which are essential if the effect of gate controls are to be properly forecast.

Rainfall measurement network

The proposals for enhancing the raingauge network are not radical, with only two additional gauges proposed to provide a more even coverage which will be of benefit for rainfall-runoff modelling. Of course little benefit will accrue from this enhancement during uniform rainfall over the Soar, but in other situations the benefits may be more significant. Greater resilience of forecasts from the rainfall-runoff model for Rothley Brook, and for the ungauged lateral inflows draining from the east into the middle Soar, will be the main benefit. These gauges when used for local radar rainfall calibration will also lead to improved accuracy in spatial rainfall estimates, at least on average, as indicated by IH's research over the Thames basin. The proposal to increase the resolution of the raingauges, from 0.5 mm to 0.2 or 0.1 mm, is justified in terms of improved radar calibration and of improved updated forecast accuracy from the use of a 15 minute model time step, and the consequential need for greater rainfall resolution when moving from the current one hour interval model time step. Improvement in forecast accuracy when a 15 minute time interval is employed for forecast updating of rainfall-runoff models has been demonstrated in IH's research over the Thames basin.

The use of both Frontiers and HYRAD systems for radar rainfall forecasting will bring benefits in terms of extending the lead time of forecasts. This will also make more feasible the forecasting for flood risk sites higher up the Soar and on its tributaries. A notable example is Rothley where flood warnings are not presently given on account of the short lag in catchment response to rainfall. It is important to exercise caution on the benefits of rainfall forecasts, on account of their relatively low accuracy. The justification for using both HYRAD and Frontiers forecasts is the demonstrated improved accuracy of the former for lead times up to two hours.

Weather station

The proposed upgrade to the Brooksby climate station to incorporate the full set of sensors of a standard automatic weather station has two main benefits. Penman evaporation (PE) estimates will be of benefit when used in the soil-moisture accounting component of the catchment runoff model. Whilst a simple sine curve approximation over the year is sometimes used, near-real time estimates are obviously a better reflection of evaporation demand. With telemetry and the ability to automate the PE calculation on the modelling computer, these data become immediately available for use in the forecasting system. The second benefit is to snowmelt modelling, where temperature and possibly wind speed and humidity are used.

7.3 FLOOD FORECASTING AND WARNING SYSTEM

Hydrodynamic river model

The major failing in the forecasting models currently used for the Soar is that the reach model cannot accommodate conditions of backwater and variable gate controls. As a consequence, the main benefit from improved modelling will be expected to arise in such conditions through the use of the ISIS hydrodynamic river model. This will include the main Soar downstream of Leicester and the Wreake where it is affected by backwater from the main Soar and from gate controls. It is also expected that improved modelling of flood plain flows will be a benefit of the hydrodynamic model approach.

The benefits of ISIS as an RFFS model algorithm will extend beyond its immediate use in the Soar catchment. In particular, extension of the forecasting system to other parts of the Severn-Trent region will demand adoption of a hydrodynamic modelling approach in the tidal reaches of both the Severn and the Trent. The RFFS in Yorkshire has demonstrated the viability of using a real-time hydrodynamic model for flow and level forecasting, through its application to the tidal Ouse and Derwent tidal barrier.

Incorporation of gate control algorithms as part of the hydrodynamic model will provide for the first time in the Soar an explicit representation of the effect of gate movements on river levels and flows. This will have the added benefit of allowing the model to be used as part of a decision support system for gate operation. The gate operator will be able to ask "What if?" questions on possible gate movement strategies and see the likely consequences before implementing a strategy for real. Greater confidence of gate operation and a reduction in flood risk are the expected benefits.

Hydrological reach and catchment models

A conservative recommendation to continue with the use of the DODO reach model and CRM rainfall-runoff model has clear benefits in protecting existing investment in the application of these models and in the understanding of them by NRA staff. Introducing new models to replace them can only be justified through a demonstration that there are benefits to be gained through improved accuracy. For this reason the recommendations include an off-line trial of these models with the KW and PDM models proposed in the Stage 1 Report.

A more important advantage of the RFFS-ICA forecasting environment proposed is that as advances in modelling are made, or preferences change, new models can be readily accommodated through the generic model algorithm interface. Indeed the RFFS allows for more than one type of model to be configured into the real-time system to make forecasts for the same point, if this flexibility is required.

A consequence of the generic model interface design is that model selection becomes a less critical issue, with the opportunity to periodically review the choice of models against the present state-of-the-art. The benefit is an extended life for the forecasting system.

Forecast updating

The form of error predictor used to incorporate current measurements of flow to form improved, updated forecasts is unsatisfactory. It's two phase form can lead to rather odd looking forecasts and in general is neither helpful nor easy to interpret. A simpler approach based on an ARMA error predictor is recommended. This can be guaranteed to provide a stable adjustment which asymptotes to the simulation forecast with increasing lead-time. A multivariate form of this predictor is available for use with the ISIS hydrodynamic model. The benefits are a simpler, easier to interpret scheme. Use of off-line optimisation to fit the ARMA error predictor parameters for each gauged reach or catchment should also ensure greater accuracy than that obtained with the present scheme, which employs fixed parameters at all sites. A special fitting scheme is available, if needed, to accommodate for situations where there are significant errors in the observations used for updating.

Model calibration facility

A number of useful features of the RFFS Calibration Facility have been identified previously. Perhaps the most important is the pooled calibration across several events. This avoids many individual calibrations for each event and a later, ad hoc inference of a compromise parameter set. The benefit is saving in staff time for model calibration and a better optimum parameter set. Interactive visualisation facilities for manual parameter estimation bring further benefits in this area. The ARMA error predictor models, referred to above, can be calibrated as an integral part of the hydrological model from which the errors derive. Facilities to display different types of forecast graphically - fixed-lead-time and fixed-origin - help to understand the model performance expected in real-time as well as supporting the model calibration process.

Forecast construction

The following summarise the main benefits of adopting the RFFS-ICA for managing forecast construction:

(i) A generic model algorithm interface which can accommodate an infinite variety of model types. This means that new models can replace old ones, without changes to the "inner code", as modelling advances are made or model preferences change. Use of a generic model algorithm interface means that quite radical extensions, for example to incorporate water quality algorithms, can be made with ease. In the case of the Soar forecasting requirement this feature is particularly important in easing the task of integrating the ISIS hydrodynamic model into the real-time forecasting environment.

(ii) Full resilience to missing data, allowing the model to function, albeit less accurately, even with the total absence of telemetry data.

(iii) The ability to run a network model for the whole network or selected parts of the network. Sub-networks can be dynamically definable during a run of the model if required, or can be pre-configured. The sub-network functionality is particularly appropriate where repeated runs on a particular part of the network are required to support "what if?" decision-support runs, such as in scheduling future flood control gate movements. With extension of the system to the tidal reaches of the Severn and Trent, a typical use of sub-network configuration would allow the non-tidal model to be run faster and more frequently to support flash flood forecasting on the fluvial river.

(iv) The ability to readily incorporate weather radar data into the system for use with catchment models, with a run-time switch to revert to raingauge data when radar data are judged to be more reliable (and vice versa). The switch might also be used as a "what if?" to judge the uncertainty of the flow forecast associated with the rainfall input.

(v) A re-run option which allows a model run previously enacted to be repeated with new options. This is used particularly for decision-support where the exact data used for one run must be used for the next, except that involved in the "what if?" option being considered. If this is not done, in real-time there is no guarantee that new data are not affecting the outcome rather than the option being investigated.

Other functions which are partly supported by the present FFS include:

(vi) The ability to reconfigure the system to incorporate new forecast points or telemetry sites for an existing system, or to a completely new river network, without expensive recoding. Network structure is data defined, allowing low cost modifications as well as using the same software to be used for subsequent implementations. Not needing to modify the program code, as well as having cost advantages, also makes new implementations less error prone.

(vii) The use of a state formulation to allow models to be initialised from a past set of state values, avoiding a long warm up for model initialisation. This means that the model can be run intermittently but yield a "seamless" result as if the model had been run continuously.

System environment

Existing investment in the RECS system for telemetry management is protected through the recommendation that this is retained to provide a telemetry interface to the RFFS. Whilst RECS currently receives 15 minute and event data these are consolidated to an hourly interval for database access. This needs to be modified so that database access to the 15 minute data is provided in order to meet the modelling requirement for data at this interval.

As a staged enhancement of the existing system it is proposed that initially an interface from the RFFS to the existing REMUS forecast display system be established. REMUS needs to be replaced by a system running under Windows 3.1, or better. The recommendation for Phase II is that it be replaced by the new RFFS shell GUI under development at IH and due for completion in 1996. This will be supported under Windows 3.1, or better. The benefits are a phased implementation and investment, and a state-of-the-art GUI.

Computing provision

The NRA's plan to purchase a VAX 3100/Model 95 (plus additional disk storage) provides an appropriate computer platform to support the new forecasting system. Staying with Digital has clear benefits given the importance of maintaining an operational flood forecasting and warning system throughout the development project time period.

Severn-Trent wide implementation

The recommendations envisage a Phase III project which will be a Systems Analysis Study to extend the new forecasting system to the entire Severn-Trent region, including the tidal reaches of the Trent and Severn. Thus the benefits of implementation on the Soar will be greatly extended, with the Soar really serving as a pilot development and implementation study for the region as a whole. The Systems Analysis study will review the requirements for flow forecasts in the region and propose a strategy for implementation including costs and time schedules. A subsequent implementation of this strategy will allow the full benefits of the developments made in the Soar to be realised throughout the Severn-Trent Region.

7.4 OVERVIEW OF BENEFITS

The requirements for flood warning identified in the Stage 1 report highlighted that the key areas needing warning were on the Lower Soar, downstream of the confluence with the Wreake, and on the middle and lower Wreake. These are the areas that have been designated as river reaches requiring a hydrodynamic approach to modelling on account of variable backwater induced by navigation level and flood gate control. It represents a quite radical departure from the current use of a simple conceptual hydrological channel flow routing model in which the effect of backwater is not accommodated. The failure of such models, particularly in the vicinity of flood gates such as at Frisby on the Wreake, are evident from the assessment of forecasts for past events in Section 4. The reliability of forecasts have been so uncertain that flood duty officers have lost confidence in the use of the Flow Forecasting System and have tended to switch to monitoring the flood and its trend rather than rely on the forecasts. In this regard it is suggested that the benefits of a replacement system for the Soar be viewed as the full benefit of a forecasting system, implying that the benefit accrued from the existing forecasting system has zero value.

Clearly the potential benefits of flood warning for the Soar will not be fully realised with the proposed system as it too will not give perfect forecasts. Since the key forecast points relate to reaches which are represented by the ISIS hydrodynamic model it is of interest to look more closely at the accuracy of forecasts one might expect to obtain from this model. An error analysis is carried out in Appendix 6 which suggests that for conditions pertaining to the main channel of the River Soar an upper band on the error of forecasting the 100 year flood may be 0.3 m at any site. This doesn't take into account any errors in forecasting lateral inflows or the improvement in forecast accuracy due to updating, which whilst ineffective at large lead times will be considerable at short lead times. Scope for improving this upper band on accuracy exists through the use of improved calibration data for more sites and larger flood events and through access to more accurate survey data of the flood plain topography.

An examination of the sources of unreliability in the present flood warning system suggest that the following benefits will derive from the recommendations of this study:

(i) Improved measurement of catchment average rainfall by installing two new raingauges, utilising data from five further gauges within NRA Anglian Region, obtaining better resolution by using smaller buckets, replacing the low resolution Type 1 radar data with much higher resolution Type 2 and employing the improved radar calibration and forecasting facilities available through HYRAD, including access to Frontiers forecasts.

(ii) Improved and extended measurement of river stage and flow by installing new gauging stations at Freemans Weir and the Eye at Brentingby, enhancing the performance of existing stations at Kegworth, Pillings Lock, Littlethorpe, Syston and Eye Kettleby and utilising the control gates for flow estimation via extended telemetry and a current metering programme.

(iii) Better resolution of all monitored data by employing a 15 minute data storage time step giving more accurate flood forecasts.

(iv) Improved soil moisture accounting by upgrading the Brooksby climate station, leading to better rainfall-runoff modelling.

(v) Greater flexibility for rainfall-runoff modelling by gaining access to additional algorithms such as the PDM model which offers real-time state updating.

(vi) Greater flexibility for channel flow routing by gaining access to the KW model.

(vii) More scientific representation of flow phenomena such as backwater influences, inundation of floodplains and the operation of control structures by implementing the ISIS hydrodynamic model.

(viii) More efficient and effective calibration of the hydrological and hydraulic model parameters via user friendly, visual calibration and optimisation tools.

(ix) Improved updating scheme by employing a simpler, more stable error predictor.

(x) Greater flexibility in forecast construction, with the system providing for extension to new catchments, models and forecast variables, such as water quality.

The Consultants believe that these recommendations will lead to a significant improvement in the reliability of the flood warning service for the River Soar Catchment and restore the confidence of the Flood Duty Officers in the system.

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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

PAPER: LOCAL CALIBRATION OF WEATHER RADAR OVER LONDON

In: M.E. Almeida-Teixeira, R. Fantechi, R. Moore, V.M. Silva (eds), Advances in Radar Hydrology, European Commission, 1994.

LOCAL CALIBRATION OF WEATHER RADAR OVER LONDON

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ABSTRACT

The London Weather Radar Local Calibration Study, initiated in October 1987, aimed to combine measurements of rainfall from radar and a network of 30 telemetering raingauges in real-time to produce a more accurate combined estimate of the rainfall field. Procedures were developed for the calibration of weather radar based on fitting multiquadric surfaces to the calibration factor values, conventionally defined as the ratio of raingauge to coincident weather radar grid-square estimates of rainfall. A wide range of methods was considered and assessed using data from 23 rainfall events. The method finally adopted for operational implementation provided an average improvement in accuracy of 22% relative to that obtained by the radar without calibration. The Local Calibration System has been operating since 14 March 1989 in support of flood warning activities over London and the Lee Valley.

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Introduction

A once-in-50 year flood in the London area can cause damage to residential properties approaching £17 m (Haggett, 1986). Substantial potential savings exist if timely and accurate warning of imminent flooding can be given. The London Weather Radar Local Calibration Study was initiated in recognition that weather radar data from the Chenies radar serving the London area can contribute to the realisation of these potential savings. Chenies weather radar provides a unique source of information on rainfall variations over London and its surrounding area.

The main aim of the Study was to use the 30 telemetering raingauges available for the London and Lee Valley area (Figure 1) as the basis of a regional calibration procedure. An existing calibration performed at the radar site used only 5 raingauges as part of a domain-based calibration procedure (Collier et al, 1983): this introduced discontinuities in the radar field at the domain boundaries. The aim was to produce a smooth adjustment procedure employing the full raingauge network, providing more accurate and reliable estimates of spatial rainfall variations, in particular to support flood warning operations. The main focus of the Study was the development of procedures for the calibration of weather radar based on fitting surfaces to the calibration factor values, conventionally

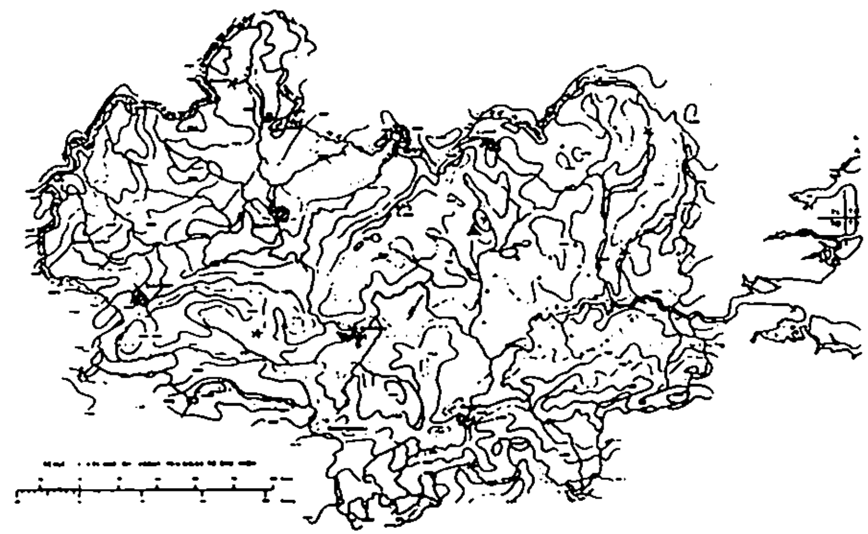

Figure 1 *Locations of the radar and raingauges within the Thames basin and annual average rainfall in mm (Δ London raingauges; • Lee Valley raingauges; * Meteorological Office "at-site calibration" gauges)*

defined as the ratio of raingauge to coincident weather radar grid-square estimates of rainfall. Consideration was given to a wide range of calibration procedures. A comprehensive program for the assessment of the different calibration methods was developed as the major data-analytic tool for the Study. Some important aspects of the Study are highlighted in this paper together with an outline of the procedure finally adopted for operational implementation. Further details are provided in (Moore et al, 1989a, 1989b and 1991).

The surface fitting method

A range of options for combining radar and raingauge data are considered in Moore(1990). These range from space-time models of the rainfall field, which incorporate the covariance structure of the rainfall field and measurement errors, to simpler formulations based on optimal linear interpolation (Gandin, 1965; Jones *et al.*, 1979), Kriging (Matheron, 1971; Creutin and Obled, 1982) or surface fitting. It is the last technique that has been adopted, for reasons of computational efficiency, directness of approach and simplicity. In fact strong links between surface fitting, optimal interpolation and Kriging can be established (Lancaster & Šalkauskas, 1986). Whilst the latter two techniques decompose the problem into constituents which require specification of the spatial correlogram or variogram, the surface fitting provides a simple and direct method of merging radar and radar data in which uncertainties are accomodated implicitly through the method used to fit the calibration factor surface. The basis of the method is to fit a mathematical surface to calibration factor values calculated at n raingauge locations and to scale the radar rainfall field by the coincident factor values to derive a more accurate calibrated radar field. As a result of trials, the specific definition of calibration factor adopted was $z_i = (R^i_g + \epsilon_g)/(R^i_r + \epsilon_r)$. Here R^i_g and R^i_r are the i'th raingauge measurement and the coincident radar grid-square value for a 15 minute interval. The parameters ϵ_g and ϵ_r are small constant values which ensure that the calibration factor is defined for radar values equal to zero.

The particular surface fitting method adopted is based on an extended form of the multiquadric presented by Hardy (1971). First, let z_i be the calibration factor values defined at the n raingauge locations, having grid coordinates $\underline{x}_i = (u_i, v_i)$. The multiquadric calibration surface is defined as the weighted sum of n distance, or basis functions centred on each gauge; that is

$$s(\underline{x}) = \sum_{j=1}^{n} a_j\, g(\underline{x}-\underline{x}_j) + a_0 \qquad (1)$$

where $\{a_j, j=0,1,2,\ldots,n\}$ are parameters of the surface. The distance function adopted as a result of trials was the simple Euclidean distance

$$g(\underline{x}) = \|\underline{x}\| = \sqrt{(u^2+v^2)} \qquad (2)$$

which corresponds to building up the surface from a set of n right-sided cones, each centred on one of the n raingauge locations.

Formally, estimation of the a_j weights is achieved as follows. Equation (1) for

$$s(\underline{x}_i) = \sum_{j=1}^{n} a_j\, g(\underline{x}_i-\underline{x}_j) + a_0 = z_i \qquad (i=1,2,\ldots,n) \qquad (3)$$

may be expressed in matrix form as

$$\underline{G}\,\underline{a} + a_0\underline{1} = \underline{z} \qquad (4)$$

where $\underline{G}$ is an n by n matrix with the (i,j)'th element given by $G_{ij} = g(\underline{x}_i - \underline{x}_j)$, $\underline{1}$ is a unit vector of order n, and $\underline{z}$ is the vector containing the n calibration factor values. As one approach to avoiding anomalies in the surface form away from n raingauge locations, an additional requirement for flatness at large distances is imposed through the constraint

$$\underline{a}^T\underline{1} = 0. \qquad (5)$$

For the Euclidean distance function of cone type this constraint corresponds to a requirement of zero-slope with increasing distance from the raingauge network. Solution of equation (4) subject to constraint (5) for the weighting coefficients gives

$$\begin{aligned} a_0 &= (\underline{1}^T\underline{G}^{-1}\underline{z})/(\underline{1}^T\underline{G}^{-1}\underline{1}) \\ \underline{a} &= \underline{G}^{-1}(\underline{z}-a_0\underline{1}) \end{aligned} \qquad (6)$$

It was found to be important to form a conservative calibration factor surface by adopting a fitting method which allowed the surface to depart from the actual calibration factor values. This was achieved by allowing the Euclidean distance $g(\underline{x}_i-\underline{x}_i) = g(\underline{0})$, normally zero, to take a value -K. This results in a surface which passes within a distance $a_i K$ of the calibration factor value for the i'th raingauge. The problem of discontinuities is avoided by using this form in the estimation of the weights, a_i, and using the normal form in calculating the surface values for radar calibration of the full field. The constraint of equation (5) ensures that the "errors", introduced by using $g(0) = 0$ in equation (1) (and not $-K$) when forming the surface for calibration, add up to zero.

An illustration of the form of a fitted surface and the resulting calibrated radar field are shown in Figures 2 and 3.

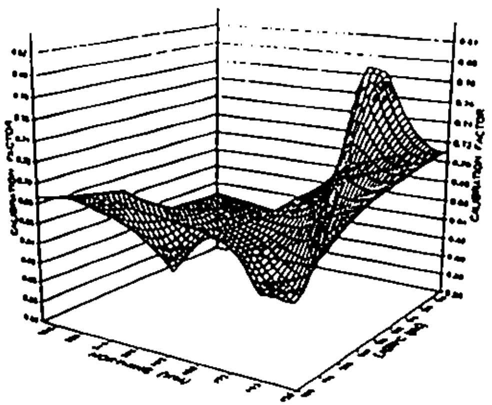

Figure 2 Calibration factor surface for 16.30 14 March 1989

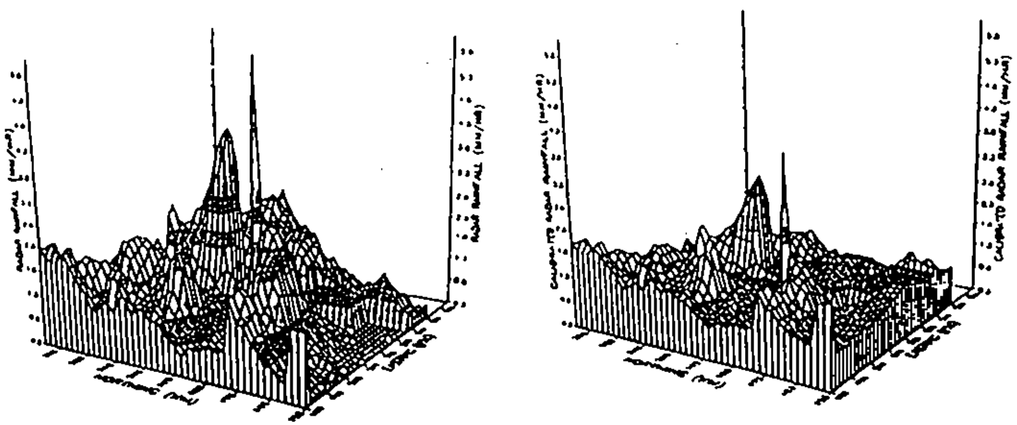

Figure 3 Radar fields for 16.30 14 March 1989 before and after calibration

Assessment of methods

The Study considered many variants of the above procedure before recommending it for operational implementation. Seven forms of calibration factor definition were evaluated, including reciprocal, trimmed and logarithmic formulations. Account was taken of the position of a gauge within the radar grid square by forming calibration factors which used the average of nine, four or one grid-squares as the radar value. The choice of a coarser time-interval than 15 minutes for constructing the calibration factor surfaces was also investigated. Compensation for quantisation errors in the raingauge data, due to the use of tipping-buckets, was investigated by forming a conservative calibration factor by incrementing the raingauge value by the bucket increment towards the radar value when appropriate. Different forms of surface, employing smoothed Euclidean, exponential and reciprocal distance functions, were evaluated along with different estimation schemes which minimised surface roughness or constrained the surface to a constant value at large distances.

The assessment was carried out using data from 23 rainfall events over an area of about 60 km by 60 km containing up to 30 raingauges, equivalent to a gauge density of one gauge per 120 km^2 area. A selective deletion procedure was used whereby one gauge was omitted, the surface fitting scheme applied and used to form an estimate of the rainfall at the deleted gauge. This was repeated n times for each gauge giving n sets of rainfall estimation error: repetition of this for all 15 minute rainfall fields making up the 23 rainfall events allowed a pooled log root mean square error performance statistic to be formed. Each variant described above was explored using this strategy and a recommendation for operational implementation was finalised. The space- and time-averaged forms of calibration factor and quantisation correction were not found to be worthwhile implementing on the basis of this assessment procedure.

Assessment against simple rainfall estimators

It was judged important to assess the final calibration procedure against some alternative simple rainfall estimation schemes. These included an estimate of the rainfall field using (i) a simple arithmetic average of the available raingauges, (ii) a multiquadric surface fitted to the raingauge values, and (iii) a simple arithmetic average of the calibration factor values. The results are summarised in Table 1. These show that the radar, without raingauge calibration, is better than an estimate using the raingauge network alone, despite its density and the use of a sophisticated surface

Table 1 Assessment of Alternative Rainfall Estimation Techniques

Method	log rmse	% improvement in log rmse
Uncalibrated Radar	.068	0
Raingauge Average	.084	-24
Surface fitting to Raingauges	.072	-6
Calibration factor average	.058	15
Surface fitting to calibration factors	.053	22

fitting interpolation method. Even the application of a simple raingauge calibration applied to the radar data improves the accuracy by 15% and the use of the more sophisticated surface fitting method increases this further to 22%, on average.

Event Assessment

It is of interest to investigate whether the average increase in accuracy of 22% is achieved uniformly across all events or whether synoptic conditions exert an influence. Table 2 provides a breakdown of the performance on an event basis for the uncalibrated radar and the recommended calibration method. Also highlighted are those events which experienced thunder and hence can be generally associated with convective activity. Despite thunder being recorded in 13 of the 23 events only in 3 of these does the calibration procedure cause the rainfall estimate to worsen, and then by only a very small amount. It may therefore be concluded that the conservative nature of the calibration method ensures that rainfall estimation is reasonably resilient to the localised and steep rainfall gradients that make calibration difficult in convective situations. In conditions of widespread frontal rain these results indicate that calibration can improve the accuracy by as much as 45%.

Table 2 Assessment of surface fitting calibration method relative to uncalibrated radar on an event basis using the log rmse criterion; T indicates that thunderstorm activity is present for the event

Event	Uncalibrated radar	Surface fitting calibration method	% improvement in log rmse	
1. Oct 1987a	0.053	0.036	32	
2. Oct 1987b	0.148	0.088	41	
3. Nov 1987b	0.089	0.068	24	
4. Mar 1988a	0.036	0.030	17	T
5. Mar 1988b	0.031	0.022	29	
6. Mar 1988c	0.018	0.012	33	
7. Apr 1988a	0.051	0.048	6	T
8. May 1988	0.064	0.066	-3	T
9. Jun 1988a	0.038	0.032	16	T
10. Jun 1988b	0.115	0.118	-3	T
11. Jul 1988a	0.030	0.029	3	T
12. Jul 1988b	0.044	0.036	18	T
13. Jul 1988c	0.042	0.040	5	T
14. Jul 1988d	0.064	0.066	-3	T
15. Jul 1988e	0.051	0.035	31	
16. Jul 1988f	0.108	0.086	20	T
17. Jul 1988g	0.091	0.056	38	
18. Aug 1988a	0.128	0.117	9	T
19. Aug 1988b	0.063	0.042	33	
20. Feb 1989b	0.081	0.061	25	T
21. Mar 1989a	0.041	0.023	44	
22. Mar 1989b	0.095	0.052	45	
23. May 1989a	0.093	0.056	40	T
Average across events	0.068	0.053	22	

Conclusion

An assessment using data from 23 rainfall events has allowed operational implemementation of the radar calibration to proceed with scientific justification: the Radar Calibration System has now been running successfully since 14 March 1989 in support of flood warning activities over London and the Lee Valley. The assessment indicates that the calibration provides a 22% improvement in accuracy relative to that obtained by the radar without calibration; improvements as great as 45% may be achieved in widespread rainfall and the risk of reducing the average accuracy during localised covective events appears slight. Even without raingauge calibration the radar has been shown to provide better estimates of spatial rainfall than can be obtained using the dense network of raingauges in isolation. An additional procedure which estimates spatial rainfall using only raingauges was implemented in September 1989 to complement the calibration procedure and to replace it in the event that the radar malfunctions.

Acknowledgements

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Appendix 3

PAPER: LOCAL RAINFALL FORECASTING USING WEATHER RADAR: THE LONDON CASE STUDY

In: M.E. Almeida-Teixeira, R. Fantechi, R. Moore, V.M. Silva (eds), Advances in Radar Hydrology, European Commission, 1994.

LOCAL RAINFALL FORECASTING USING WEATHER RADAR: THE LONDON CASE STUDY

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ABSTRACT

The London Weather Radar Rainfall Forecasting Study was initiated in October 1989 to provide rainfall forecasts on a 2 km grid over the Thames basin, focussing on lead times up to 2 hours and capable of producing updated forecasts every 15 minutes. In contrast, the UK national system of radar forecasting, known as Frontiers, provides a coarser resolution product on a 5 km grid extending over the UK, for a 6 hour lead time updated every half hour . The requirement for more frequent, higher resolution forecasts reflects hydrological needs for flood warning, particularly forecasting flooding in urban and smaller rural river basins. An outline is presented of the development, assessment and implementation of the advection-based radar rainfall forecasting method now in operational use over London and the Thames basin.

Introduction

The benefits accruing from a radar-based rainfall forecasting system have been assessed at £3.72 m per annum over England and Wales (Collinge, 1989). This assessment was made in the context of the UK Meteorological Office's Frontiers forecasting system (Conway & Browning, 1988) which aims to provide forecasts, updated every half hour, up to 6 hours ahead for a 5 km grid with national coverage. The London Weather Radar Rainfall Forecasting Study was motivated by recognising that the national Frontiers product would not meet the water industry's specific requirements for very short term rainfall forecasts with high resolution in space and time, which are needed particularly for forecasting flooding in urban and smaller rural catchments. Specifically the Study aimed to develop a radar-based rainfall forecasting system with emphasis on forecasting up to two hours ahead every 15 minutes for a 2 km grid extending over an area within a radius of 75 km of the radar. A further requirement was that the system be implemented operationally as part of a regional flood warning system run by the National Rivers Authority Thames Region at Waltham Cross.

The main approach to rainfall forecasting investigated within the Study is one that assumes an underlying advection model and uses simple linear extrapolation to forecast future rainfall fields. This paper presents an outline of the development and assessment of different advection-based radar rainfall forecasting methods which provided the foundation for recommending the forecasting system now in operational use over London and the Thames basin.

