'FRONTIERS' EVALUATION OF RADAR–BASED RAINFALL AND RIVER FLOW FORECASTS APRIL 1992 TO MARCH 1993

The Met.Office

NRA

FRONTIERS
Operational Assessment Group
(FOAG)

FINAL REPORT
APRIL 1992–MARCH 1993

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1. Introduction

Following the completion of the Met. Office (MO)–National Rivers Authority (NRA) evaluation of FRONTIERS precipitation accumulation forecasts in March 1992 and the publication of the Final Report, it was agreed that the lack of flood events necessitated a continuation project. In addition, a general lack of thunderstorm events in either the NRA Thames or North West regions meant that this work was unable to provide data from which any conclusions could be drawn regarding the performance of the FRONTIERS system in such meteorological situations. Since thunderstorm rainfall is a major cause of flood events in both regions of the NRA and elsewhere in England and Wales, it was felt imperative that further studies be undertaken.

2. Background

2.1 Basis of project

As for the previous collaboration between the MO and the NRA, a Steering Group (FOAG: FRONTIERS Operational Assessment Group) was established under the aegis of the MO Director of Operations and the NRA Technical Director to coordinate the R&D activities as they related to the project aims. The membership of this group is given in Annex A and contained a range of expertise from operational hydrologists and weather forecasters to researchers. Although the NRA undertook to pay the MO for the FRONTIERS forecasts during the period of the project (April 1992–March 1993) (section 2.3), no additional funding was available for new R&D activities. Hence the participants carried out the necessary work within existing programmes.

The Steering Group met on a quarterly basis, and an interim report was prepared covering the six-month period April–September 1992. Numerous working papers were produced, the substance of which are contained in this report.

2.2 Aims of the project

The terms of reference for the Steering Group are given at Annex B. The basic aims of the project were to improve the availability of the FRONTIERS precipitation forecasts (both instantaneous and accumulations) and clarify their performance both meteorologically, and as input to operational hydrological flood forecasting procedures. The March 1992 report had identified a number of tasks which required attention, and this report reviews the status of these tasks one year on. Finally future research needs are considered and recommendations made.

2.3 Funding arrangements

At the beginning of the Project it was agreed that the NRA Thames and North West Regions would pay for the receipt of the FRONTIERS forecasts. However, the charge would be dependent upon the data availability. If the availability of the forecast accumulations was 95% or above, a full charge of £3,750k per quarter for each NRA region would be made by the MO. For every 1% the availability fell below this figure, a 1% reduction in the charge resulted. When the availability fell below 75% the charge was reduced by 2% for each subsequent 1% fall in availability, Table 1.

Table 1: Relationship used between data availability and charge made by MO to NRA as percentage of base charge

Availability (%)	Charge(%)
100	100
95	100
90	95
80	85
75	80
70	70
60	50

Periods of prearranged down-time (e.g. for routine system maintenance) were excluded from the availability calculation which was carried out independently by the MO and the NRA.

2.4 FRONTIERS system

In April 1992 the FRONTIERS system was transferred from the control of the research side of the MO (it was operated by forecasters in the Central Forecast Office, Bracknell) to a new section based in the Central Forecast Office, Bracknell responsible for the operational maintenance of the system. No further development of the system took place other than necessary software maintenance. The details of the FRONTIERS system are contained in the March 1992 report, and therefore are not reproduced here.

3. Availability of data

3.1 Single-site radar and network data

The availability of single-site radar data has been determined by counting the number of 15-minute images which are correctly received on the RADARNET computer at Bracknell. If RADARNET fails to receive an image then the problem may lie with the radar hardware, the on-site radar processing system, the communication circuits or with RADARNET itself. Annex C contains the percentage availability for all radars between March 1992 and March 1993. Note that the monthly average availability of Chenies (north of London) was 92.2% and for Hameldon Hill (NW England) was 89.9% (computer and radar hardware faults causing the loss of data were rectified). Note that these figures do not include the downtime to the NRA users. Variations on a daily basis are also illustrated by the March 1993 figures for all sites.

3.2 Instantaneous and accumulation forecasts

The NRA Thames Region has closely monitored the availability of both instantaneous and accumulation forecasts from the FRONTIERS system from January 1991 to March 1993. Average availability figures are presented in Table 2 and they show a steady improvement throughout the study period. The instantaneous forecast availability averaged over the whole of 1991 was 86.5% and this increased to 94.3% in 1992 and 95.5% in the first quarter of 1993. The accumulation forecast availability averaged 73.5% in 1991 increasing to 87.5% in 1992 and 93.6% in the first quarter of 1993.

Accumulation forecasts, which are important hydrologically, reached their highest availability in February 1993 with 94.9% just short of the target required of 95%. This compared starkly with only 50.8% availability in May 1991.

It should be stressed that the figures presented in Table 2 are average figures for each month during the study period. For flood warning purposes, it is important that data availability does not decrease in periods of heavy rainfall, hence the analysis was extended to determine the amount of data that was available for all events selected in the study catchments. Figures 1-3 show FRONTIERS accumulation forecast availability plotted against total rainfall for each event (based on rain-gauge data) for the Silk Stream, Beverley Brook and Roding catchments. It is clear from the graphs that FRONTIERS data availability bears little relation to rainfall amount, and does not decrease significantly during periods of heavy rainfall.

Table 2: FRONTIERS forecast availability — NRA Thames Region — Jan 1991 to Mar 1993

Month	Instantaneous	Accumulations
Jan 1991–Dec 1991		
Jan	89.6	84.9
Feb	90.2	62.4
Mar	87.8	79.9
Apr	73.0	54.0
May	60.8	50.8
Jun	89.8	78.3
Jul	95.2	84.8
Aug	92.3	84.4
Sept	93.8	76.3
Oct	92.8	76.6
Nov	86.1	73.0
Dec	86.7	78.2
Year Average	86.5	73.5
Jan 1992–Dec 1992		
Jan	85.4	80.9
Feb	87.4	74.3
Mar	93.6	82.3
Apr	96.9	93.7
May	97.0	92.7
Jun	96.1	90.6
Jul	97.8	85.3
Aug	98.6	81.4
Sept	92.6	90.6
Oct	92.7	91.1
Nov	95.8	93.6
Dec	97.1	93.6
Year Average	94.3	87.5
Jan 1993–Mar 1993		
Jan	93.9	92.4
Feb	95.8	94.9
Mar	96.8	93.4
First Quarter Average	95.5	93.6

3.3 Analysis of data loss

Some problems were experienced with the transfer of FRONTIERS forecast and accumulation data to NRA North West and NRA Thames during the early stages of the assessment period.

Initially the FRONTIERS software insisted on the inclusion of both radar and satellite data in the image on which the forecasts were based before the transmission of the forecast and accumulation products to the NRA Regions. Once this condition was removed, the percentage availability of data to the NRA Regions improved dramatically, from the mid-60s to around 90.

After this improvement further problems were traced to software errors in the FRONTIERS product distribution software which caused either loss of the last part of a transmission or the transfer of images of a slightly different size from that expected by the NRA resulting in each line of an image being slightly offset from the previous line. Tracing of this fault was particularly difficult as the problem was only experienced when the FRONTIERS operator took one particular route out of the many possible through the operational software.

4. Performance of Chenies and Hameldon Hill in measuring precipitation

4.1 Radar/rain-gauge ratios for real-time adjustment

Figures 4 and 5 show the radar/rain-gauge ratios for the radar adjustment gauges implemented as part of the radar systems at Hameldon Hill and Chenies. These data were used to adjust the Hameldon Hill radar data in real-time, but were not used in this way with the Chenies radar data. Both radars appeared to overestimate the rainfall before adjustment during winter and spring. Although the Fine Jane gauge is shown on Figure 4, it is not used for real-time adjustment as it is affected by ground clutter. The availability of rain-gauge data for adjustment of the radar data at all radar sites is shown in Table 3.

Table 3: Radar rain-gauge availability — March 1992 to March 1993

Site	Gauge	Mar 92	Apr 92	May 92	Jun 92	Jul 92	Aug 92	Sept 92	Oct 92	Nov 92	Dec 92	Jan 93	Feb 93	Mar 93	Mean Mar 92–Mar 93
Clee Hill	Frankley	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Staunton	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Caersws	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Hameldon Hill	Abbeystead	92.1	97.8	77.0	97.3	98.4	90.5	72.3	83.9	91.1	95.6	82.1	90.1	90.4	89.4
	Worthington	86.8	98.1	81.8	97.4	99.0	94.6	73.1	93.5	94.0	96.8	82.7	89.8	98.2	91.2
	Hollingsworth	93.2	92.3	57.5	98.9	98.9	94.6	73.1	90.2	94.2	96.7	82.7	89.9	98.4	89.3
	Swineshaw	87.5	87.5	81.9	98.9	99.1	94.7	72.5	93.4	93.9	96.4	82.7	89.9	98.4	90.5
	Fine Jane	93.2	98.4	81.9	97.7	98.9	94.4	73.1	93.6	94.2	96.8	82.6	89.8	98.2	91.8
	Scar House	93.1	99.6	81.9	99.2	99.3	94.2	75.4	93.6	96.6	96.8	84.3	90.1	55.4	89.2
	Redmires	93.1	99.5	81.9	99.2	99.3	94.2	75.4	93.6	96.6	96.8	84.3	90.1	55.4	89.2
	Lower Dunsforth	93.1	99.6	81.9	99.2	99.3	94.2	75.3	93.6	96.6	96.8	84.3	90.2	55.4	89.2
	Farndale	93.1	99.5	81.9	99.2	99.3	94.2	75.4	93.6	96.6	96.8	84.3	90.1	55.4	89.2
Chenies	Cranleigh	98.1	98.2	96.4	97.0	97.5	97.3	99.2	96.5	97.7	99.1	99.3	97.2	99.3	97.9
	Chieveley	98.1	98.1	96.4	97.0	97.4	97.8	97.7	96.4	97.7	99.0	99.3	97.1	99.3	97.8
	Stanstead	98.1	98.2	96.4	97.0	97.5	98.0	99.3	96.5	97.7	99.1	99.3	97.2	99.3	98.0
	Grimsby	98.1	98.2	96.4	97.1	97.6	94.8	99.3	92.8	94.6	99.1	95.8	97.1	96.3	96.7
	Chigwell	98.2	98.2	96.4	97.1	87.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	36.7
Castor Bay	Silent Valley	0.0	0.0	0.0	0.0	0.0	0.0	0.0	32.2	77.9	89.1	43.4	92.6	98.6	33.4
	Glarryford	0.0	0.0	0.0	0.0	0.0	0.0	88.7	99.4	99.4	99.5	99.0	93.0	98.9	52.1
	Divis Mountain	0.0	0.0	0.0	0.0	0.0	0.0	0.0	81.3	99.4	95.0	47.5	93.0	98.8	39.6
	Edenfel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	78.0	99.5	47.6	93.0	98.9	32.1
	Loughall	0.0	0.0	0.0	0.0	0.0	0.0	39.9	99.0	96.8	99.5	48.5	93.0	98.9	44.3
	Fivemile Town	0.0	0.0	0.0	0.0	8.5	0.0	89.0	99.4	99.4	99.5	99.0	92.9	98.4	52.8
Predannack	Camborne	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	St Mawgan	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	St Marys	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ingham	Braunston	99.0	98.6	59.4	62.1	98.2	99.7	96.8	97.1	99.5	99.5	98.4	99.5	99.1	92.8
	Ludford	98.9	82.4	97.6	99.5	98.6	99.7	99.3	98.0	99.5	99.5	98.4	99.5	99.4	97.7
	High Mowthorpe	95.3	82.7	84.1	93.7	97.5	98.2	82.5	96.4	98.7	99.4	52.1	97.2	99.4	90.6
	Hollinsclough	99.1	98.6	99.5	47.5	96.7	69.7	99.1	91.4	89.3	79.0	91.2	99.5	99.4	89.2
	Worksop	97.9	97.9	97.7	96.9	98.3	99.5	99.3	98.1	98.0	99.3	98.2	99.2	99.2	98.4
	Yaddlethorpe	99.1	98.5	99.5	99.5	98.6	99.2	97.3	97.2	99.5	99.5	98.4	99.4	99.4	98.9
Crug-y-gorllwyn	Treherbert	15.2	98.2	83.6	0.0	0.0	61.2	95.6	98.6	99.5	98.3	99.6	98.9	51.2	69.2
	Posticill	0.0	0.0	0.0	0.0	0.0	0.0	0.0	58.6	57.0	28.0	99.1	99.2	94.3	33.6
	Llandrindod	0.0	0.0	0.0	0.0	0.0	0.0	22.4	98.8	98.9	94.5	99.6	99.0	97.3	47.0
	Maenclochog	0.0	0.0	0.0	0.0	0.0	61.2	82.5	93.3	99.6	96.3	97.6	99.2	96.6	55.9
	Canaston	15.2	98.7	97.5	0.0	0.0	61.2	85.3	78.5	71.1	95.5	99.1	96.6	88.8	68.3
	Dinas	63.8	0.0	0.0	0.0	0.0	0.0	88.5	98.8	98.9	55.5	4.2	41.8	43.6	38.1

4.2 PARAGON analyses

Throughout the period of this project the Chenies and Hameldon Hill radar data have been routinely compared with rain-gauge data. The results of these comparisons have been issued as Radar Data Assessment Reports. In Figure 6 are tables and graphs for each site for June 1992 and January 1993.

The radar rainfall is the areal average for a 5 km square centred on the gauge location, this value being formed by interpolation from the four fixed 5 km squares surrounding the gauge location. The radar-gauge combinations are as specified in the table header. Distance and bearing of the gauge from the radar site are also given.

In the occurrence tables:

M = Data missing
O = No rain recorded
RAIN = Rain recorded

The values are percentages of the total numbers of days or hours in the period.

Assessment Factor (AF) = Radar rainfall (R)/Gauge rainfall (G)

AFs involving R or G less than 0.5 mm are rejected. No AFs exist for zero or missing values of R or G.

Statistics of AFs are given for June 1992 and January 1993. Within any period the frequency distribution of the sample of AF values shown in the figure is highly skewed but the distribution of LOG AF values is more symmetrical with the quoted mean M and the standard deviation S and corresponding standard errors SE(M) and SE(S). LOG AFs with deviation from the mean of greater than ±3 SD are eliminated.

The (harmonic) mean AF of the sample is 10**M. There is approximately 68% probability that the true mean AF lies in the range 10**(M−SE(M)) to 10**(M+SE(M)) and that an individual AF in the sample lies in the range 10**(M−S) to 10**(M+S). Thus M and S (or 10**M and 10**S) measure, respectively, the bias and variability of radar rainfalls compared with collocated gauge rainfalls for the sample, while SE(M) and SE(S) measure the uncertainty in bias and variability.

4.3 NRA Assessments

4.3.1 Performance of Chenies radar

As part of the detailed evaluation of the FRONTIERS products carried out by the NRA Thames Region, radar subcatchment data from Chenies weather radar were used to provide a comparison with the performance of the FRONTIERS forecasts in generating flood forecasts. For events studied in 1991 these radar data were found to produce lower root-mean-square errors in flow forecasts than the FRONTIERS forecasts or the rain-gauge data in both of the two urban catchments studied. However, when the analysis was repeated for storm events in 1992 the uncalibrated radar data produced higher RMSE errors on average than FRONTIERS forecasts for all lead times and rain-gauge data. In addition, it was quite evident from operational experience, that Chenies was significantly overestimating rainfall intensities during the summer period in 1992, and consistently underestimating rainfall intensities in the winter period in the same year. By plotting normalized RMSE errors for all events studied in the Silk Stream and Beverley Brook catchments during 1991 and 1992 the extent of the problem can be clearly illustrated (Figures 7 & 8). This is re-enforced when radar/rain-gauge ratios are plotted against time for the same period for the four Chenies calibration gauges (Figure 5).

In September 1992 the NRA Thames Region requested that the Chenies Operational Working Group be reconvened to discuss the accuracy problems. At the meeting held in January 1993 a strategy was formulated to fully investigate and rectify the inconsistent performance of the radar.

The Met. Office undertook a detection capability exercise using data from the Chilbolton radar and confirmed that Chenies performs poorly both with respect to detection of rainfall and quantitative measurement. An intensive investigation of the radar hardware at Chenies took place over several days in March 1993, and the main conclusions of this investigation are given below:-

(i) A 5 dB one way waveguide loss was measured on 3/3/93. When similar measurements were made on 9/3/93 and 16/3/93 no such high-level loss could be measured. The waveguide system had not been changed in any way between 3/3/93 and 16/3/93, apart from opening and remaking joints to try and measure the loss. The only change in test conditions was that on 9/3/93 the waveguide pressurizing system was found to have failed, but when this was left running for one week and waveguide loss tests repeated, no significant loss was found.

(ii) The sensitivity of the receiver had drifted away from the nominal setting of 23/10/92. Assuming no losses in the waveguide, Chenies should now be overeading significantly (by 3 or 4 times). A colour level check, which measures the input power level at which the processed rainfall changes to the next level on the software display, confirmed that the receiver is over-sensitive. The receiver characteristic will have to be set back to the nominal value of 23/10/92. Following this, it may be appropriate to remove a factor of 2 which is applied to rainfall values in the software. (This factor is not applied to any other radar sites, but was found necessary at Chenies during the period after installation.)

(iii) The orientation of the antenna was checked using a sunshot technique which suggested that the aerial is pointing 0.3 degrees lower than expected. It has yet to be determined what affect the 0.3 degree elevation error has on the general performance, although it is likely that ground clutter will have been increased. If this has occurred as a result of a shift in the squint for mechanical reasons then an increase in clutter should be apparent. (after Buchanan, Lissaman, Smith and Callaghan, internal report).

The effects of the inconsistent performance of Chenies has not only been felt by flood forecasters in the NRA; it is quite clear from the results presented in this report that the FRONTIERS forecasts themselves, generated for short lead times ahead, are also being adversely affected. Average flow RMSE errors for the Silk Stream at Colindeep Lane for 27 events in 1992 presented in Figure 9 show a maximum for the one hour ahead lead time forecasts. This result is reproduced, when the analysis is repeated for convective events only (Figure 13). However when only frontal events are analysed the T + 5 and T + 6 forecasts give the maximum errors (Figure 12). This result indicates that the tendency for Chenies to overestimate in the summer months of 1992, when convective events were prevalent, is possibly adversely influencing the FRONTIERS forecasters to produce inaccurate rainfall forecasts for short lead times ahead.

At the Chenies Operational Working Group meeting held in March 1993 it was decided as a matter of priority to closely monitor the performance of Chenies over the next three months. A major objective is to remove the factor of 2 which is applied, uniquely at Chenies, to rainfall values in the at-site software but only when there is consistent evidence to warrant such action.

4.3.2 Performance of Hameldon Hill radar

The FRONTIERS products were evaluated in the NW Region in terms of assessing the value of the instantaneous 6-hour forecasts, and the flow forecasts from the rainfall forecasts. Hameldon Hill data was not used directly in the flow models, but its availability in contributing to the network actuals has most probably an effect on the FRONTIERS forecasts, at least in the initial period of a forecast.

The monthly average availability for 92/93 (see Annex C) for Hameldon Hill was 89.9%. This relatively low figure was due to various computer and radar hardware faults over the early part of the period, which were finally resolved in September 1992. Since October 1992 the availability has been over 96% for each month.

5. Overall assessment of FRONTIERS forecasts

5.1 Assessment of instantaneous accuracy using CSI, HNK, POD, FAR

The statistical parameters described in the March 1992 Report used to compare the FRONTIERS forecasts with forecasts using persistence have been evaluated throughout the period of this study. Figure 14 shows the values of the Critical Success Index (CSI), the Hans and Kuiper Index (HNK), Probability of Detection (POD) and the False Alarm Ratio (FAR) for forecasts at T + 1 hour. It is clear that the FRONTIERS forecasts are significantly better than persistence. At T + 3 hours Figure 15 shows that FRONTIERS forecasts still outperform persistence, but not by much. The values recorded in April 1993 (the March 1993 figures are not available) show a large improvement in performance. It remains to be seen whether this can be maintained.

The performance of FRONTIERS illustrated in Figures 14 and 15 is encouraging. However it should be noted that there is a marked difference between frontal and convective rainfall situations. Figures 16 and 17 show the values of the statistical parameters averaged over four "thunderstorm" days and over four "frontal" days. FRONTIERS outperforms persistence forecasts in both synoptic situations, although the performance on the thunderstorm days is much worse.

5.2 Analysis at London Weather Centre

For a variety of reasons, mainly connected with the resiting of London Weather Centre to a new building during March 1992, London Weather Centre did not carry out routine monitoring of the FRONTIERS product until October 1992. The following analysis is therefore based only on the period October 1992 to February 1993. During this period a log was kept by the Senior Forecaster on duty, on a shift by shift basis, indicating the usefulness or otherwise of the rainfall radar echoes shown on the FRONTIERS screen.

The forecasters' log gave only a qualitative indication of the performance of the FRONTIERS forecast frames when echoes were moved over south-east England. A more detailed analysis frame by frame in real time was attempted on one occasion, but because of the high forecaster workload during the periods of extensive rain it proved impossible to keep up with the FRONTIERS data and the scheme was abandoned. The forecaster reverted to the coarser analysis below.

The comments for each shift were considered to be concerned with showers or with frontal rain and occurred as in Table 4.

Table 4: Situations analysed by London Weather Centre

	Showers	Frontal
OCT	16	7
NOV	4	25
DEC	4	10
JAN	3	11
FEB	10	8
	37	61

The forecasters' comments on each of the situations in Table 4 were grouped into those that gave FRONTIERS a merit comment for usefulness, e.g. good timing, echoes realistic with ground truth, satisfactory, etc. and those occasions which were unsatisfactory, e.g. poor timing, echoes not decayed, echoes too heavy for ground truth, etc. The term merit does not mean that the product was perfect but implies useful advice on timing and/or rainfall amounts.