Radar Rainfall Forecasting Methods

An advection model of rainfall field movement forms the basis of all forecasting methods considered in the Study (Moore et al, 1991). Simple linear extrapolation is used to project the current radar rainfall forward, according to the advection velocity, to form forecast fields at successive lead times. The velocity vector is inferred from the current and a previous radar rainfall field by identifying a displacement of the latter which best matches the former.

Formally, using x and y to denote location on the west-east and south-north axes respectively, the x-component of the storm velocity, v_x, is derived from the following description of rain cell position:

$$x(t + \tau) = x(t) + v_x \tau \qquad (1)$$

where x(t) denotes the position on the x-axis at the forecast time origin t and τ is the lead time of the forecast. Inference of the velocity vector (v_x, v_y) uses, as the citerion of correspondence, the log root mean square error

$$rmse = \left(n^{-1} \sum_{i,j} e_{i,j}^2\right)^{1/2} \qquad (2)$$

where the error $e_{i,j}$ is defined as

$$e_{i,j} = \log\{(1 + R_{i,j})/(1 + \hat{R}_{i,j})\} \qquad (3)$$

and $R_{i,j}$ is the observed radar rainfall for the (i,j)'th pixel and $\hat{R}_{i,j}$ the forecast amount, based on projecting a previous field at the given velocity. For velocities which do not result in displacements which are integer multiples of the radar grid length the formation of $\hat{R}_{i,j}$ involves the use of the following four-point interpolation formula applied to four adjacent radar cell values:

$$\hat{R}_{i,j} = (1-p)(1-q)\ R_{k,l} + p(1-q)\ R_{k+1,l} + q(1-p)\ R_{k,l+1} + pq R_{k+1,l+1} \qquad (4)$$

Expressions for the position (k,l) and the weights p and q, which depend on the velocity vector (v_x, v_y), are given in Moore et al (1991).

Identification of a velocity pair which minimises the rmse criterion involves a shrinking-grid search procedure at each forecast time origin. A coarse but extensive grid of velocity pairs is initially used and this is progressively reduced over three steps to smaller but finer grids centred on the previous step's best velocity pair. In all three steps only velocities which result in displacements which are integer multiples of the grid length are used in order to avoid the computational expense of interpolation. At the fourth and final step a direct interpolation in the error-criterion field is made, based on a four-point interpolation, to arrive at the final velocity pair to be used for that forecast time origin. Using this approach a velocity inference and two hour rainfall forecast construction over a 76 km radius field requires only 12 cpu seconds on a VAX4200 computer.

Each of the forecast algorithms considered in the assessment incorporate the same radar preprocessing scheme. This provides for automatic detection and correction for persistent anomalies and transient clutter. Also included is a procedure to construct a composite field, incorporating radar data available out to a range of 210 km on a 5 km grid, in order to forecast as much of the target 76 km radius field as possible at higher lead times.

Assessment of Methods

An evaluation of the above basic advection approach to forecasting against a number of alternatives was carried out using radar rainfall fields from 15 storm events. Preliminary results suggested the use of a hybrid formulation in which the advection forecast, $\hat{R}_{i,j}$, is shrunk towards the field average value, $\bar{R}$, with increasing lead time, τ, so as to produce the modified forecast:

$$\tilde{R}_{i,j} = \begin{cases} \bar{R} + a\left(\hat{R}_{i,j} - \bar{R}\right) & \hat{R}_{i,j} > 0 \\ 0 & \hat{R}_{i,j} = 0 \end{cases} \qquad (5)$$

where the shrinkage factor $a = f^{\tau}$, and f is a constant. For the lead times up to 2 hours considered in the evaluation, this hybrid formulation performed better than persistence (a no change forecast), a rain/no-rain pattern matching approach to velocity inference and extensions of the advection method to incorporate acceleration and intensification.

The results of the assessment of a selection of different methods are presented in Figure 1. Included in Figure 1 are the results of the "best advection" method which is the best attainable forecast using the pure advection approach, derived by inferring the velocity using the current and forecast fields; clearly this is not realisable in practice but provides a useful performance benchmark. Note the anomalous increase in rmse beyond 100 minutes merely reflects sampling effects caused by the progressive loss of the forecast field for higher lead times for some methods (a requirement is imposed for all methods to be able to make forecasts for inclusion in the rmse criterion for a given lead time). In general, the pattern of rainfall forecasts obtained using the hybrid formulation are reasonable up to a lead time of one hour (Figure 2).

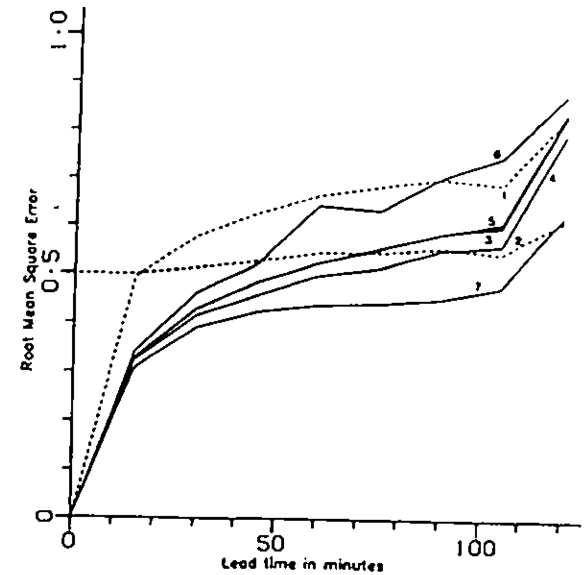


Figure 1 *Assessment of radar rainfall forecasting methods over 15 storm events using the rmse performance criterion. The methods are: 1. Persistence; 2. Field average; 3. Standard advection; 4. Standard advection with shrinkage; 5. Acceleration and advection; 6. Intensification and advection with shrinkage; 7. Best advection.*

Observed at 16.15

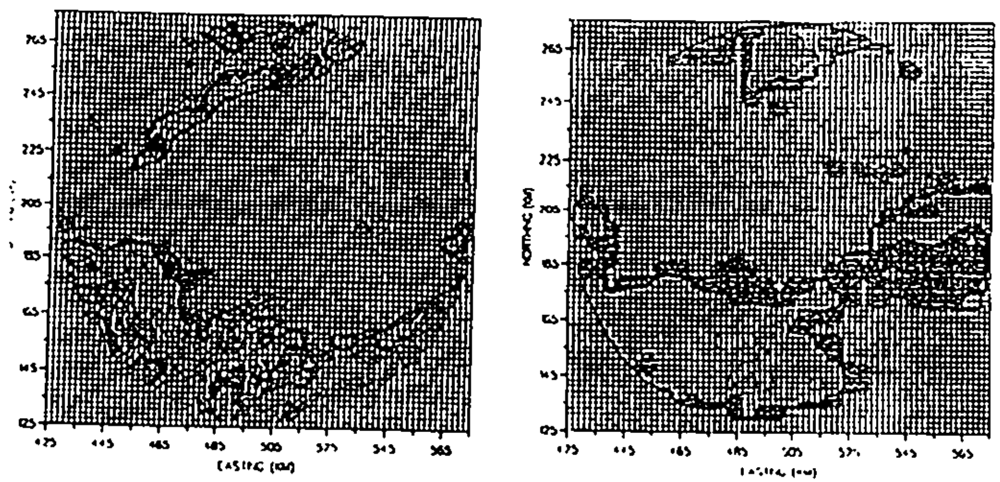


Figure 2 *The observed 76 km radius rainfall field at 16.15 20 December 1989 and the corresponding one-hour ahead forecast made at 15.15*

Conclusions

The main conclusions arising from the London Weather Radar Rainfall Forecasting Study are summarised below:

(1) A forecasting method based on an underlying simple advection model and shrinking the forecasts towards the field average value with increasing lead time provides the best performance.

(2) More complex methods incorporating an acceleration or intensification component, or using a rainfall threshold to define a rain/no-rain pattern field from which to infer the advection velocity, did not perform as well.

(3) The general pattern of the forecast rainfall fields are reasonable up to about one hour ahead

(4) A novel shrinking-grid search procedure for identifying the storm velocity from two time-displaced radar images, involving interpolation in the forecast error field in the final step, proved to be both reliable and efficient: a two hour forecast, at 15 minute intervals over a radius of 76 km, is generated in 12 seconds on a VAX4200 using this procedure.

(5) Results obtained have been sufficiently encouraging to proceed with operational implementation.

Acknowledgements

The Study has received the financial support of the Commission for the European Communities, the National Rivers Authority (NRA) Thames Region and the Ministry of Agriculture, Fisheries and Food. Particular thanks are due to the members of the Study Steering Committee - Chris Haggett, Peter Borrows (NRA Thames Region) and Chris Collier (UK Meteorological Office) - and to Martin Crees (NRA Thames Region) for data and software integration support.

References

Collinge, V.K. (1989) Investment in Weather Radar by the UK Water Industry, Weather Radar and the Water Industry, British Hydrological Society Occasional Paper No. 2, 1-13, Institute of Hydrology.

Conway, B.J. & Browning, K.A. (1988) Weather forecasting by interactive analysis of radar and satellite imagery. Phil. Trans. R. Soc. Lond., Ser. A, 324, 299-315.

Moore, R.J., Hotchkiss, D.S., Jones, D.A., and Black, K.B. 1991. London Weather Radar Local Rainfall Forecasting Study: Final Report. Contract Report to the National Rivers Authority Thames Region, Institute of Hydrology, September 1991, 124 pp.

Appendix 4

ISIS BROCHURE

OVERVIEW

ISIS is a software system for simulating flow, water quality and sediment transport in canals, rivers and estuaries. ISIS has been developed to provide engineers and managers with a comprehensive range of 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 Ltd and Sir William Halcrow & Partners, ISIS combines the skills and experience of these two leading organisations to offer proven hydraulic and water quality modelling capabilities within a state-of-the-art user environment.

ISIS has been designed as a suite of modules which may be used independently or as an integrated system, allowing the user to select only those capabilities required for a given study. The modular approach allows ISIS to grow as new and improved capabilities are added, ensuring that ISIS will always offer the very best modelling technology available and so protect the user's investment.

PEDIGREE

ISIS derives from the well known and proven SALMON and ONDA hydraulic and water quality engines and benefits from three decades of development and application experience for simple and complex systems worldwide.

ISIS FLOW MODULE

At the heart of ISIS is ISIS Flow, a fully hydrodynamic flow and level simulator for open-channel systems. ISIS Flow incorporates steady and unsteady flow solutions and can be used to model in-bank and overbank flows in branched and looped networks. ISIS Flow is also ideally suited to simple analyses such as derivation of backwater curves in single channels. ISIS Flow is both highly specified and easy to use. The hydraulic engine upon which ISIS Flow is based has been applied in a large number of hydraulic studies and projects in Britain and overseas since the 1970's.

Full Hydrodynamic Modelling

ISIS Flow will model any looped, branched open channel system and is suitable for modelling both natural river systems with floodplains and man made channels such as irrigation systems.

It is based on the full St Venant equations for open channel flow.

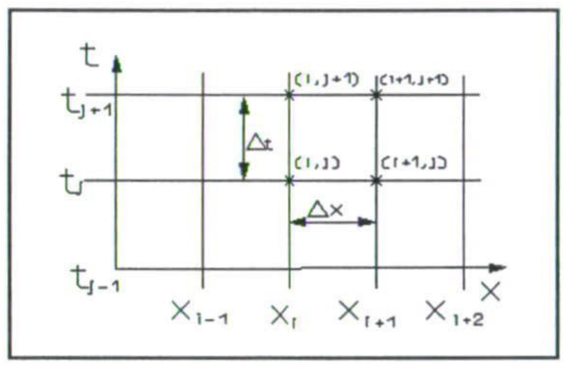
Mass Balance

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

Momentum Conservation

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{\beta Q^2}{A}\right)+gA\frac{\partial H}{\partial x}-g\frac{AQ|Q|}{K^2}+q\frac{Q}{A}\cos\alpha=0$$

The discretization is based on the Preissmann 4-point implicit (Box) scheme



For example, the derivative with respect to space is discretised as

$$\frac{\partial f}{\partial x}=\frac{1}{2\Delta x}\left[\theta\left(f_{i+1}^{j+1}-f_i^{j+1}\right)+(1-\theta)\left(f_{i+1}^{j}-f_i^{j}\right)\right]$$

Steady Flows

ISIS Flow includes the steady flow module described below. The steady state solver computes backwater profiles for design of channels and structures, even in looped systems. Steady state solutions are also used as initial conditions for unsteady model runs.

Flood Plains

ISIS Flow can model flow on flood plains by three methods:

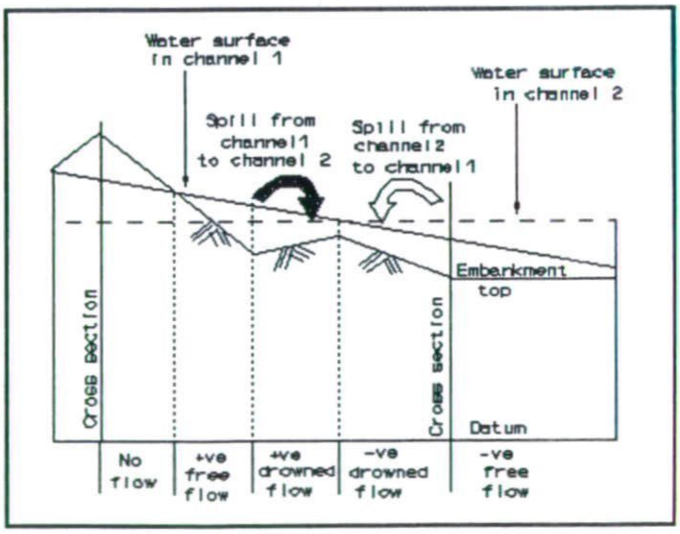
Firstly, as an integral part of the channel for areas where there are no flood embankments. The cross section is subdivided into vertical panels with conveyance calculated for each panel. A relative path length can be specified for each panel to simulate differences in distance travelled in meandering rivers. Roughness can be varied between and within panels. Panels can be set to have no conveyance to simulate dead zones behind buildings.

Secondly, flood plains and channels with different water levels where there is no conveyance on the flood plain.

Thirdly, flood plains and channels with different water levels where there is conveyance on the flood plain.

Spill Unit

In the last two methods of flood plain modelling, channel and flood plain are usually separated by a spill unit. The spill unit is a weir where the crest level of the weir varies with distance.



Drowned and free flows into or out of the channel are integrated along the length of the spill to give an accurate representation. Use of a flat top weir to model uneven embankment tops, as is commonly used in other programs, can give very severe errors in volumes of spillage across flood embankments.

Structures

ISIS Flow is very strong on structures and includes many different types with full modelling of hydraulic controls and all modes of flow.

Weirs
- broad crested
- sharp crested
- triangular profile
- uneven broad crested
- broad crested side spill
- uneven crested side spill

Sluices
- multiple radial or vertical
- tidal drainage
- tidal retention

Head losses
- bridges
- channel constrictions
- channel expansions
- arch bridges

Conduits
- irregular
- circular
- full arch
- sprung arch
- rectangular

Miscellaneous
- flumes
- tidal drainage flume
- siphons
- pumps

Steep Channels

ISIS Flow is able to model steep channels with supercritical flows through a modification to the momentum equation. The method used by ISIS Flow to model steep channels has been compared extensively with more rigorous techniques and has been found to provide a good degree of accuracy for supercritical flows providing the rate of change of flow area with distance is not too severe.

Example applications

The following are examples of recent studies using modelling software now available within ISIS Flow:

- Gumti-Titas & Atrai Basin, Bangladesh
- Thames, Severn, Great Ouse and Taff, UK
- River Alpone, Italy
- Abary River Control Project, Guyana
- Aguan Valley Master Plan, Honduras
- Rio de la Plata, Argentina, Uruguay and Paraguay
- PAT feeder canal, Pakistan
- GAP irrigation systems, Turkey

ISIS QUALITY MODULE

ISIS Quality is used together with ISIS Flow to simulate water quality in river and channel networks. ISIS Quality is run using the stored hydrodynamic data from ISIS Flow. This approach provides the user with significant flexibility by allowing, for example, multiple runs of ISIS Quality using the same ISIS Flow hydrodynamic results.

ISIS Quality computes concentrations using a finite difference approximation to the advection diffusion equation. An explicit implementation of the SMART algorithm, recently developed by Gaskell and Lau (1988), is used to approximate the advection term. Two alternative algorithms, QUICK and first order upwinding, are also available and the user is given the opportunity to decide which of the three algorithms they wish to use.

Water Quality Processes in ISIS Flow

ISIS Quality is capable of modelling a range of water quality variables and processes simultaneously. These include:

- Conservative and decaying pollutants
- Coliforms
- Salt
- Water temperature
- Sediment
- Oxygen balance
- Water/Sediment oxygen interactions
- Phytoplankton, macrophytes and benthic algae

ISIS Quality allows the user to run only those processes that are of interest. However, the river and estuary environment is a complex one in which many processes interact; consequently ISIS Quality ensures that all inter-dependant processes are simulated together.

Simulation method used by ISIS Quality

ISIS Quality models the transport of pollutants along open channel reaches by the one-dimensional advection-diffusion equation,

$$\frac{\partial(CA)}{\partial t} = -\frac{\partial(uCA)}{\partial x} + \frac{\partial}{\partial x}\left(DA\,\frac{\partial C}{\partial x}\right) + S$$

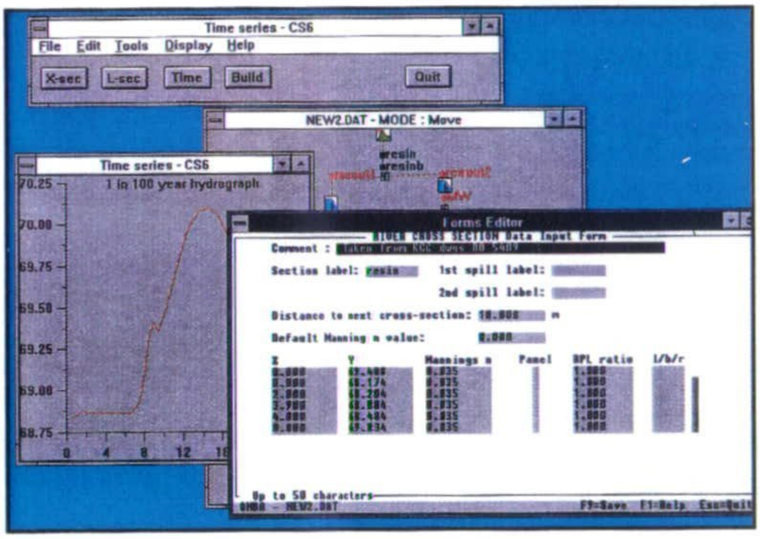
C = pollutant concentration (kg/m^3)
A = cross-sectional flow area (m^2)
u = cross-sectionally averaged flow velocity (m/s)
D = diffusion coefficient (m^2/s)
x = distance (m)
t = time (s)
S = source/sink term; representing decay, growth, erosion, deposition, etc (kg/m/s).

As the equation is one-dimensional all the variables represent cross-sectionally averaged quantities.

Example applications

The following are examples of recent studies using modelling software now available within ISIS Quality:

- River Tagus, Portugal
- River Stour, UK
- South Creek, Australia
- River Mersey, UK
- River Trent, UK
- Berowra Creek, Australia
- Bhola Irrigation Project, Bangladesh
- Port Kelang, Malaysia
- Bicol River Basin Project, Philippines



ISIS HYDROLOGY MODULE

The ISIS Hydrology module provides a number of alternative hydrological techniques for modelling catchment and sub-catchment runoff to provide input conditions for ISIS Flow.

For UK sites the well established Flood Studies Report (FSR) Unit Hydrograph method is used. A wide range of options are available dependent on the information available; for example, rainfall can be specified explicitly or by the standard regression equations by simply selecting a return period. The second method is an alternate based on FSR Supplementary Report No 16 for highly urbanised sub-catchments.

For other countries the US Soil Conservation Service (USSCS) Unit Hydrograph method is available where the unit hydrograph is defined through a Curve Number dependent on soil type, land use and hydrologic condition. A user derived unit hydrograph and rainfall loss model can also be specified, and hydrographs from other hydrological models can be input very easily.

ISIS STEADY FLOW MODULE

The ISIS Steady Flow module is available for users who do not require the full hydrodynamic capabilities of ISIS Flow. ISIS Steady Flow computes backwater profiles for design of channels and structures, even in looped systems. Steady state solutions are widely believed to be difficult for looped systems. ISIS Steady Flow incorporates two solution methods both applicable to looped branched systems. The direct method is greatly superior to the more commonly used pseudo-time-stepping method and involves an extension of a fourth order Runge-Kutta solver. The direct method gives a highly accurate solution and has an adaptive grid size.

ISIS SEDIMENT MODULE

ISIS Sediment simulates sediment transport using hydrodynamic results from ISIS Flow. ISIS Sediment can model cohesive, non-cohesive and graded sediments over simulation periods ranging from a few days to many years and using either fixed or mobile bed methods. Where mobile bed simulations are carried out the user may select from a number of alternative methods for updating the bed geometry.

Erosion of cohesive sediments is simulated using an excess shear type equation, with deposition determined from the shear stress, particle fall velocity and sediment concentration. Suspended sediment is transported by application of the advection-diffusion equation. Non-cohesive sediment transport is modelled using standard formulae, including Ackers and White and Engelund-Hansen.

ISIS WORKBENCH

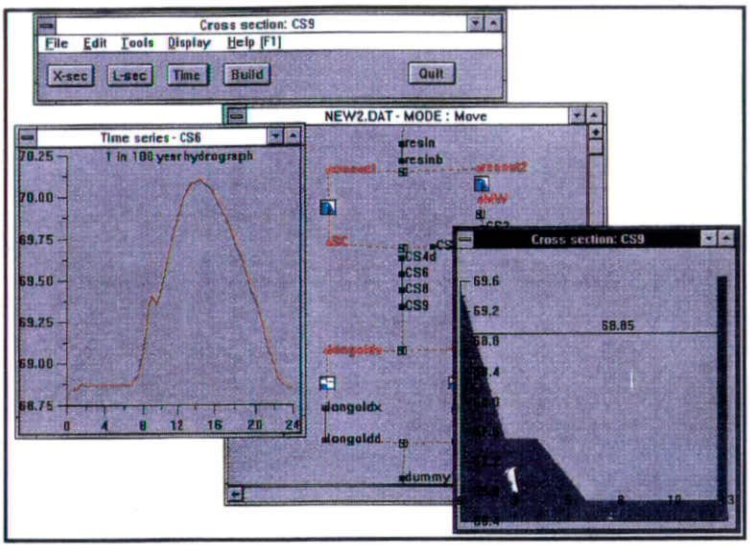
The ISIS Workbench significantly improves productivity of the modelling process with tools to assist in building models, editing data, presenting results and organising files. A fully object orientated network visualiser enables complex systems to be built graphically by selecting units that represent 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 to assist with project quality assurance procedures

QUALITY CONTROL

The ISIS software has been developed using quality assurance procedures complying with BS5750/ISO9001 standards and accredited under the British Standards Institute TickIT scheme. Quality control includes several hundred automatic comparisons against hand calculations, standard data sets and analytical solutions.

FUTURE DEVELOPMENTS

Currently in development are ISIS modules for simulation of long term hydrology, flow routing and simple water quality. Future plans include integration with Geographical Information Systems (GIS) and Digital Terrain Models (DTM).



HARDWARE AND OPERATING SYSTEMS

ISIS is available for PCs running Microsoft Windows and unix workstations running Motif. Please contact your ISIS agent for further details.

TRAINING, SUPPORT AND LICENSING

A standard license agreement is provided with full maintenance including telephone advice, bug fixing and provision of updates. Special support, including consultancy, can also be provided.

Training is tailored to user experience and needs. Small groups are preferred to give personal attention. Training sessions can be arranged on the users premises if required. Please contact your ISIS agent for details of these services.

FURTHER INFORMATION

For more information on ISIS please contact your agent or one of the following:

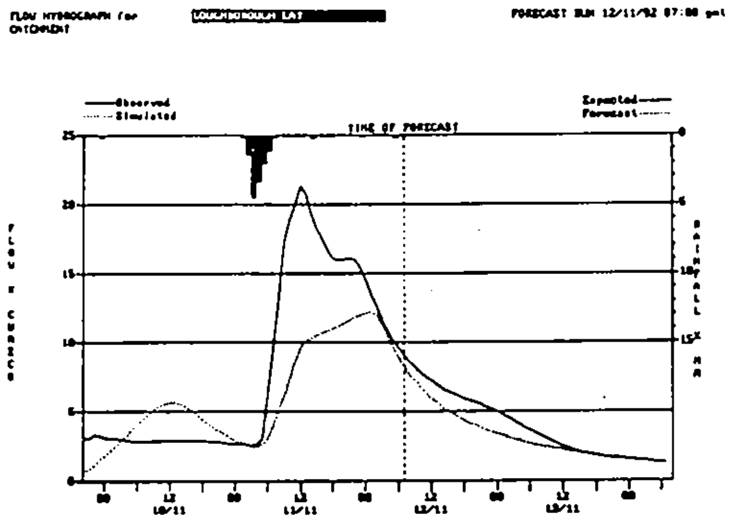
HR Wallingford, Wallingford, Oxfordshire OX10 8BA, UK
Tel +44 (0) 1491 83 53 81, Fax +44 (0) 1491 83 22 33

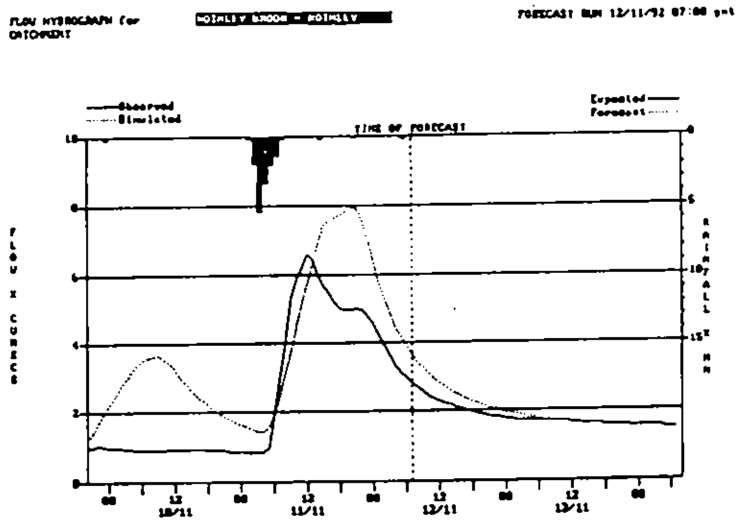
Halcrow, Burderop Park, Swindon, Wiltshire, SN4 0QD, UK
Tel +44 (0) 1793 81 24 79, Fax +44 (0) 1793 81 20 89

Appendix 5

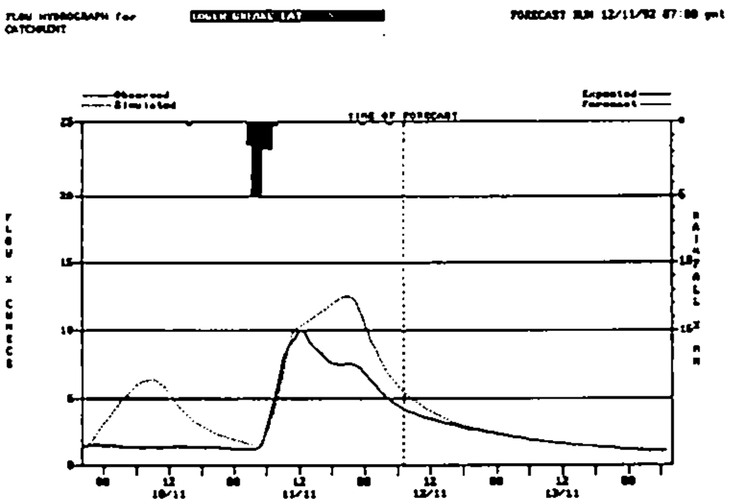
FLOOD FORECAST EVENT ANALYSIS

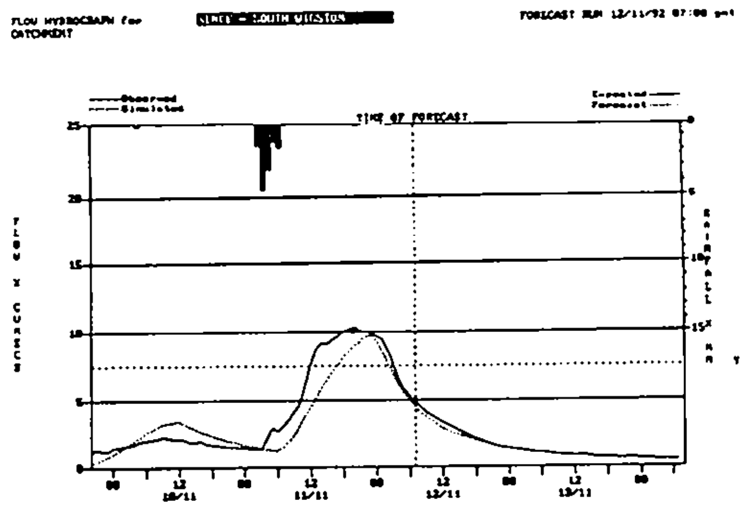
Figure A5.1 Flood forecasts for Event 1: 12 November 1992

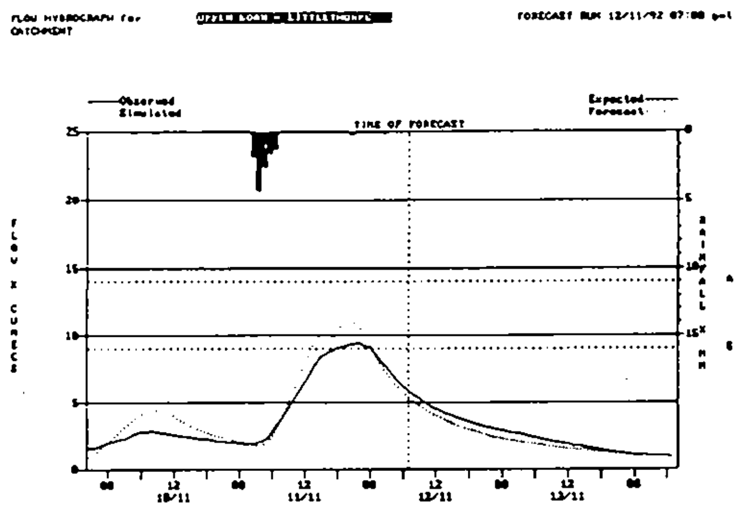

FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 12/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
RAINFALL X MM

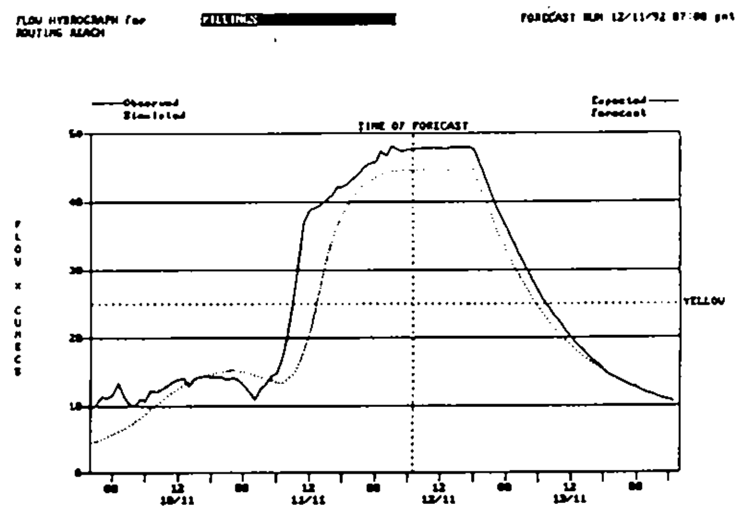

FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 12/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
RAINFALL X MM

Event 1

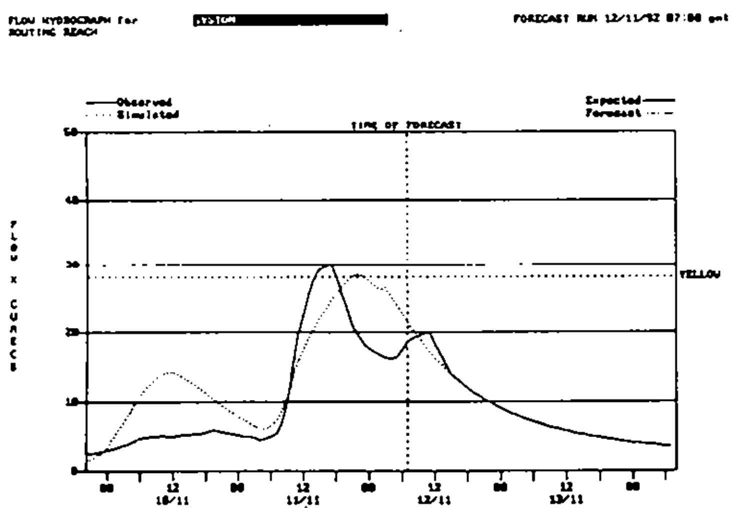

FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 12/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
RAINFALL X MM


FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 12/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
RAINFALL X MM


FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 12/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
RAINFALL x MM


FLOW HYDROGRAPH for ROUTING REACH
FORECAST RUN 12/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
YELLOW

Event 1


FLOW HYDROGRAPH for ROUTING REACH
FORECAST RUN 12/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
YELLOW

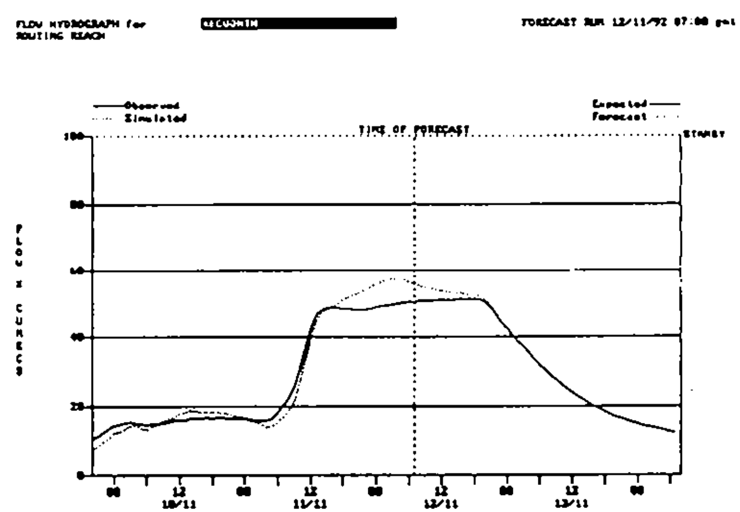
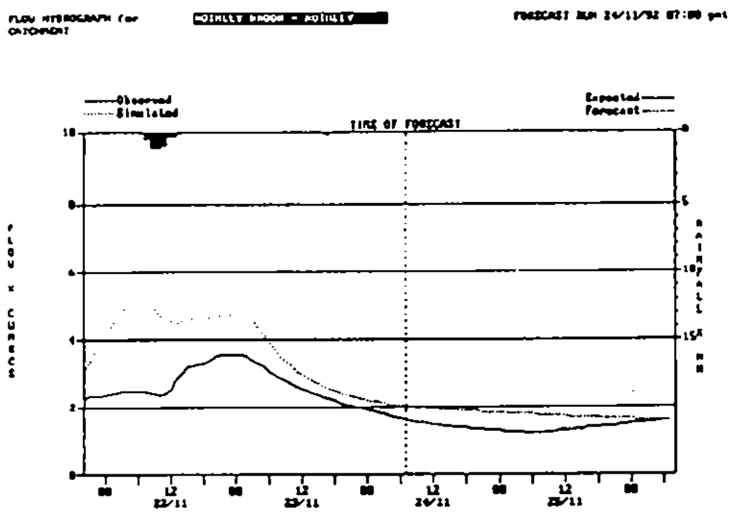
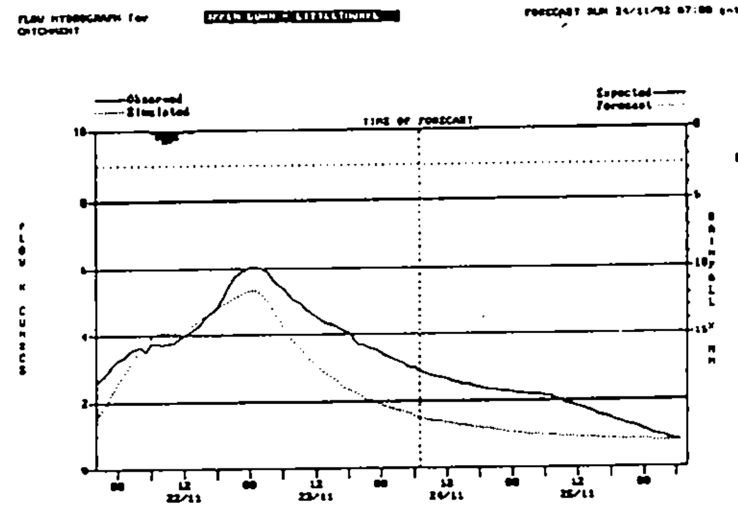

FLOW HYDROGRAPH for ROUTING REACH
FORECAST RUN 12/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
STANDBY

Figure A5.2 *Flood forecasts for Event 2: 24 November 1992*

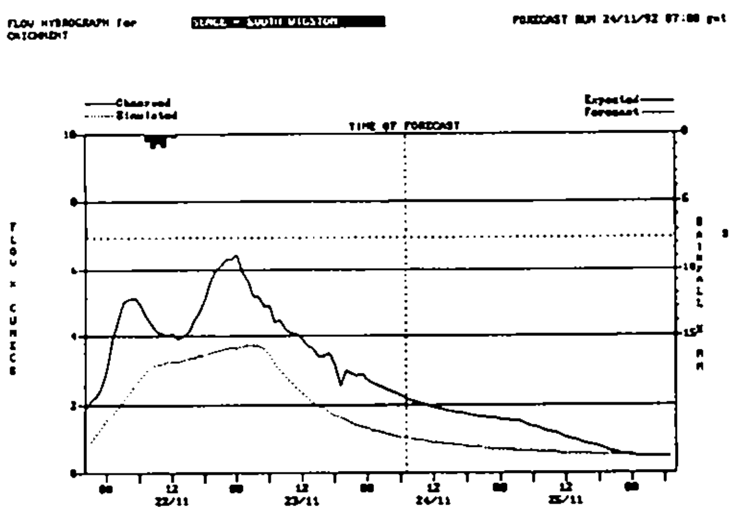


FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 24/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
RAINFALL x MM

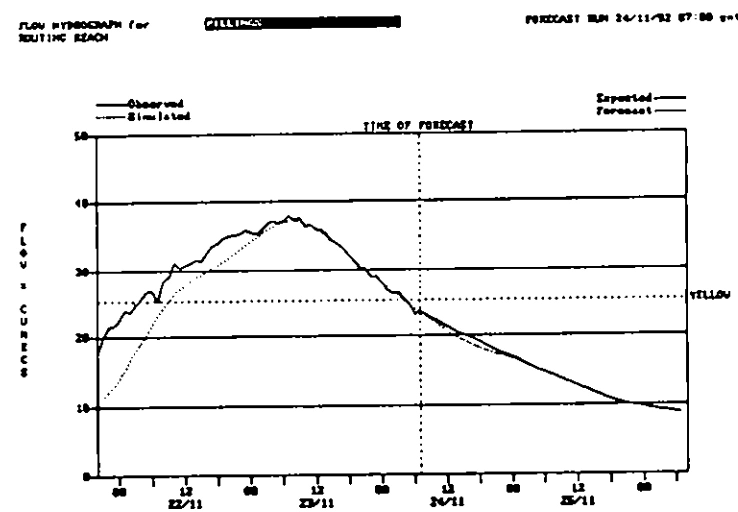


FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 24/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
RAINFALL x MM

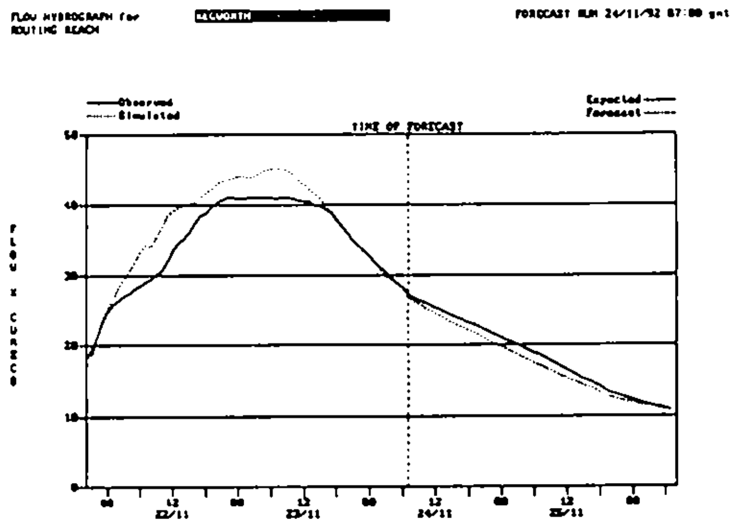
Event 2



FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 24/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
RAINFALL x MM

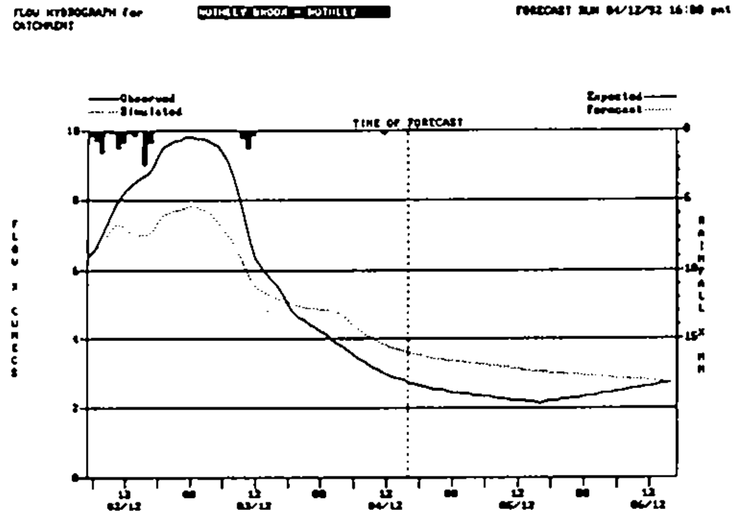


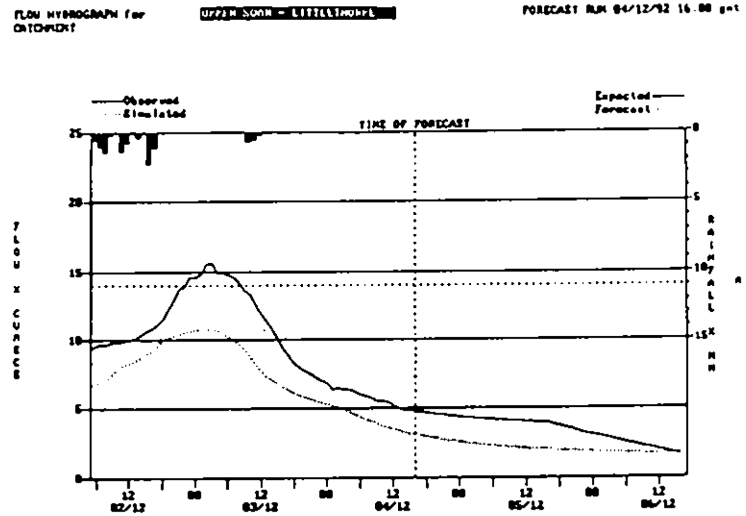
FLOW HYDROGRAPH for ROUTING REACH
FORECAST RUN 24/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
YELLOW


FLOW HYDROGRAPH for
ROUTING REACH
KEGWORTH
FORECAST RUN 24/11/92 07:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW x CUMECS
50
40
30
20
10
0
00
12
22/11
00
12
23/11
00
12
24/11
00
12
25/11
00

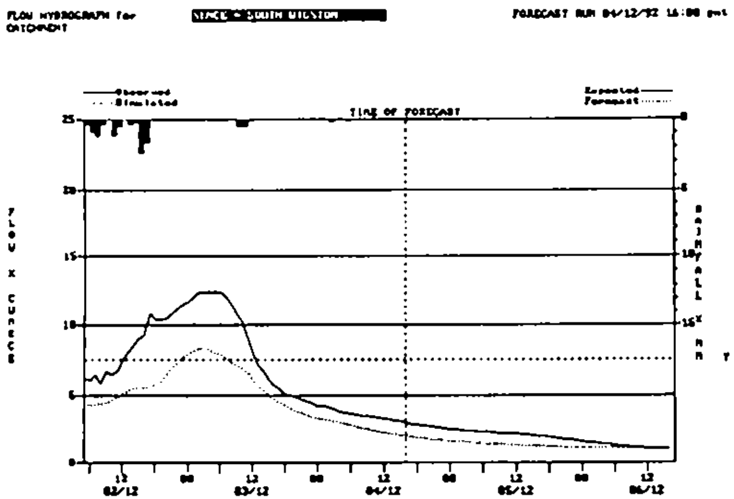
Event 2

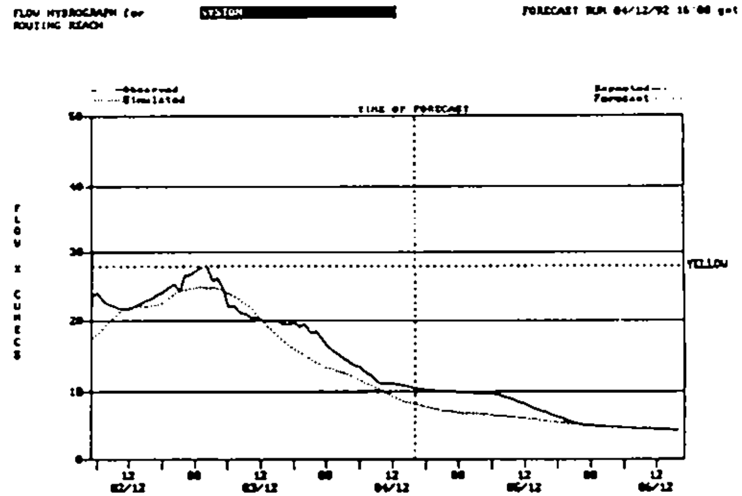
Figure A5.3 Flood forecasts for Event 3: 4 December 1992

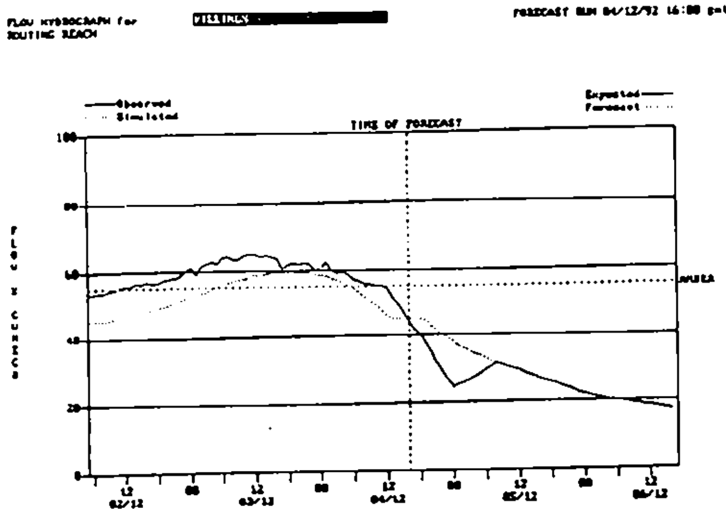

FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 04/12/92 16:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
RAINFALL X MM


FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 04/12/92 16:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
RAINFALL X MM

Event 3


FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 04/12/92 16:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
RAINFALL X MM


FLOW HYDROGRAPH for ROUTING REACH
FORECAST RUN 04/12/92 16:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
YELLOW


FLOW HYDROGRAPH for
ROUTING REACH
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
100
80
60
40
20
0
12
02/12
00
12
03/12
00
12
04/12
00
12
05/12
00
12
06/12

Event 3

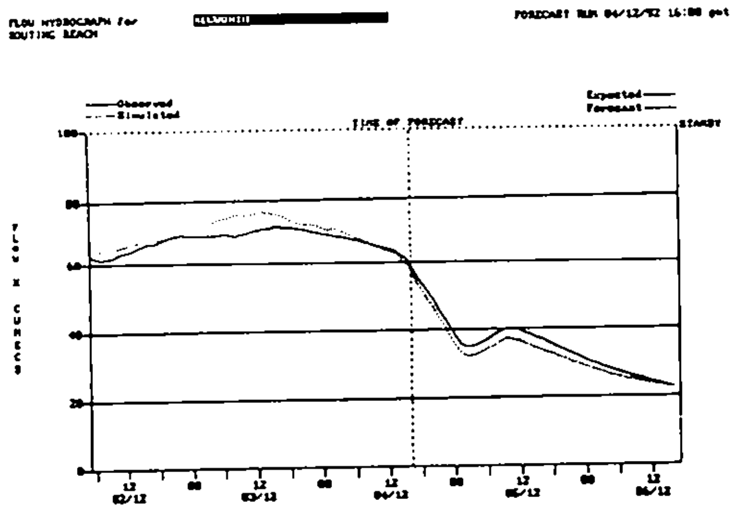
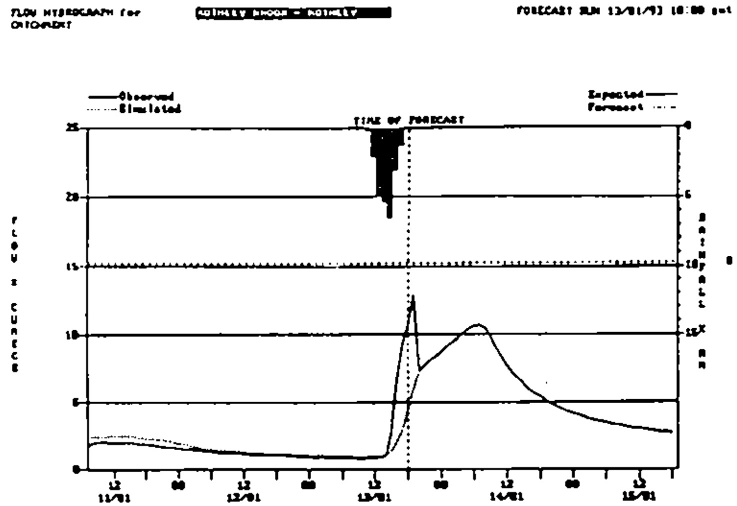
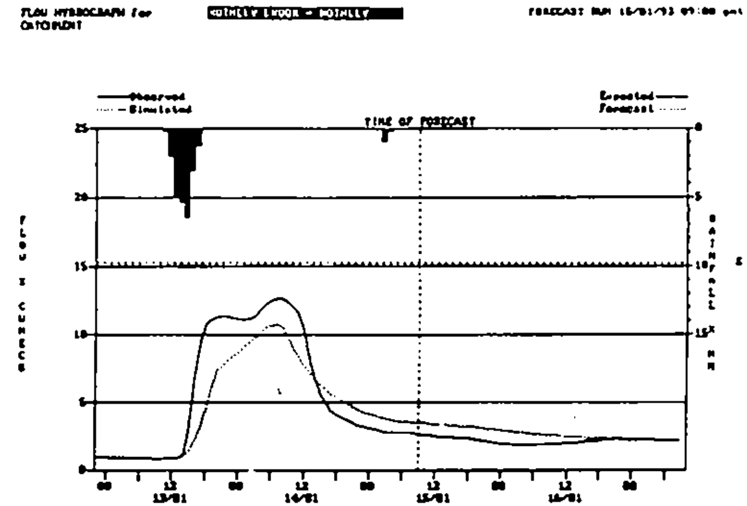

FLOW HYDROGRAPH for
ROUTING REACH
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW X CUMECS
100
80
60
40
20
0
12
02/12
00
12
03/12
00
12
04/12
00
12
05/12
00
12
06/12