Table 5 shows the impressions formed by the forecasters of the accuracy of the FRONTIERS frames when dealing with showers. Table 6 shows impressions of accuracy during periods of frontal rain.

Table 5: Impressions formed by the forecasters: showery situations only

	All	Merit	Poor/Misleading
OCT	(16)	8	8
NOV	(04)	2	2
DEC	(04)	2	2
JAN	(03)	0	3
FEB	(10)	4	6
	37	16 (43%)	21

Table 6: Impressions formed by the forecasters: frontal situations only

	All	Merit	In Merit Col but some reservations	Poor	Misleading
OCT	(07)	5	1	2	–
NOV	(25)	24	10	–	1
DEC	(10)	8	0	1	1
JAN	(11)	11	5	–	–
FEB	(08)	8	5	–	–
	61	56 (85%)	21	3	2

The logged events and opinions, of the five senior forecasters gathered between October 1992 and February 1993, show that the FRONTIERS system produced more useful advice (merit 85% of occasions) when dealing with frontal rain. In showery situations however, the merit percentage was much lower (43% of occasions).

All the showery situations which were given a poor or misleading comment were also logged as a failure to decay the echoes as the FRONTIERS frames moved the rain towards and over south-east England. There were 21 frontal rain situations with a merit and reservations comment. Of these 17 included in the reservations a comment that implied an increase in accuracy would have been achieved if FRONTIERS had decayed the echoes with time as the rain moved into the London area.

This analysis was conducted during the winter half of the year when rainfall bearing systems moving toward London are coming from areas of high sea temperatures and/or high ground to cold low ground. Therefore unless development is forecast, decay of rainfall echoes would be expected.

Two frontal rain situations were labelled misleading. One was a complex situation with both development and decay taking place at different times over south-east England with FRONTIERS showing the reverse. In the second FRONTIERS had the echoes moving in the wrong direction.

5.3 Analysis at Manchester Weather Centre

5.3.1 Operational precipitation forecasting at Manchester Weather Centre

Heavy rainfall warnings have been issued for the Northwest Region for over 20 years using the same empirical forecast rules developed by Holgate (1975) at Preston (the main Met. Office for the Northwest in the early 1970s).

Increasingly sophisticated computer models and radar technology have added to the forecasters' ability to apply these rules. The radar display in particular is of great benefit in identifying potential warning situations close to the event, and the development of FRONTIERS now quantifies the accumulative rainfall totals over individual catchment areas for six hour periods.

The methodology followed at Manchester Weather Centre is as follows. The first indication of a potential heavy rainfall situation is given from perusal of the output from the Global and Limited Area Model (LAM) computer runs. LAM output is available at the weather centre four times a day from model runs at data time 0000, 0600, 1200 and 1800 hours. These forecast charts show areas of rain and give 6-hourly rainfall totals on a 75-kilometre grid. The forecasters use their judgement to assess the probable rainfall using these and other elements of the model output. In particular they use the wind speed and direction and the partial thicknesses, together with the speed and movement of rain bearing systems, to evaluate rainfall totals over the region. A warning is not often issued more than twelve hours before the event as the forecaster needs confidence that the predicted developments are in fact taking place. Collaborating evidence from surface observations and radiosondes and from the improved radar coverage now available to the forecaster on the Outstation Display System (ODS), will sway the decision one way or the other.

An example is shown in Figures 18–20 of an occasion (21 Jan 93) where the forecaster issued a warning for an event "A" (30 mm or more over Cumbria), based on expectation of enhanced rainfall due to strong winds onto the catchment area, together with high humidity. The rainfall totals from the gauges show that although Castlethwaite had nearly 16 mm rain in three hours, and 23 mm in six hours, totals generally fell short of expectation (see Figure 18). The LAM forecast 5 mm in six hours at the nearest grid point in the north (see Figure 19), which was about half the subsequent total. The empirical rules developed by Holgate (see Figure 20) suggest the forecaster should have issued a type "B" warning (15 mm for catchments 11 to 14), and the total at Trawden suggests that this could have been justified. In this case the forecaster appears to have been influenced by the low rainfall totals from the LAM over Lancashire, and the direction of the wind flow, which would result in some shelter for the southern catchment areas.

The Holgate criteria relate the synoptic situation directly to a warning action, "A", "B" or "C", for particular catchment groups. The results are summarized in tabular form as shown in Figure 20, or they are available as a flow diagram of action to take as a result of choices about (1) the synoptic situation, (2) the humidity profile, and (3) the gradient wind speed. The example given above would take the forecaster to the 3rd case on Figure 20, which indicates action for warning type "B", but qualifies it by asking the forecaster to consider the frontal orientation and activity, plus likely orographic enhancement. In our example these considerations must have been influential in persuading the forecaster not to issue a type "B" warning in this case, and rainfall totals of 2 mm to 6 mm over catchments 11 to 14 support his action.

5.3.2 Assessment of the operational forecasting procedure

There is no systematic assessment undertaken at present, but the relevant rain-gauge values are presented after each warning issued so that the forecaster can assess the effectiveness of the warning. Past assessment (Final Report, March 1992) has indicated that forecasters over-warn, erring on the side of caution, however, it was also shown that MWC warning criteria are rarely missed. Rainfall warnings are more likely to be missed when there is instability giving heavy showers and thunderstorms. An additional warning service started in June 1992 to cover the situation where thunderstorms are expected to give substantial rainfall totals (10 mm or more), in any catchment area.

5.3.3 Conclusions drawn from assessment of forecasting procedure

The forecasters use empirical rules developed and tested over many years, together with modern computer and radar technology, to give a warning service and routine forecasts to the NRA. There are more warnings issued than events justify, which indicates some caution on the part of the forecasters. Feedback from the customer should alert the forecasters as to the relative importance of giving an adequate warning or risking a false alarm.

5.3.4 Assessment of FRONTIERS forecasts

The FRONTIERS 6-hour forecasts of precipitation distribution (not quantity) have been assessed by the Senior Forecasters at Manchester. These forecasts have been on continuous display in the forecast room since mid-1991 and some 700, 12-hour periods in which precipitation was forecast, were assessed in real time. The area considered was the whole of England and Wales, the Irish Sea and part of the southern North Sea.

Half of the forecasts gave misleading advice. Most of these misleading forecasts attempted to predict shower distribution and since showers very rarely last for more than 2 hours, forecasting the persistence of these for 6 hours is inherently doomed to failure. Other poor results arose from successive runs giving moving echoes. Sometimes, successive runs will move obviously spurious echoes through the forecast sequence, or fail to move obvious trough-lines of showers in a coherent manner. Over the last few months an increase in the number of these types of poor advice has been noticed. When areas of precipitation are developing FRONTIERS does not help either, since the shape and size of echoes are kept constant in its forecasts, whereas in the real atmosphere these change significantly in the 6 hours.

Half of the FRONTIERS forecasts were sensible and verified well. However, the consensus among the forecasters at Manchester is that the number of occasions when the forecasts contribute something of real value is small. FRONTIERS is at its best when moving frontal rain or large non-varying clusters of showers or dynamic rain. Forecasters confirm that the FRONTIERS forecast is sensible, by using continuity of recent radar echoes.

6. Assessment of river flow forecasts

6.1. NRA Thames Region

6.1.1 Procedures and models used

The details of the procedures and models used in the study are contained in the March 1992 report, and therefore are not reproduced here.

6.1.2 Analysis

(i) Event Selection

The basic selection criteria used in this assessment was outlined in the Final Report of POSFFAG, which covered the period from October 1990 to December 1991. This same method of selection is used to identify events for the final evaluation of FRONTIERS accumulation data presented here.

During the reporting period from January 1992 to February 1993, all events in which the recorded flow exceeded a specified threshold were identified. This threshold value is different for each of the three river catchments and takes into account the mean annual flood of the catchment and the resulting number of events selected. Obviously the majority of events chosen have not led to significant flooding. The two that have, and another smaller frontal event are focused upon in more detail in the case-studies detailed in Section 7.

To avoid biasing the results and making any comparisons invalid, only events where at least 80% (by volume — following substitution of missing data by an alternative source) of each data type are available (rain-gauge, radar and FRONTIERS forecasts at all lead times) are accepted for the final analysis.

Using these methods of selection, the following numbers of events could be used for assessment in each of the three river catchments:

Silk Stream at Colindeep Lane	: 27 (4 exceeding 1 in 2 year river flow)
Beverley Brook at Wimbledon Common	: 23 (0 exceeding 1 in 2 year river flow)
River Roding at Loughton	: 12 (1 exceeding 1 in 2 year river flow)

It might be expected that FRONTIERS will perform better under certain meteorological conditions, for example in a simple frontal situation rather than in the more complex convective scenario, where significant development and decay may be taking place. In order to look at this question, in addition to forming statistics over all selected events, a distinction is also made between events which are considered to be dominated by convective processes, and those which are largely due to the existence of a weather front. Guidance on the classification of events was obtained from the Met. Office, and only those events which are considered to be wholly either frontal or convective are used in the analysis. Using this information the following numbers of frontal and convective events are included in the assessment for each of the three river catchments.

Silk Stream at Colindeep Lane	:	13 frontal events 8 convective events
Beverley Brook at Wimbledon Common	:	12 frontal events 8 convective events
River Roding at Loughton	:	5 frontal events 1 convective event

(ii) Results

(a) Silk Stream at Colindeep Lane

Results generated for events occurring during 1991, reported in the Final Report of POSFFAG, showed a wide variation between events of the relationship between FRONTIERS forecast lead-time and root-mean-square error (RMSE). This is also true for the more recent period from January 1992 to February 1993. This means that Figure 9, which shows the average RMSE for all 27 events identified at Colindeep Lane, masks these differences between events and should be treated with caution, as should all the average RMSE statistics quoted. Figure 9 does show that average RMSE actually decreases with lead-time rather than increasing as might be expected. It is thought that this may be due to the increasing influence of rainfall data from Chenies radar at shorter lead-times. The problems experienced with Chenies radar, which may be causing this effect, have already been discussed in Section 4.3. In fact using uncalibrated radar data alone gives a much higher average RMSE, whilst Harrow Weald rain-gauge data give an average RMSE of the same order as the FRONTIERS forecasts.

The 27 events used to form the averages in Figure 9 include some rather small events. Of course, to flood forecasters, it is the more significant events which are most important and which FRONTIERS must predict well. Figure 10 shows the average RMSE for different lead-times for the 10 events which produced the highest peak observed flows during the period. It can be seen that the T + 1 forecasts still lead to the highest average RMSE and the T + 6 forecasts to the lowest, whilst all the RMSEs are a factor of two larger. FRONTIERS forecasts at all lead-times outperform both uncalibrated radar data and Harrow Weald rain-gauge data for the 10 largest events. A similar analysis with only the 4 largest events, that is those in which the level at Colindeep Lane reaches at least low sensor (approximately equivalent to a 1 in 2 year level), is shown in Figure 11. Once again FRONTIERS forecasts outperform radar data and rain-gauge data on average, although here the RMSE does increase with increasing lead-time except for the T + 1 forecasts.

Figures 12 and 13 show average RMSEs for 13 frontal and 8 convective events respectively. There are marked differences between the two different types of meteorological situation. Firstly, RMSEs for convective events, regardless of the source of rainfall data, are much higher than for frontal events. The large RMSE for FRONTIERS T + 1 forecasts is very evident in the convective events, but cannot be seen in the frontal events. Uncalibrated radar data perform badly in both frontal and convective situations. Harrow Weald rain-gauge data actual gives the worst results for frontal events, although the rain-gauge performs fairly well for convective events, relative to the FRONTIERS forecasts.

(b) Beverley Brook at Wimbledon Common

Figure 21 shows the average RMSE for all 23 events identified at Wimbledon Common. The average RMSE does generally tend to increase with increasing lead-time, although the T + 5 forecasts do not perform as well as the T + 6 forecasts, and also, as with Colindeep Lane, the T + 1 forecasts produce a large average RMSE. Uncalibrated radar data once again led to the highest RMSE of all and data from the two rain-gauges at Hogsmill and Cheam produce RMSEs of the same order as the FRONTIERS forecasts.

Average RMSEs for the 10 events which produced the highest peak observed flows during the period January 1992 to February 1993 are shown in Figure 22. It can be seen that there is still a general trend of increasing RMSE with increasing lead-time although the T + 5 forecasts produce a higher average RMSE than the T + 6 forecasts and the T + 1 forecasts produce a large average RMSE. Once again, uncalibrated radar data led to the highest RMSE overall and the rain-gauges give a RMSE similar to that of the FRONTIERS forecasts.

No events during the reporting period led to a level at Wimbledon Common as high as low sensor (approximately equivalent to a 1 in 2 year level).

Figures 23 and 24 show average RMSEs for 12 frontal and 8 convective events respectively. There are marked differences in the results for the two different meteorological situations. Firstly, the large RMSE for FRONTIERS T + 1 forecasts is very evident in the convective events but cannot be seen in the frontal events. Uncalibrated radar data perform badly in convective situations but better under frontal conditions. As was seen in the Silk Stream catchment, the rain-gauges give higher RMSEs than radar subcatchment data for the frontal events but they produce low RMSEs in convective conditions. In fact Cheam rain-gauge gives the lowest average RMSE over all the convective events.

(c) River Roding at Loughton

Average RMSEs for all 12 events identified at Loughton are shown in Figure 25. For this river catchment, the average RMSE does generally increase with increasing lead-time as might be expected. There is no sign of the high RMSE for T + 1 FRONTIERS forecasts as seen in the other two catchments. Also, in contrast to the other study areas, uncalibrated radar data led to the lowest RMSE of all, performing slightly better than the T + 1 FRONTIERS forecasts. Data from the two rain-gauges at Thornwood and Epping produce RMSEs of the same order as the FRONTIERS forecasts although Thornwood gives a smaller average RMSE than Epping.

Average RMSEs for the 10 events which produced the highest peak observed flows during the period January 1992 to February 1993 are shown in Figure 26. As only the two smallest events have been excluded from the analysis, the change in the relative RMSEs is not noticeable. However, the actual average RMSEs are higher over the lesser number of events.

Only one acceptable event during the study period led to a level at Loughton as high as low sensor (approximately equivalent to a 1 in 2 year level), on 10th January 1993. The RMSEs for this single event are displayed in Figure 27. Average RMSE does generally increase with increasing lead-time although the RMSE for the T + 2 forecasts does slightly exceed that for the T + 3 forecasts. In this particular case, the two rain-gauges perform very well, but the uncalibrated radar data gives an RMSE of the same order as the FRONTIERS forecasts.

Figures 28 and 29 show average RMSEs for 5 frontal and 1 convective event respectively. There are marked differences in the results for the two different meteorological situations. In the frontal events, there seems to be no trend in RMSE with lead-time, T + 3 giving the lowest and T + 5 the highest RMSE. Both uncalibrated radar data and rain-gauge data lead to RMSEs of the same order as the FRONTIERS forecasts. For the one convective event identified there is a very strong trend of increasing RMSE with increasing lead-time. Uncalibrated data perform best overall and the two rain-gauges give the highest RMSEs, Epping rain-gauge giving a significantly larger RMSE than any other data source.

6.2 NRA North West Region

6.2.1 Procedures and models used

The FRONTIERS 6-hour forecasts are displayed in the NRA North West flood forecast room, with a view to assessing their value for helping in flood warning activities.

The process is rather subjective and it is very difficult to be quantiative, although the overall impression (similar to MWC's forecasters' view is that around half the forecasts were useful).

However, in an event, there is not a lot of time to assess the confidence that should be placed in the forecast. With the problems of inconsistencies in the velocity of rain areas and the growth/decay issue in this area, the contribution of the pictures is variable, but can be helpful.

Some of the inconsistencies may be reduced or removed as the procedures applied to the forecasts become more automated through the Nimrod project. This, and discussion of the 'confidence level' with the local Weather Centre forecasters, may improve the value of the forecast displays.

In order to assess the potential of FRONTIERS forecasts for hydrological flow forecasting the NRA North West Region placed a contract with the Water Resources Section of the Department of Civil Engineering, University of Salford to provide appreciation of the performance of FRONTIERS instantaneous rainfall forecasts in flow forecasting for a part of the country other than south-east England with different types of catchments, i.e. steep rural rather than urban, and also to complement previous work done on NW flow models.

Transfer function flow models (see March 1992 Report) were used to assess both FRONTIERS forecasts and rainfall forecasts derived from a cross-correlation procedure (CCF, developed by Salford for the NRA Wessex Region and known as the WRIP procedure) similar to that developed by the Institute of Hydrology for the NRA Thames Region. Forecasts were assessed using a root-mean-square error (RMSE) in a similar way to that used in the Thames Region.

6.2.2 Analysis

(i) Event Selection

Very few high flow events were experienced in the period, all having return periods of 2 years or less. A large event, 1 in 18 years, which occurred in December 1991, was used.

Three different types of catchment were chosen, all within range of Hameldon Hill, with catchment areas from 40 to 186 km^2. Only 8 events were used eventually in the analysis:

R. Darwen at Wood	40 km^2	1 event
Sankey Brook at Causey Bridges	154 km^2	3 events
R. Roch at Blackford Bridge	186 km^2	4 events

(ii) Results

Detailed results for these catchments and events are contained in the assessment report (Han and Cluckie, February 1993) and the main findings are:-

- The availability of FRONTIERS data caused severe problems for the data analysis, but great improvements have been made in the last few months and was confirmed by the later event data as shown in Figure 30.

- For the comparison of rainfall forecasting with CCF, FRONTIERS produced more stable and accurate rainfall forecasts in the long term when compared with the CCF method, Figure 31. However, in the short-term forecasts, CCF achieved better results than FRONTIERS forecasts. This implies that a more appropriate short-term (i.e. first 2 hours) procedure could be developed which exploits automatic methods.

- From the hydrological modelling point of view, the first 3 hours FRONTIERS forecast produces significant benefit and the forecast accuracy deteriorates after this time (Figure 32).

- In the flow forecasting mode, FRONTIERS forecasts outperforms other rainfall options, and generally improves the hydrological forecasting. However, as the flow feedback from the telemetered outstations plays an important role, similar forecast accuracy are achieved by all the rainfall options for the first two time-steps (which in the case of the present study was for a two-hour period). The difference begins to show after three hours though this was more obvious for small catchments. From the 8 events analysed, the FRONTIERS forecasts were able to improve river flow forecasting when compared with subjective rainfall options. However, the improvements were very limited in a few cases.

7. Case-studies

7.1 Methodology used by the NRA Thames Region in assessing case-studies

A number of significant flood events occurred in 1992 which gave rise to varying degrees of flooding in the three study catchments. It was decided to analyse three of these events in some detail to ascertain the relative performance of FRONTIERS in generating flood forecasts; 9 June 1992 and 22 September 1992, which were predominantly convective events, and the frontal event covering the period 24 November to 3 December 1992. In contrast to the methodology adopted in section 6, a fixed origin variable lead time approach was used to mimic the use of FRONTIERS in operational flood forecasting procedures. Post-event flow predictions made with rain-gauge and radar data are also included for comparison.

In looking at the modelled flow hydrographs presented in these case studies it is necessary to bear in mind the following points when making judgements about rainfall forecast performance;

(i) the methodology does not quite mimic that which would be implemented operationally due to the fact that the FRONTIERS accumulation data are not transmitted until at least half an hour after the time for which they apply. In these examples, it has been assumed that the FRONTIERS forecasts become available at the time of origin of the forecasts;

(ii) rainfall recorded by an appropriate telemetered rain-gauge is used as the observed rainfall prior to the forecast origin. In some cases these estimates of point rainfall are not representative of the rainfall falling on the whole catchment and this can lead to poor predictions of river flow. In other words, it is not only the forecast rainfall which causes poor forecasts of future river flow, the observed data may also be a contributing factor;

(iii) the modelled flow hydrographs obtained using the subcatchment rainfall data from Chenies radar are affected by the technical problems discussed in Section 4.3;

(iv) the Isolated Event Model was designed to be used in small fast-responding river catchments and is not really suitable for use in large rural catchments such as the River Roding at Loughton. This may lead to what appear to be poor modelled flow predictions which are in fact not due to inaccurate rainfall forecasts but rather to the poor performance of the model itself;

(v) as FRONTIERS only produces rainfall forecasts out to 6 hours ahead it cannot be expected to predict river flows well over very long events. It is only when an area of rainfall comes "into sight" that its response will be reflected in the modelled flow hydrograph.

7.2 30 April 1992 (meteorological analysis only)

7.2.1 Introduction

At 0001 UTC on 30 April 1992, a warm front was approaching the west of the region, moving at about 25 kt. It continued at this speed across the region, giving mainly small amounts of rain. By 1200 UTC, the warm front lay north to south across Yorkshire. At the same time, the cold front of the system was beginning to move south-eastwards across Northern Ireland, with something of a trough to the rear of it. The cold front had moved at 25 kt as well during the previous 6 hours, and was forecast to continue to do so, clearing the region by midnight on 1 May 1992.

The midday data received was indicating that the warm sector air over the region, was moist to about 10 000 ft, and satellite pictures indicated that there were breaks in the cloud. Earlier doubt had been expressed by one of the forecasters during the morning handover about rain amounts, since the warm sector did not have any really thick cloud.