Figure A5.4 Flood forecasts for Event 4: 11-15 January 1993

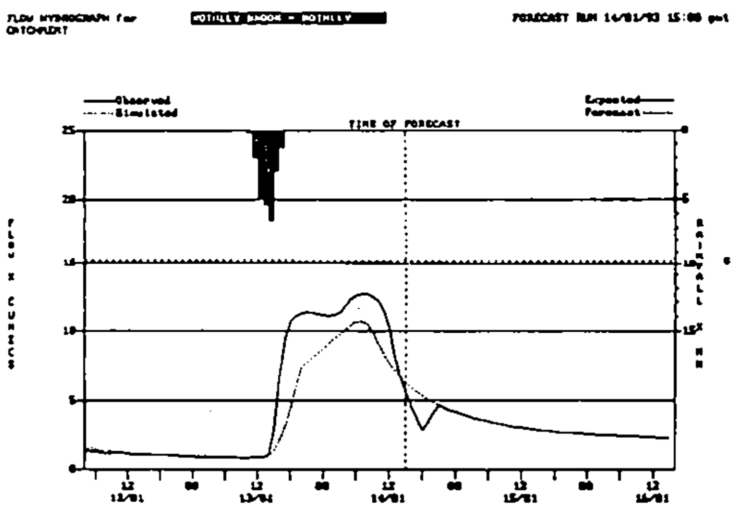
Event 4 Run 2



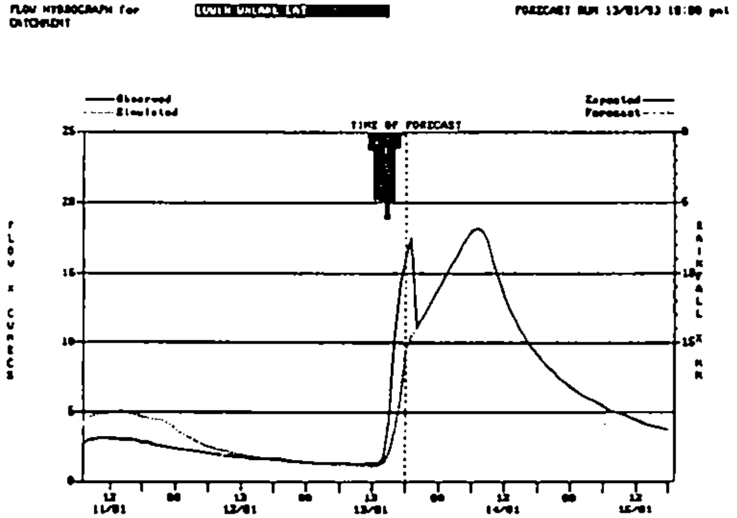
Event 4 Run 5



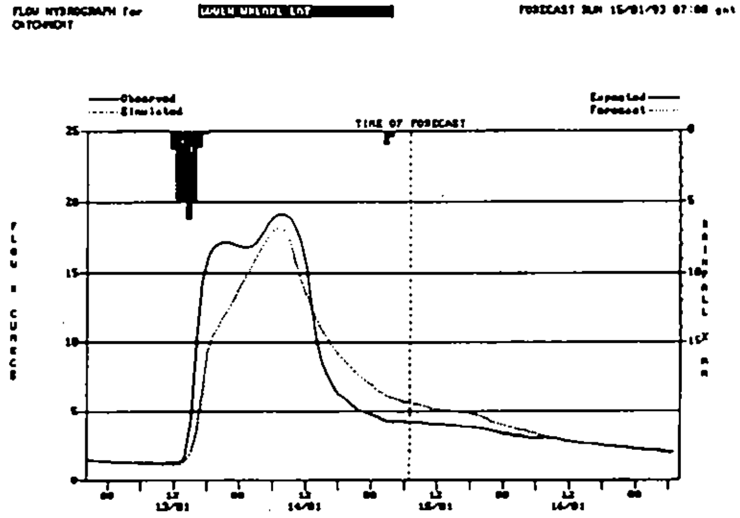
Event 4 Run 3



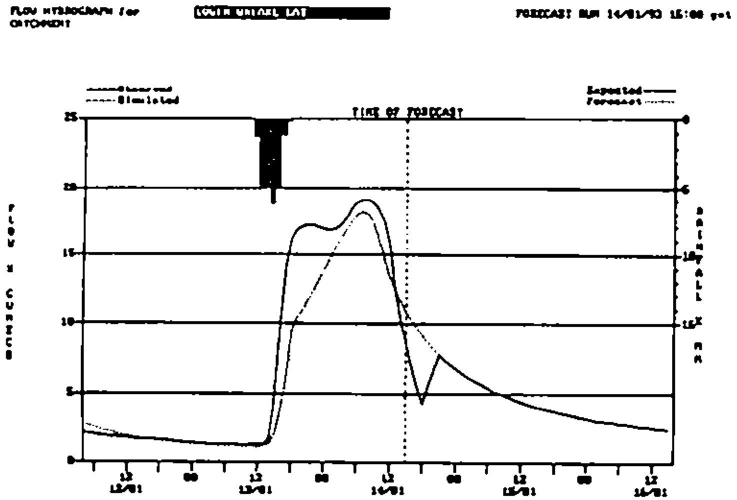
Event 4 Run 2



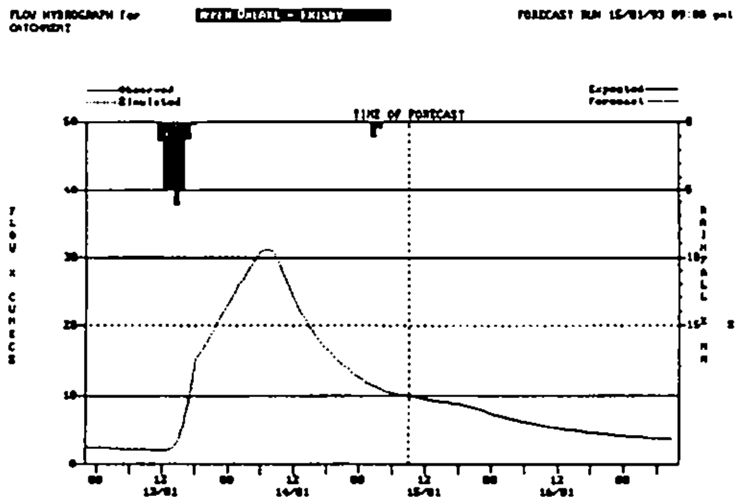
Event 4 Run 4



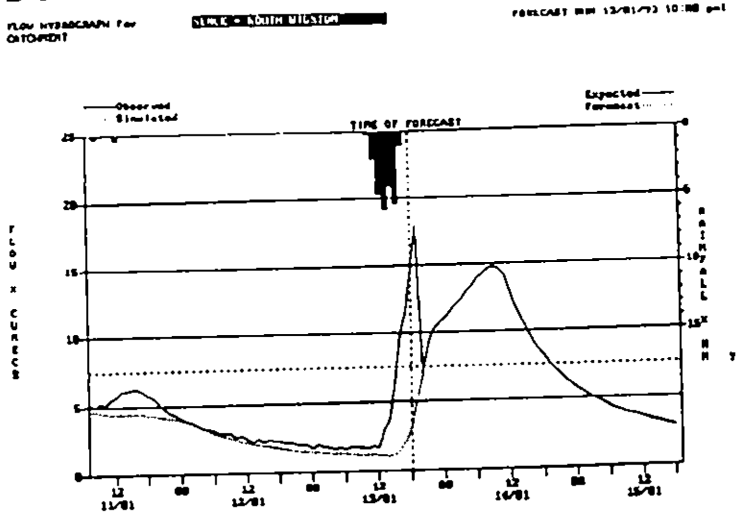
Event 4 Run 3



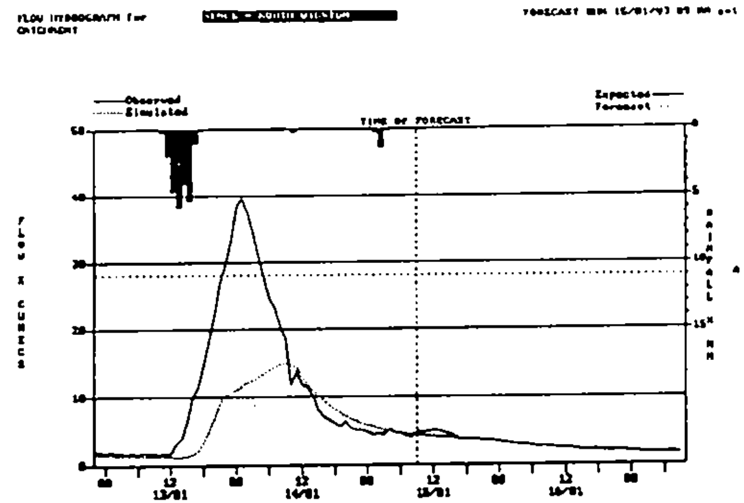
Event 4 Run 5



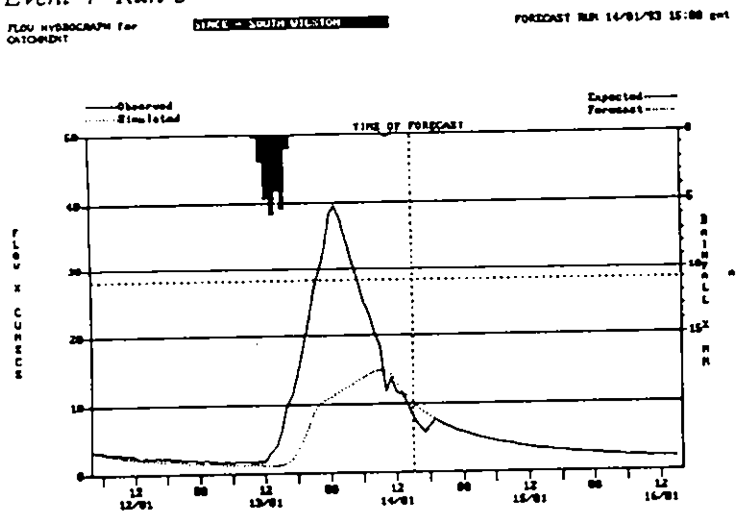
Event 4 Run 2



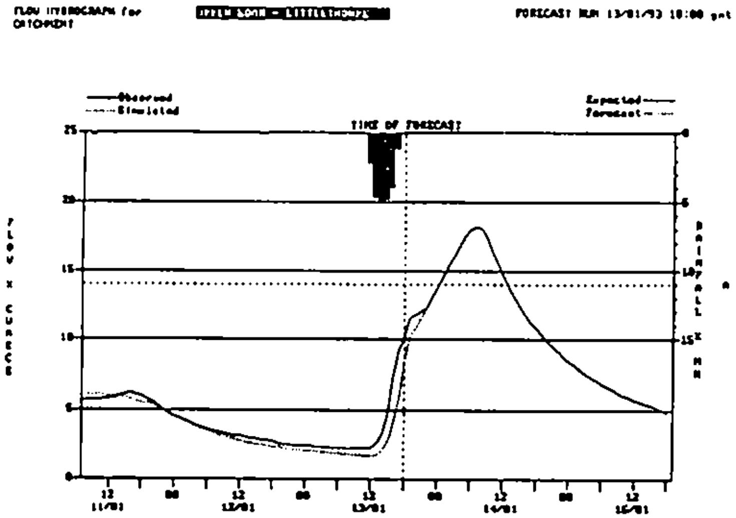
Event 4 Run 5



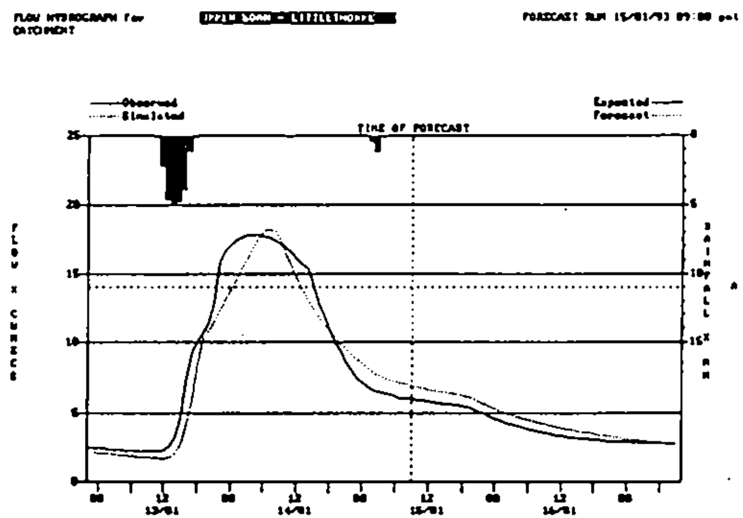
Event 4 Run 3



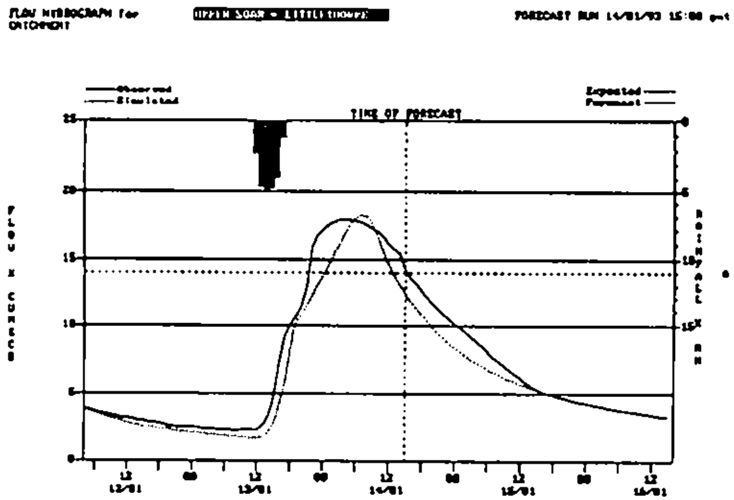
Event 4 Run 2



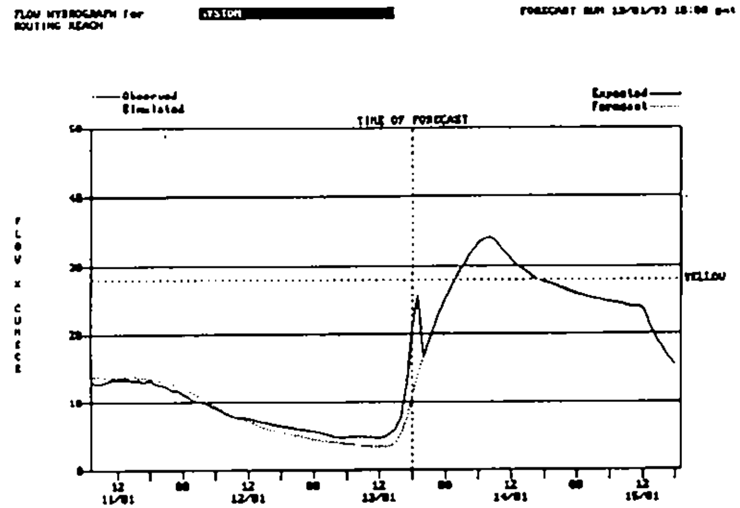
Event 4 Run 5



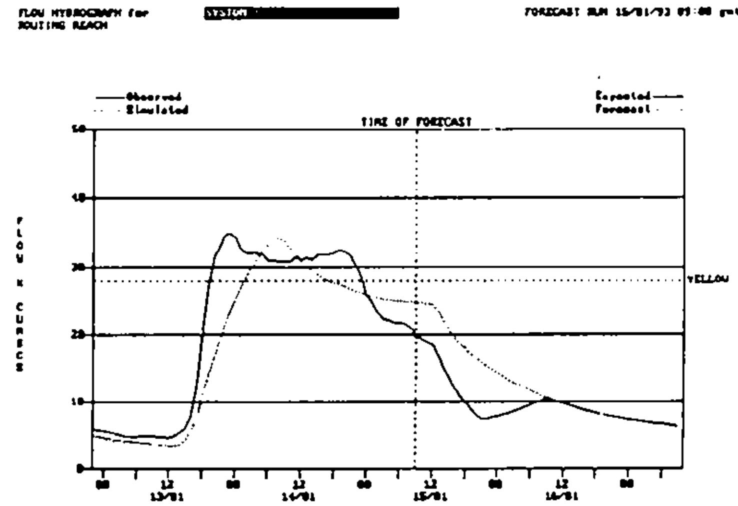
Event 4 Run 3



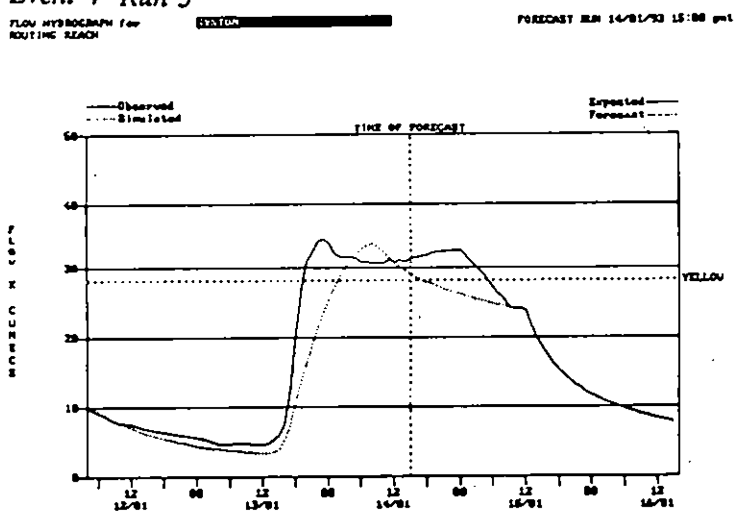
Event 4 Run 2



Event 4 Run 5



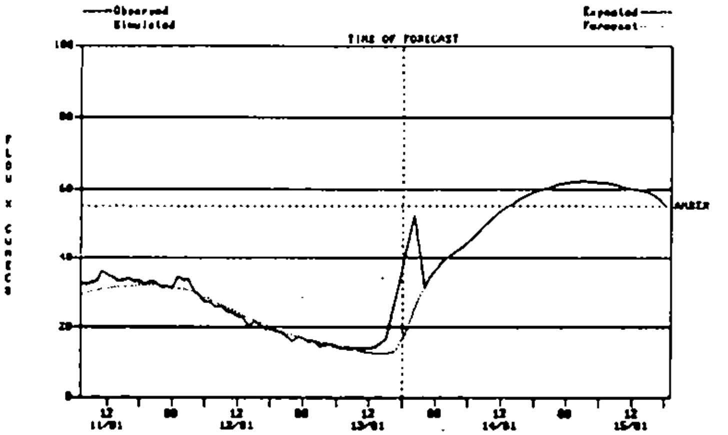
Event 4 Run 3



Event 4 Run 2

FLOW HYDROGRAPH for ROUTING REACH FILLINGS [redacted]

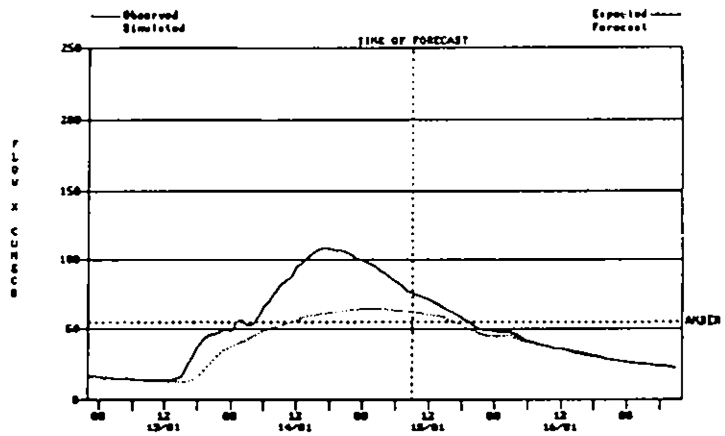
FORECAST RUN 13/01/93 18:00 gmt



Event 4 Run 5

FLOW HYDROGRAPH for ROUTING REACH FILLINGS [redacted]

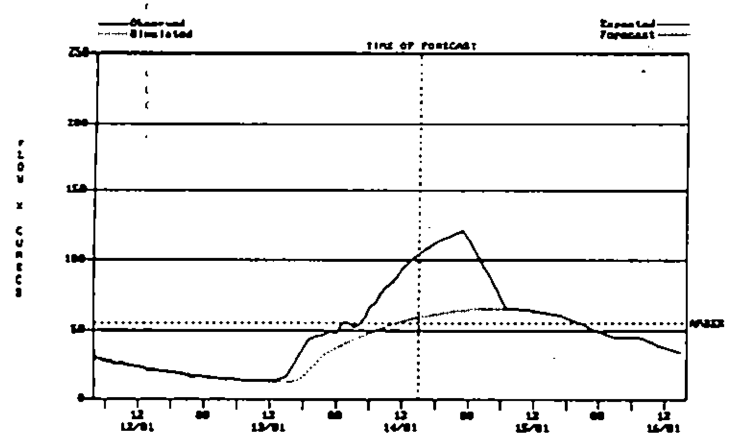
FORECAST RUN 15/01/93 09:00 gmt



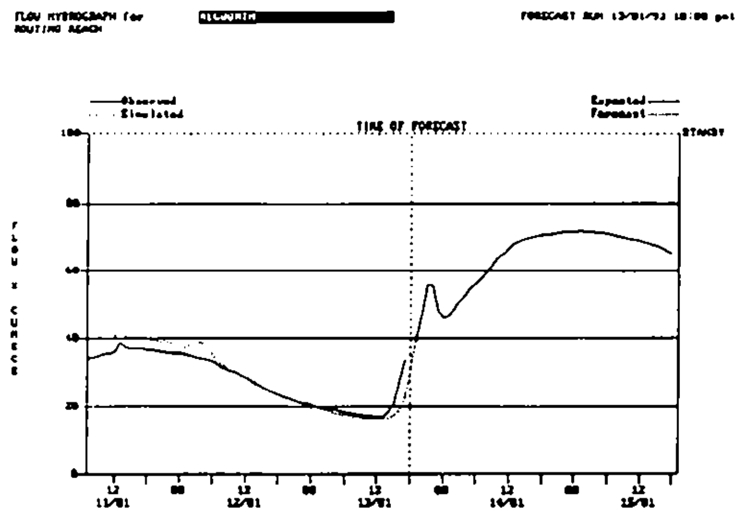
Event 4 Run 3

FLOW HYDROGRAPH for ROUTING REACH FILLINGS [redacted]

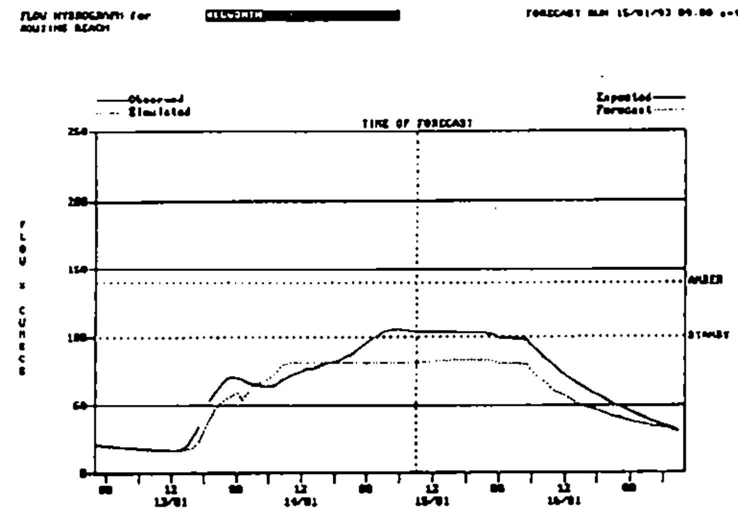
FORECAST RUN 14/01/93 15:00 gmt



Event 4 Run 2



Event 4 Run 5



Event 4 Run 3

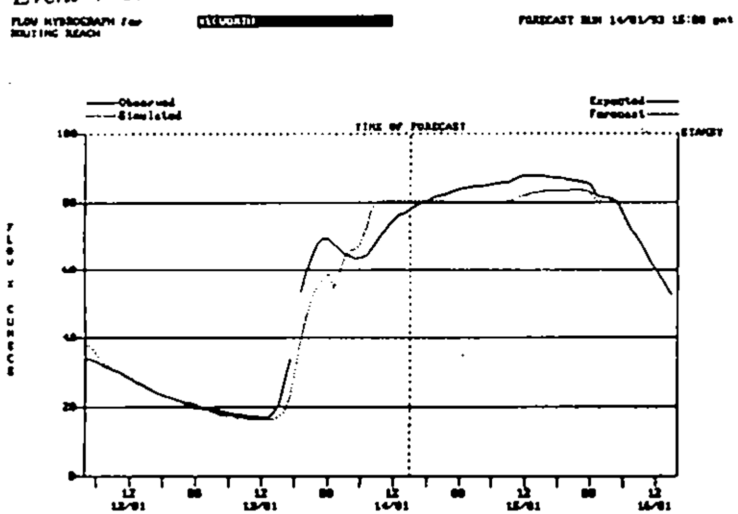
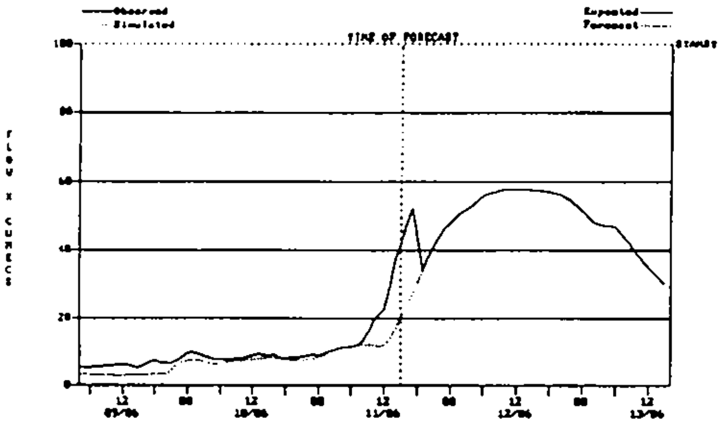


Figure A5.5 Flood forecasts for Event 5: 11-13 June 1993

Event 5 Run 1

FLOW HYDROGRAPH for ROUTING REACH   KILWORTH   FORECAST RUN 11/06/93 15:00 bst



Event 5 Run 3

FLOW HYDROGRAPH for ROUTING REACH   KILWORTH   FORECAST RUN 13/06/93 07:00 bst

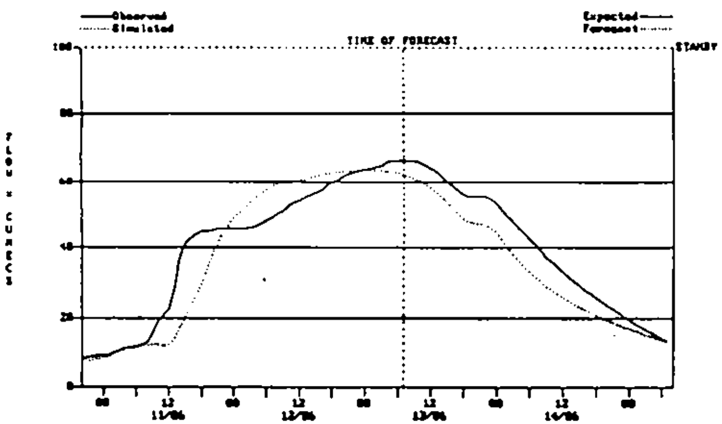
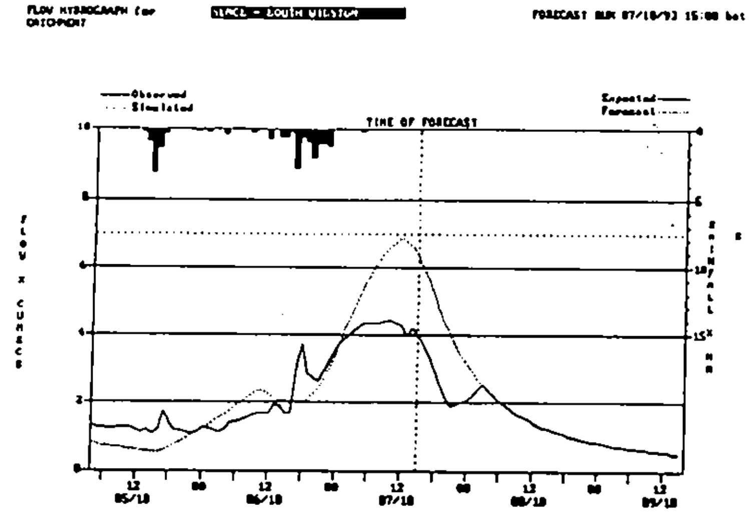
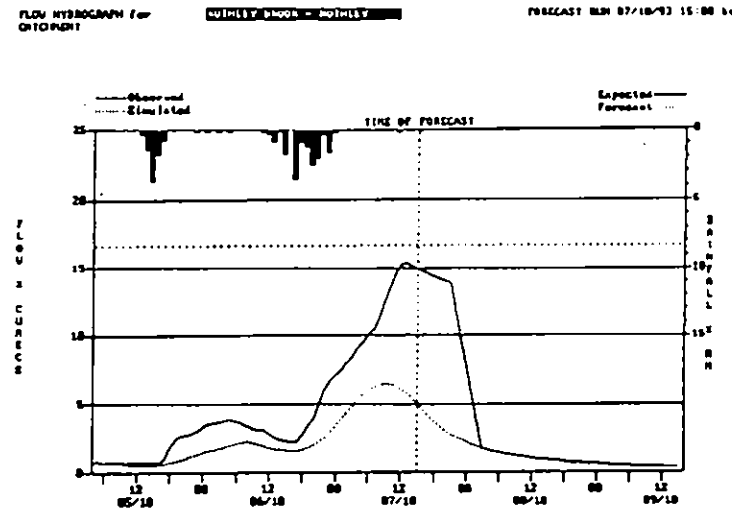