7.2.2 Micro-radar sequence

Between 1300 UTC and 2100 UTC, some 8 hours, Manchester Airport recorded 10 mm of rain, with just over 4 mm during the passage of the cold front. The radar sequence represented this well. The region as a whole is more difficult to assess from the radar displays, but a quantitative assessment yields about 24 mm. This largely fell during a 6 hour period, and would have been classified as a type B warning for areas 11 to 14. A type A for 1 to 10 seems unlikely, and the Wirral was not involved.

7.2.3 Conclusion

A general type A warning (see section 5.3.1) was not justified, and the midday data was marginal for a type B warning. However, the evidence from the radar with hindsight, suggested that in fact a type B occurred, but this can only be confirmed from the gauge readings for the day.

7.3 9 June 1992

7.3.1 Introduction

A number of very intense convective storms affected the London area which gave rise to widespread surface water flooding throughout the capital and river flooding specifically from the River Ravensbourne and its tributaries. One of the study catchments, the Silk Stream was also affected and overtopped to flood gardens and roads in the Colindale area in north-west London.

The synoptic situation at midday on the 9 June 1992 over southern England and Wales is shown in Figure 33. Also shown is an analysis of the boundary layer flow. An extensive convergence zone oriented north west to south east is evident over southern England and Wales consistent with the location of the thunderstorms. The radiosonde ascent at midday for Crawley (Figure 34) shows the air to be very unstable, and an evaluation of the Convectively Available Potential Energy (CAPE) gives a value of 1500 m^2 s^{-1} indicative of the likely occurrence of thunderstorms.

Figure 35 shows the distribution of radar echoes at 1500 UTC. Storm cells are occurring along the length of the convergence zone. Rainfall intensity values of many tens of millimetres per hour are measured by the C-band radar located at Chenies north of London (Figure 33), although there are limitations in the quantities of these values. Nevertheless, the occurrence of severe flooding, particularly at Lewisham in south London (Figure 33) is evidence that substantial rainfall did occur. Figure 36 shows the hyetograph for a gauge located near the centre of the heaviest rainfall; 70 mm fell in just over two hours.

7.3.2 The radar measurements of rainfall

Figure 37 shows a sequence of rainfall profiles taken from the radar site towards the south east through the centre of the maximum storm cell activity. In fact the line of the profile rotates slowly anticlockwise (about 20° on one hour). This will be important in considering the nowcasts (observations and forecasts for a few hours ahead) made. The profiles indicate very large instantaneous rainfall rates, in excess of 120 mm h^{-1}.

The radar making these observations operates at C-band, 5.6 cm wavelength, and therefore the measurements are effected by attenuation of the power in the radar beam by heavy rain. In addition, the measurements will also suffer from attenuation produced by a water film on the radome housing the radar antenna, this also being a function of rainfall rate. Fortunately on this occasion rainfall at the radar site was light, and radome-induced attenuation will have been negligible.

Attenuation of the radar beam as it passes through heavy rainfall is corrected in the real-time software in use at the radar site. The following formula is used (Harrold, 1965),

$$\text{Two-way attenuation} = 0.0044R^{1.17}\ \text{dB km}^{-1}. \qquad (1)$$

The general formulation for the attenuation relationship was proposed by Hitschfeld and Bordan (1954), and its application is known to be unstable to small overestimates of the measured reflectivities (systematic biases) (see for example Debrieu *et al.* 1992). Whilst equation (1) is regarded in general as a good approximation to the magnitude of the attenuation effect, it has not been extensively tested in the United Kingdom environment within very heavy rainfall. Radar data such as those shown in Figure 37 are overestimates of rainfall in the centre of the storm cell during the period of maximum rainfall from about 1530 to 1800 UTC by a factor of at least 1.5, as shown by the rain-gauge data in this region (Figure 36). Hence we might expect the application of equation (1) to be unstable on this occasion.

To examine whether some part of this overestimate may have been due to an inadequacy in equation (1) or its application, the radar values at 1615 UTC shown in Figure 5 have been processed to remove the real-time attenuation correction. It should be noted however that errors will remain as the radar values after correction using equation (1) exceed the maximum value which can be recorded (about 123 mm h^{-1}). The result is shown in Figure 38, with the real-time generated values for the radar data at 1615 UTC. It is clear that there was substantial attenuation which may in fact have attenuated the radar echoes on the side of the storm furthest from the radar site to almost zero on occasions. Also shown in this figure is a rainfall profile corrected using the modified attenuation formula given in equation (2), which will be justified in the following paragraphs.

Two way attenuation

$$
\begin{aligned}
&= 0.0044R^{1.17}\ \text{dB km}^{-1} && R < 50\ \text{mm h}^{-1} \\
&= 0.43\ \text{dB km}^{-1} && 50 < R < 90\ \text{mm h}^{-1} \qquad (2) \\
&= 0.0044\ (R-90)^{1.17}\ \text{dB km}^{-1} && R > 90\ \text{mm h}^{-1}
\end{aligned}
$$

Equation (2) produces rainfall values which would lead to rainfall amounts closer to the rain-gauge total (Figure 36). However, such a change in the real-time processing will not remove the detrimental effects of systematic biases in the radar estimates. Consideration of the routine radar/rain-gauge comparisons carried out for Chenies by the Meteorological Office suggest that a systematic bias of 1.5 may be present in the data. Removal of this bias would increase the correspondence between the radar and gauge estimates. Therefore we must also consider whether equation (2) is physically realistic or whether such a change to the attenuation correction is inappropriate given that it may only be a reaction to the effect of calibration problems.

The real-time radar software uses the radar equation to relate mean received power to the sixth power of the diameters of the hydrometeors and hence rainfall rate. Rayleigh scattering from raindrops is assumed (see for example Collier, 1989). The occurrence of hail within the radar beam will produce enhanced radar echoes, and this approximation is no longer valid, Mie scattering being more appropriate. The differences in rainfall rate are not large. For example at 100 mm h^{-1} consideration of Mie scattering produces a reduction of about 5 mm h^{-1}! More importantly hail produces quite different attenuation from raindrops. Battan (1971) suggests values of two-way attenuation for dry hail which may be appropriate at the mid-levels of the 9 June storm. The attenuation is a function of the size of the hail. Using the relationship between hydrometeor diameter and rainfall rate given in equation (3) with equation (1) and the data given by Battan (1971), we may derive values for the ratio of actual rainfall rate

$$\text{Medium hydrometeor size, } D = 0.92\ R^{0.21}\ \text{mm} \qquad (3)$$

to observed rainfall rate as a function of observed rainfall rate for both raindrops and hail. The result is shown in Figure 39 in which it is clear that the attenuation produced by dry hail is much less than that produced by large raindrops. However, there is likely to be a mixture of hail and raindrops in thunderstorms, and therefore it is necessary to select a compromise attenuation relationship such as that given in equation (2) which is also plotted in Figure 39. It should be noted that there are no unique relationships between attenuation and rain or hail size. Equation (2) is very much empirical and requires extensive checking.

Hail was observed in a few places on 9 June, although not near Lewisham. Therefore, it is quite reasonable to assume that hail would have occurred at medium levels within the thunderstorm cells observed on this occasion. Hence high radar reflectivity values are probably produced by hail and raindrops and consequently application of equation (2) would seem to be appropriate.

Radar is also known to overestimate rainfall in the presence of strong downdraughts which certainly exist in thunderstorms. Without Doppler radar measurements of hydrometeor motion, or high-resolution numerical model analyses, it is not possible to assess with complete confidence whether this could have caused the over-estimation. However, the extremely large radar-values shown in Figure 37 occur over a horizontal scale of at least 10 km. Intense updraughts and downdraughts in moderate size thunderstorms are only likely to have a horizontal scale of 1–2 km. Finally, Figure 35 shows an area of echoes about 15 km east-south-east of the most intense echoes. This echo area remains almost stationary, and it may be due to anomalous propagation in the cold outflow from the main storm cell. The 5 km × 5 km upper beam (1.5°) radar data suggest that this echo area is indeed due to such anomalous propagation effects, as the echo is intense on the surface beam (0.5°), but absent on the 1.5° beam.

We have assumed throughout this discussion that the radar receiver is calibrated correctly. This seems to be the case, and therefore we must conclude that the real-time attenuation correction currently applied at the radar site should be modified along the lines of equation (2). However the analysis reported in this paragraph is rather crude and further work on attenuation correction at C-band frequencies is essential.

7.3.3 Nowcasts of rain

Two methods of producing very short period forecasts of rainfall for use by the National Rivers Authority Thames Region in a flood forecasting model (MO/NRA 1992) were operative on this day. FRONTIERS man-computer forecasts were generated in real-time on a 5 km × 5 km grid in the Central Forecast Office, Met. Office, Bracknell (Brown *et al.* 1992). Forecasts were also produced using a cross correction technique with the 2 km × 2 km grid radar data. This procedure, known as the local forecasting technique, has been developed by the Institute of Hydrology (Moore *et al.* 1992). An example of the FRONTIERS forecast and its verification is shown in Figure 40 with an example of a forecast made with the local forecasting technique. A storm developed ahead of the main line of convection which decayed.

Both forecasting procedures led to poor flow forecasts in the region of very heavy rainfall. However, the local forecasting technique was somewhat better than FRONTIERS. Careful examination of each set of forecasts reveals that the FRONTIERS system identified the anticlockwise rotation of the convergence zone (main line of convection) mentioned in section 1, whereas the local forecasting technique appears to have picked up the motion to the south-east "implied" by new cell generation (Figure 37). The motion implied by new cell generation is around 7 m s^{-1}, whereas that evident from the convergence zone rotation is about 4 m s^{-1}. Although these speeds are small, they are in directions at right angles to each other, and therefore will result in quite different forecasts.

Since new cells are being generated, a forecast which moves an existing cell into a position where a cell grows is likely to produce a somewhat better forecast. However, it is clear from Figure 37 that any linear extrapolation technique, of which both the procedures used are examples, will be very unsatisfactory. As new cells grow rainfall rates from zero to tens of millimetres per hour occur within 5–10 minutes, whereas the storm system as a whole lasts for several hours.

7.3.4 River flow forecasting

Figures 41(a)–41(c) show modelled flow hydrographs which would have been generated by three separate FRONTIERS accumulation transmissions at different stages throughout the event. Rainfall recorded by Harrow Weald rain-gauge is used as the observed rainfall prior to the forecast origin and FRONTIERS forecast accumulations for the six hours following. Beyond 6 hours ahead, rainfall is assumed to be zero. The observed flow is given in blue for comparison. It can be seen that FRONTIERS substantially underpredicts the rainfall to come at 1300 UTC on 9 June 1992 (Figure 41(a)) but at 1600 UTC an excessive amount of rain is forecast (Figure 41(b)) causing a huge flow to be predicted. Figure 41(c) gives the modelled flow profile produced by the FRONTIERS accumulation forecasts at 1800 UTC. The predicted recession is rather slower than that actually observed due to forecasts of further rain by FRONTIERS.

Figure 41(d) shows the response which would have been expected if rainfall data from the tipping-bucket rain-gauge at Harrow Weald had been used throughout the event. This is obviously not a simulation of operational real-time procedures but helps to put the performance of FRONTIERS rainfall forecasts into perspective. The rain-gauge data tends to give an overestimate of river flow. Figure 41(e) displays the modelled hydrograph generated from radar subcatchment data. It shows a vast overestimation leading to impossibly high predicted flows. The reasons for the overestimation of rainfall by Chenies radar are discussed in section 4.3. Overall, FRONTIERS forecasts were felt not to be at all helpful during this largely convective event.

7.4 22 September 1992

7.4.1 Introduction

A complex low pressure system with associated weather fronts gave rise to severe flooding in eastern and south-eastern England. Outbreaks of rain occurred over the Thames Region of the NRA throughout 22 September 1992 and the weather system moved little during the day. By 2100 UTC the front began to occlude and this process signalled the start of a period of prolonged and heavy rainfall with thundery activity. All three study catchments were affected, but only in the Silk Stream catchment did property flooding take place.

Animated satellite imagery showed clearly that the case was one of 'organized' cyclogenesis commonly seen in various upper patterns and which can occur over different scales. This was an example of a small-scale variety on the north-east side of an upper vortex. (It was not just a case of thunderstorms moving up from France in warm air on the forward side of an upper trough (the Spanish Plume) as on several occasions during the summer of 1992.)

The exceptionally heavy rainfall totals (mostly between 18 UTC on 22nd September and 06 UTC on 23rd) were due to an area of ascending potentially unstable air which was quasi-stationary because the velocity of the developing low moving from the south was nearly equal and opposite to the relative winds from the NE. The rain was concentrated in one place but the system did not produce exceptional rainfall rates in the Lagrangian Frame of reference (in a coordinate system moving with the system) compared with other systems. The dew-points were not exceptionally high.

7.4.2 Local Area Model (LAM) analyses

The 00 and 12 UTC runs of the LAM did eventually simulate the small area of cyclogenesis ahead of the upper vortex but in neither case was it early enough in the 00 UTC run, the cyclogenesis was not sufficiently marked, resulting in,

- not enough warm, moist air being advected on the northern side of the vortex
- insufficient ascent
- not enough precipitation.

It did eventually produce rainfall but 12 hours too late and too far east. The rainfall was significantly underestimated.

The 12 UTC run did eventually produce rainfall totals in the correct area, with 41 mm near Bedford, but a little too late and for too long. Bearing in mind the model's grid length, these totals would suggest locally heavy falls of rain. From this case, there does not seem to be any obvious justification for seriously doubting the treatment of moisture and production of rainfall in the LAM, although it could be argued that convective rain should perhaps have been produced earlier, as in the mesoscale model (see section 2.3).

The unbogussed and humidity-bogussed 12 UTC runs gave practically identical solutions. The comparison suggest that the representation of the humidity in the bogussed area (East Anglia) was not a problem.

A comparison of tropopause Potential Vorticity (PV) maps from the 00 UTC and 12 UTC runs suggest little difference in the upper-level forcing between the runs. In fact, the 00 UTC run appears to be slightly stronger than the 12 UTC run but both are slightly weaker than our estimate of reality. However, the position of the warm, moist air which contributed to the system development (shown very well on the satellite images) was deficient when comparing the 12-hour forecast from 00 UTC with the analysis for 12 UTC.

The upper fields at 12 UTC from the 00 and 12 UTC runs were similar; the model's upper winds mostly agreed with the observed winds over the Continent to within a few knots. However there were some differences noted in the analysis at 500 hPa over Europe where the gradient from the model was too weak. It was in the period after this that the model (00 and 12 UTC runs) and observed winds diverged, the model winds being some 20 knots lighter at midnight. This could explain why the cyclogenesis was retarded in both model runs.

It was also noticed that the upper vortex acquired its circular shape earlier (with a stronger easterly component on its northern side) in the 12 UTC run than the 00 UTC run. This more rounded shape agreed better with the observations. Perhaps the 00 UTC run of the model may not have captured earlier upper-level forcing, due for example to a short-wave trough moving around the eastern side of the vortex.

It is interesting that there have been other occasions in 1992 which showed similarities to this case. Also the case of 19 October 1991 exhibited a very similar synoptic pattern with a disrupting upper trough, a cyclogenesis on the forward side of it and some heavy, thundery rain on the northern flank which was not well predicted by the model. The advection of warm air round the northern side was not well modelled. It would be useful to look at this case (and others) and see whether there are other similarities in the detail to the 22 September case from which conclusions can be drawn.

Other similar small cyclogeneses in more mobile upper patterns containing less unstable air have also been observed to be mishandled. This is a subjective judgement based on regular inspection of the model forecasts and would have to be substantiated. If so, this provides more evidence for the forcing to be poorly simulated in these situations.

7.4.3 The mesoscale model simulations

A factor suggesting smaller-scale effects could be important is that the mesoscale model run at 06 UTC can be made to produce reasonable solutions for the rainfall, using certain specified variants of data assimilation and/or physics. Accumulations were higher in the mesoscale model than the 06 UTC LAM, probably because of the higher resolution:

- resolving smaller-scale areas of higher accumulations
- producing stronger vertical motions forced by tighter gradients.

The patterns of 850 hPa Wet Bulb Potential Temperature (WBPT) in the 06 UTC LAM and mesoscale model are nearly identical, suggesting that the larger-scale forcing in both models is essentially the same, as might be expected. The tongue of high WBPT extending from the NE over SE England is pronounced.

The mesoscale model generates heavy dynamic rain after midnight on the 23rd, in agreement with the earlier assertion that the larger-scale forcing (that must be generating it) is retarded. The pattern of the dynamic rain agrees with the conceptual model; the rates are consistent with those observed but are rather too far west. The instantaneous rates and accumulations of rainfall depend on whether the mesoscale data assimilation was included and also the parameters in the convection scheme.

The mesoscale model is capable of generating convective rain over a large area of central and southern parts of the UK throughout the period, presumably because the air was unstable enough for convection to be initiated using a certain representation of the physics.

The best mesoscale forecast did not include data assimilation. Therefore this should be compared with the LAM without data assimilation and the same physics to see if the higher resolution produced a different evolution or just higher rates and accumulations. The dependence on data assimilation indicates that the forecasts were sensitive to the definition of the initial fields at 06 UTC. This needs further investigation. Runs with data assimilation were less sensitive to changes in physics than those without mesoscale data assimilation.

Changes to the convection scheme did not just change rainfall rates but altered the timing and location of the highest accumulations and instantaneous distribution of precipitation, presumably through feedback of vertical redistribution of heat and moisture.

7.4.4 The effect of topography

It has been suggested that the case was not well simulated because of topographical effects. It is possible that the initial development of convective cells could have been influenced by local topography but the satellite imagery and the scale of the precipitation over a large area of generally flat land both suggest the effect of topography is not critical and that larger-scale factors are at work.

Other factors against are that,

(a) there is no evidence from the radar imagery of any firm correlation of cell growth with, for example, areas of higher ground,

(b) the ascents suggest that convection was apparently not generated from the ground,

(c) accumulations of convective rain in the mesoscale model were less than the accumulations of dynamic rain,

(d) the location of the convective precipitation in the mesoscale model run is not tied to topography; it also covers a large area,

(e) the Operational Local Area Model, with its coarser grid and poor representation of the orography, is eventually capable of producing heavy rain.

7.4.5 Radar forecasts

Figure 42 shows the FRONTIERS forecast made at 2100 UTC on 22 September 1992 for 2200 UTC (one hour ahead), the forecast made at 1800 UTC for 2200 (four hours ahead) and the actual radar image for 2200 UTC. It is clear that the FRONTIERS forecasts are poor on this occasion. This level of performance is as expected given the convective nature of the event.

7.4.6 River flow forecasts

At Colindeep Lane on the Silk Stream, the highest flow on record was attained during this event and substantial flooding to more than 100 properties occurred.
Figures 43(a)–43(c) show modelled flow hydrographs which would have been predicted using the FRONTIERS accumulation transmissions at 1800 UTC, 22 September 1992, 0000 UTC 23 September 1992 and 0600 UTC 23 September 1992 respectively. It can be seen that FRONTIERS substantially underpredicts at 1800 UTC on 22 September 1992 and continues to generally underpredict throughout the event, leading to a false sense of security. For comparison, Figures 43(d) and 43(e) show the response which would have been expected if rainfall data from the tipping-bucket rain-gauge at Harrow Weald or from Chenies weather radar respectively had been used throughout the event. The rain-gauge data lead to a large overestimate in the predicted flow, suggesting that the point rainfall at Harrow Weald is not representative of the whole catchment for this event.

On the other hand the radar data appears to perform very well, especially up to the time when the Silk Stream overtops into the flood plain and the simple Isolated Event Model in use becomes unreliable.

Figures 44(a)–44(c) show modelled flow hydrographs for Wimbledon Common on the Beverley Brook which would have been generated by the FRONTIERS accumulation transmissions at 2200 UTC 22 September 1992, 0100 UTC 23 September 1992 and 0500 UTC 23 September 1992 respectively. It can be seen that FRONTIERS underpredicts at 2200 UTC on 22 September 1992 but then tends to generally overestimate the rainfall throughout the remainder of the event. For comparison, Figures 44(d) and 44(e) show the response which would have been expected if rainfall data from the tipping-bucket rain-gauge at Cheam or from Chenies weather radar respectively had been used throughout the event. Both data sources lead to an over prediction of river flow by a factor of about two.

Even the largely rural catchment of the River Roding at Loughton responded to the high rainfall accumulations of this event, the first noticeable response since June 1991. Figures 45(a)–45(c) show modelled flow hydrographs for this catchment which would have been generated by the FRONTIERS accumulation transmissions at 2200 UTC 22 September 1992, 0300 UTC 23 September 1992 and 0200 UTC 24 September 1992 respectively. It can be seen that once again FRONTIERS slightly underpredicts the peak flow at 2200 UTC on 22 September 1992 but then forecasts fairly well throughout the rest of the event, although Figure 45(c) indicates that the predicted flow is beginning to rise again in response to additional rainfall forecast by FRONTIERS which in reality has little effect. For comparison, Figures 45(d) and 45(e) show the response which would have been expected if rainfall data from the tipping-bucket rain-gauge at Thornwood or from Chenies weather radar respectively had been used for the entire event. The rain-gauge data lead to a large overestimate in the predicted flow, suggesting that the point rainfall at Thornwood is not representative of the whole catchment for this event. On the other hand the radar data appears to perform very well.

For this event as a whole, FRONTIERS data were found to be generally misleading in the two more urban catchments of the Silk Stream and Beverley Brook but perform fairly well in the larger rural River Roding catchment.

7.5 24 November–3 December 1992

7.5.1 Introduction

A deep depression tracking across south-east England brought strong winds and heavy rain to many areas. Falling on an already saturated catchment, this rainfall produced high flows both in London and in the more rural catchments to the north of London. The catchment worst affected was the River Roding in Essex where extensive flood plain flooding occurred but the other two study catchments also experienced fairly high flows.