Figure A5.6 Flood forecasts for Event 6: 7-8 October 1993

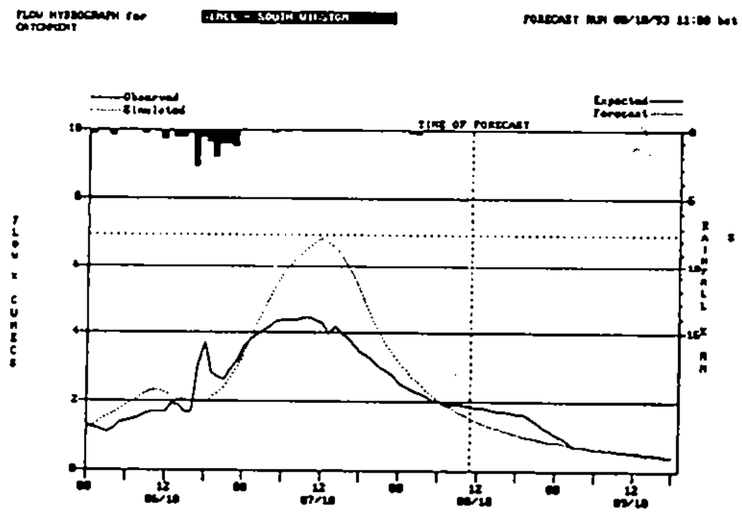
Event 6 Run 1



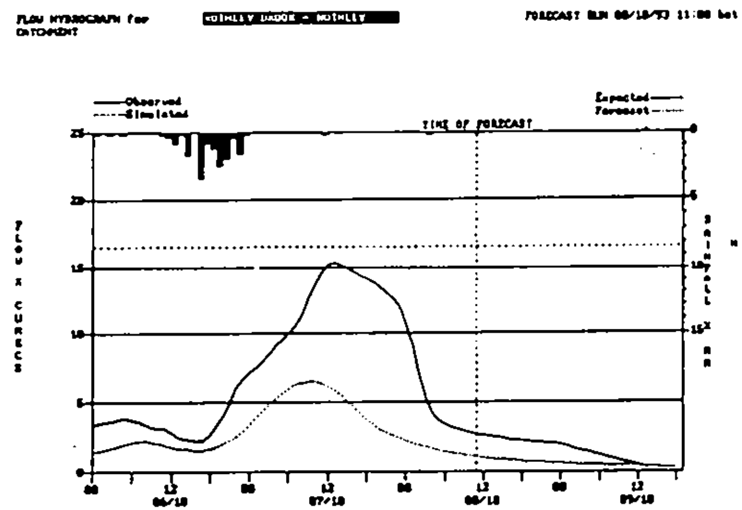
Event 6 Run 1



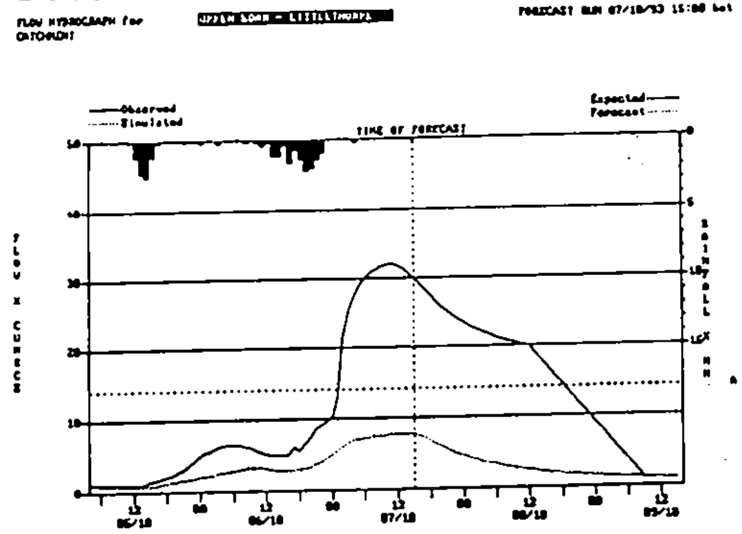
Event 6 Run 2



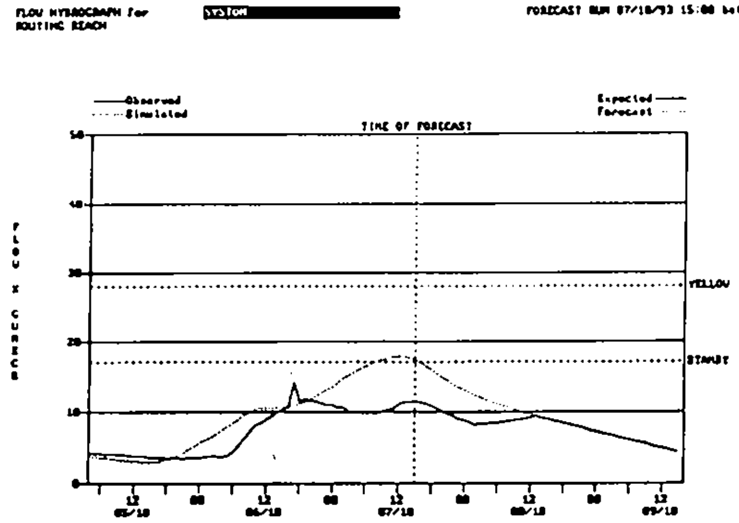
Event 6 Run 2



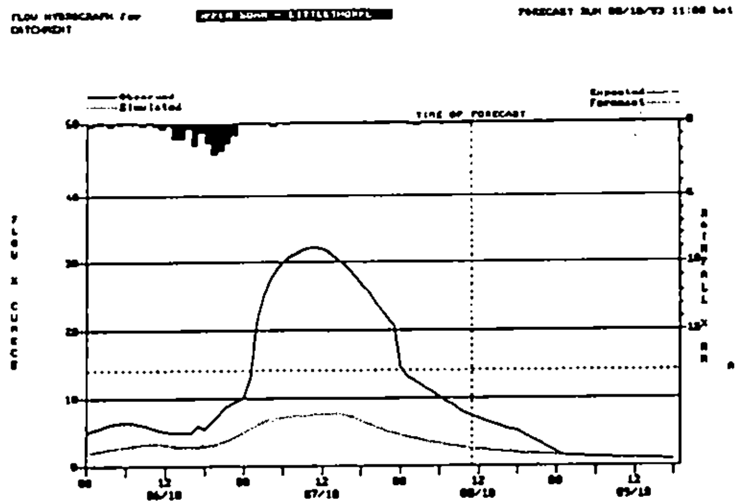
Event 6 Run 1



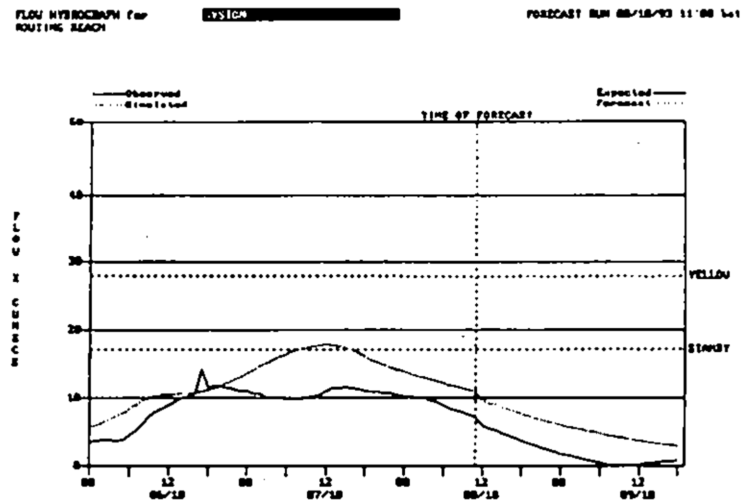
Event 6 Run 1



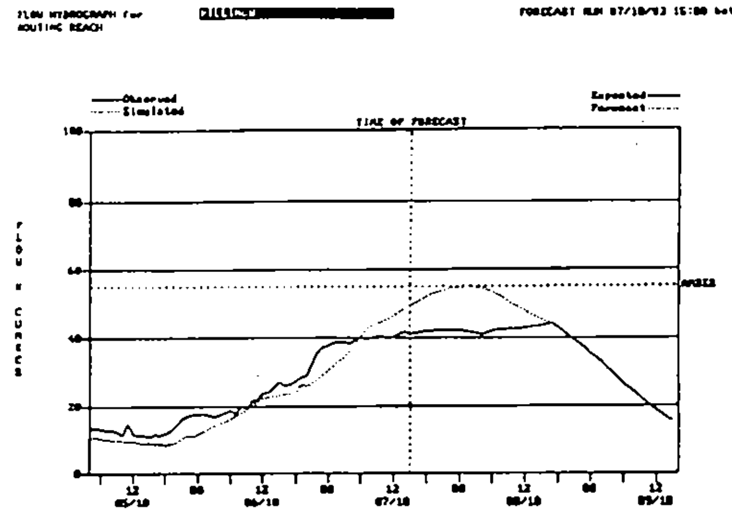
Event 6 Run 2



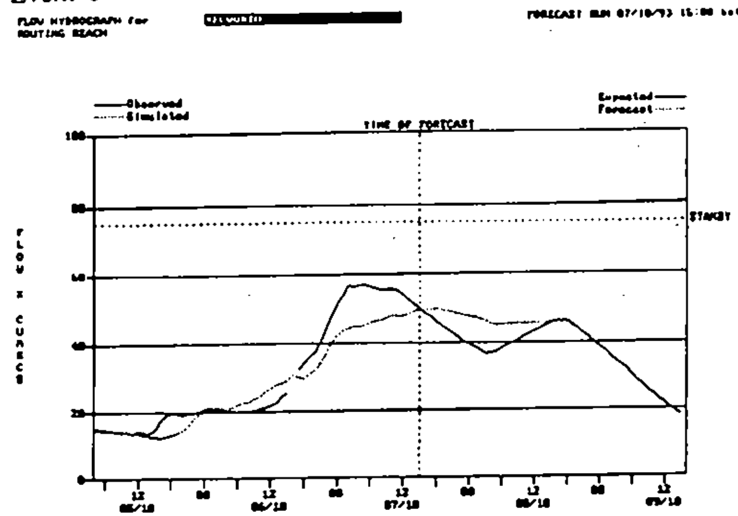
Event 6 Run 2



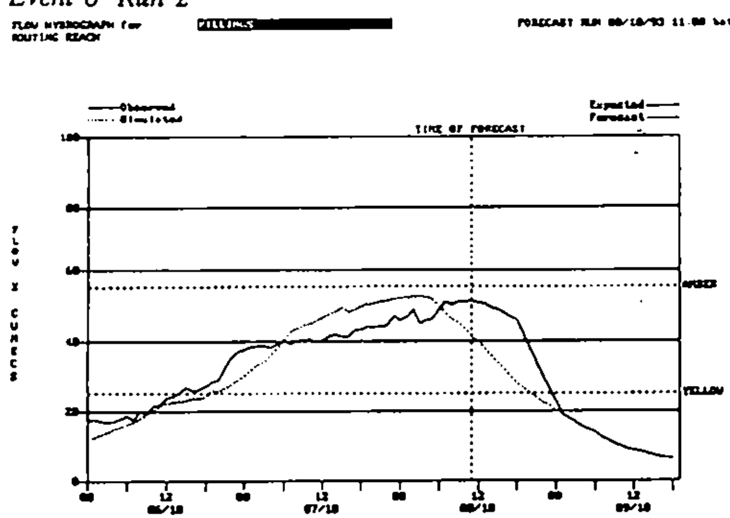
Event 6 Run 1



Event 6 Run 1



Event 6 Run 2



Event 6 Run 2

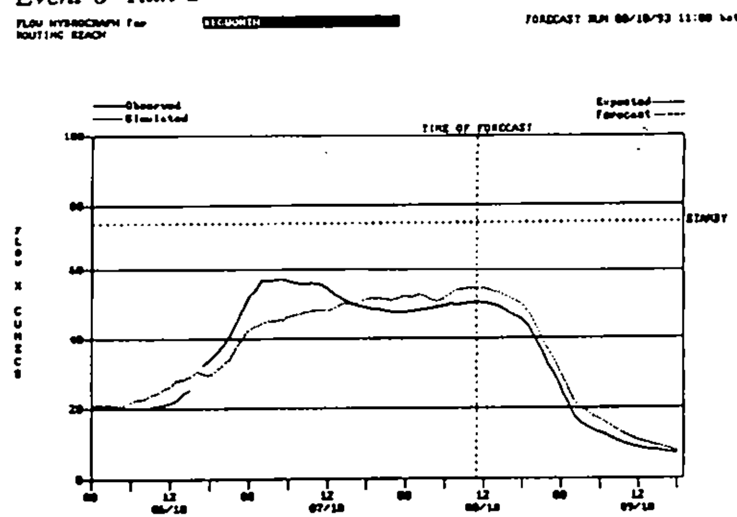
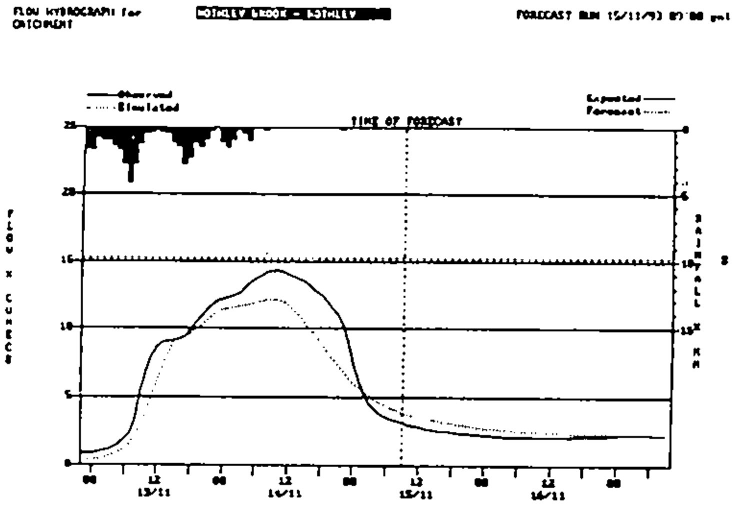
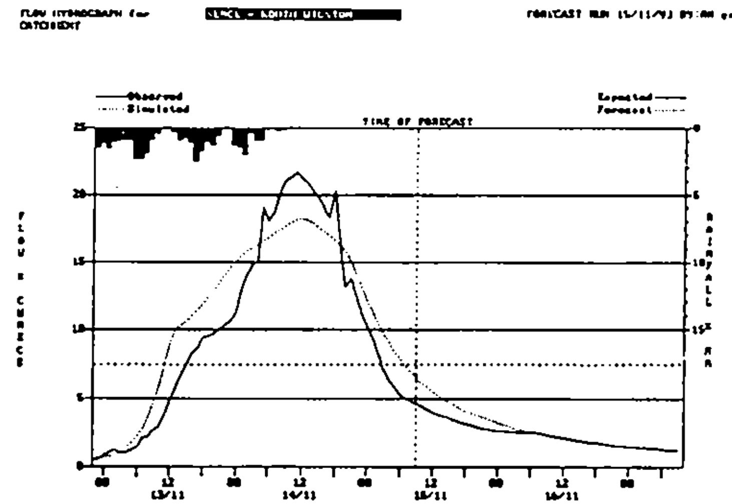
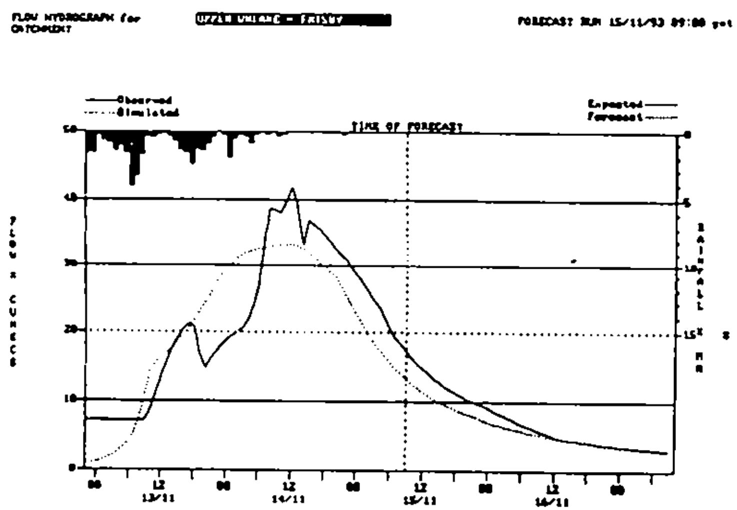


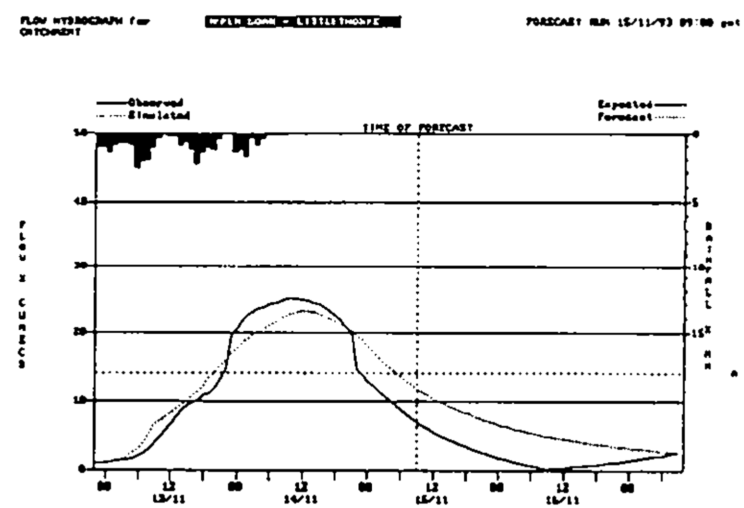
Figure A5.7 Flood forecasts for Event 7: 15 November 1993

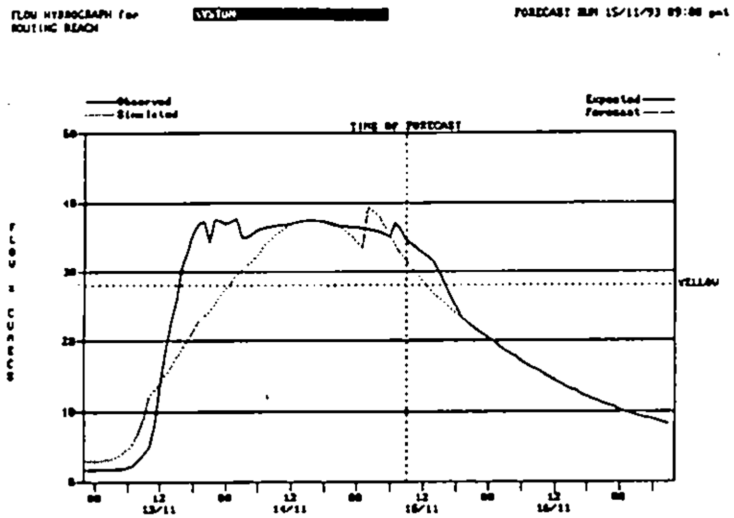

FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 15/11/93 09:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST

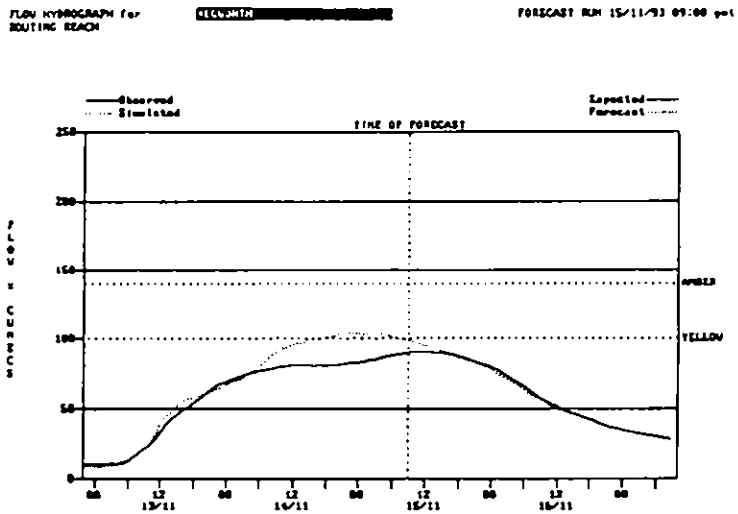

FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 15/11/93 09:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST

Event 7


FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 15/11/93 09:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST


FLOW HYDROGRAPH for CATCHMENT
FORECAST RUN 15/11/93 09:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST


FLOW HYDROGRAPH for ROUTING REACH
[redacted]
FORECAST RUN 15/11/93 09:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW × CUMECS
YELLOW
13/11
14/11
15/11
16/11


FLOW HYDROGRAPH for ROUTING REACH
[redacted]
FORECAST RUN 15/11/93 09:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW × CUMECS
AMBER
YELLOW
13/11
14/11
15/11
16/11

Event 7

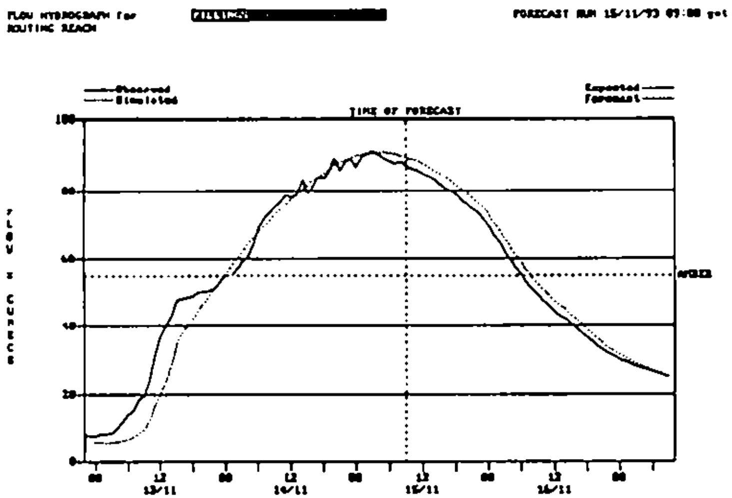
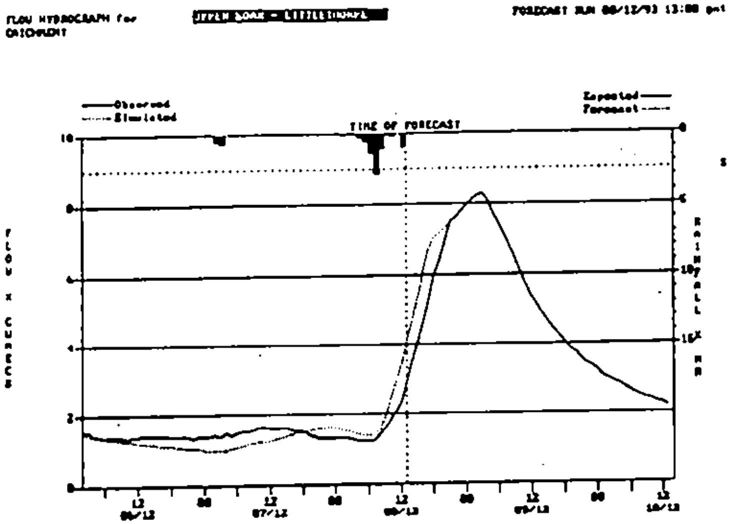
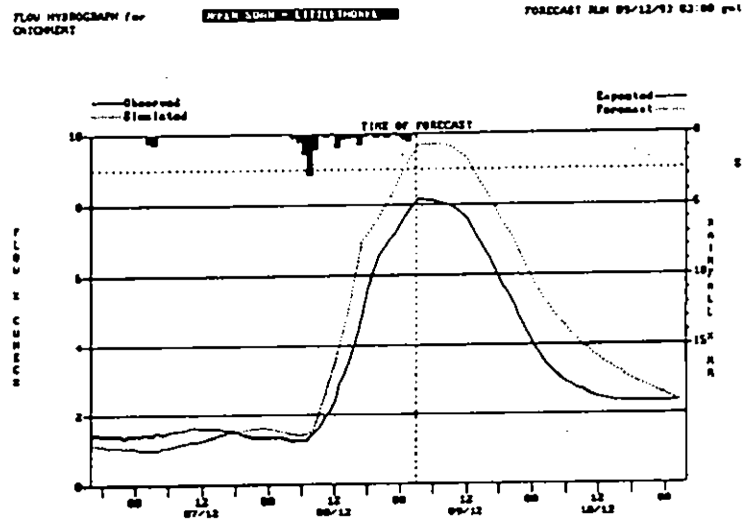

FLOW HYDROGRAPH for ROUTING REACH
[redacted]
FORECAST RUN 15/11/93 09:00 gmt
Observed
Simulated
Expected
Forecast
TIME OF FORECAST
FLOW × CUMECS
AMBER
13/11
14/11
15/11
16/11