7.5.2 River flow forecasts

Figures 46(a)–46(c) show modelled flow hydrographs for Colindeep Lane on the Silk Stream which would have been generated by the FRONTIERS accumulation transmissions at 1800 UTC, 2000 UTC and 2300 UTC on 25 November 1992 respectively. It can be seen that using FRONTIERS the initial hydrograph rise is predicted fairly well at 1800 UTC but then further rain is forecast which does not materialize leading to a large overestimation in peak flow. Further into the event this second period of heavy rainfall is no longer predicted and modelled flows do not differ greatly from observed flows. For comparison, Figures 46(d) and 46(e) show the response which would have been expected if rainfall data from the tipping-bucket rain-gauge at Harrow Weald or from Chenies weather radar respectively had been used throughout the event. The rain-gauge data lead to an overestimation of the predicted flow, whilst the radar data significantly underestimates.

There is a very similar picture when this event is analysed for Wimbledon Common on the Beverley Brook. Figures 47(a)–47(c) show modelled flow hydrographs for this catchment which would have been generated by the FRONTIERS accumulation transmissions at 1700 UTC, 2000 UTC and 2300 UTC on 25 November 1992. FRONTIERS forecasts both the rise and recession very well although tends to overestimate the predicted peak flow at 2000 UTC. Once again rain-gauge data lead to a large overestimate in the predicted flow, whilst the radar subcatchment data leads to an underestimation of the flow (Figures 47(d) and 47(e) respectively).

The peak flow at Loughton on the River Roding reached 32 cumecs, estimated to be about a 1 in 8 year flow. Figures 48(a)–48(c) show modelled hydrographs for this catchment which would have been generated by the FRONTIERS accumulation transmissions at 0130 UTC 25h November 1992, 2000 UTC 25 November 1992 and 1330 UTC 26 November 1992 respectively. The initial rise in flow is predicted fairly well using FRONTIERS. However at this stage the rainfall that generated the steep rise in flow is not forecast by FRONTIERS as it is beyond 6 hours ahead. Further into the event FRONTIERS does predict further heavy rain but this results in a slight underestimation of the forecast flow. It can be seen that the flow recession is not modelled well but it is felt that this is due to inadequacies within the Isolated Event Model rather than with the rainfall forecasts used. Figures 48(d) and 48(e) show the response which would have been expected if rainfall data from the tipping-bucket rain-gauge at Thornwood or from Chenies weather radar respectively had been used throughout the event. The rain-gauge data perform very well, predicting the magnitude of the first peak particularly accurately. Once again the radar data underestimates substantially.

In general, FRONTIERS forecasts were felt to have performed quite acceptably during this mainly frontal event.

8. Progress on tasks related to the recommendations in the MO/NRA Report, March 1992.

(Numbers in square brackets [] refer to specific recommendations in the report.)

[13(a)] Data availability

Data availability has steadily improved throughout this project, and has now reached a level close to that necessary for hydrological river flow forecasting.

[13(b)] Showers and thunderstorms

Convective events (showers and thunderstorms) are inadequately predicted by extrapolation techniques because of their rapid non-linear development and decay, and they are beyond the resolution of even the finest current operational NWP models. Conceptual (semi-qualitative) models offer a way of filling this forecasting gap by providing a physically consistent representation of a cell and its evolution, including the non-linearities. Progress has been made at the Met. Office on using object-oriented software techniques to represent the life cycle of a convective cell, including the production of 'daughter' cells, in terms of a conceptual model. Cells, and their states of development, are identified automatically by matching radar and satellite observations to those predicted from the conceptual model. Initial results have been promising and work continues to refine the technique, to make use of higher-resolution and more diverse observations, and to identify automatically the situations in which it is appropriate to apply the model.

[13(c)] Negative orographic (rain shadow) corrections.

Whilst rain shadow effects are understood they are not yet incorporated appropriately in FRONTIERS. Research work is continuing to modify the orographic correction factors used in such circumstances.

[13(d)] Accumulations in slow moving or stationary situations.

Such situations can, in principle, be dealt with by FRONTIERS. However, the difficulty in recognising cases when movement may slow down, or systems develop *in situ*, remains, and further research is required.

[13(e)] Mitigation of bright-band and range effects.

A new 7-parameter model of the vertical radar reflectivity profile, including the melting layer, has been applied to predict bright-band echo enhancement. An iterative scheme, taking account both of the modelled profile and of its intersection by a realistically represented radar beam, adjusts the model parameters to fit the radar observations and thus estimates the true rainfall rate at the ground. Initial case studies have shown that a significant improvement can be achieved, but further work is needed to confirm this, assess reliability and to improve the method. This work is part of the automation of the radar analysis stage of FRONTIERS, within the Nimrod project (see below).

A separate study involving the application of the Area-Time Integral method to the recognition of bright-band cases has led to a simple technique of bright-band identification and correction. It has been reported by Cheng and Collier (1993).

A further procedure based upon a microphysical model of the bright band has been developed by Dr P Hardaker, a case student with the University of Essex and the Met. Office. Details are contained in a PhD thesis submitted to the Department of Mathematics, University of Essex, and a paper is being prepared for publication.

[13(f)] Integration of the mesoscale model and FRONTIERS

The Met. Office has embarked on a major project called Nimrod whose purpose is to integrate NWP (mesoscale model) and nowcasting (FRONTIERS) techniques in order to provide the best possible forecasts over the UK of a range of weather parameters, including precipitation, in the period 0-6 hours ahead. Radar and satellite observations will contribute to the model analyses, and model products will be used to help in the interpretation of radar observations and in the production of nowcasts. Forecasts of precipitation will be made by both the NWP and nowcasting parts of Nimrod; the nowcasting part will operate on a half-hourly cycle as at present (though more rapid cycles using higher resolution radar data may be introduced later) and the eventual introduction of hourly mesoscale model runs is envisaged. Methods will be developed to allow forecasts from the two sources to be selected and combined to produce the best forecast sequence on any given occasion.

[13(g)] Automation of FRONTIERS

Work on the automation of parts of the FRONTIERS nowcasting system has been under way for some time, and the Met. Office is now committed to automating the FRONTIERS nowcasting system as the first stage in the Nimrod programme. This involves work on several processes that at present rely upon intervention by a forecaster, including the treatment of bright-band effects and range corrections outlined above.

Identification and removal of 'anaprop' (spurious radar echoes resulting from anomalous propagation of the radar beam) is important in order to avoid contaminating the forecast with imaginary rain, but removal of genuine rainfall echoes must also be avoided. It is expected that automatic anaprop recognition will depend upon combining evidence from several sources. Thus radar data have been accumulated to form anaprop climatologies, and ray-tracing programs have been developed to indicate the likelihood of anomalous beam propagation on a particular occasion. Work is about to start on the use of surface observations of weather. Doppler radar data are expected to be useful for distinguishing anaprop and will be incorporated into the scheme as they become available, but a scheme based on other methods will be introduced in the meantime, if it works well enough.

Orographic corrections to rainfall amounts have proved to be beneficial. The corrections themselves are calculated automatically in FRONTIERS but the controlling meteorological parameters (humidity and wind) are selected by a forecaster. Methods of using mesoscale model products to provide this information automatically are being investigated, in particular the height of the model humidity field that best correlates with enhancement, and the threshold humidity for enhancement to occur.

The satellite analysis stage of FRONTIERS attempts to infer the distribution of rainfall beyond the range of the radars. The basic method depends upon correlating the satellite and radar data within the radar area. Should correlation yield an unsatisfactory product, the satellite precipitation fields may be obtained from predefined tables, or the forecaster can select manually the satellite classes associated with precipitation. Use of the manual method, and results from research, indicate deficiencies in the FRONTIERS correlation procedure. Work is in progress to produce an optimized version of the correlation technique, which will automatically select the best satellite precipitation field from visible or IR alone or from a combined field. Initial studies have been reported by Cheng *et al.* (1993).

An automated forecast procedure has been developed and is undergoing tests on a set of cases chosen to represent the range of important types of situation encountered in the UK. The procedure incorporates linear extrapolation, based on segmentation and cross-correlation of successive radar images, selection and use of mesoscale model winds to advect precipitation patterns, and direct use of mesoscale model precipitation forecasts. The forecasting method to use on a particular occasion is chosen automatically on the basis of recent performance, since this will vary from one situation to another. The intention is later to merge forecast components from all these methods so as to provide an optimal, and smooth, forecast sequence covering the range 0–6 h.

[14] Fluvial flood damage database

Nothing to report.

[15] Assessment of Local Forecasting System by the NRA Thames Region and the Institute of Hydrology

This work has been completed and reported by Moore *et al.* (1993).

[16] Opportunities for joint research between the Met. Office and the NRA.

A proposal has been made to the NRA by the Met. Office for a joint project to develop a convective forecasting system based upon the use of the object oriented approach mentioned under 13b, instability indices and radar and satellite imagery analysis. The approach to be investigated has been outlined by Collier and Lilley (1993).

9. Conclusions

In contrast to 1991, 1992 was a much wetter year with the average rainfall in the Thames Region about 110% of standard average. It was characterised by a much larger number of flow events, on average 21 in the study catchments, compared with only 5 on average in 1991. In September 1992 the highest recorded flow was attained in the Silk Stream catchment and over 100 properties were flooded. However the North West Region had average rainfall in 1992, and very few high flow events occurred, with only appreciable flooding in some areas in January 1992. No significant events took place in the study catchments. The following conclusions and recommendations are made,

(i) The availability of FRONTIERS forecasts, both instantaneous and accumulations has improved significantly during the second year of the study. Over the last 6 months of the study (October 1992–March 1993) instantaneous forecasts have achieved 95.4% availability and accumulation forecasts 93.2% on average; the latter being just short of the target set of 95%. In contrast, during the first 6 months of 1991 instantaneous forecasts averaged 81.9% availability and accumulation forecasts only 68.4%.

(ii) It has been demonstrated that the availability of FRONTIERS accumulation forecasts does not decrease significantly during periods of heavy rainfall which is an important result for flood warning operations.

(iii) The rather inconsistent performance of the Chenies weather radar during 1992 has caused concern and has resulted not only in less reliance on the data for quantitative flood forecasting, but also in possible impairment of the quality of FRONTIERS forecasts in the Thames catchment. The Met. Office is putting much effort into resolving the accuracy problems identified at Chenies which is welcomed.

(iv) Based on the results presented in section 6 of this report, it can be seen that on average FRONTIERS forecasts performed well for all lead times when compared with model runs using observed rainfall data. However, there is still a wide and apparently random variation in performance between events and until this performance improves its full potential for operational use is not yet realized.

(v) In the two urban catchments studied (Silk Stream and Beverley Brook) there appears not to be a firm relationship between forecast accuracy and lead time. Indeed, in both cases, the T + 1 forecasts produced larger RMSE errors than the T + 6 forecasts. As previously discussed, the influence of suspect rainfall measurement by Chenies radar may partially account for inaccuracies at short lead times. However, in the rural Roding catchment a firm relationship was demonstrated, with the errors progressively increasing with lead time.

All three catchments in the North West demonstrated consistent increasing errors with lead times. This perhaps indicated that Hameldon Hill's consistent performance has not affected the FRONTIERS forecasts in this area.

(vi) Flood forecasting dictates that there is a strong requirement for FRONTIERS to perform well during events that give rise to high river flow and flooding. To test for this the analysis was repeated first for the 10 largest events recorded in each catchment and then for the events that exceeded the 1 in 2 year flow and average statistics were generated. The results produced in Table 7 indicate that the performance of FRONTIERS decreases with increasing event size. However, the size of the catchment in the North West Region does not seem to make a great deal of difference to the performance, although the larger events tend to have large errors with time than smaller events, as shown in Table 8.

(vii) It was considered desirable to determine the relative performance of FRONTIERS for storms of differing synoptic type, namely for frontal and convective events. Table 3 shows that in general the flow forecasts generated by FRONTIERS for convective events produced higher errors than those generated by frontal storms.

(viii) Detailed analysis of the case-study events in section 7 produced results that reinforce those discussed in paragraphs (vi) and (vii) above. FRONTIERS performed well in frontal situations such as occurred in November and December 1992 for all study catchments. Its ability to accurately forecast rainfall in the convective events, however, is generally poor although performance is better for the larger rural catchment in such circumstances. In short, therefore, FRONTIERS seems to forecast frontal rainfall well especially in larger catchments but has great difficulty in forecasting convective rainfall in small urban catchments to any degree of accuracy (Table 9).

Table 7: Average RMSE errors for flood events of increasing magnitude

	Roding	Silk Stream	Beverley Brook
All events	3.51 (12)	2.06 (27)	2.55 (23)
10 largest events	4.03 (10)	3.79 (10)	2.73 (10)
Events exceeding 1 in 2 yr flood	10.19 (1)	6.06 (4)	– (0)

( ) number of events used in analysis

Table 8: RSME values versus lead time related to 1 hour ahead forecast values for three catchments in the NRA North West Region

	peak flow m^3/s	1	2	3	4	5	6
R Darwen @ Ewood ($40 km^2$)	32	1	2.0	2.7	3.3	3.9	4.7
Sankey Brook @ Causey Br. ($154 km^2$)	10	1	1.7	2.2	2.8	3.3	4.0
	16	1	1.5	2.0	2.5	3.0	3.7
	23	1	1.4	2.2	3.0	3.8	6.0
R Roach @ Blackford Bridge ($186 km^2$)	52	1	1.7	2.0	2.3	3.0	3.7
	85	1	1.5	1.7	2.2	2.7	3.2
	105	1	2.0	3.2	3.7	5.0	5.7
	200	1	2.0	3.0	3.7	4.3	4.8

(Values taken from graphs in report by Department of Civil Engineering, University of Salford)

Notes

1. RMSE of flow forecasts using FRONTIERS increases with lead time, fairly consistently for all events and catchment sizes

2. Event size seems to have some effect — larger events tend to have larger errors with time

3. Catchment size does not seem to affect results

Table 9: Average RMSE errors for flood events generated from storms of differing synoptic type

	Roding		Silk Stream		Beverley Brook	
Frontal	2.54	(5)	1.45	(13)	2.56	(12)
Convective	7.84	(1)	2.94	(8)	2.73	(8)

( ) number of events used in analysis

10. Recommendations and future work

(a) Flood forecasters in NRA Thames Region, despite still having reservations about the accuracy of FRONTIERS-generated rainfall forecasts, consider that the system provides useful information which, in conjunction with other available tools, is helping to increase the timeliness and accuracy of flood forecasts especially in river catchments with short response times. It is recommended that the NRA continues to receive these forecasts and continues to liaise closely with the Met. Office to secure improvements in accuracy.

(b) The performance of FRONTIERS is still quite variable between events and the system appears to perform less well in large events. However, the Met. Office is planning to improve matters by blending radar-based forecasts with numerical model predictions through the NIMROD project. To ensure that this project produces significant improvements in the spatial and temporal forecasting of rainfall required by flood forecasters, it is recommended that the precise needs of the NRA are taken fully into account at an early stage through regular liaison.

(c) Results presented elsewhere (Moore *et al.* 1993, Han and Cluckie, 1993) suggest that a local forecasting advection procedure performs better than FRONTIERS for lead time up to 2 hours ahead. Such a procedure provides better spatial and temporal resolution, (2 km — 15 minute updates), which is important for urban flood forecasting, and can generate rainfall forecasts almost immediately on the users' computer. FRONTIERS takes 30–40 minutes to generate a forecast. It is recommended, therefore, that NRA Regions should consider implementing both systems to generate flood forecasts operationally, with the local system offering rainfall predictions up to say 2 hours ahead and FRONTIERS from 2 to 6 hours ahead.

(d) It is clear from results presented in this report and elsewhere that both FRONTIERS and local radar-based rainfall forecasting procedures do not perform well for convective situations. It is recommended that an alternative approach, other than advection, should be investigated. Towards that end, the proposed joint project between the Met. Office and the NRA to develop an operational thunderstorm warning system based on the use of artificial intelligence techniques with radar, satellite and numerical model output is supported.

(e) The assessment of quantitative catchment rainfall totals being undertaken by Manchester Weather Centre for the NRA North West Region for events reaching the warning criteria, should be continued.

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ANNEX A: Membership of FOAG

Prof. C G Collier	Met. Office Bracknell (Chairman)
P Borrows	NRA Thames Region
C M Haggett	NRA Thames Region
J M Knowles	NRA North West Region
R Hatton	NRA South West Region
Dr P K James	Met. Office Bracknell
Ms M Clarke	Met. Office Bracknell (Secretary)
Dr B J Conway/Mrs G Ryall	Met. Office Bracknell
W K Wheeler	Met. Office Bracknell
G L Underwood	London Weather Centre
S N Wass	Manchester Weather Centre

ANNEX B: Terms of Reference of the FOAG

- ❐ Operational Availability
  Monitor and seek to improve the Operational Availability of FRONTIERS Forecasts and Accumulations

- ❐ Assessment
  Routinely assess and seek to improve the quality of FRONTIERS Forecasts both meteorologically (Met. Office) and hydrologically (NRA)

- ❐ Case-studies
  Pursue case-studies designed to clarify the performance of FRONTIERS in orographic, showery and bright-band situations

- ❐ Integration of FRONTIERS with Current Heavy Rain Forecast Methods
  Identify the strengths of each forecast method with a view to specifying how the strengths of each could be combined operationally

- ❐ Detailed study of FRONTIERS Performance in Flood Events

- ❐ Identify Future Research Needs

ANNEX C: Tables of radar data availability

Radar single-site data availability — March 1992–March 1993

MON	BEAC	CAST	CHEN	CLEE	COBB	CORS	CRUG	DUDW	HAME	INGH	PRED	WARD	AVE	DUBL	JERS	SHAN	AVE
MAR 92	16.9	83.7	81.1	89.4	89.5	79.8	87.6	74.9	74.4	86.7	88.6	89.0	78.5	34.5	89.7	45.4	56.5
APR 92	62.5	59.2	69.0	68.9	67.9	69.0	65.7	69.7	66.9	56.9	68.3	68.9	66.1	68.6	46.2	33.7	49.5
MAY 92	95.2	80.1	97.8	91.8	91.5	98.6	76.1	97.6	89.5	95.7	98.3	98.7	92.6	97.0	94.8	9.6	67.1
JUN 92	98.1	83.4	96.8	85.9	59.4	98.6	54.1	85.1	87.3	96.9	96.4	93.8	86.3	93.0	93.7	0.4	62.4
JUL 92	94.8	92.8	96.1	96.1	51.2	92.6	54.9	88.6	96.0	95.1	94.9	90.8	87.0	93.0	95.3	5.0	64.4
AUG 92	96.5	96.0	99.2	96.9	73.0	94.8	98.8	97.5	84.0	94.9	99.0	99.6	94.2	96.8	92.5	91.6	93.6
SEP 92	86.7	85.4	99.5	89.5	76.1	94.9	90.6	99.5	87.1	97.3	98.6	99.7	92.1	91.4	93.7	99.3	94.8
OCT 92	77.0	94.7	97.1	96.1	87.0	99.0	88.1	98.9	98.3	90.8	98.0	92.9	93.2	84.0	96.9	96.5	92.4
NOV 92	89.4	88.1	97.2	96.2	80.6	99.5	98.4	77.5	96.6	98.5	98.0	99.3	93.3	85.0	96.3	81.0	87.4
DEC 92	95.7	85.3	94.0	94.7	27.4	98.3	96.9	94.4	96.5	96.1	94.7	98.5	89.4	96.0	96.0	90.9	94.3
JAN 93	91.8	83.6	97.3	97.2	0.2	98.4	91.9	81.6	98.0	96.5	98.4	96.2	85.9	96.7	98.7	97.6	97.6
FEB 93	95.1	91.9	79.5	93.4	88.2	98.3	96.7	99.8	97.7	98.6	93.1	98.9	94.3	96.5	92.2	74.9	87.8
MAR 93	98.5	94.8	94.1	87.9	71.0	90.7	93.1	99.9	96.0	97.6	97.1	93.1	92.8	97.5	92.5	8.1	66.0
92-93	84.5	86.1	92.2	91.1	66.4	93.3	84.1	89.6	89.9	92.4	94.1	93.8	88.1	86.9	90.6	56.5	78.0
	BEAC	CAST	CHEN	CLEE	COBB	CORS	CRUG	DUDW	HAME	INGH	PRED	WARD	AVE	DUBL	JERS	SHAN	AVE