Figure A5.8 Flood forecasts for Event 8: 8-9 December 1993

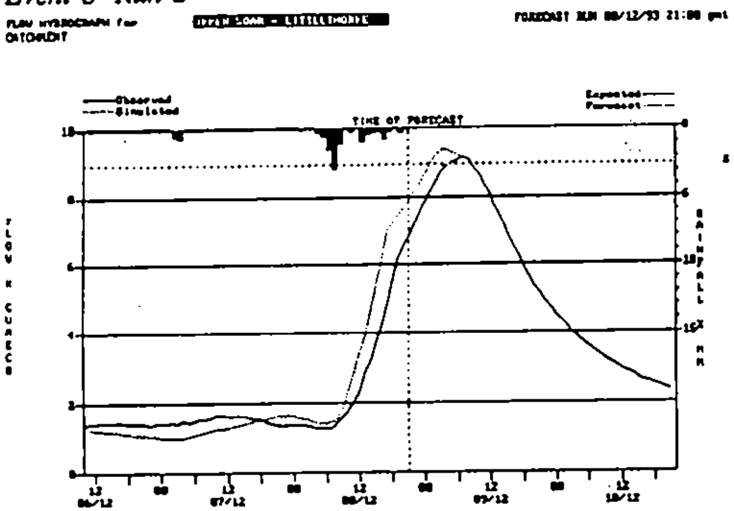
Event 8 Run 1



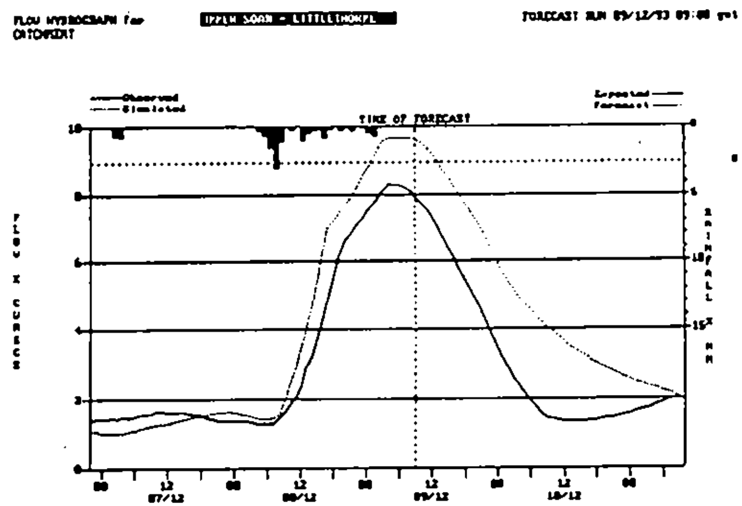
Event 8 Run 3



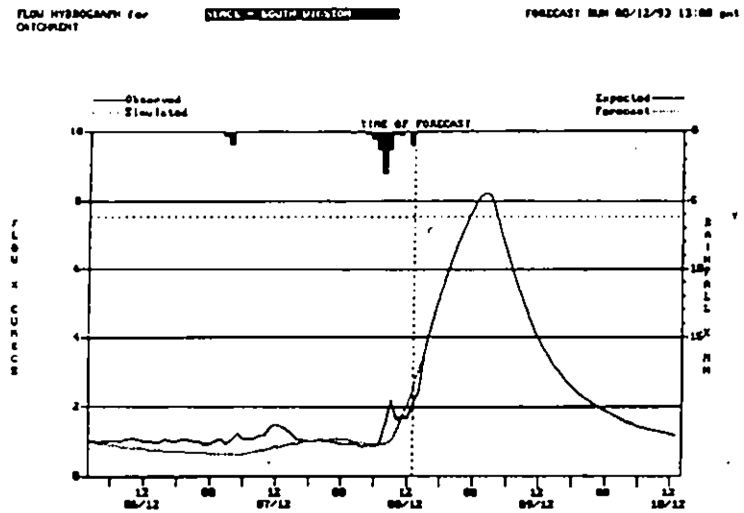
Event 8 Run 2



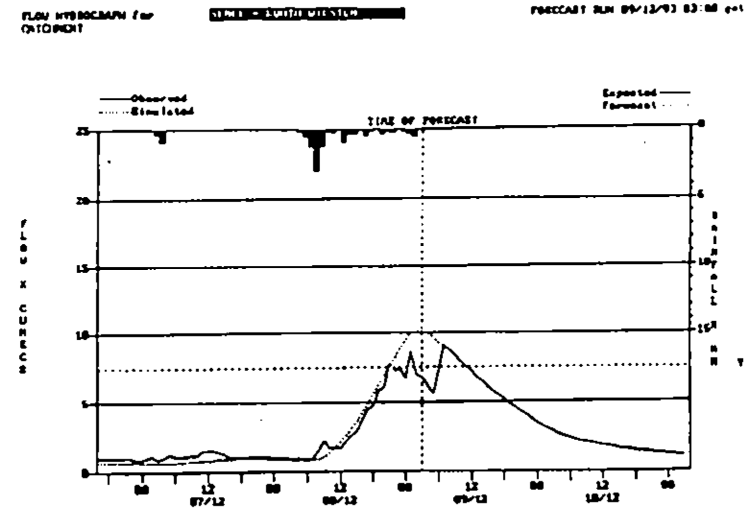
Event 8 Run 4



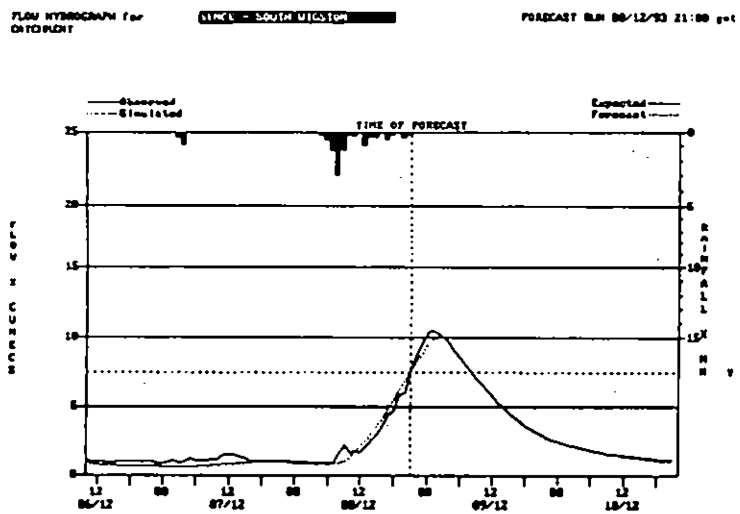
Event 8 Run 1



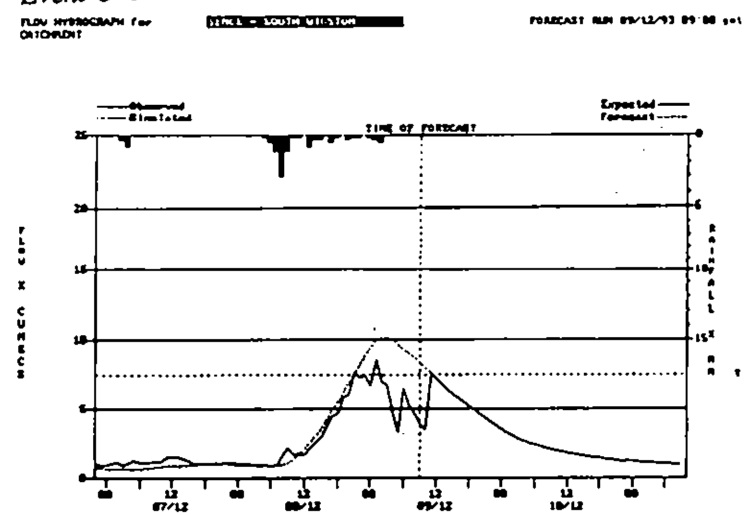
Event 8 Run 3



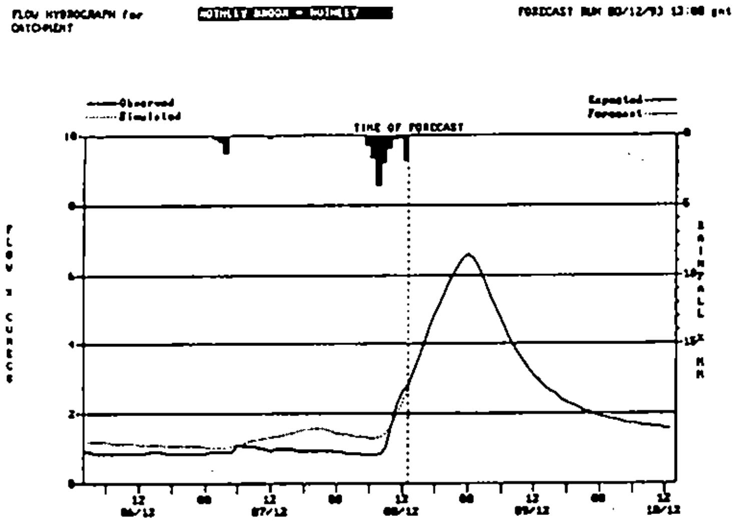
Event 8 Run 2



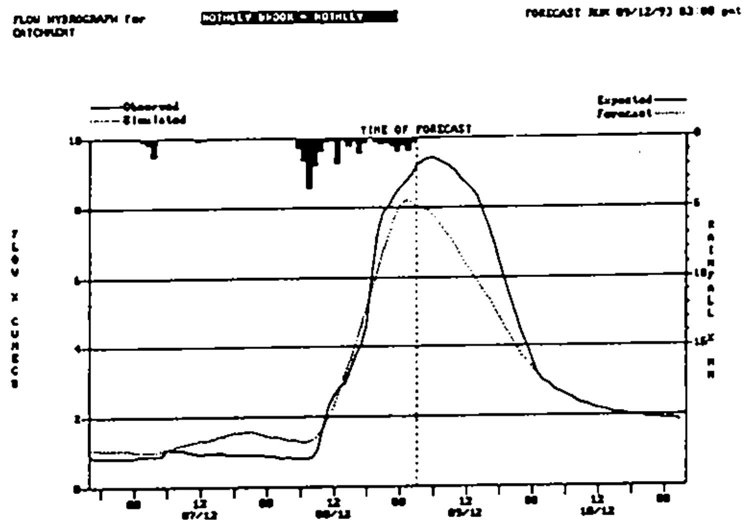
Event 8 Run 4



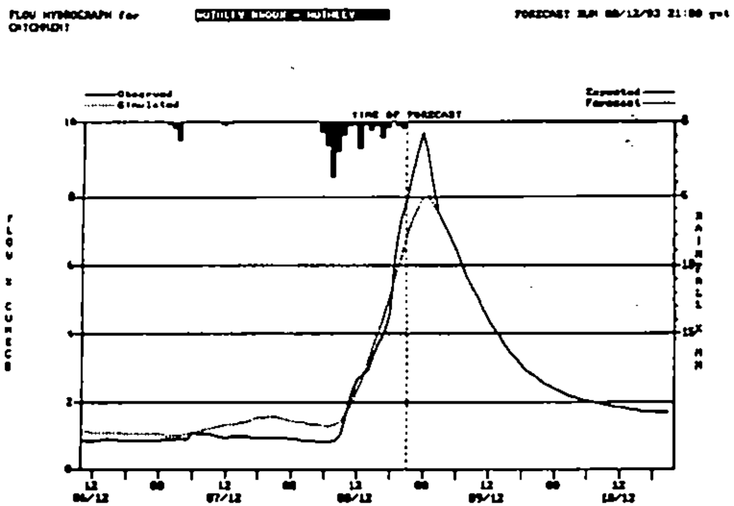
Event 8 Run 1



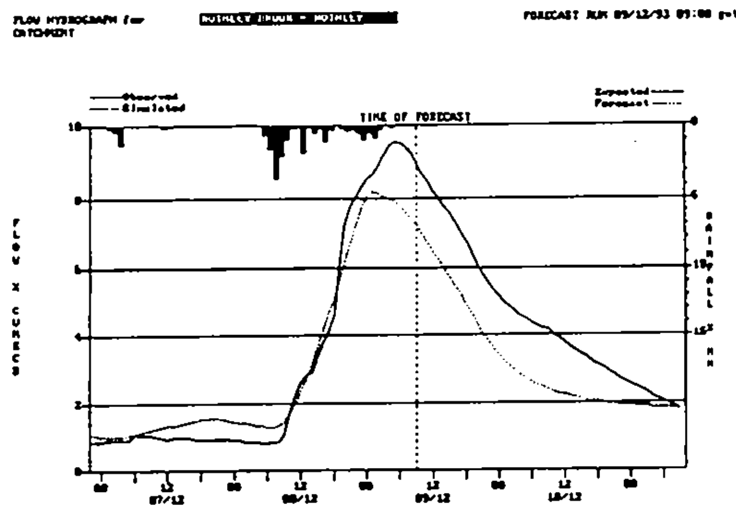
Event 8 Run 3



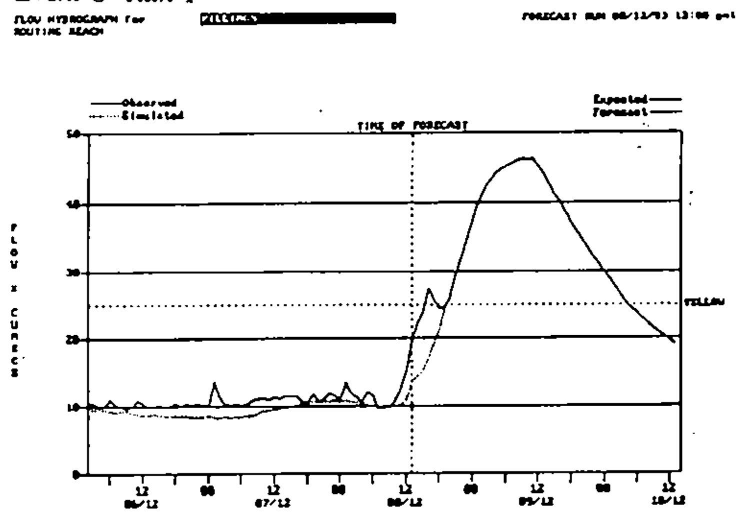
Event 8 Run 2



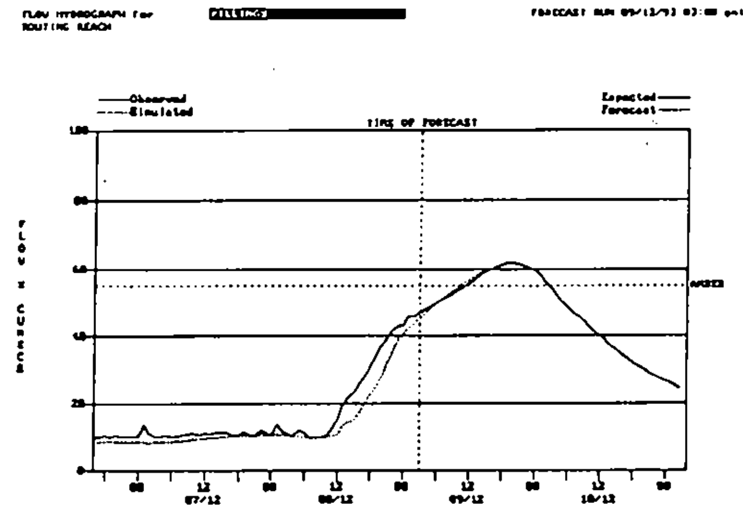
Event 8 Run 4



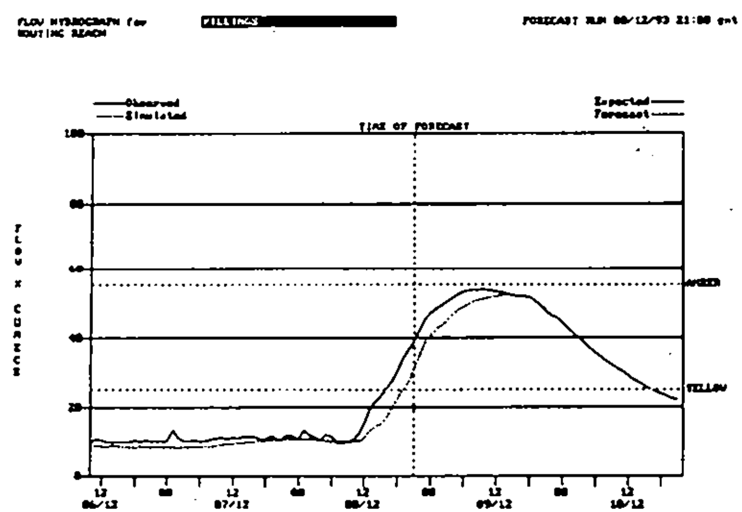
Event 8 Run 1



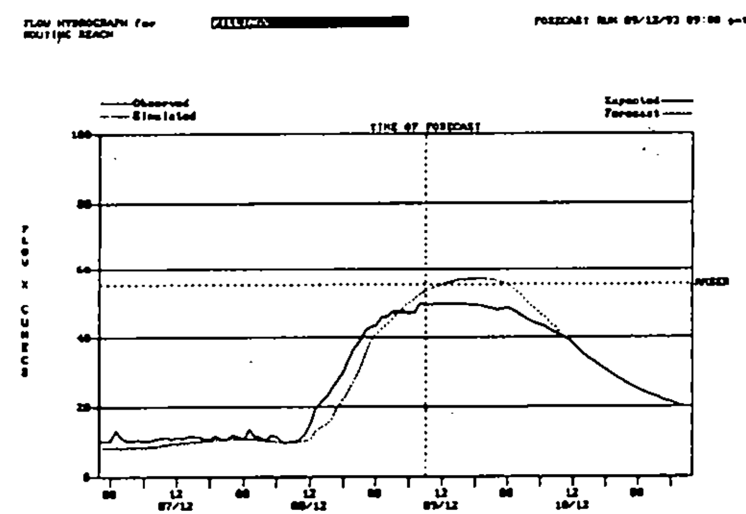
Event 8 Run 3



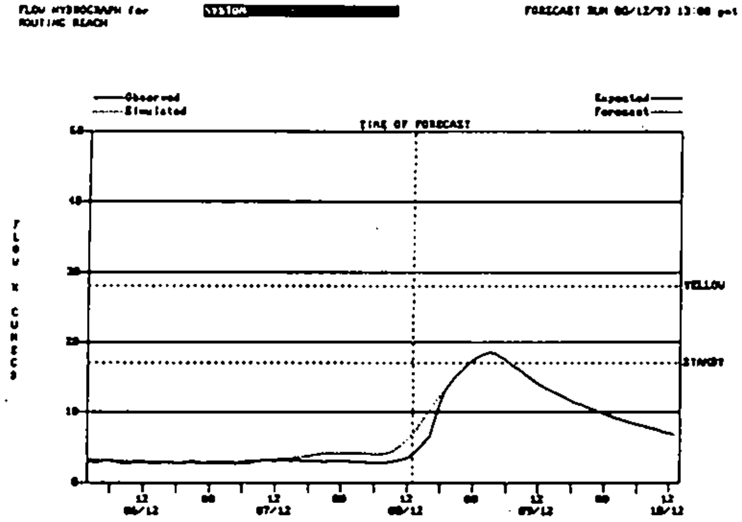
Event 8 Run 2



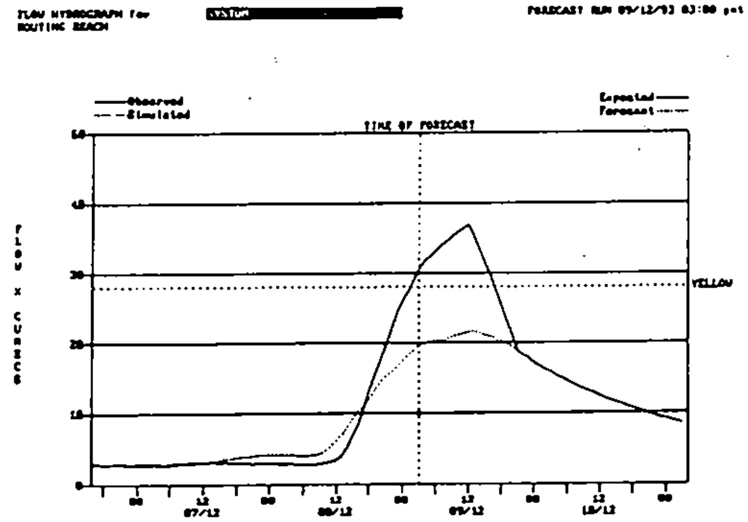
Event 8 Run 4



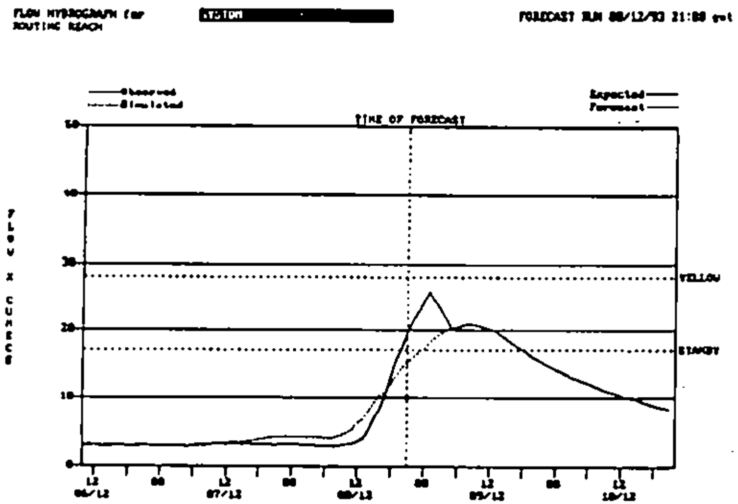
Event 8 Run 1



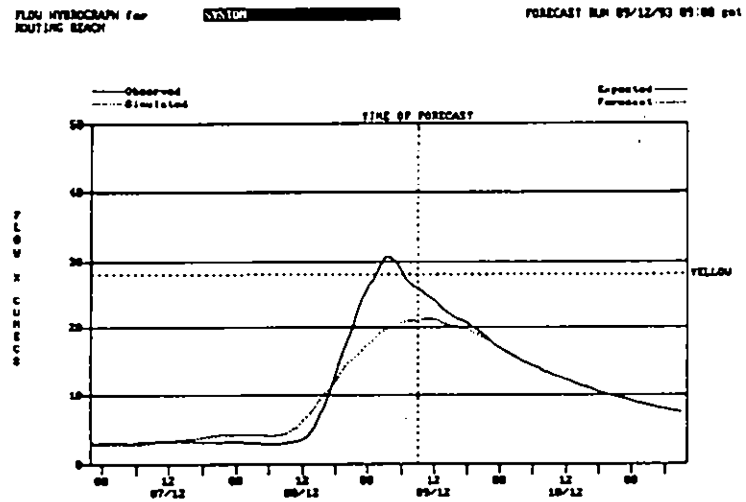
Event 8 Run 3



Event 8 Run 2

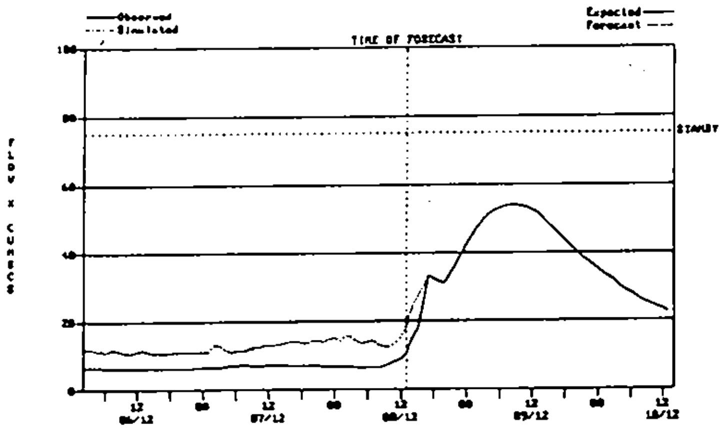


Event 8 Run 4



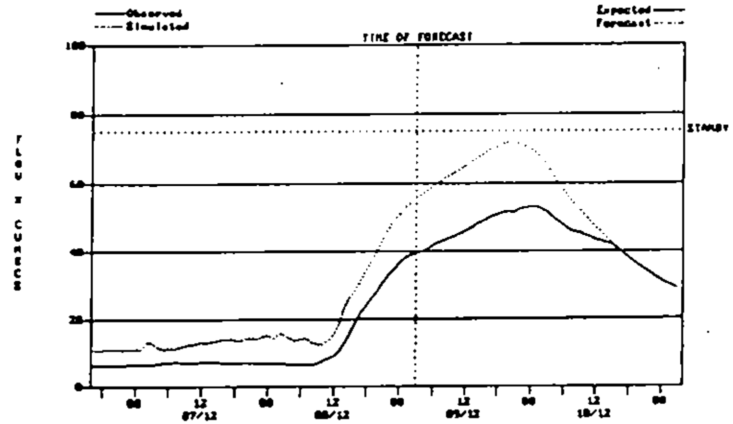
Event 8 Run 1

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 08/12/93 13:00 gmt



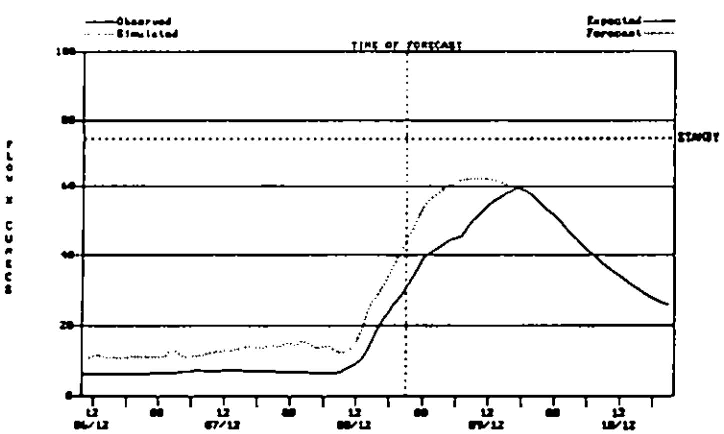
Event 8 Run 3

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 09/12/93 03:00 gmt



Event 8 Run 2

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 08/12/93 21:00 gmt



Event 8 Run 4

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 09/12/93 09:00 gmt

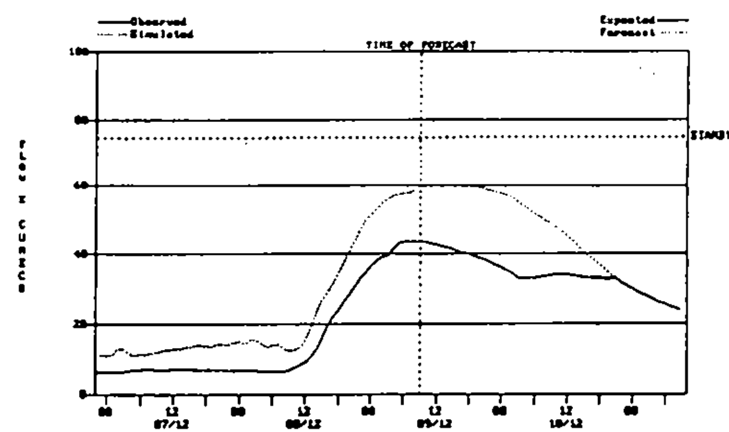
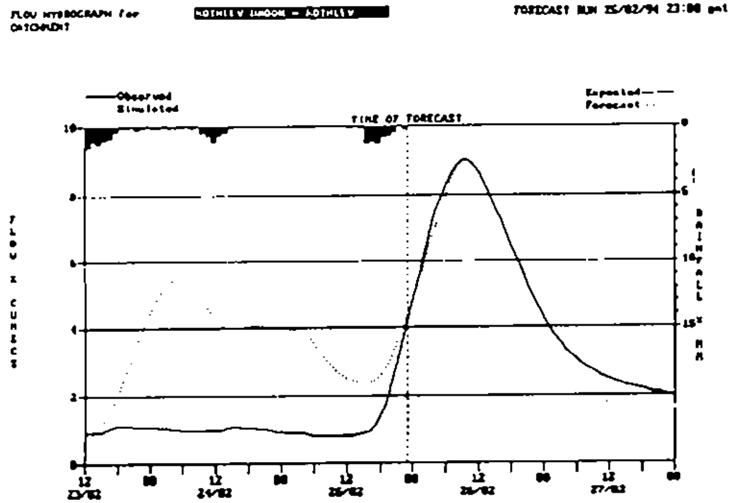
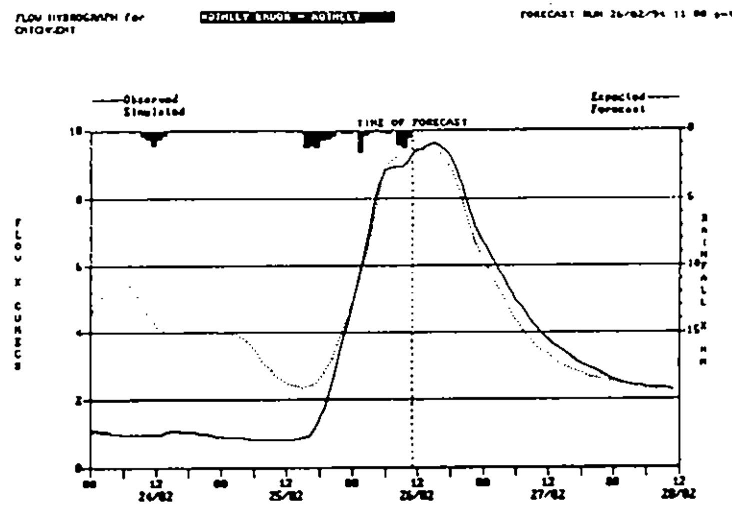


Figure A5.9 Flood forecasts for Event 9: 24-28 February 1994

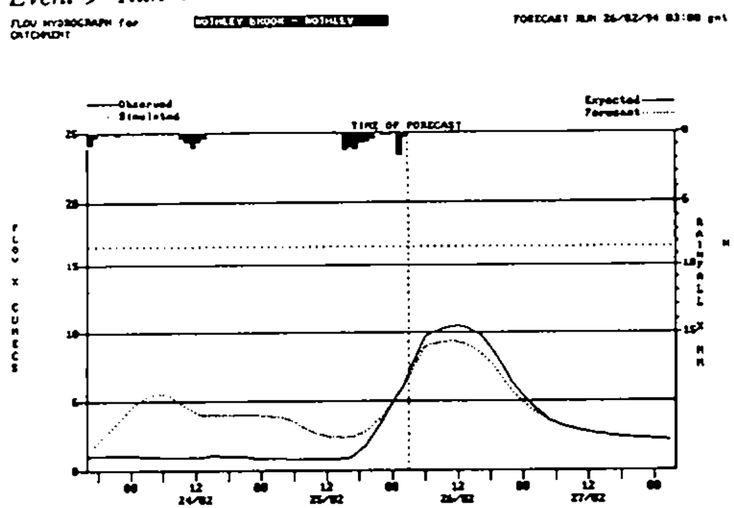
Event 9 Run 3



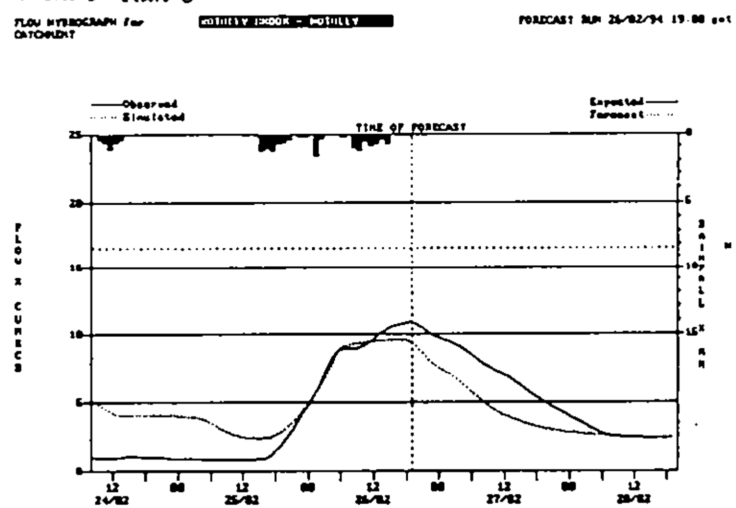
Event 9 Run 5



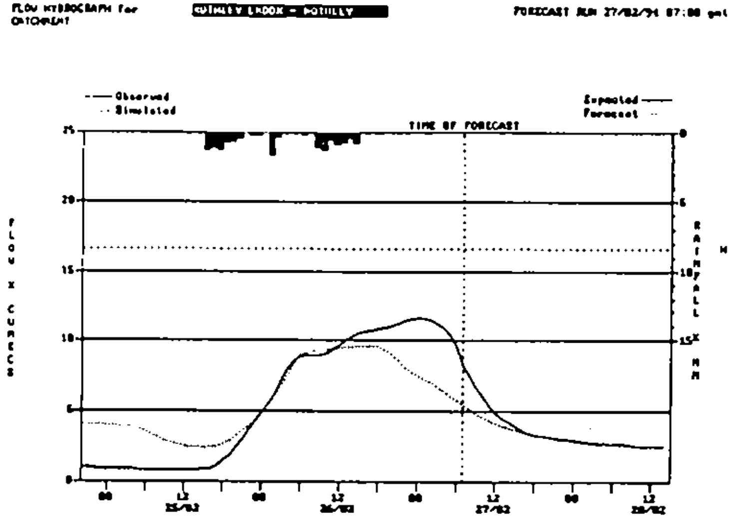
Event 9 Run 4



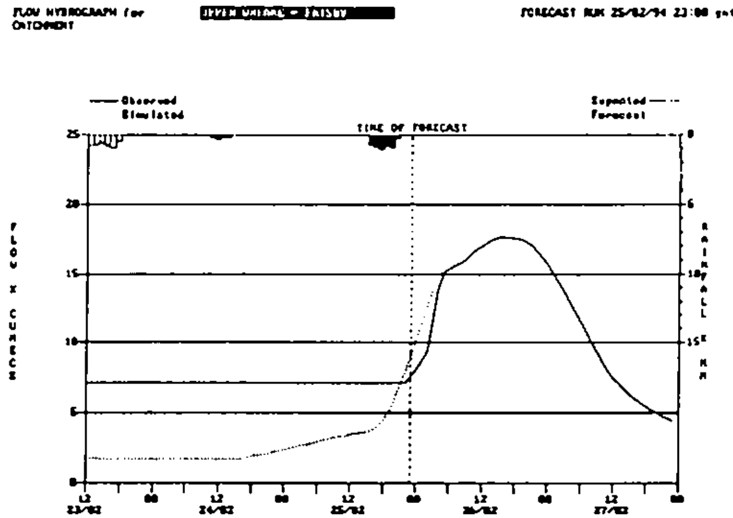
Event 9 Run 6



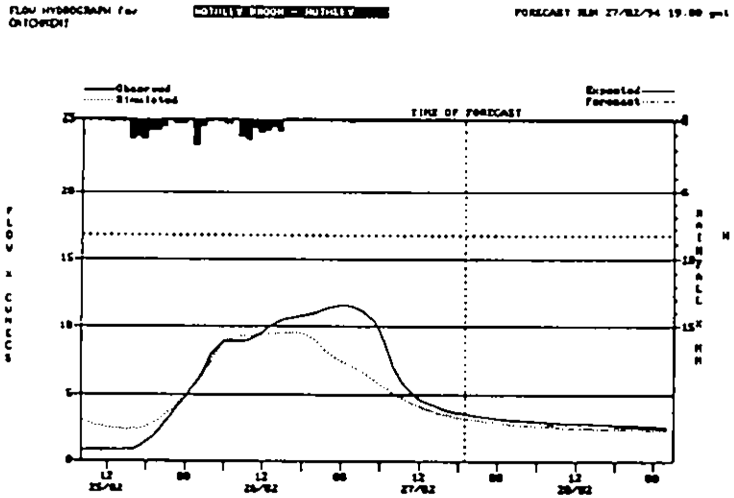
Event 9 Run 7



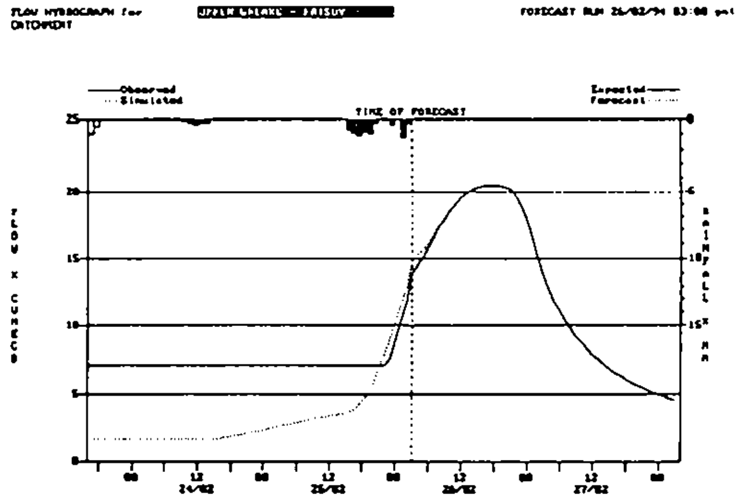
Event 9 Run 3



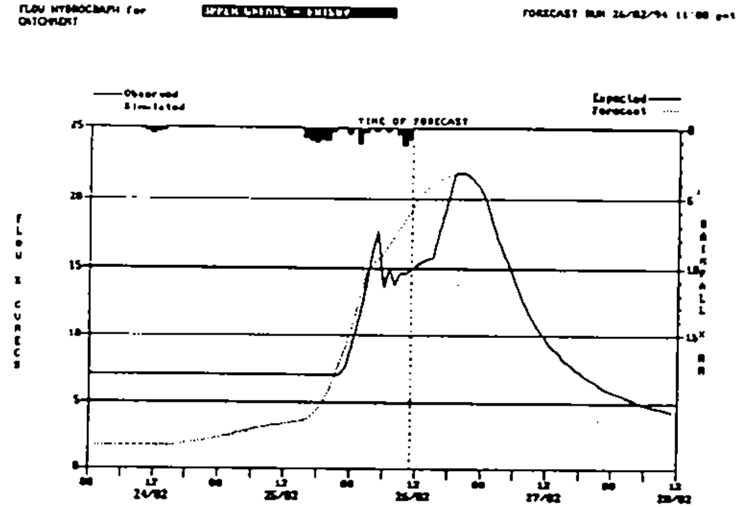
Event 9 Run 8



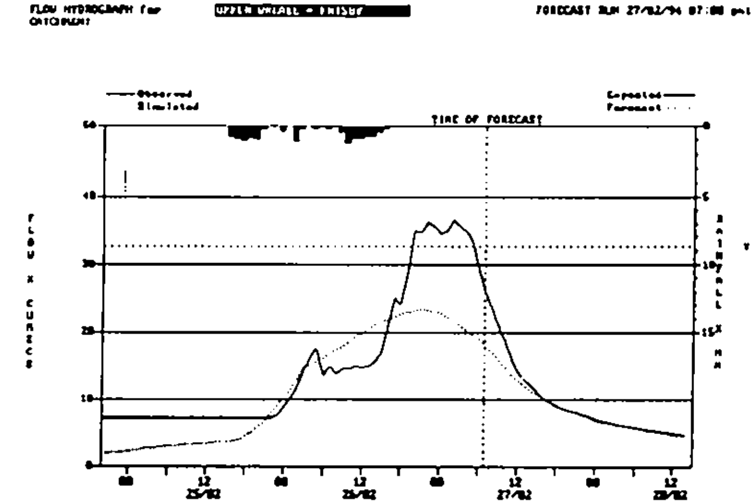
Event 9 Run 4



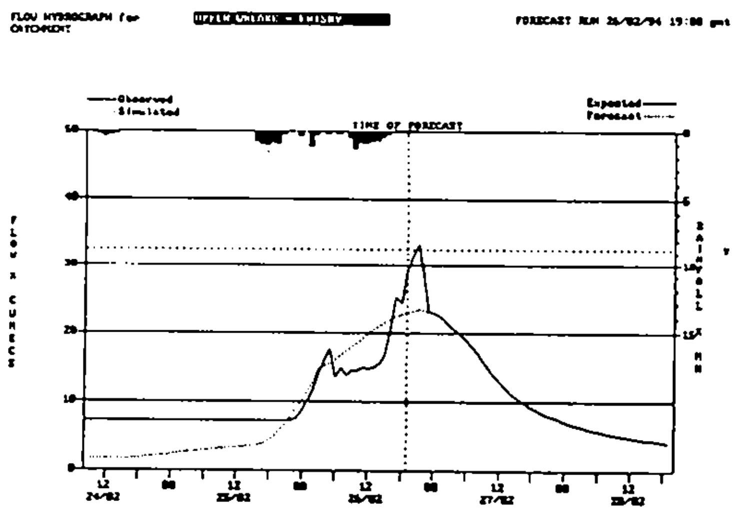
Event 9 Run 5



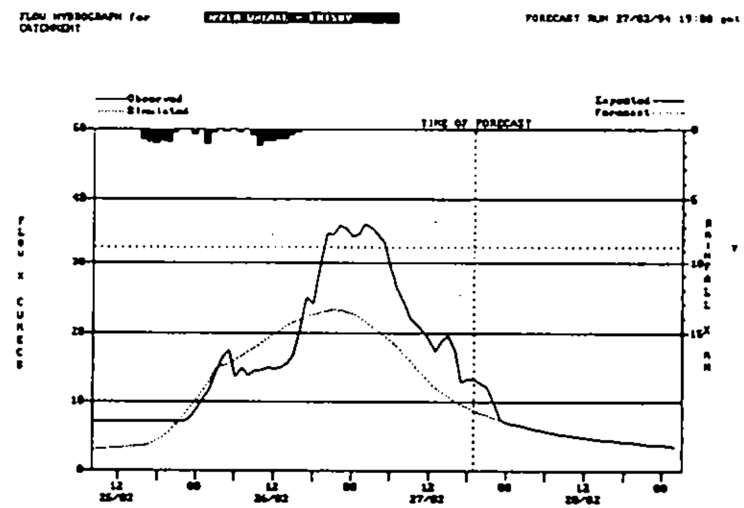
Event 9 Run 7



Event 9 Run 6

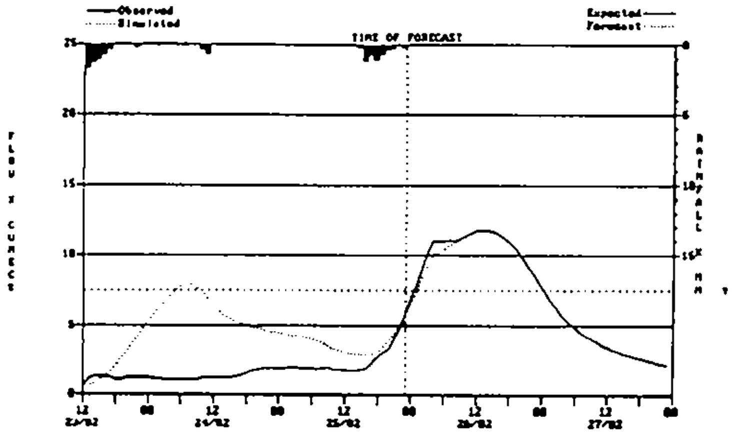


Event 9 Run 8



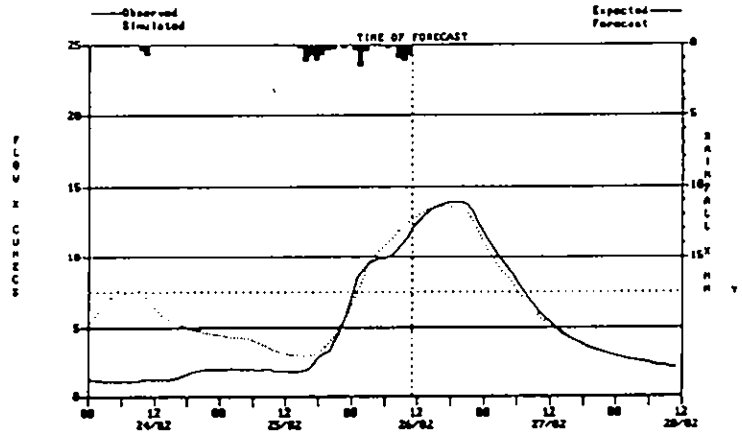
Event 9 Run 3

FLOW HYDROGRAPH for CATCHMENT | STAGE - SOUTH WIGSTON | FORECAST RUN 25/02/94 23:00 gmt



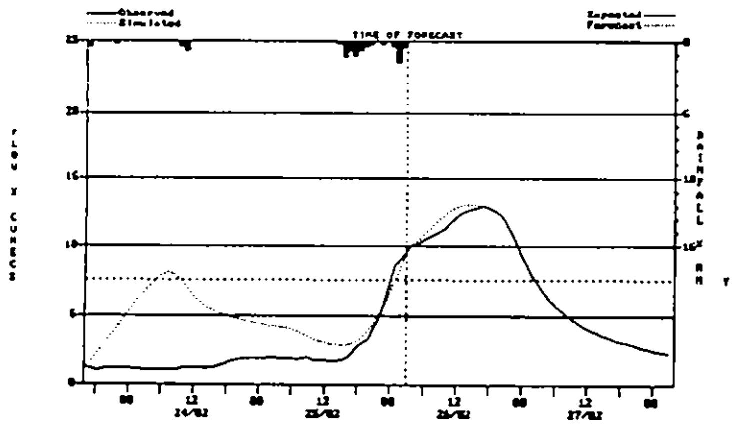
Event 9 Run 5

FLOW HYDROGRAPH for CATCHMENT | STAGE - SOUTH WIGSTON | FORECAST RUN 26/02/94 11:00 gmt



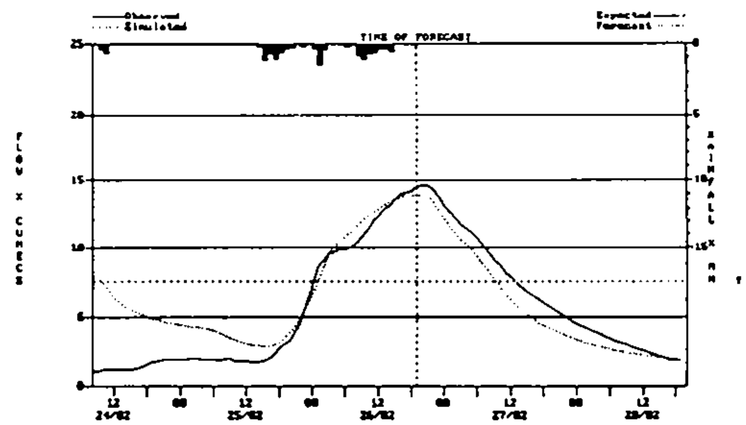
Event 9 Run 4

FLOW HYDROGRAPH for CATCHMENT | STAGE - SOUTH WIGSTON | FORECAST RUN 26/02/94 03:00 gmt

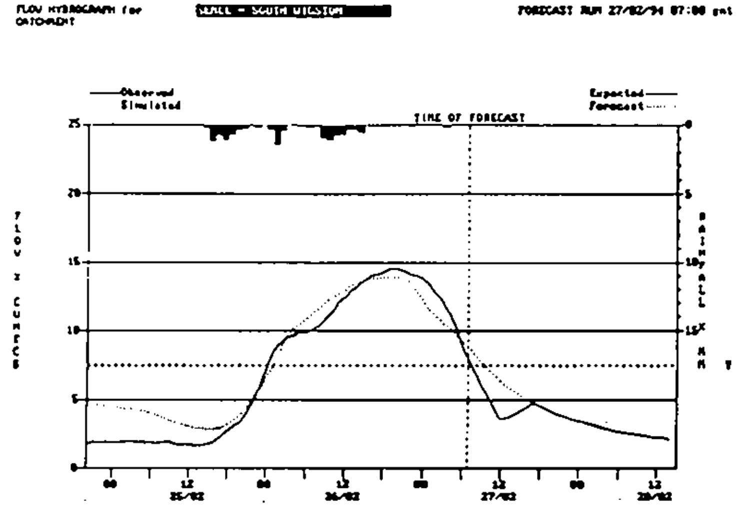


Event 9 Run 6

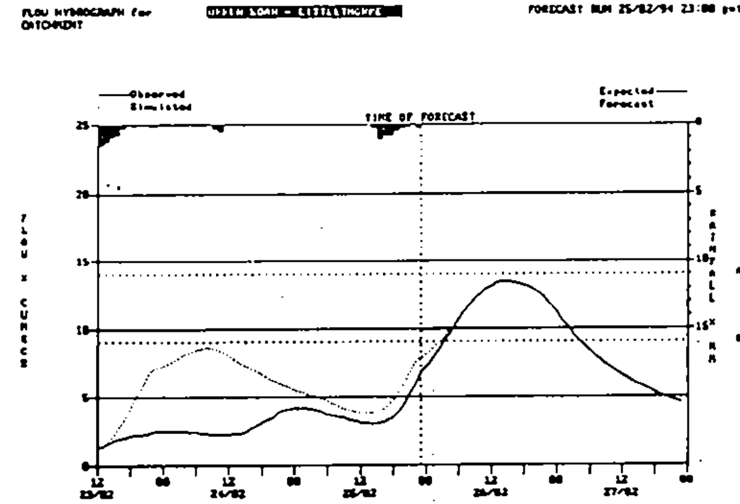
FLOW HYDROGRAPH for CATCHMENT | STAGE - SOUTH WIGSTON | FORECAST RUN 26/02/94 19:00 gmt