Radar single-site data availability — March 1993

DAY	BEAC	CAST	CHEN	CLEE	COBB	CORS	CRUG	DUDW	HAME	INGH	PRED	WARD	AVE	DUBL	JERS	SHAN	AVE
1	77.1	70.8	100.0	100.0	100.0	100.0	100.0	100.0	96.9	100.0	100.0	100.0	95.4	101.0	96.9	100.0	99.3
2	100.0	85.4	81.3	99.0	100.0	100.0	97.9	100.0	97.9	99.0	97.9	45.8	92.0	95.8	90.6	59.4	81.9
3	99.0	83.3	59.4	50.0	97.9	99.0	87.5	99.0	86.5	91.7	85.4	0.0	78.2	96.9	93.8	0.0	63.5
4	100.0	88.5	89.6	69.8	97.9	100.0	89.6	100.0	89.6	92.7	80.2	41.7	86.6	100.0	94.8	0.0	64.9
5	100.0	94.8	94.8	59.4	100.0	95.8	85.4	100.0	94.8	76.0	93.8	100.0	91.2	97.9	80.2	0.0	59.4
6	100.0	87.5	90.6	78.1	100.0	100.0	89.6	100.0	89.6	91.7	78.1	100.0	92.1	97.9	95.8	0.0	64.6
7	100.0	100.0	100.0	63.5	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	96.9	101.0	99.0	0.0	66.7
8	95.8	99.0	97.9	40.6	61.5	97.9	99.0	96.9	99.0	100.0	100.0	100.0	90.6	94.8	87.5	0.0	60.8
9	100.0	99.0	79.2	49.0	96.9	100.0	100.0	95.8	100.0	100.0	94.8	100.0	92.9	96.9	87.5	0.0	61.5
10	100.0	84.4	100.0	100.0	81.3	100.0	100.0	100.0	97.9	100.0	97.9	100.0	96.8	100.0	78.1	0.0	59.4
11	100.0	85.4	100.0	89.6	74.0	100.0	100.0	100.0	82.3	87.5	99.0	100.0	93.1	99.0	84.4	0.0	61.1
12	92.7	100.0	93.8	85.4	46.9	97.9	100.0	100.0	94.8	100.0	100.0	100.0	92.6	99.0	81.3	0.0	60.1
13	100.0	100.0	100.0	100.0	34.4	100.0	99.0	100.0	100.0	100.0	100.0	100.0	94.4	94.8	89.6	0.0	61.5
14	100.0	100.0	100.0	100.0	92.7	100.0	100.0	100.0	100.0	99.0	97.9	100.0	99.1	90.6	89.6	0.0	60.1
15	100.0	100.0	100.0	100.0	76.0	88.5	100.0	100.0	100.0	99.0	100.0	100.0	97.5	93.8	91.7	0.0	61.8
16	99.0	89.6	82.3	95.8	81.3	41.7	99.0	100.0	58.3	99.0	97.9	100.0	87.0	100.0	97.9	0.0	66.0
17	100.0	100.0	100.0	92.7	80.2	100.0	97.9	100.0	100.0	100.0	100.0	100.0	97.6	95.8	95.8	0.0	63.9
18	100.0	100.0	100.0	100.0	49.0	66.7	99.0	100.0	96.9	100.0	99.0	100.0	92.5	96.9	100.0	0.0	65.6
19	100.0	100.0	84.4	99.0	0.0	0.0	100.0	100.0	100.0	100.0	99.0	100.0	81.9	99.0	93.8	0.0	64.2
20	100.0	100.0	100.0	90.6	0.0	30.2	100.0	100.0	97.9	100.0	100.0	100.0	84.9	97.9	91.7	0.0	63.2
21	100.0	99.0	99.0	99.0	0.0	100.0	99.0	100.0	99.0	99.0	99.0	100.0	91.1	95.8	94.8	0.0	63.5
22	91.7	99.0	100.0	100.0	0.0	100.0	100.0	100.0	100.0	99.0	100.0	100.0	90.8	97.9	96.9	0.0	64.9
23	100.0	99.0	100.0	100.0	0.0	100.0	100.0	100.0	97.9	97.9	99.0	100.0	91.1	99.0	94.8	0.0	64.6
24	100.0	100.0	100.0	100.0	41.7	100.0	100.0	100.0	100.0	96.9	100.0	100.0	94.9	99.0	96.9	44.8	80.2
25	99.0	97.9	87.5	92.7	100.0	100.0	100.0	100.0	96.9	100.0	100.0	100.0	97.8	95.8	97.9	46.9	80.2
26	100.0	100.0	78.1	100.0	100.0	100.0	85.4	100.0	100.0	100.0	100.0	100.0	97.0	96.9	97.9	0.0	64.9
27	100.0	100.0	100.0	100.0	97.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.8	90.6	89.6	0.0	60.1
28	100.0	100.0	100.0	100.0	99.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9	97.9	91.7	0.0	63.2
29	100.0	96.9	100.0	100.0	97.9	100.0	100.0	100.0	100.0	99.0	92.7	100.0	98.9	100.0	95.8	0.0	65.3
30	100.0	91.7	100.0	82.3	97.9	100.0	58.3	100.0	100.0	100.0	100.0	100.0	94.2	100.0	97.9	0.0	66.0
31	100.0	87.5	99.0	87.5	99.0	94.8	0.0	100.0	99.0	99.0	97.9	100.0	88.6	100.0	92.7	0.0	64.2
AVE	98.5	94.8	94.1	87.9	71.0	90.7	93.1	99.7	96.0	97.6	97.1	93.1	92.8	97.5	92.5	8.1	66.0
	BEAC	CAST	CHEN	CLEE	COBB	CORS	CRUG	DUDW	HAME	INGH	PRED	WARD	AVE	DUBL	JERS	SHAN	AVE

LIST OF FIGURES

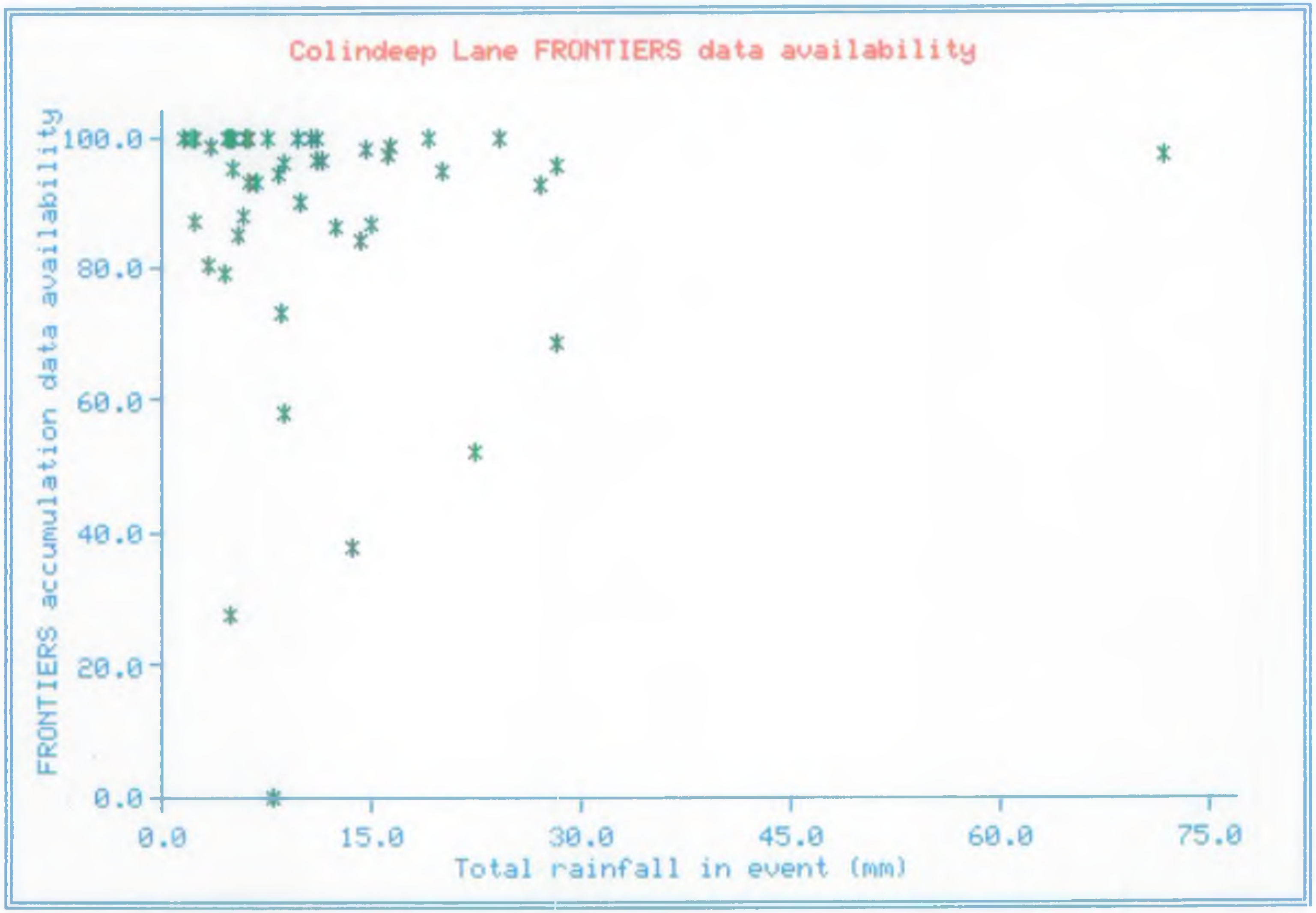


Figure : FRONTIERS accumulation data availability versus total event rainfall for events in period Jan. 1992 to Feb. 1993

Figure 1

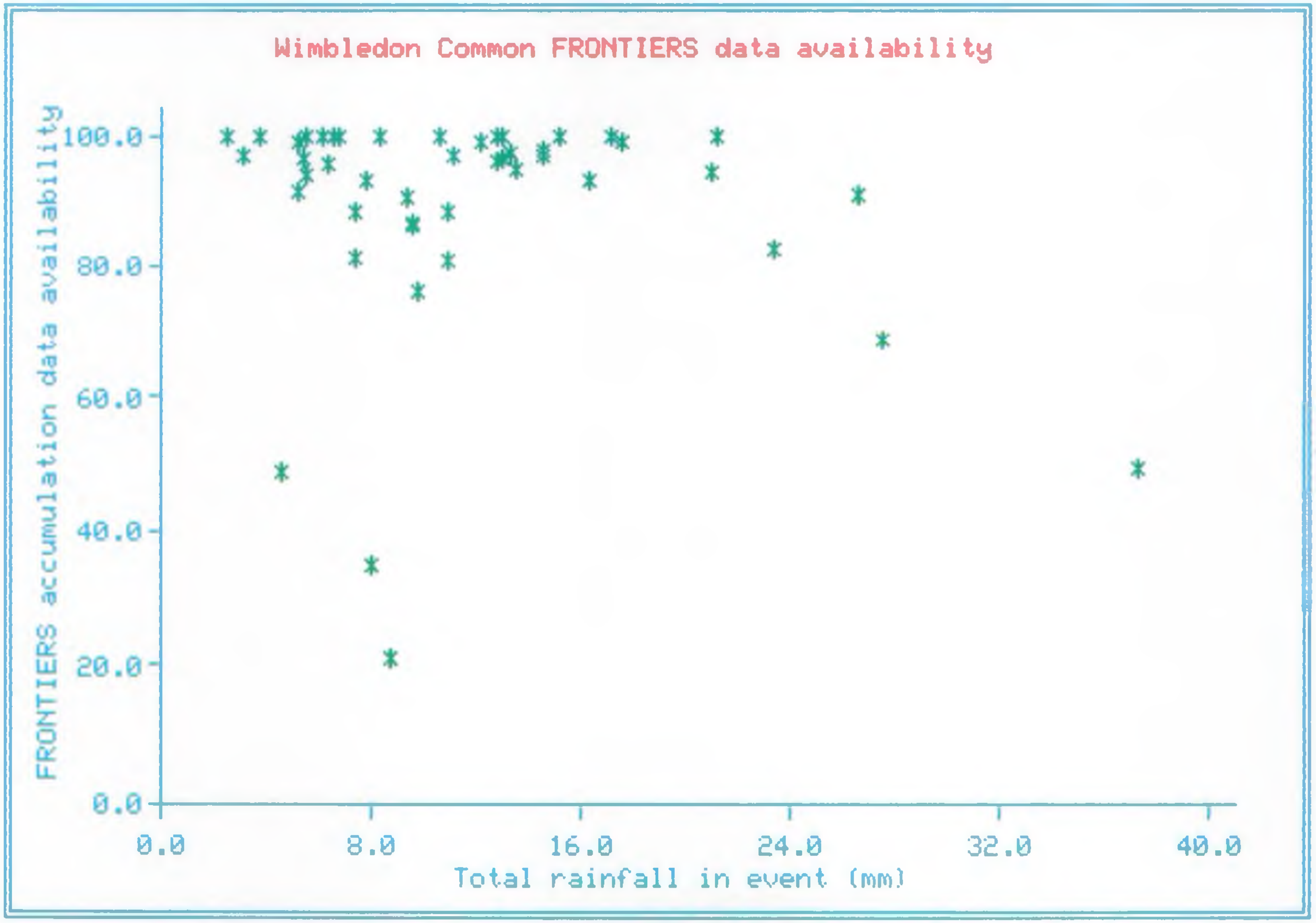


Figure : FRONTIERS accumulation data availability versus total event rainfall for events in period Jan. 1992 to Feb. 1993

Figure 2

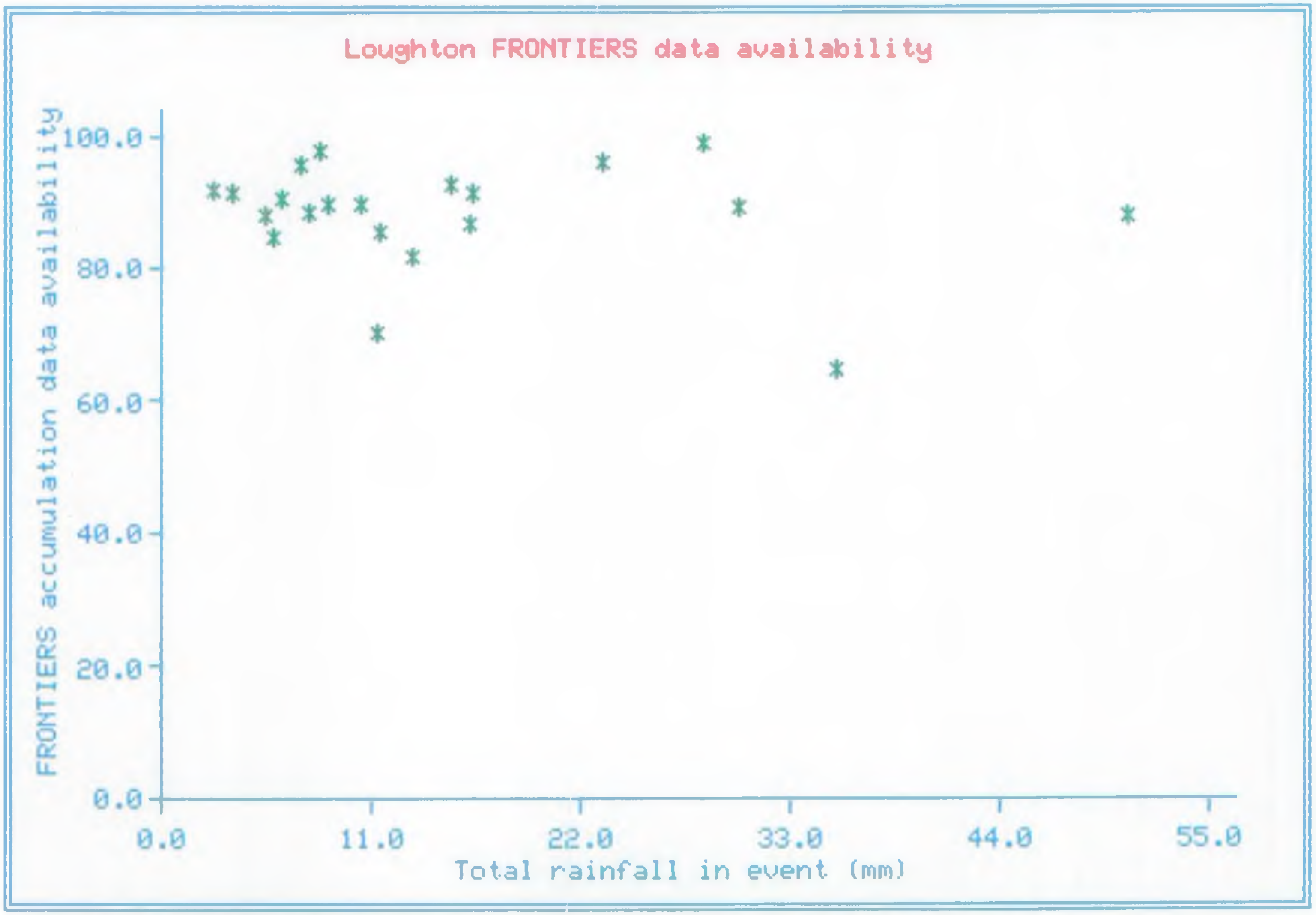


Figure : FRONTIERS accumulation data availability versus total event rainfall for events in period Jan. 1992 to Feb. 1993

Figure 3

Hameldon Gauge/Radar Series 92/93

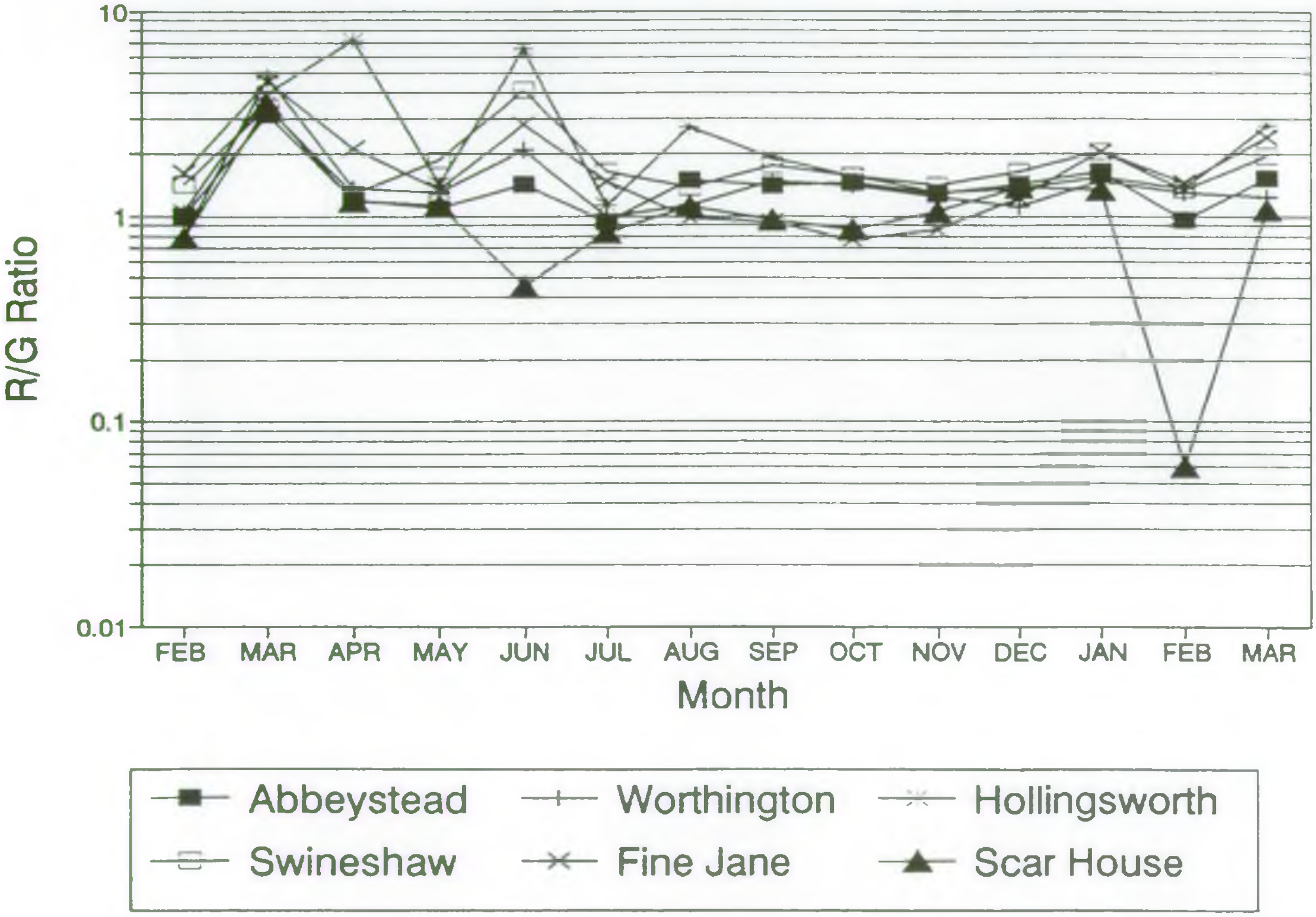


Figure 4a

Hameldon Gauge/Radar Series 92/93

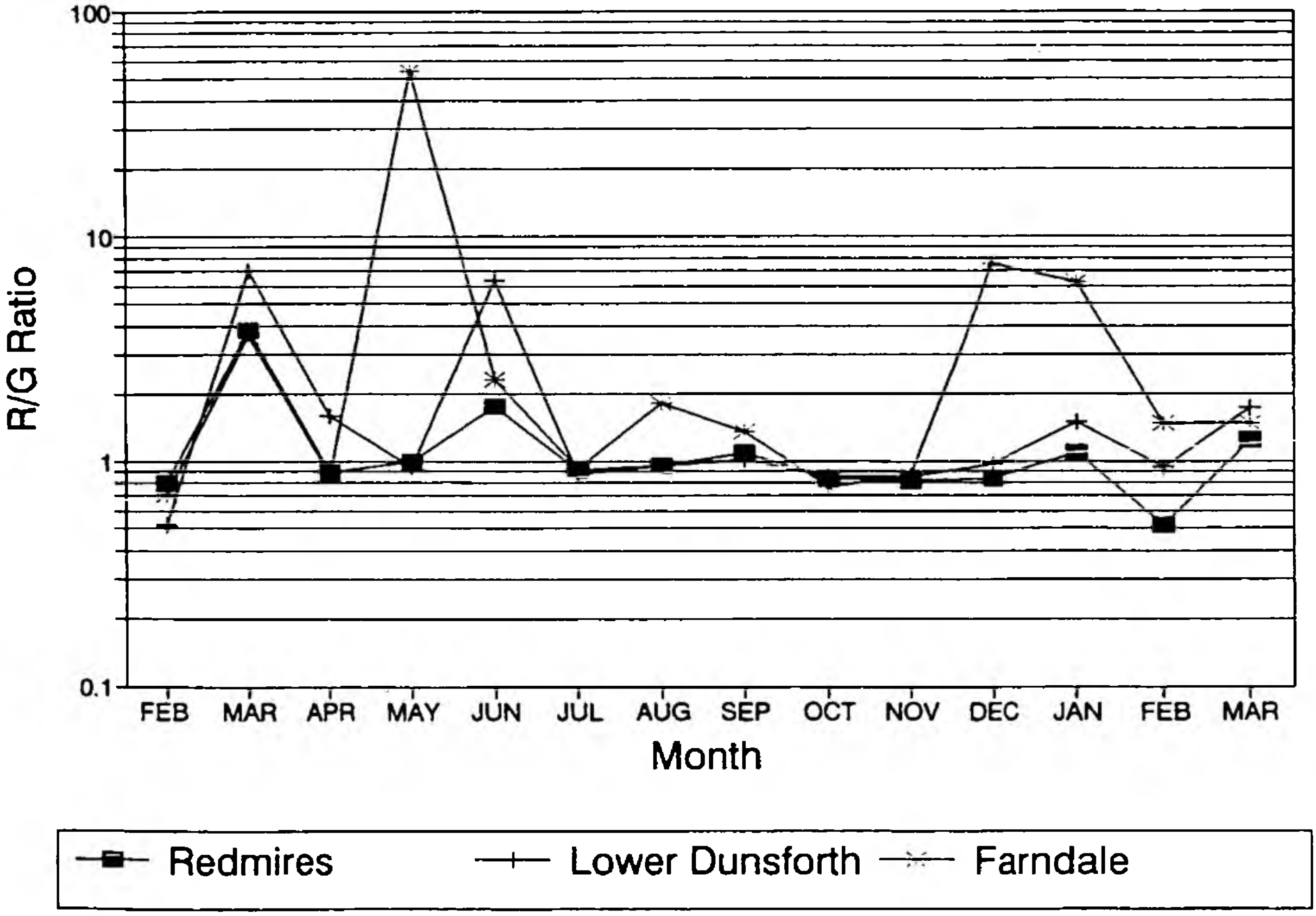


Figure 4b

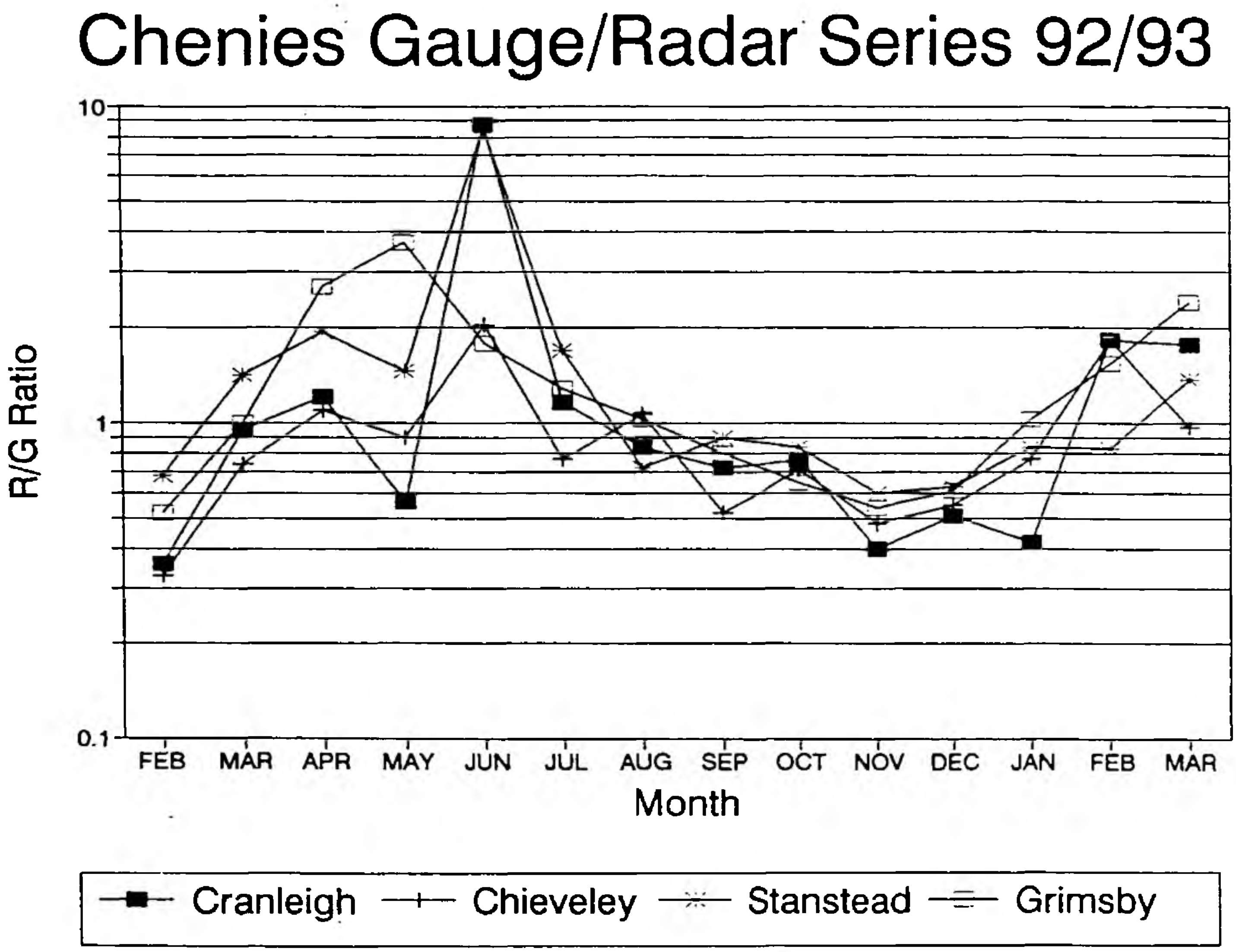
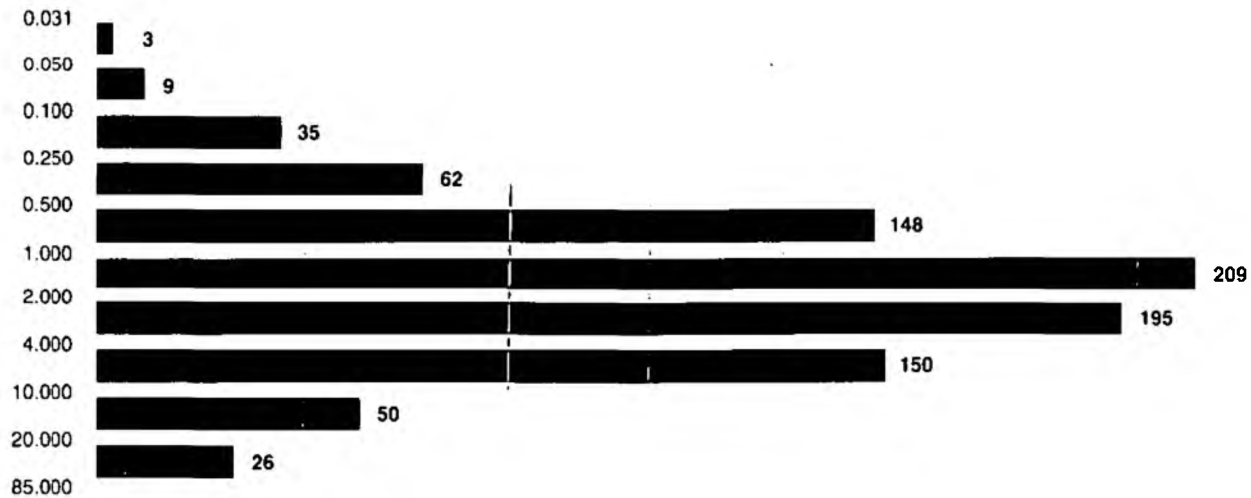

Chenies Gauge/Radar Series 92/93
10
1
0.1
R/G Ratio
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
JAN
FEB
MAR
Month
Cranleigh
Chieveley
Stanstead
Grimsby

Figure 5

CHENIES STATISTICS SUMMARY FOR JUNE 1992

LEVELS IN MM (M=MISSING)

RADAR \ GAUGE	M	0	0> <.5	>=.5	TOTAL
M	0.8%	3.2%	0.7%	0.7%	5.3%
0	17.0%	73.5%	1.7%	0.8%	93.1%
0> <.5	0.9%	2.0%	0.8%	0.7%	4.4%
>=.5	1.0%	1.5%	0.9%	1.7%	5.1%
TOTAL	19.7%	80.2%	4.1%	3.9%	



HOURLY R/G:- MEAN = 3.906 (ERROR = 0.241) SDEV = 7.171 (ERROR = 0.170) MAX = 85.00 MIN = 0.031

887 VALID HOURLY FACTORS TAKEN FROM A TOTAL SAMPLE OF 42480 RADAR-GAUGE PAIRS

93/375/1

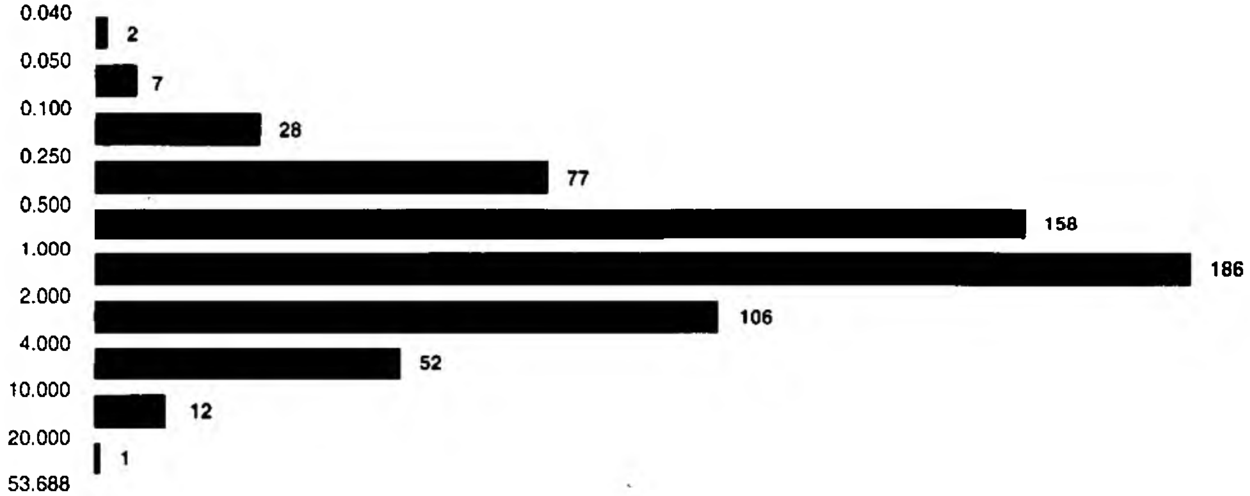
Figure 6a

Figure 6b

HAMELDON STATISTICS SUMMARY FOR JUNE 1992

LEVELS IN MM (M=MISSING)

RADAR \ GAUGE	M	0	0> <.5	>=.5	TOTAL
M	2.1%	12.5%	0.9%	0.7%	16.2%
0	14.6%	66.8%	1.4%	0.8%	83.5%
0> <.5	0.8%	1.5%	1.0%	0.7%	4.0%
>=.5	0.9%	1.1%	0.8%	1.4%	4.2%
TOTAL	18.4%	81.9%	4.1%	3.7%	



HOURLY R/G:- MEAN = 1.817 (ERROR = 0.122) SDEV = 3.061 (ERROR = 0.086) MAX = 53.688 MIN = 0.040

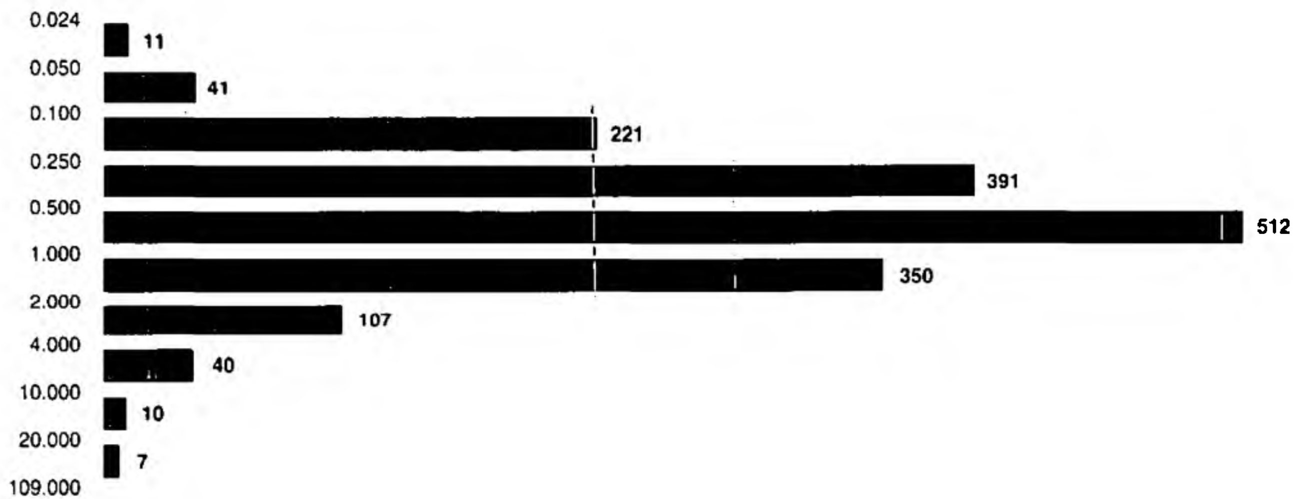
629 VALID HOURLY FACTORS TAKEN FROM A TOTAL SAMPLE OF 32043 RADAR-GAUGE PAIRS

93/375 2

CHENIES STATISTICS SUMMARY FOR JANUARY 1993

LEVELS IN MM (M=MISSING)

		GAUGE				
		M	0	0> <.5	>=.5	TOTAL
RADAR	M	1.2%	4.1%	0.9%	0.8%	7.1%
	0	20.2%	62.1%	6.3%	2.4%	91.1%
	0> <.5	1.2%	1.3%	1.5%	1.6%	5.5%
	>=.5	0.9%	0.7%	0.7%	1.9%	4.3%
	TOTAL	23.6%	68.3%	9.4%	6.7%	><



HOURLY R/G:- MEAN = 1.071 (ERROR = 0.083) SDEV = 3.430 (ERROR = 0.059) MAX = 109.000 MIN = 0.024

1690 VALID HOURLY FACTORS TAKEN FROM A TOTAL SAMPLE OF 45384 RADAR–GAUGE PAIRS

93/375/3

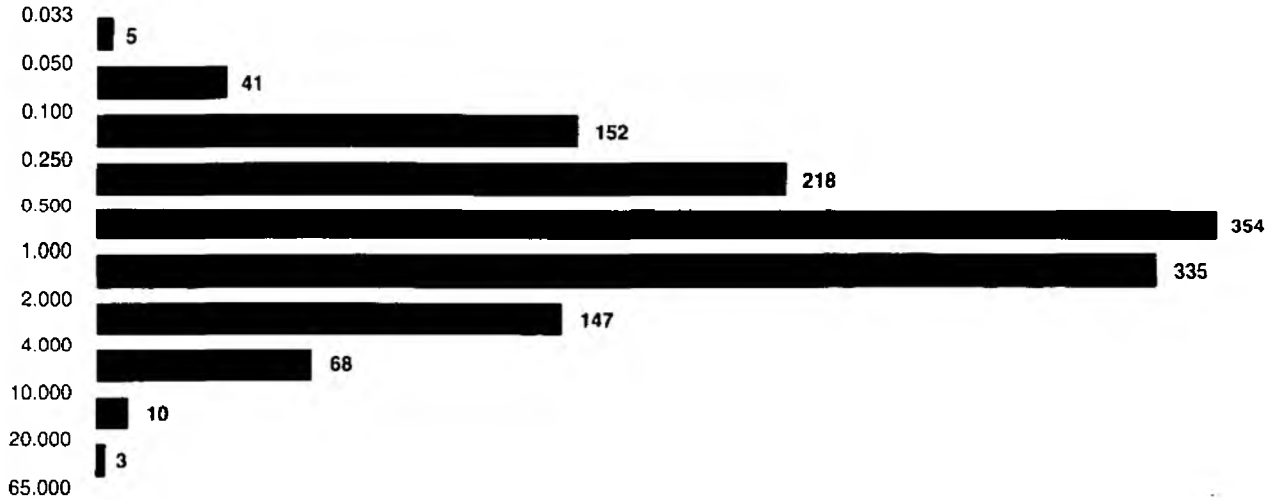
Figure 6c

Figure 6d

HAMELDON STATISTICS SUMMARY FOR JANUARY 1993

LEVELS IN MM (M=MISSING)

RADAR		GAUGE M	GAUGE 0	GAUGE 0> <.5	GAUGE >=.5	GAUGE TOTAL
R	M	4.7%	22.9%	3.6%	2.2%	33.3%
A	0	12.1%	46.6%	3.3%	1.6%	63.6%
D	0> <.5	1.1%	2.0%	1.5%	1.4%	6.0%
A	>=.5	0.9%	1.1%	1.0%	2.1%	5.1%
R	TOTAL	18.8%	72.6%	9.4%	7.2%	\ / > < / \



HOURLY R/G:- MEAN = 1.299 (ERROR = 0.070) SDEV = 2.559 (ERROR = 0.050) MAX = 65.000 MIN = 0.033

1333 VALID HOURLY FACTORS TAKEN FROM A TOTAL SAMPLE OF 33332 RADAR-GAUGE PAIRS

93/375/4

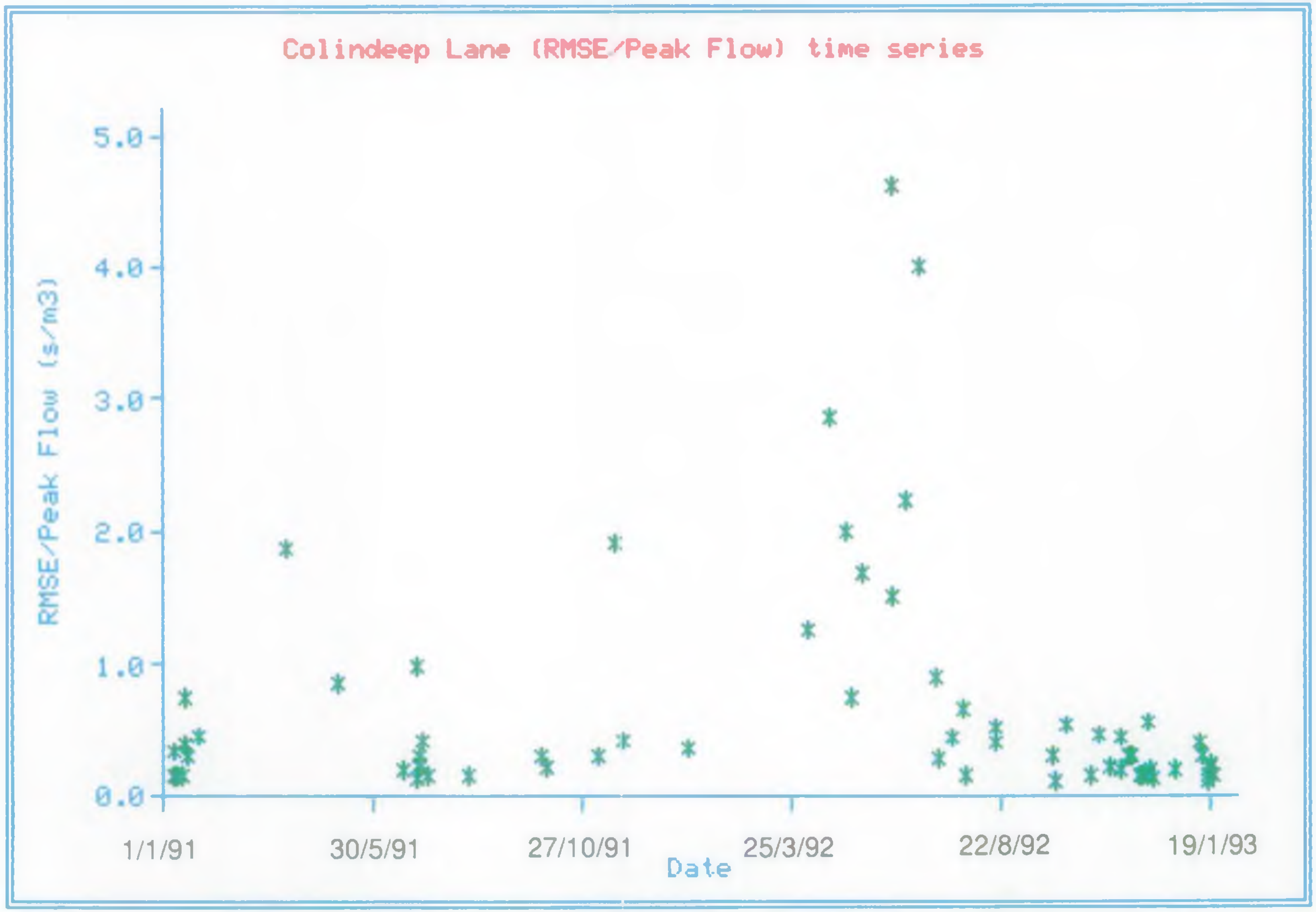


Figure 7 : Time series of (RMSE/Peak Flow) statistics for events in period January 1991 to February 1993