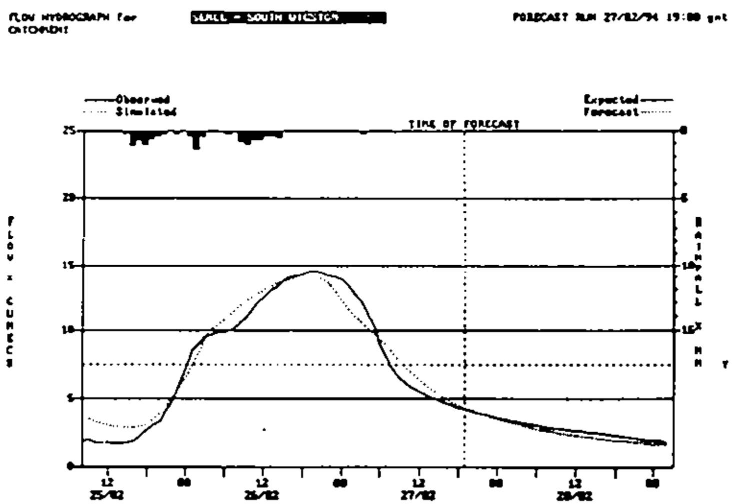
Event 9 Run 7



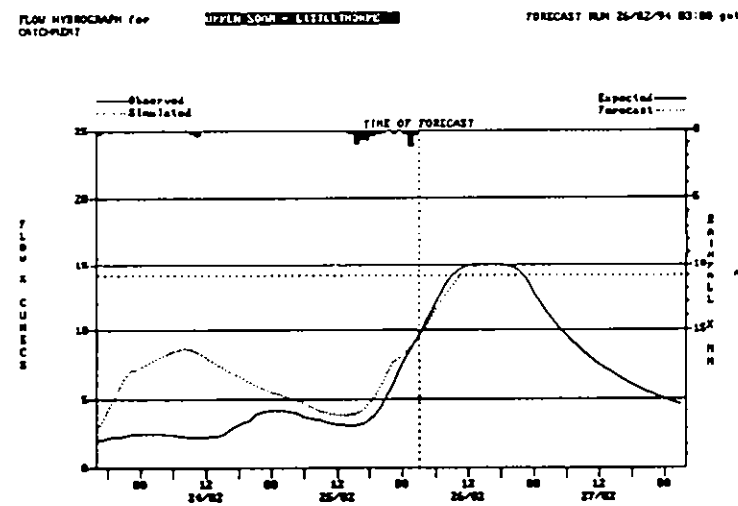
Event 9 Run 3



Event 9 Run 8

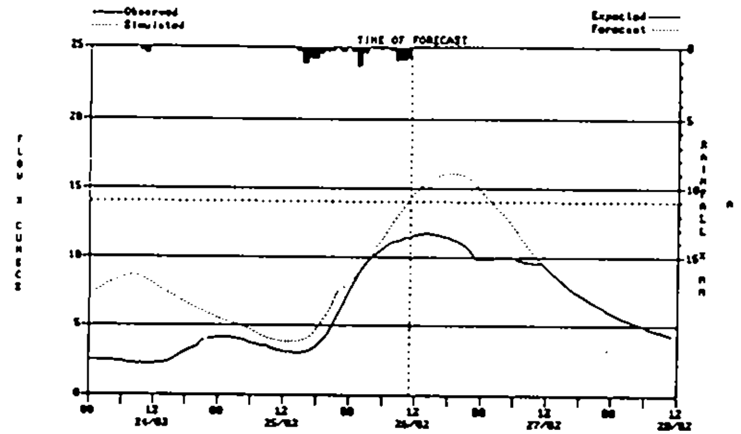


Event 9 Run 4



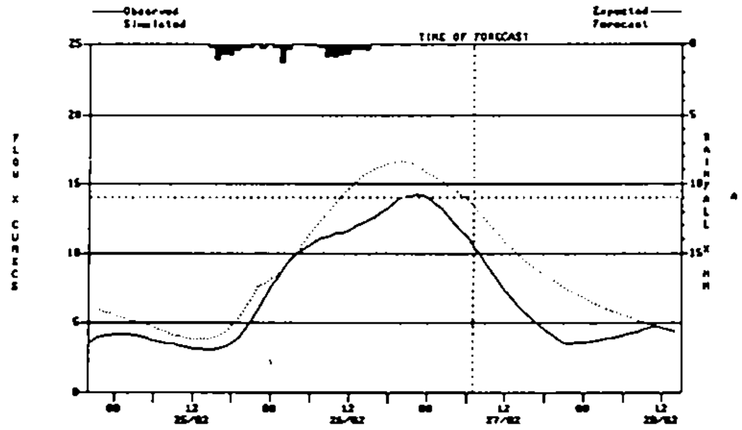
Event 9 Run 5

FLOW HYDROGRAPH for CATCHMENT   UPPER SOAR - LITTLETHORPE   FORECAST RUN 26/02/94 11:00 gmt



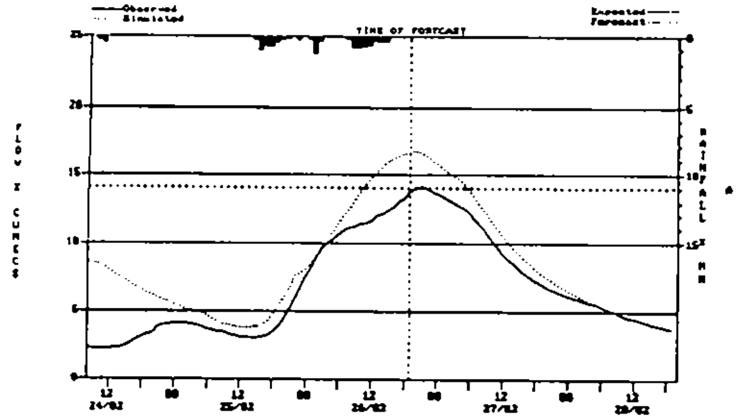
Event 9 Run 7

FLOW HYDROGRAPH for CATCHMENT   UPPER SOAR - LITTLETHORPE   FORECAST RUN 27/02/94 07:00 gmt



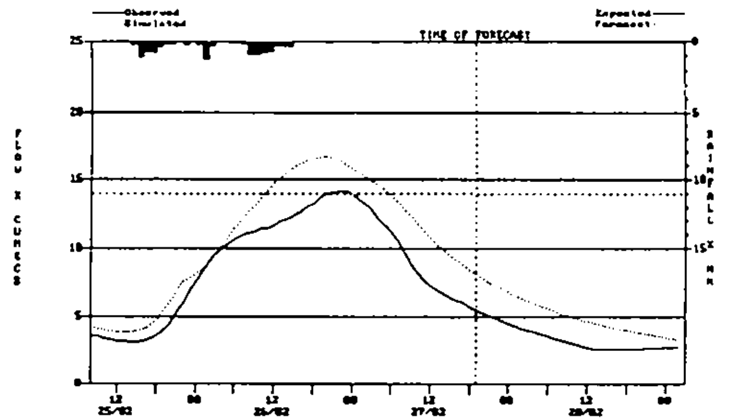
Event 9 Run 6

FLOW HYDROGRAPH for CATCHMENT   UPPER SOAR - LITTLETHORPE   FORECAST RUN 26/02/94 19:00 gmt



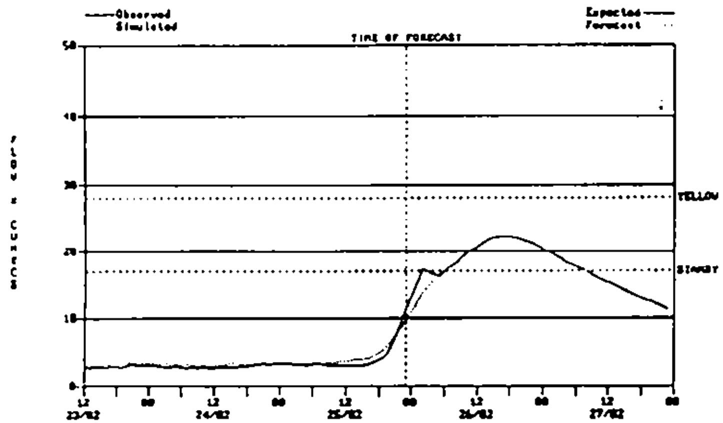
Event 9 Run 8

FLOW HYDROGRAPH for CATCHMENT   UPPER SOAR - LITTLETHORPE   FORECAST RUN 27/02/94 19:00 gmt



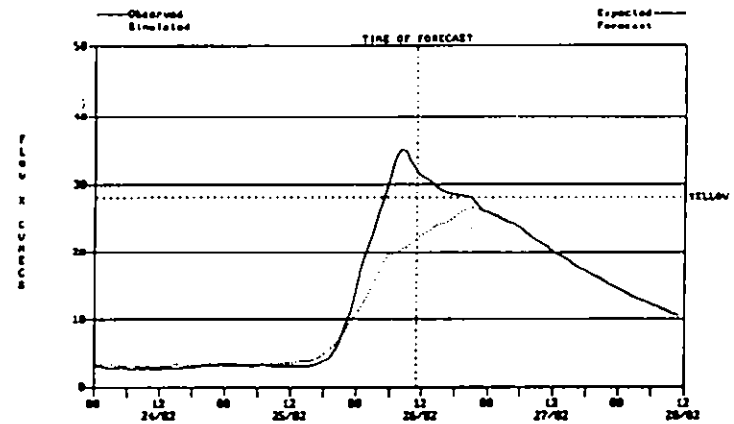
Event 9 Run 3

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 25/02/94 23:00 gmt



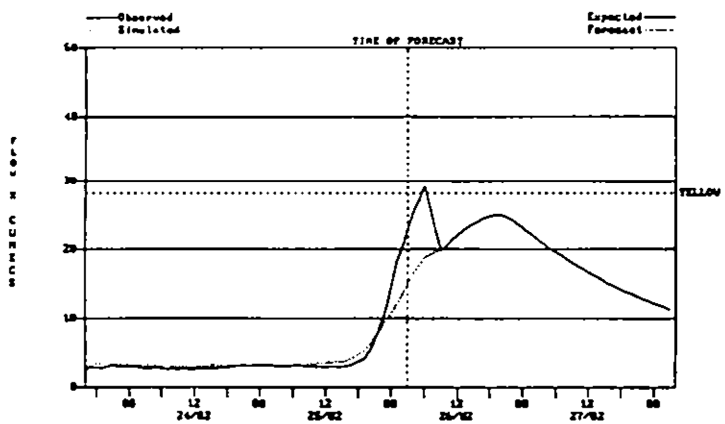
Event 9 Run 5

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 26/02/94 11:00 gmt



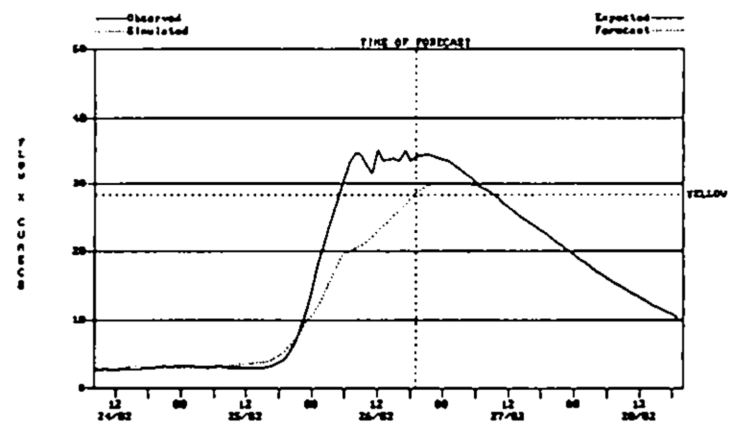
Event 9 Run 4

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 26/02/94 03:00 gmt



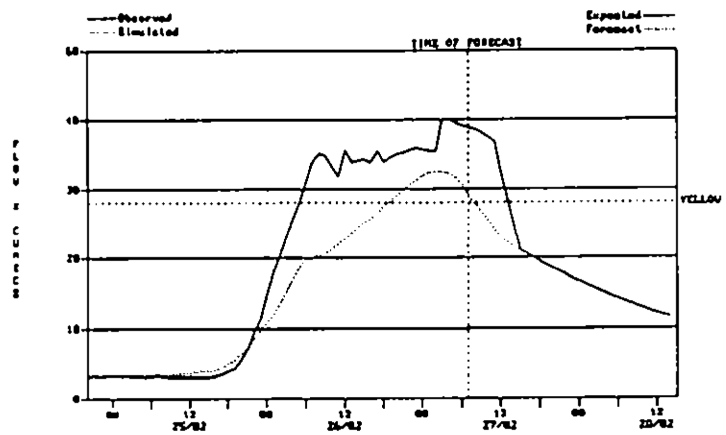
Event 9 Run 6

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 26/02/94 19:00 gmt



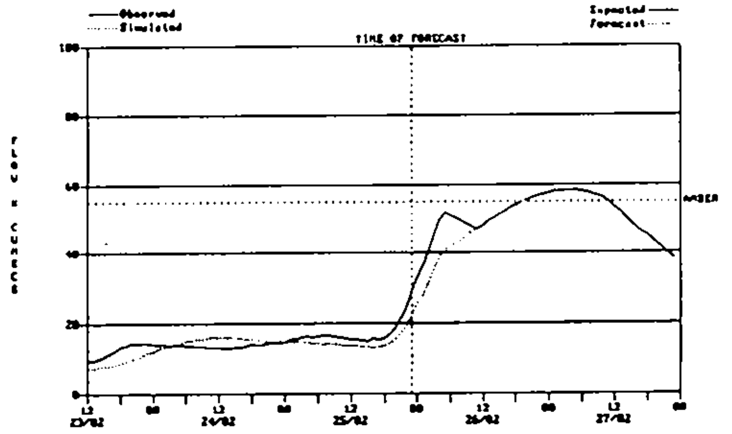
Event 9 Run 7

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 27/02/94 07:00 gmt



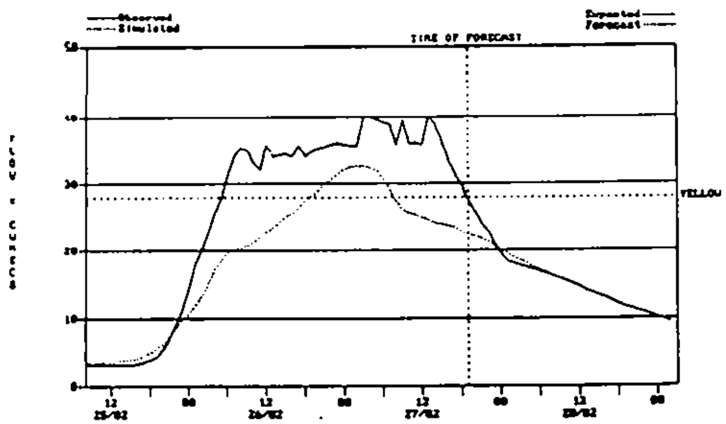
Event 9 Run 3

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 25/02/94 23:00 gmt



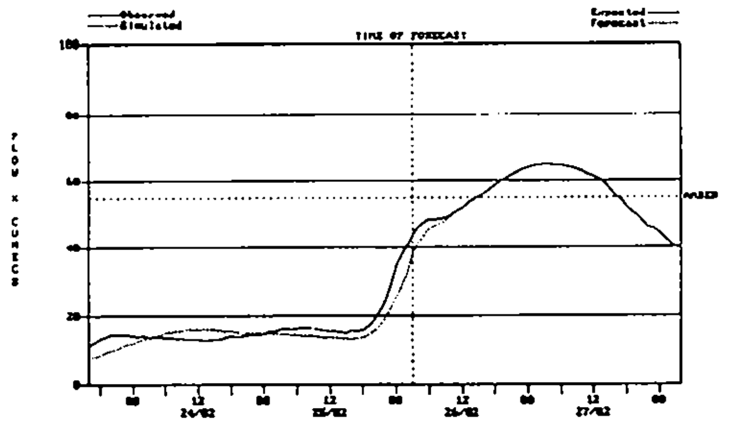
Event 9 Run 8

FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 27/02/94 19:00 gmt



Event 9 Run 4

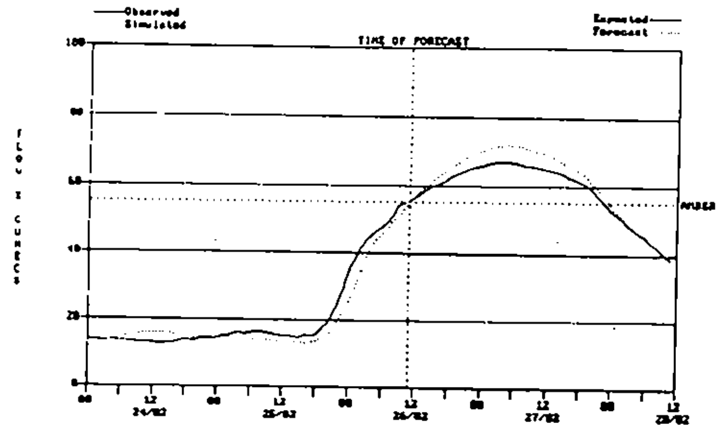
FLOW HYDROGRAPH for ROUTING REACH [redacted] FORECAST RUN 26/02/94 03:00 gmt



Event 9 Run 5

FLOW HYDROGRAPH for ROUTING REACH PILLINGS

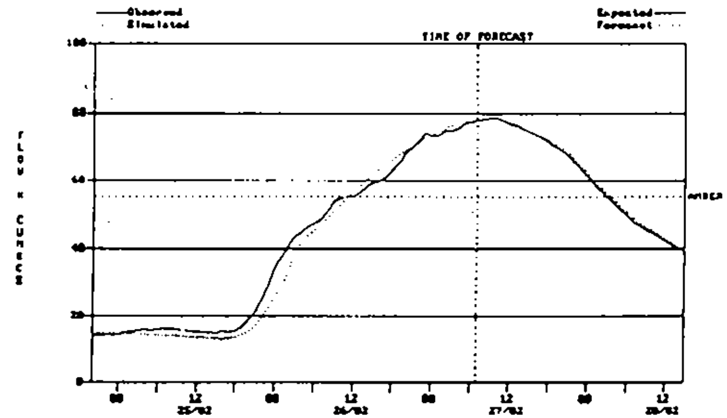
FORECAST RUN 26/02/94 11:00 gmt



Event 9 Run 7

FLOW HYDROGRAPH for ROUTING REACH PILLINGS

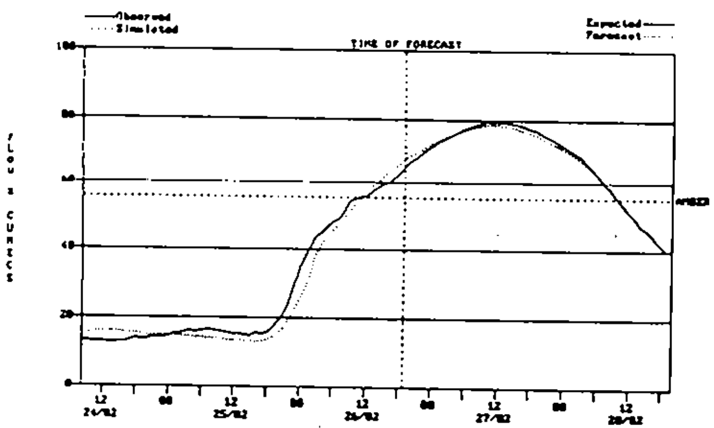
FORECAST RUN 27/02/94 07:00 gmt



Event 9 Run 6

FLOW HYDROGRAPH for ROUTING REACH PILLINGS

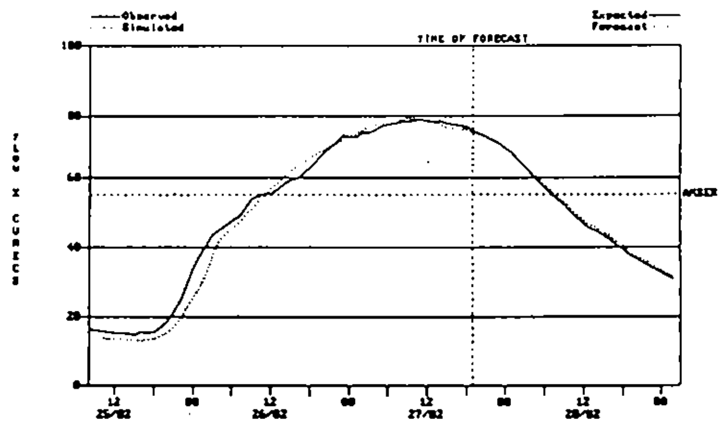
FORECAST RUN 26/02/94 19:00 gmt



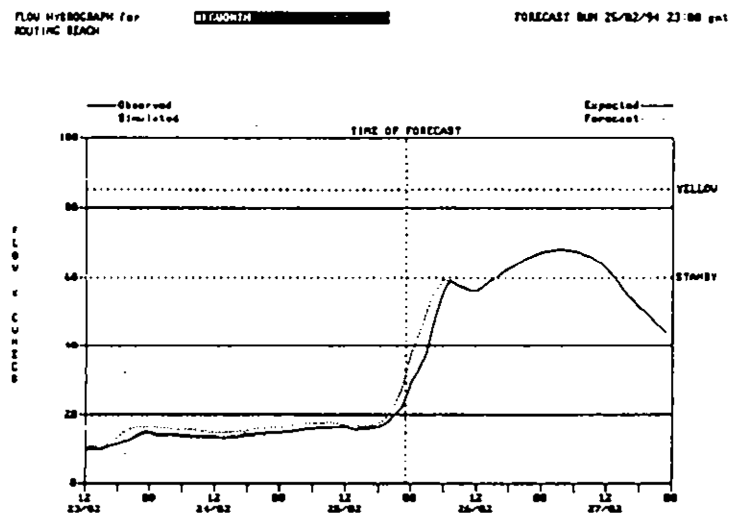
Event 9 Run 8

FLOW HYDROGRAPH for ROUTING REACH PILLINGS

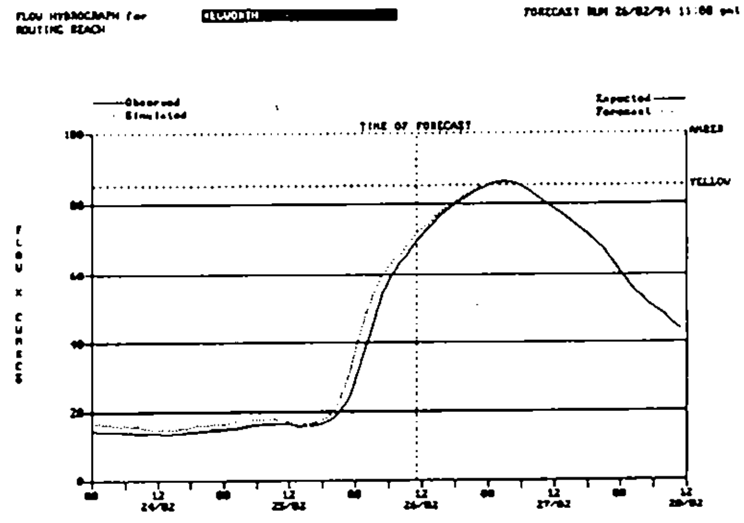
FORECAST RUN 27/02/94 19:00 gmt



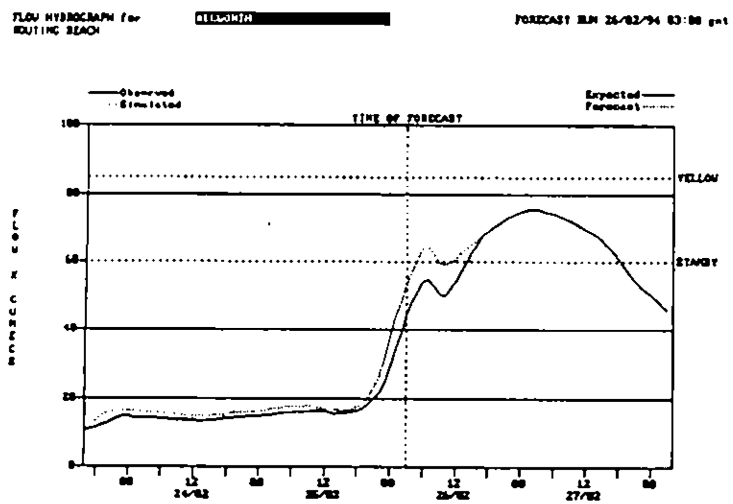
Event 9 Run 3



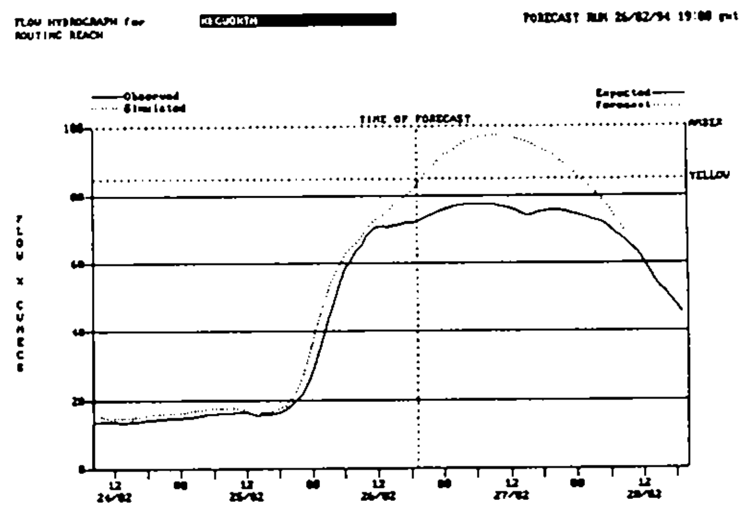
Event 9 Run 5



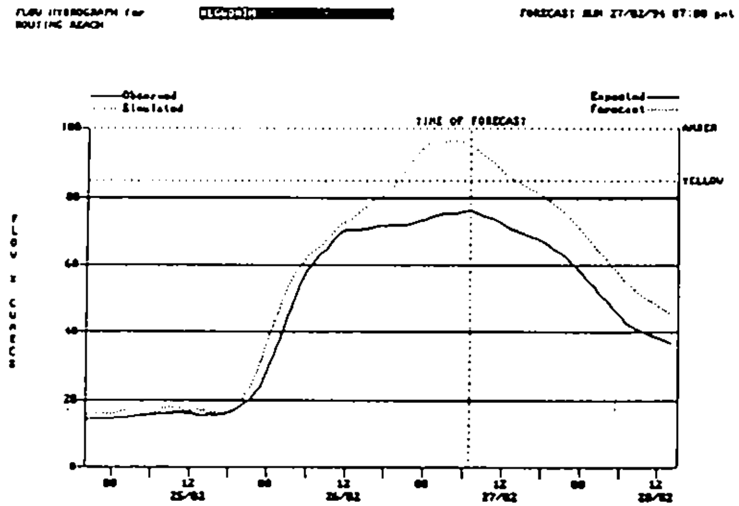
Event 9 Run 4



Event 9 Run 6



Event 9 Run 7



Event 9 Run 8

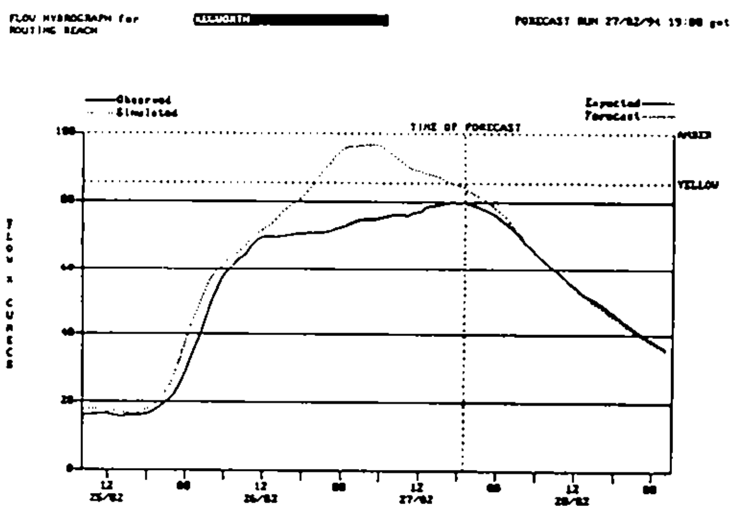
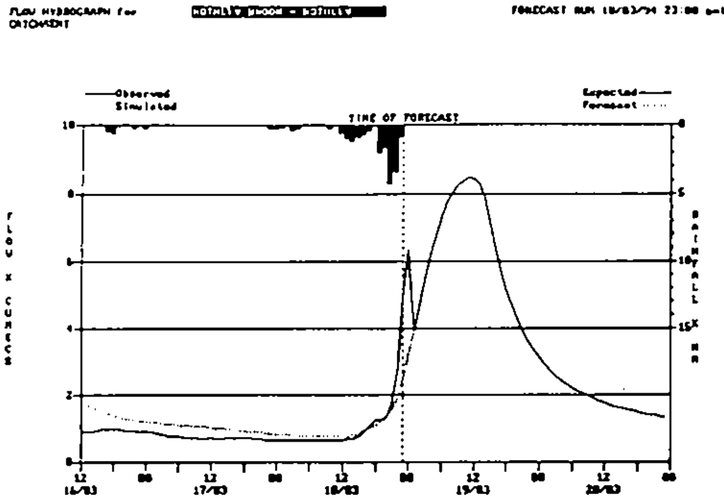
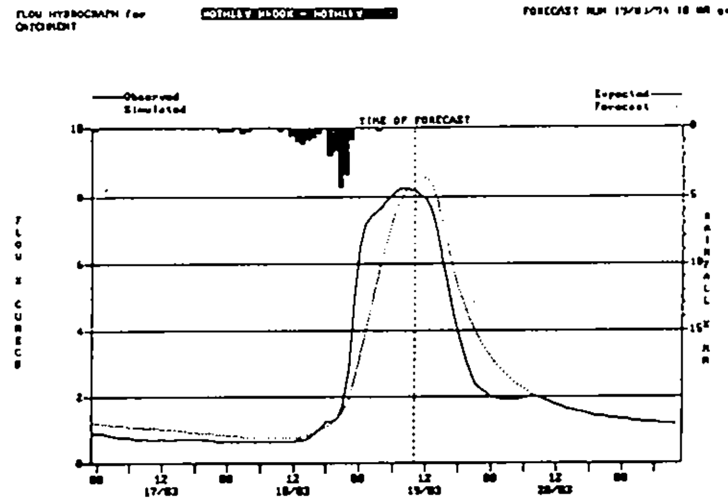