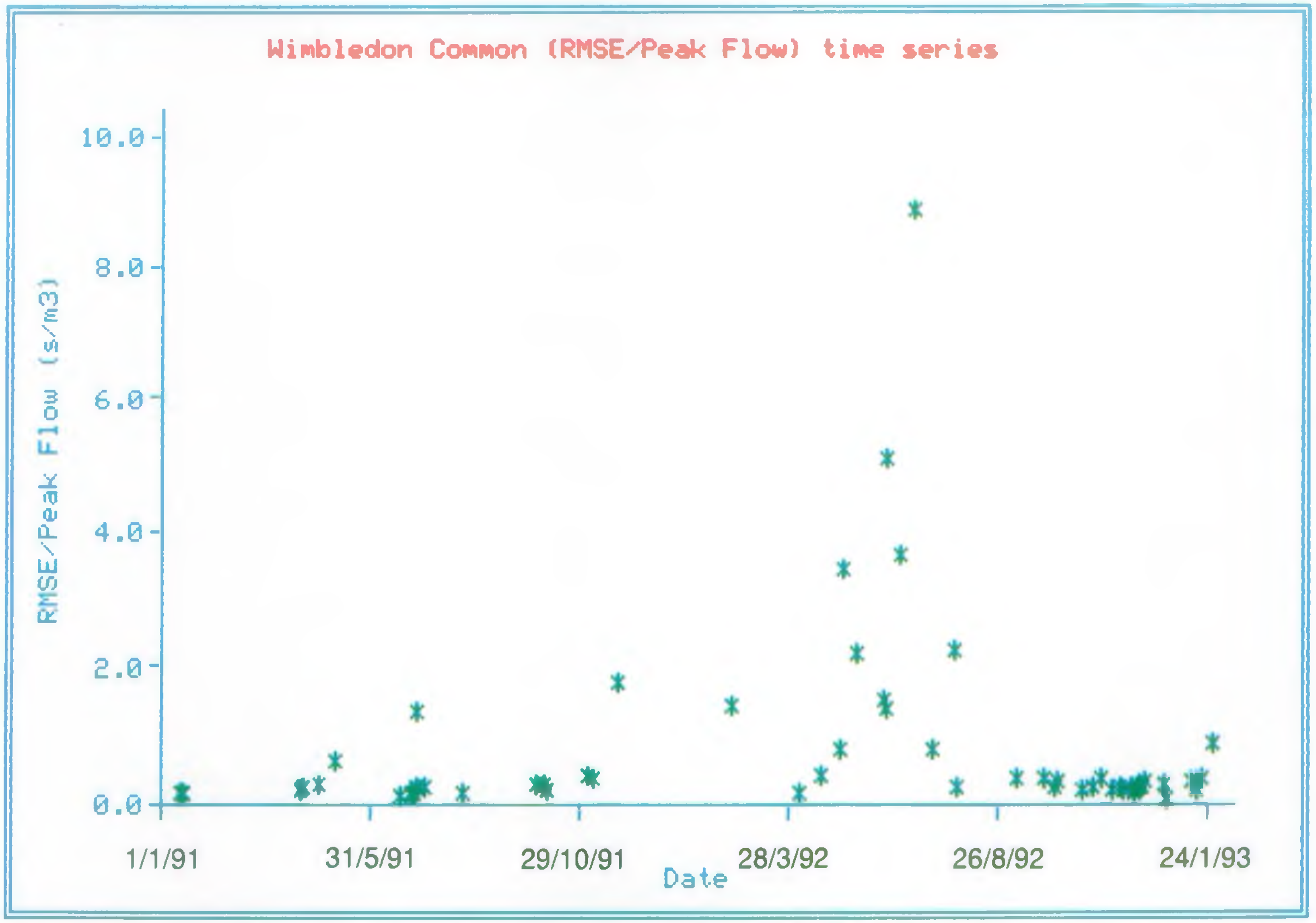


Figure : Time series of (RMSE/Peak Flow) statistics for events in period January 1991 to February 1993

Figure 8

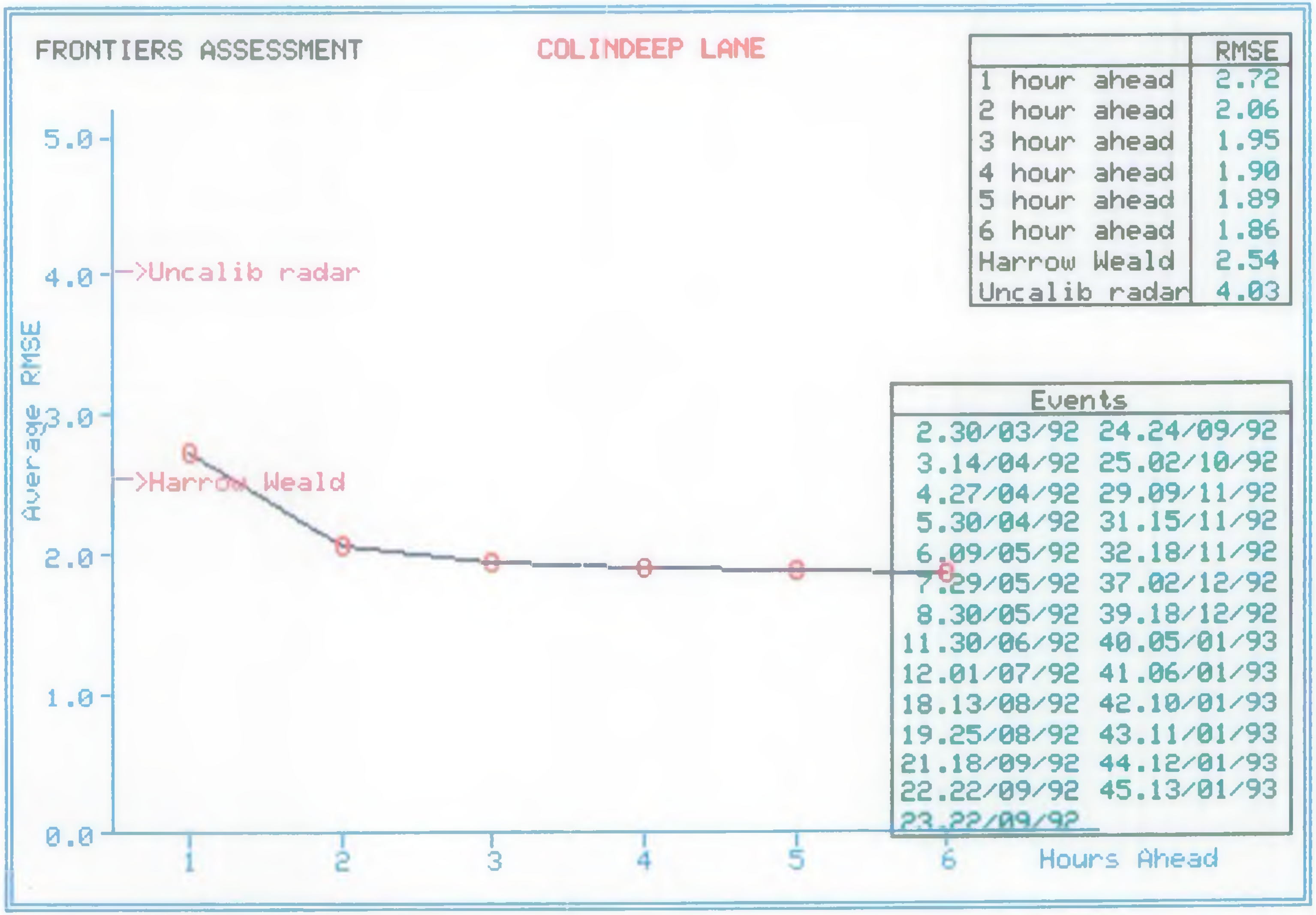


Figure : Average flow RMSE for 27 events at Colindeep Lane using Frontiers Forecasts

Figure 9

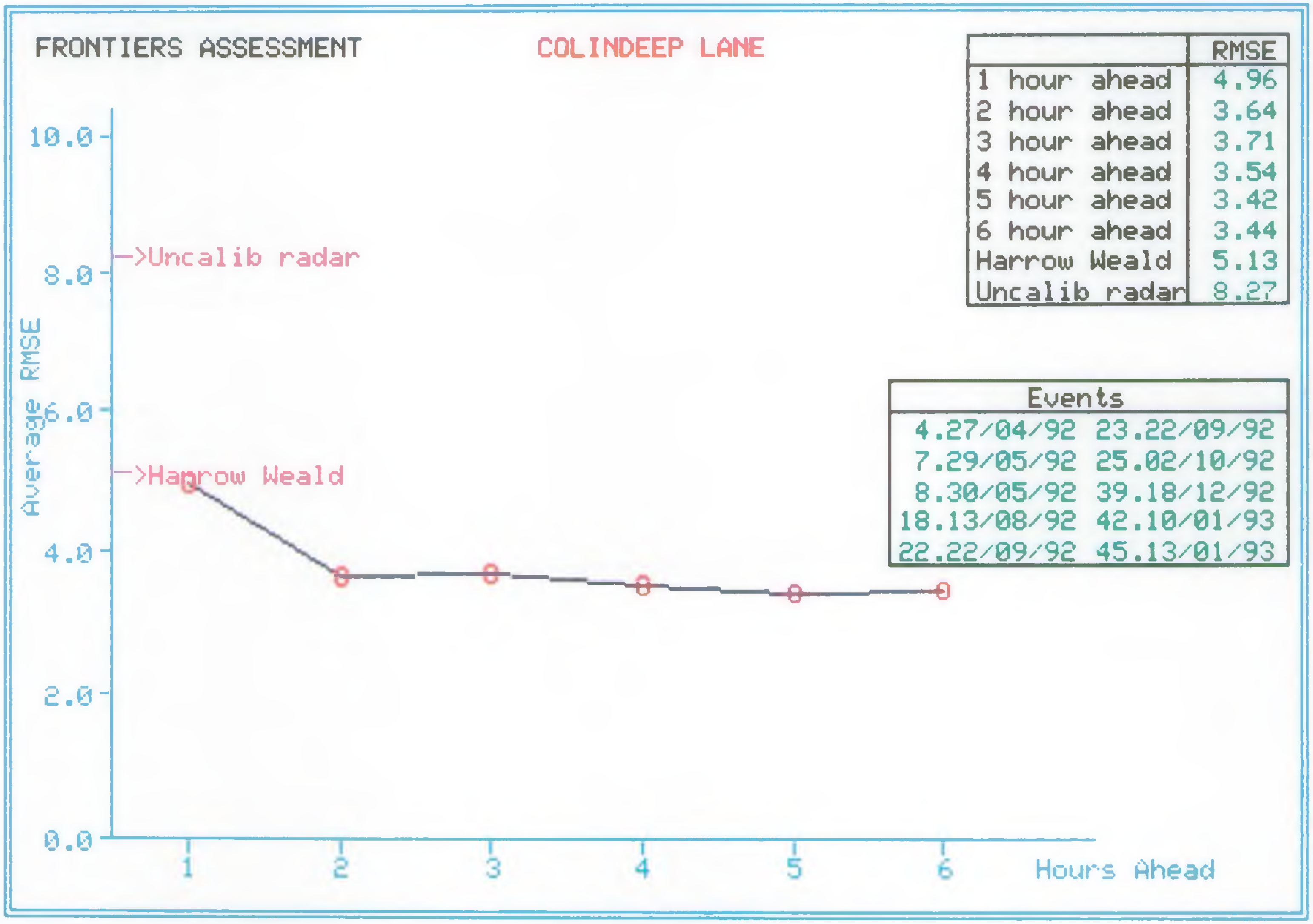


Figure : Average flow RMSE for largest 10 events at Colindeep Lane using Frontiers Forecasts

Figure 10

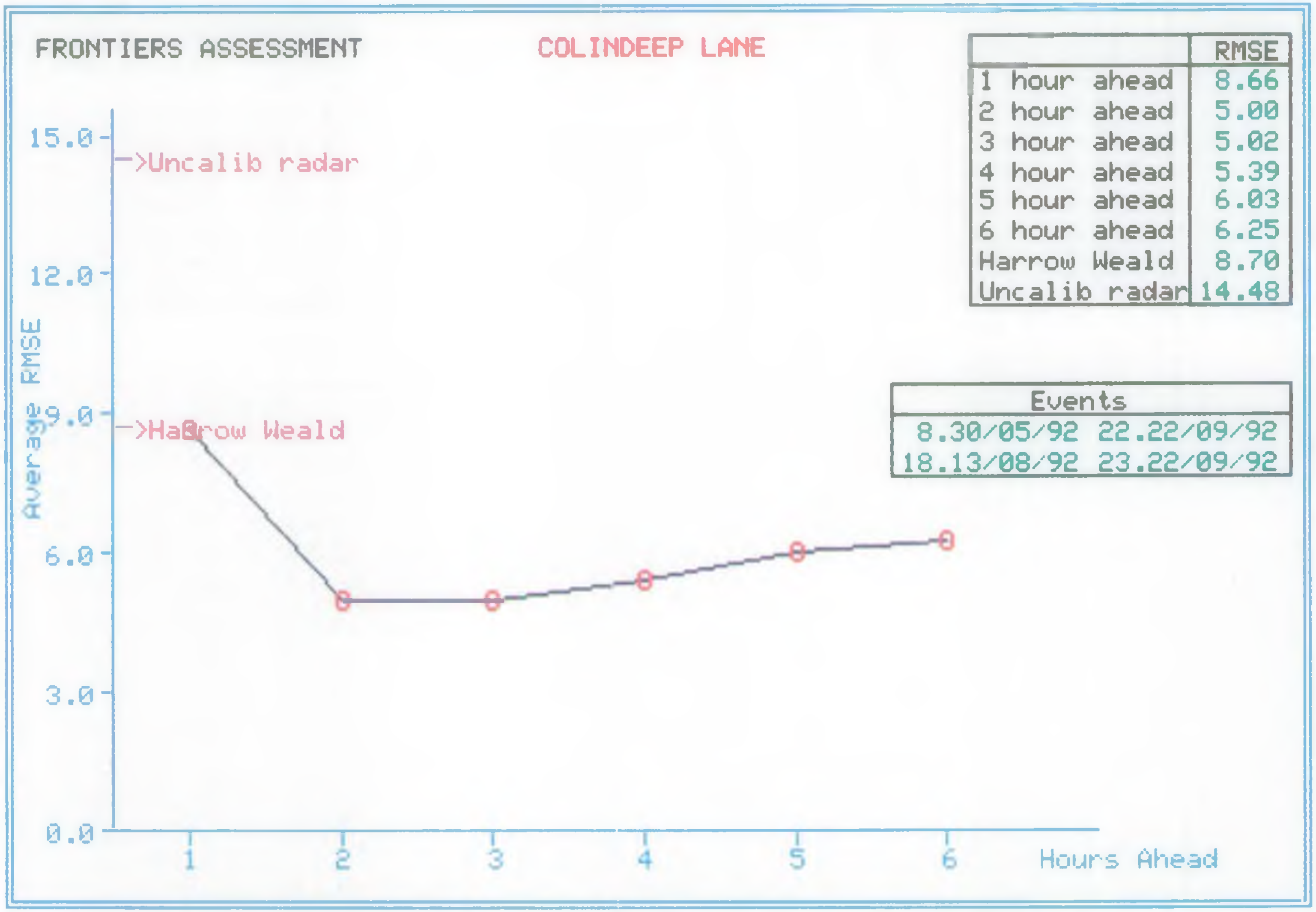


Figure : Average flow RMSE for largest 4 events at Colindeep Lane using Frontiers Forecasts

Figure 11

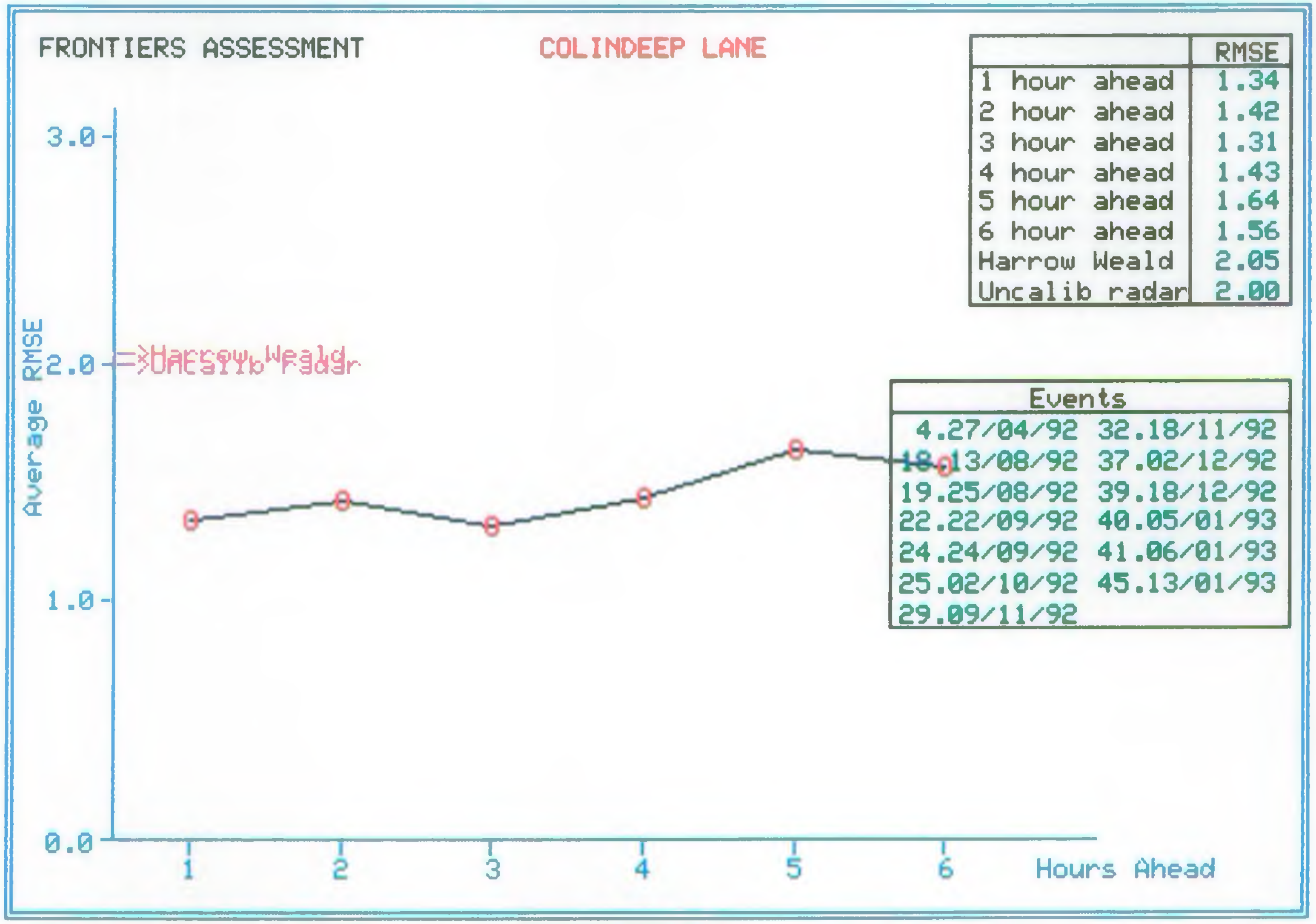


Figure : Average flow RMSE for 13 frontal events at Colindeep Lane using Frontiers Forecasts

Figure 12

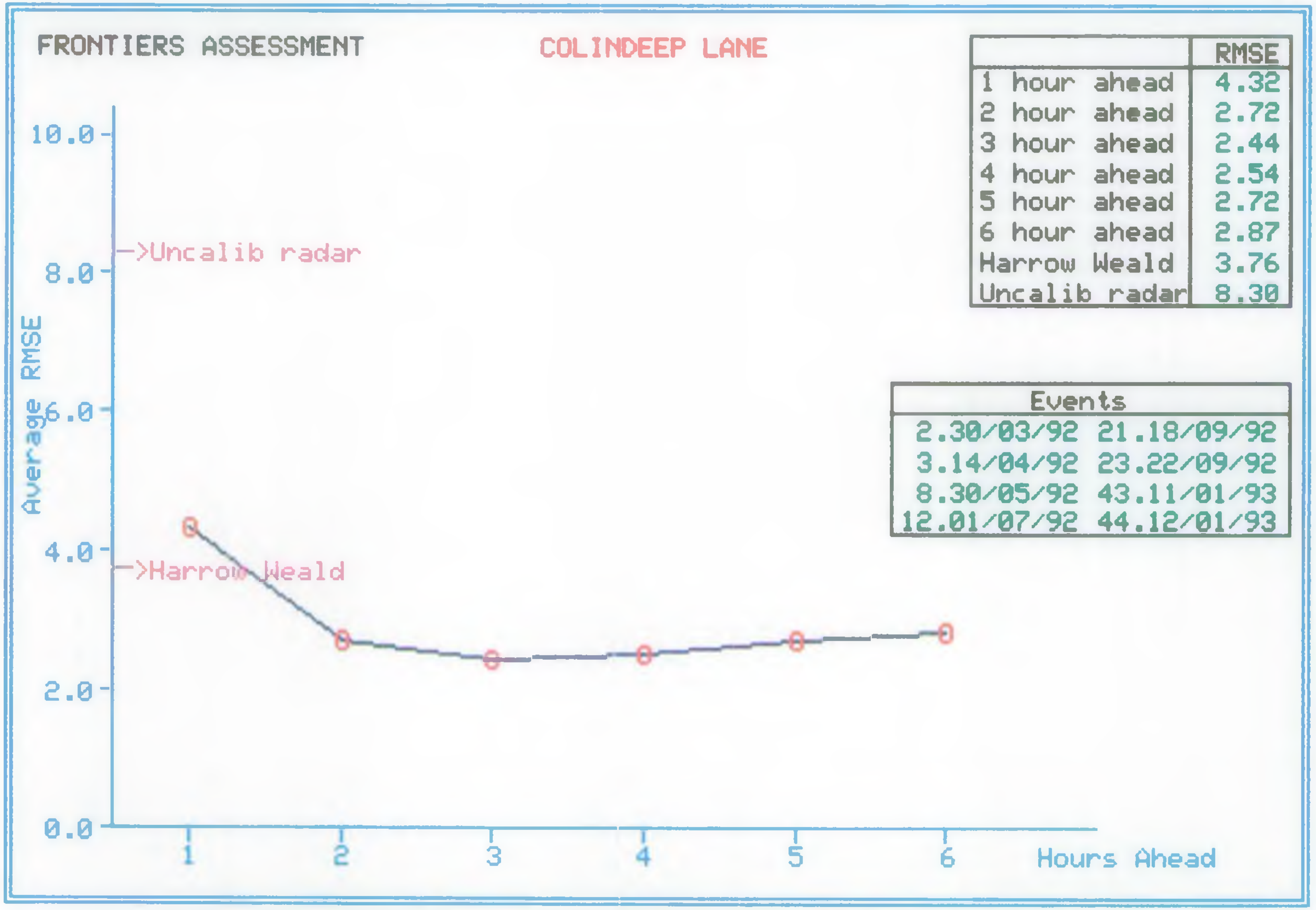


Figure : Average flow RMSE for 8 convective events at Colindeep Lane using Frontiers Forecasts