Figure A5.10 Flood forecasts for Event 10: 18-19 March 1994

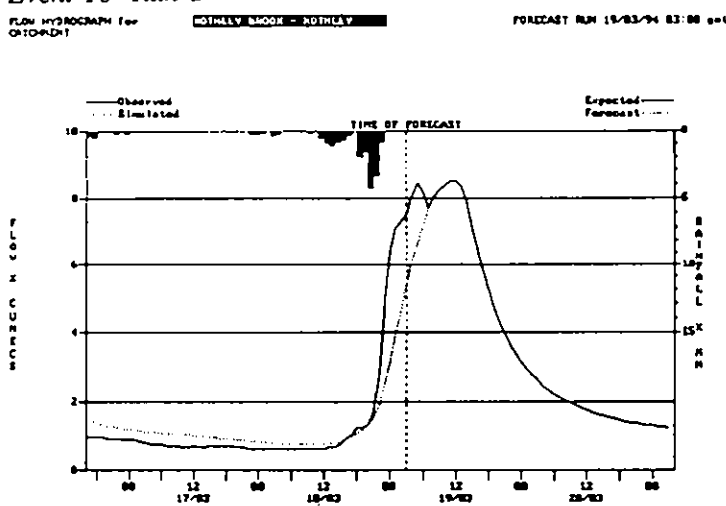
Event 10 Run 1



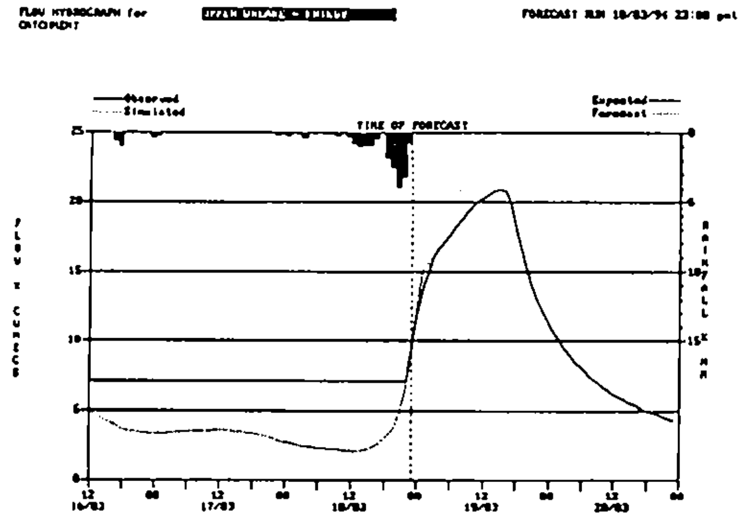
Event 10 Run 3



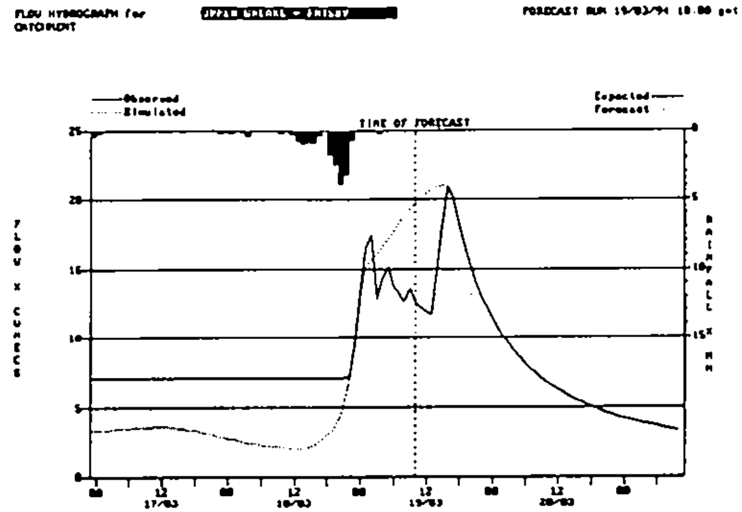
Event 10 Run 2



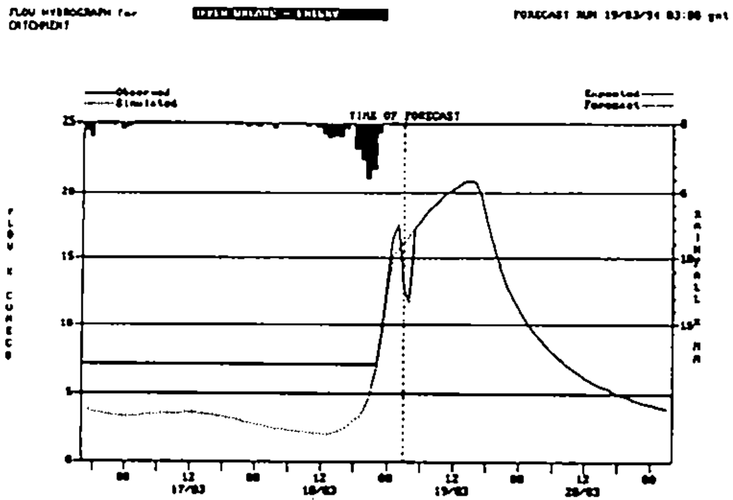
Event 10 Run 1



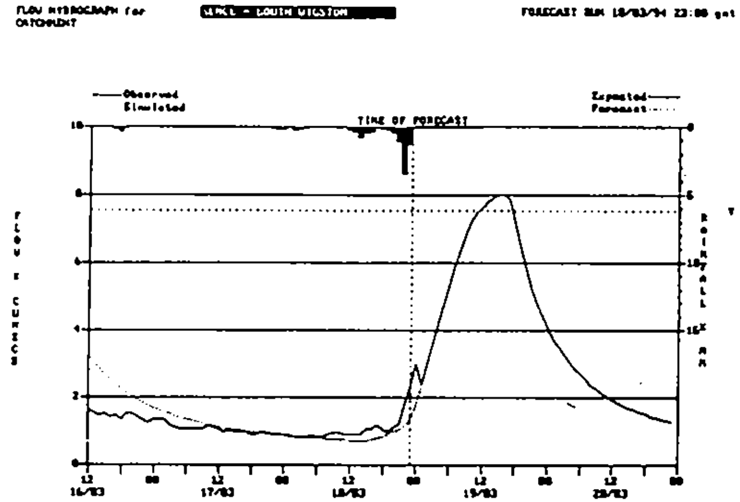
Event 10 Run 3



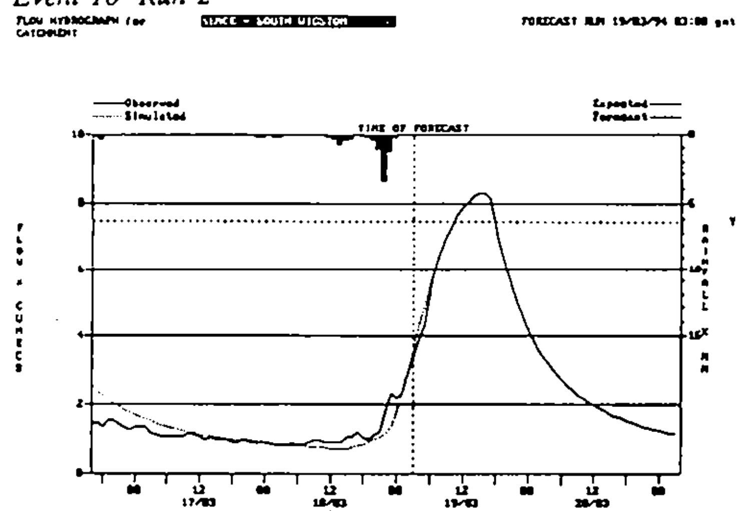
Event 10 Run 2



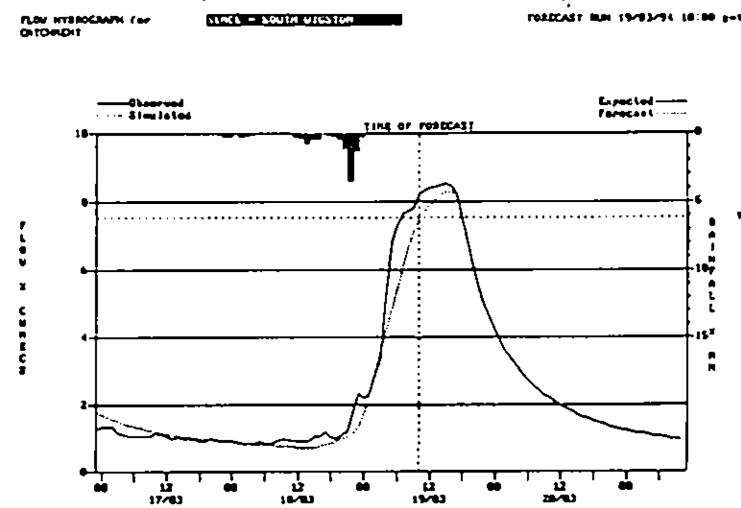
Event 10 Run 1



Event 10 Run 2

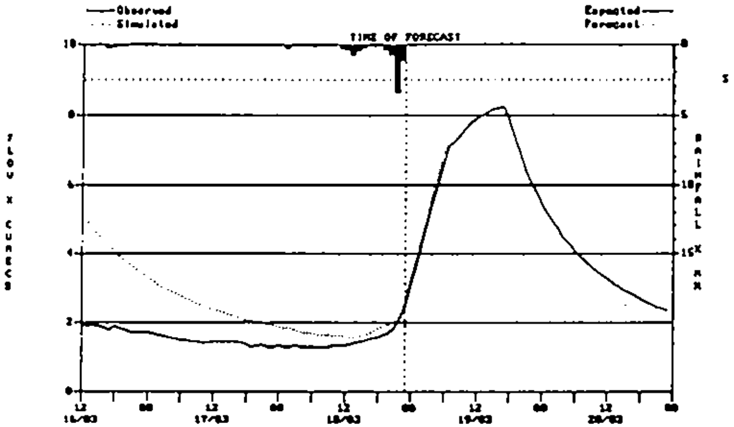


Event 10 Run 3



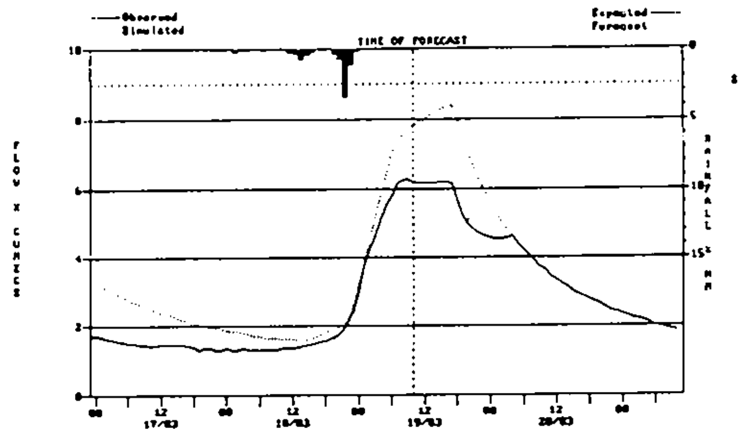
Event 10 Run 1

FLOW HYDROGRAPH for CATCHMENT RIVER SOAR - LITTLETHORPE FORECAST RUN 18/03/94 23:00 gmt



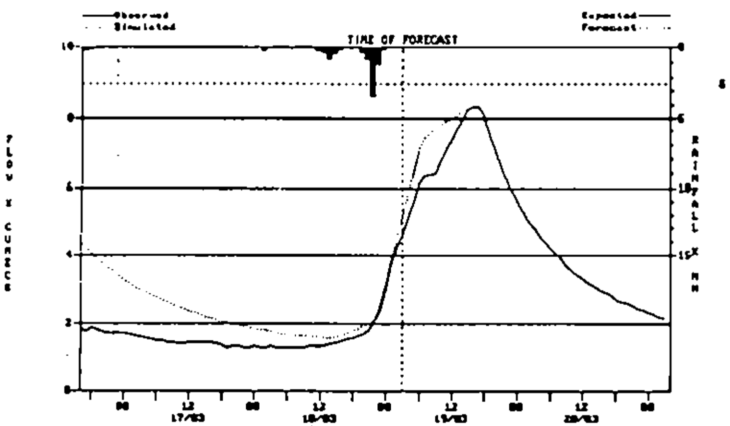
Event 10 Run 3

FLOW HYDROGRAPH for CATCHMENT RIVER SOAR - LITTLETHORPE FORECAST RUN 19/03/94 10:00 gmt

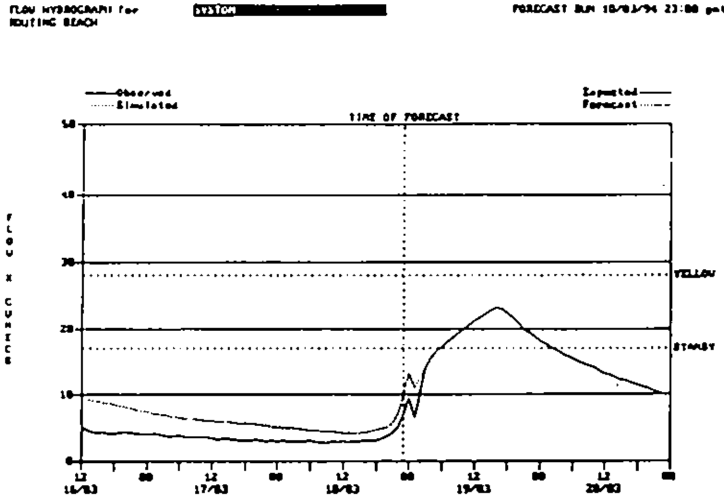


Event 10 Run 2

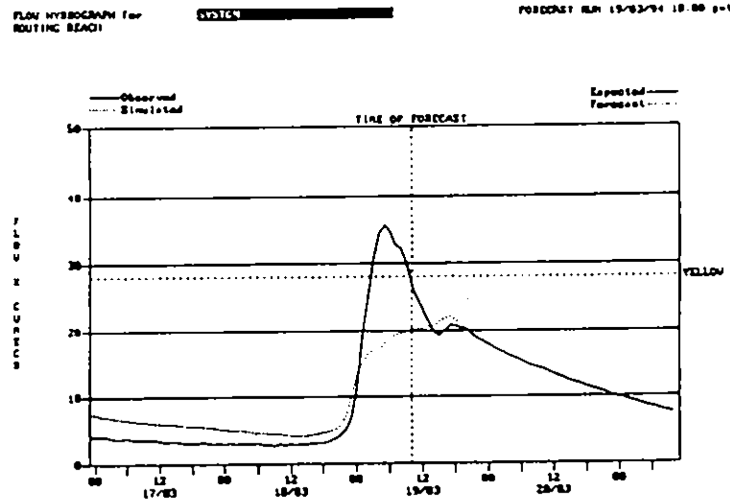
FLOW HYDROGRAPH for CATCHMENT RIVER SOAR - LITTLETHORPE FORECAST RUN 19/03/94 03:00 gmt



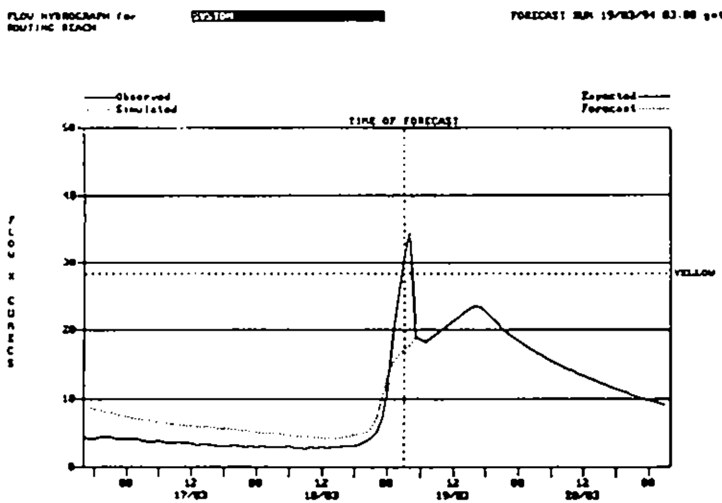
Event 10 Run 1



Event 10 Run 3

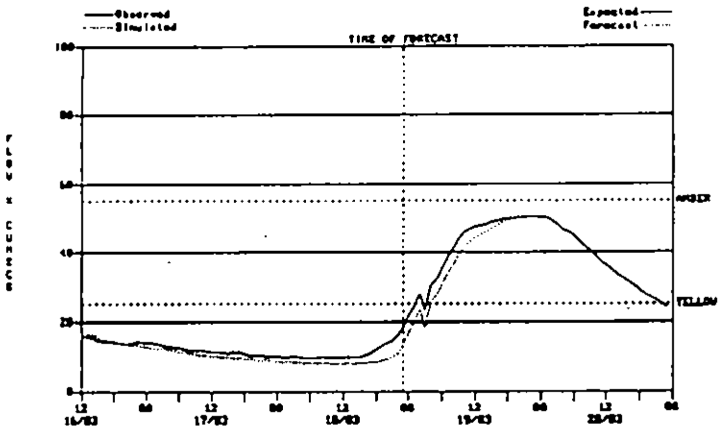


Event 10 Run 2



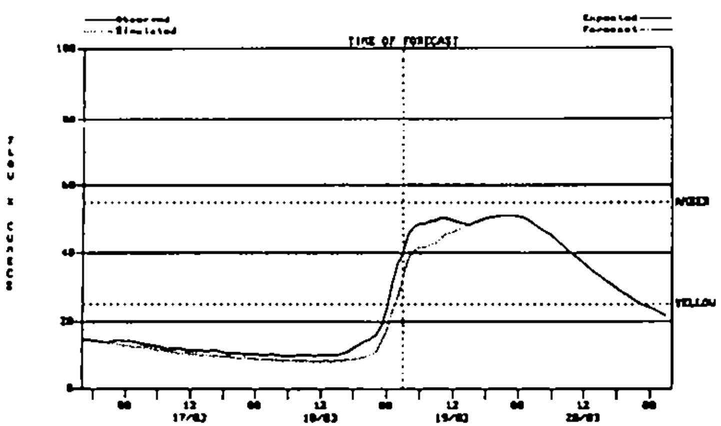
Event 10 Run 1

FLOW HYDROGRAPH for ROUTING REACH PILLINGS [redacted] FORECAST RUN 18/03/94 23:00 gmt



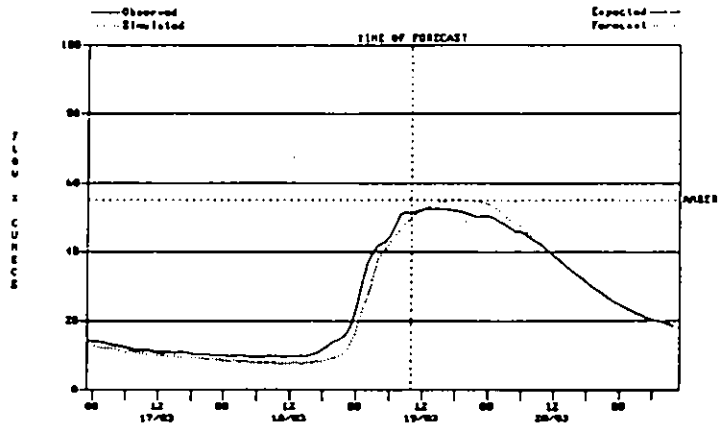
Event 10 Run 2

FLOW HYDROGRAPH for ROUTING REACH PILLINGS [redacted] FORECAST RUN 19/03/94 03:00 gmt



Event 10 Run 3

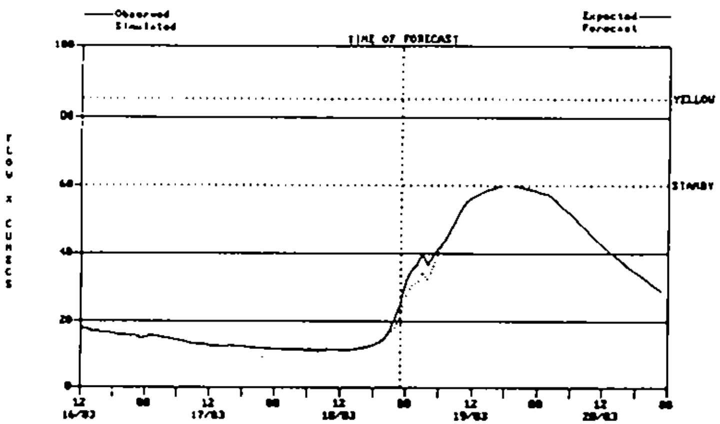
FLOW HYDROGRAPH for ROUTING REACH PILLINGS [redacted] FORECAST RUN 19/03/94 10:00 gmt



Event 10 Run 1

FLOW HYDROGRAPH for ROUTING REACH KEGWORTH

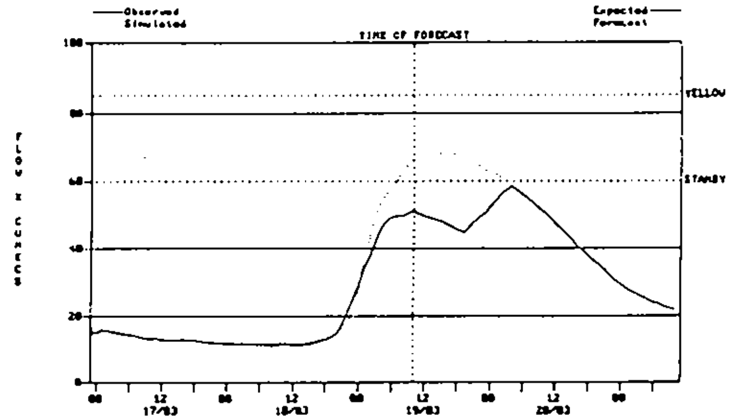
FORECAST RUN 18/03/94 23:00 gmt



Event 10 Run 3

FLOW HYDROGRAPH for ROUTING REACH KEGWORTH

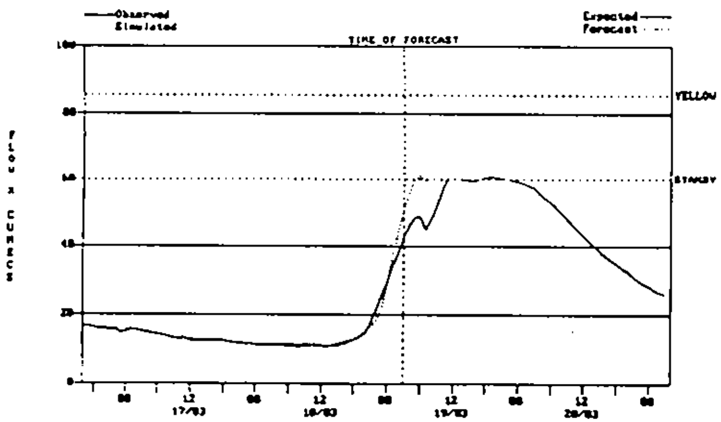
FORECAST RUN 19/03/94 10:00 gmt



Event 10 Run 2

FLOW HYDROGRAPH for ROUTING REACH KEGWORTH

FORECAST RUN 19/03/94 03:00 gmt



Appendix 6

UNCERTAINTIES IN WATER LEVEL FORECASTS

APPENDIX 6 UNCERTAINTIES IN WATER LEVEL FORECASTS

The total uncertainty associated with flood water level cannot be determined precisely for a model which does not yet exist. Thus it is necessary to use the results of similar investigations elsewhere to infer the likely range of accuracy of the level forecasts along the lower reaches of the River Soar. The studies of Burnham & Davies (1990) and of Defalque et al (1993) enable some initial estimates to be made on the uncertainties in the hydraulic model forecasts. The effects involved in an analysis of the model uncertainty include:

- flow measurement at the gauging stations;
- uncertainties in the rainfall to runoff modelling;
- uncertainties in the hydrological routing;
- topographic data accuracy for the hydrodynamic modelling;
- cross section spacing for the hydrodynamic model;
- volume of calibration data for the hydrodynamic model;
- accuracy of hydraulic model calibration; and
- extrapolation of the model above the discharge of the calibration floods.

Burnham & Davies (1990) considered the influence of topographic survey errors and quality of model calibration data on the accuracy of steady flow modelling of 100 year flood levels. They assumed that the flow was well known (no error allowed) and that the hydraulic modelling errors were negligible (sufficiently fine resolution of spatial variation). Defalque et al (1993) considered the influence of topographic error and model section spacing for a variety of steady flood discharges from half bank full to five times bank full flow.

It is not possible to give a rigorous procedure for determining the accuracy of a flood level estimate because it is difficult to categorise the sources of error fully as systematic or random. On the assumption that the sources of water level error in the hydrodynamic modelling outlined above will be independent, we suggest that the root mean square error (rmse) value should be taken to assess the overall uncertainty. This choice is pragmatic rather than theoretical but intuitively it seems implausible that all the sources of error would act purely additively on the total uncertainty, E_{total}. Thus using the appropriate equations from Burnham & Davies and Defalque et al we may define:

$$E_{total} = \{(E_{tr})^2 + (E_c)^2 + (E_d)^2\}^{0.5}$$

for the case where the flood flow Q_T is less than the calibration flood discharge Q_C and

$$E_{total} = \{(E_{tr})^2 + [(Q_T/Q_C)E_c]^2 + (E_d)^2\}^{0.5}$$

for the case where the flood Q_T exceeds the calibration flood flow Q_C (ie $(Q_T / Q_C) > 1.0$). Here, E_{tr} is the uncertainty associated with the topographic survey and roughness assessment taken from the work of Burnham and Davies, E_c is the mean magnitude of the model calibration error and E_d is the model discretisation error taken from Defalque et al. Furthermore, if we can estimate the level of uncertainty to associate with hydrological uncertainties, then this could be compounded into the rmse equations above.

We shall now make some reasonable estimates based upon the dimensions of the River Soar in the Lougborough area. The channel depth (D) is about 3.5m, the slope (S) is about 0.00025 and the backwater length is about (L)10 km. Assume that a model has been constructed on sections at 250 m centres on average (DX), it has been based on an aerial survey of the flood plain contoured at 0.25 m VI and that there is good coverage of calibration data with say 10 sites downstream of the Wreake confluence. Suppose that the hydrodynamic model has been calibrated to a mean magnitude of peak flood level of 30 mm for a 25 year flood. Following recent work for NRA Thames Region (HR, 1995) we assign the calibration reliability number Nr as 0.1 and the survey accuracy number Sn as 0.08 in the formulae of Burnham & Davies (1990). This produces the estimate of topographic and calibration uncertainty as:

$$E_{tr} = 0.63\ D^{0.35}\ S^{0.13}\ (Nr + Sn)$$

$$= 0.63 * 1.55 * 0.34 * 0.18$$

$$= 0.060\ m = 60\ mm.$$

The discretisation error from Defalque et al (1993) is

$$E_d = 0.1\ D\ DX / L$$

$$= 0.1 * 3.5 * 250 / 10000$$

$$= 0.009\ m = 9\ mm.$$

The calibration quality uncertainty is 30 mm as stated for flows up to the 25 year flood in this example. Suppose that an estimate of the uncertainty for the 100 year flow is required then assuming $Q_{100} / Q_{25} = 2.57 / 1.87 = 1.37$ from the Region 4 growth curve we have

$$(Q_T/Q_C)E_c = 1.37 * 0.030$$

$$= 0.041\ m = 41\ mm.$$

Thus the total mean magnitude of the uncertainty in level from the hydraulic modelling will be:

$$E_{total} = \{(E_{tr})^2 + [(Q_T/Q_C)E_c]^2 + (E_d)^2\}^{0.5}$$

$$= \{(0.060)^2 + [0.041]^2 + (0.009)^2\}^{0.5}$$

$$= 0.073\ m = 73\ mm.$$

In the spirit of the work of Burnham & Davies (1990), the maximum error might be expected to be larger than this estimate of the mean error magnitude. If the survey and calibration errors dominate as suggested by Burnham & Davies, then the maximum error might be estimated by:

$$E_{max} = 1.7\ (E_{total})^{0.8}$$

where the units are in metres to give an upper bound on the error at any site of about 0.2 m. Furthermore, if we assume that the hydrological uncertainties lead to a mean magnitude of level uncertainty of 0.1 m, then we can compound this with the value of E_{total} to give the uncertainty from all sources of $[(0.1)^2 + (0.073)^2]^{1/2} = 0.123$ m. In this case the probable upper bound on the error at any site rises to 0.3 m.

Obviously these figures should be treated as illustrative only and the actual precision of the forecast levels will depend upon the quality of the calibration of the model at a number of sites. The mean uncertainty in the hydraulic modelling will be reduced by

- better calibration data at more sites;
- land survey or direct digitisation from aerial photography for the flood plain topography; and
- calibration for a larger flood.