Figure 13

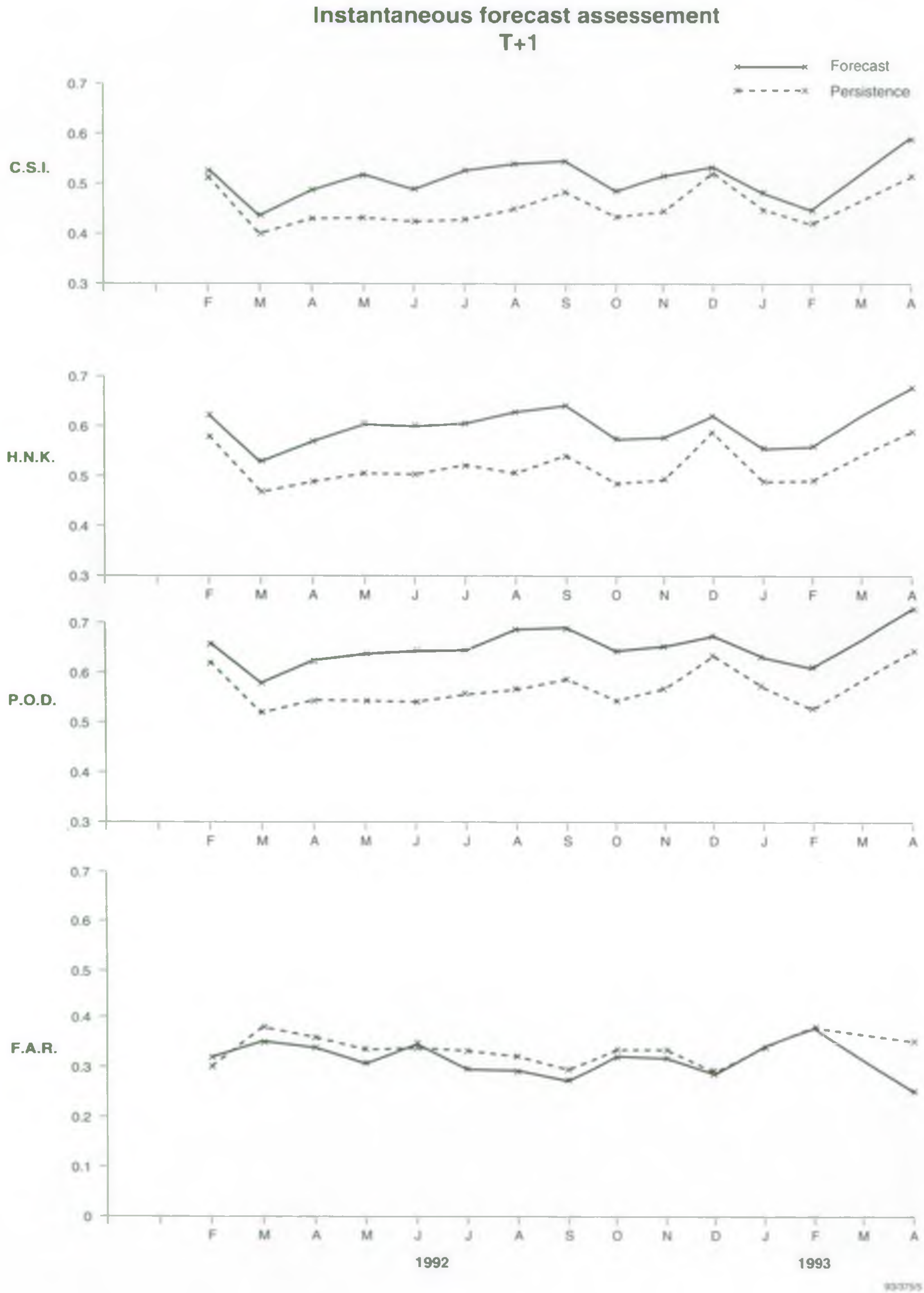

Instantaneous forecast assessement
T+1
Forecast
Persistence
C.S.I.
H.N.K.
P.O.D.
F.A.R.
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
F M A M J J A S O N D J F M A
1992
1993

Figure 14

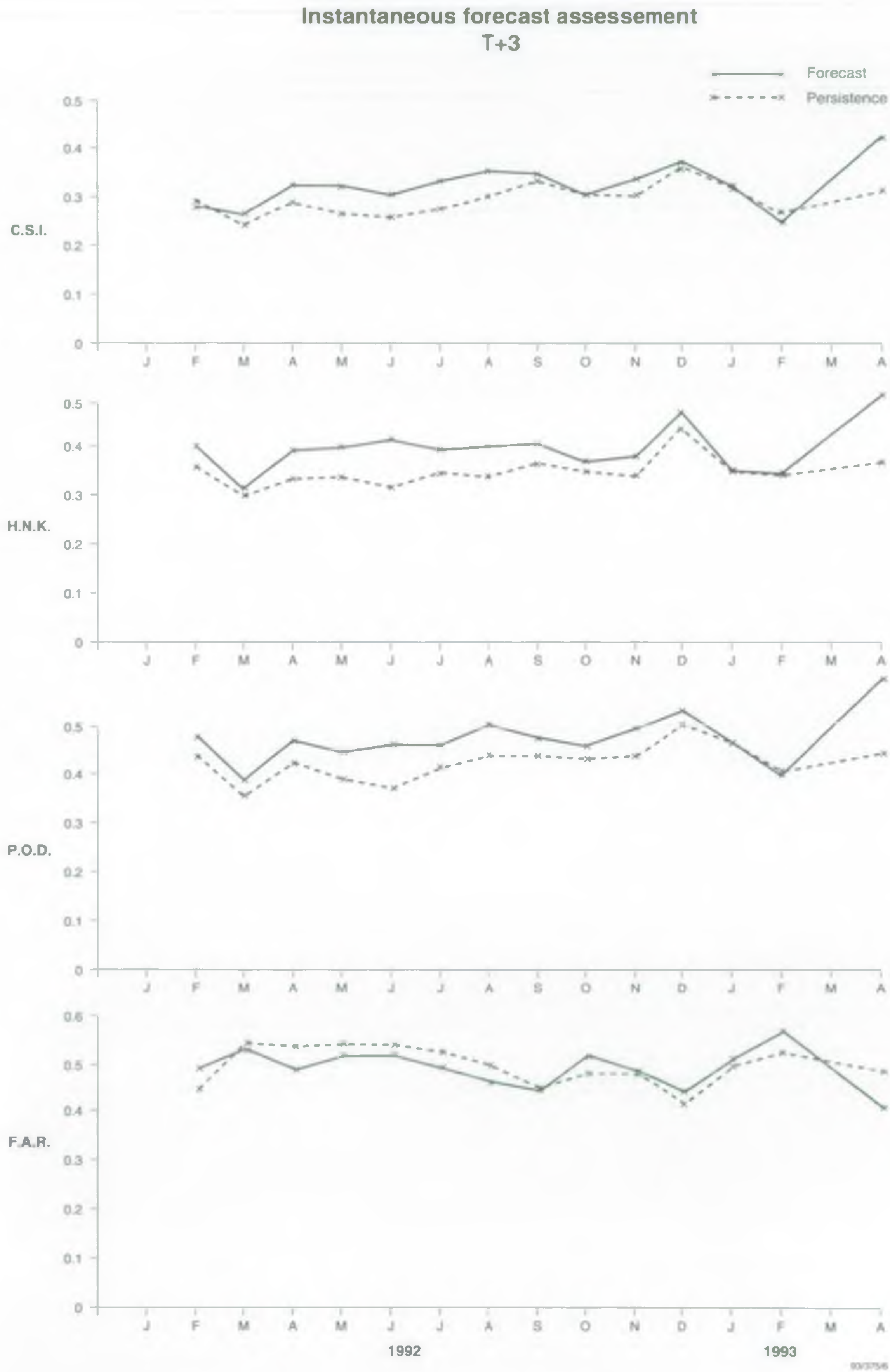
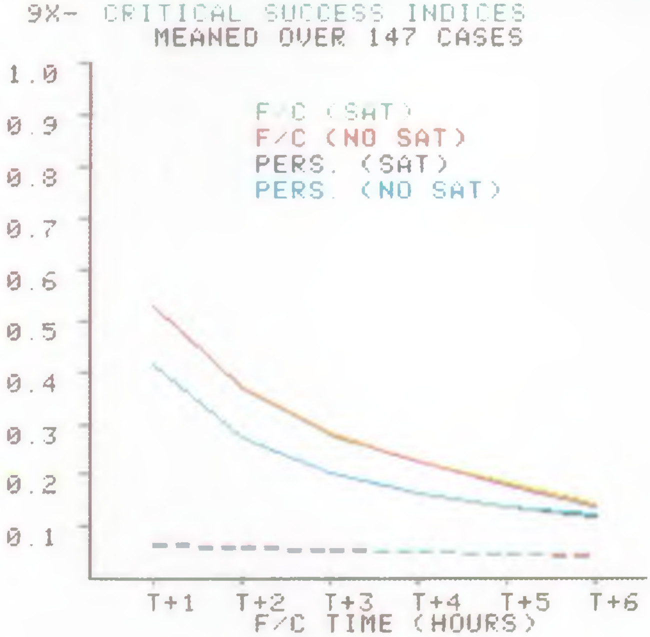
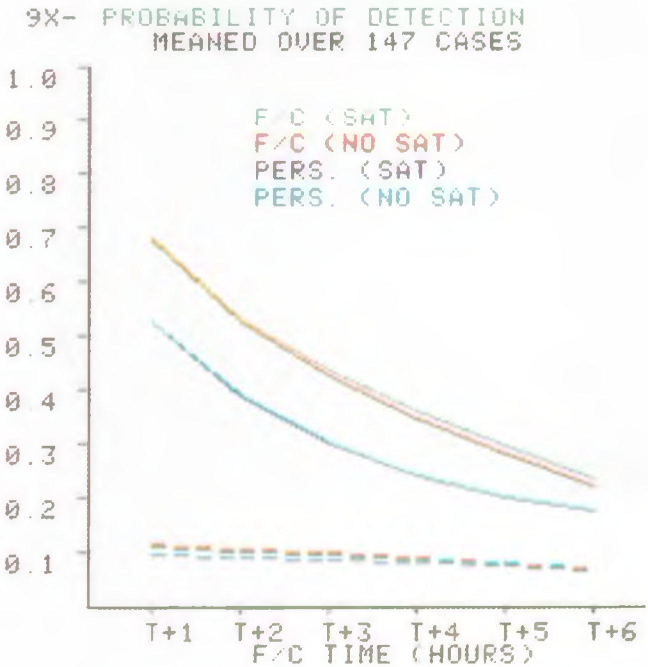

Instantaneous forecast assessement
T+3
Forecast
Persistence
C.S.I.
H.N.K.
P.O.D.
F.A.R.
0
0.1
0.2
0.3
0.4
0.5
0.6
J F M A M J J A S O N D J F M A
1992
1993

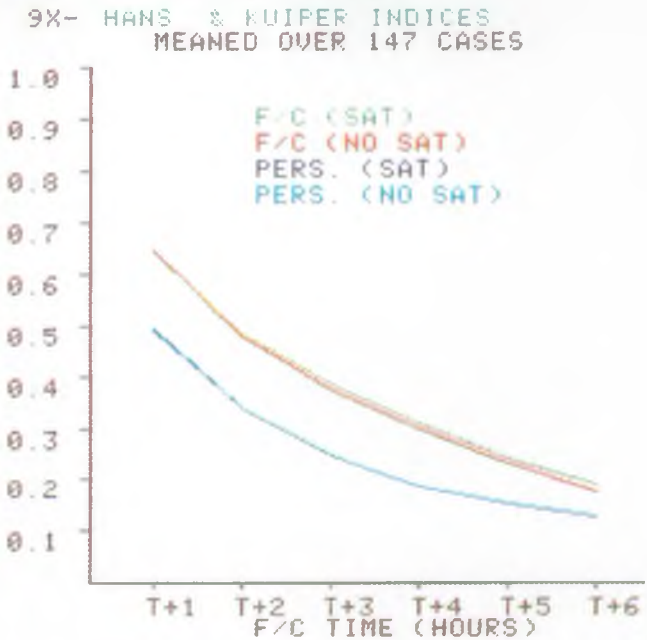
Figure 15

4 'THUNDERSTORM' DAYS (24.5.92,





30.5.92, 19.6.92, 11.7.92)



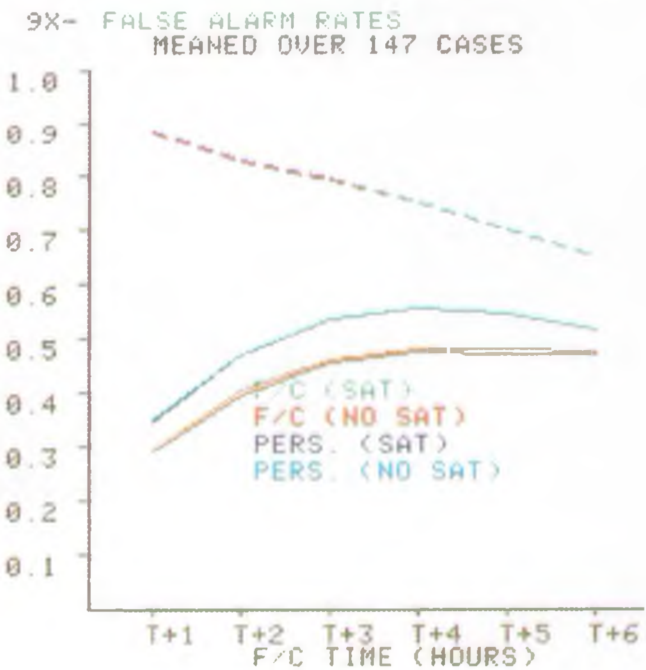


Figure 16

4 'TFRONTAL' DAYS (3.7.92, 2.10.92, 14.11.92, 6.12.92)

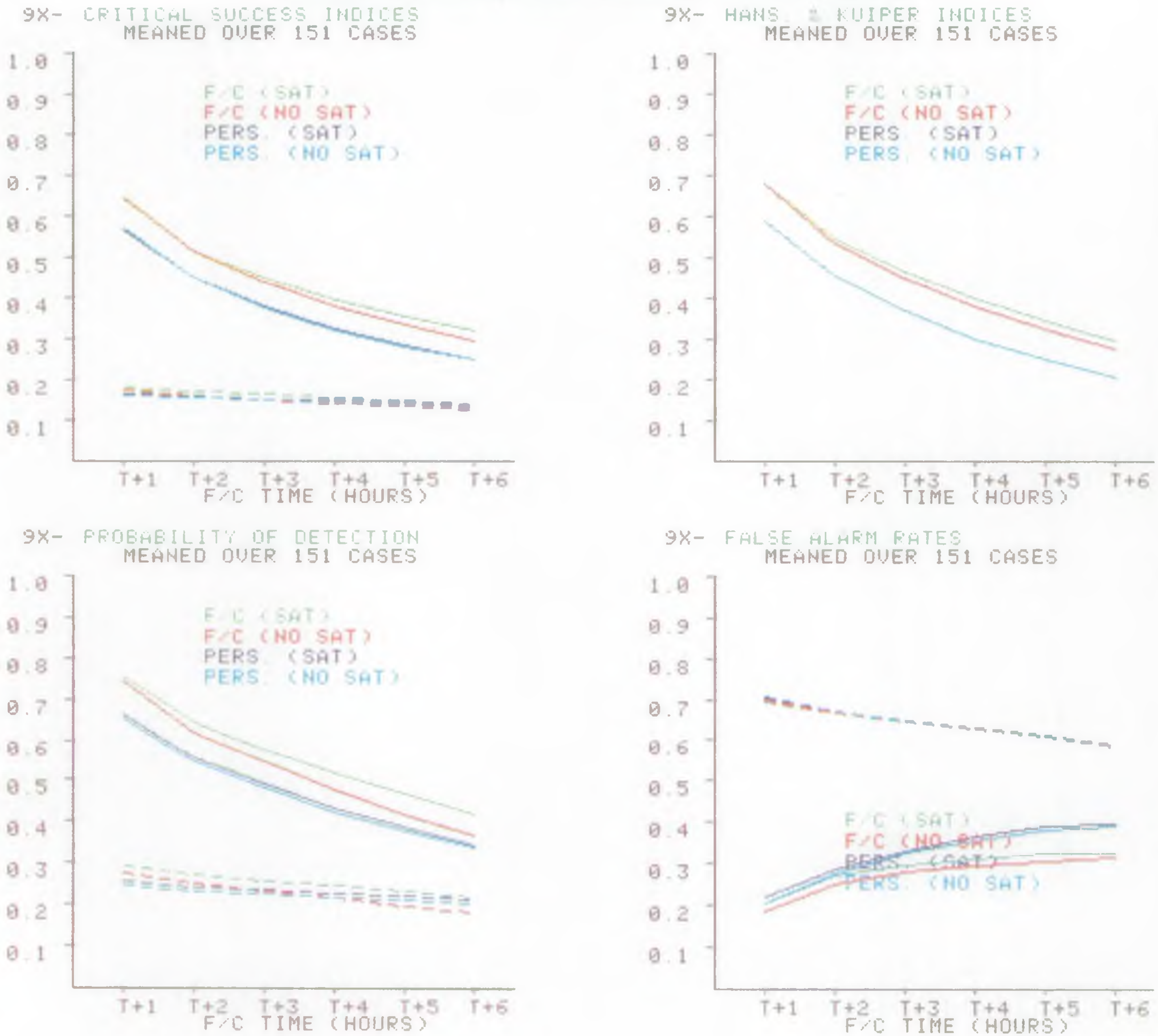


Figure 17

TO THE NATIONAL RIVERS AUTHORITY
FROM THE WEATHER CENTRE MANCHESTER
ISSUED AT 0745
ON Thursday 21st January 1993

TEXT: A PERIOD OF HEAVY RAIN IS EXPECTED BETWEEN ABOUT 1400 AND 2000 TODAY GIVING AN EVENT A IN CATCHMENTS 1 TO 7 INC, ESPECIALLY CATCHMENTS 1, 2, 3 AND 4.

VALID UNTIL 2000 ON 21st January 1993

NNNN

N.B. THIS WARNING SHOULD ALSO BE PASSED TO NRA BY TELEPHONE
ON 0925-53999 (GEN OFFICE) TRY THIS FIRST
ALT NO. 0925-34538 OR FAX 0925-413611

===

*** 21–JAN–93 17:28:19 ***

LAST FULL WARRINGTON UPDATE FINISHED AT 1713 GMT ON DAY 21

REGIONAL RAINFALL
=================

RAINGAUGES	STAND -BY		LAST HOUR	LAST 3HRS	LAST 6HRS	LAST 12HR	LAST 24HR
GILSLAND	20/6	*	.200	3.60	6.20	6.20	9.00
SKELTON	20/6	*	.800	9.19	10.9	10.9	11.5
SCALEBECK	20/6	*	.200	7.20	12.8	12.8	13.8
BARRAS	20/6	*	.796	3.58	5.77	5.77	6.77
CASTLETHWAITE	20/6	*	.200	15.8	23.4	23.4	24.2
CORNHOW	7/1+20/6	*	.000	.000	1.60	1.60	1.80
THIRLMERE	20/6	*	.400	9.00	15.7	15.7	15.9
KENTMERE/HALLOWBANK	20/6	*	.000	4.00	10.8	10.8	12.2
BENTHAM	20/6	*	.201	2.61	5.42	5.42	6.03
ABBEYSTEAD	20/6	*	.000	1.20	4.40	4.40	4.99
GEARSTONES	20/6	*	.800	13.0	20.8	20.8	23.0
TRAWDEN							

Figure 18

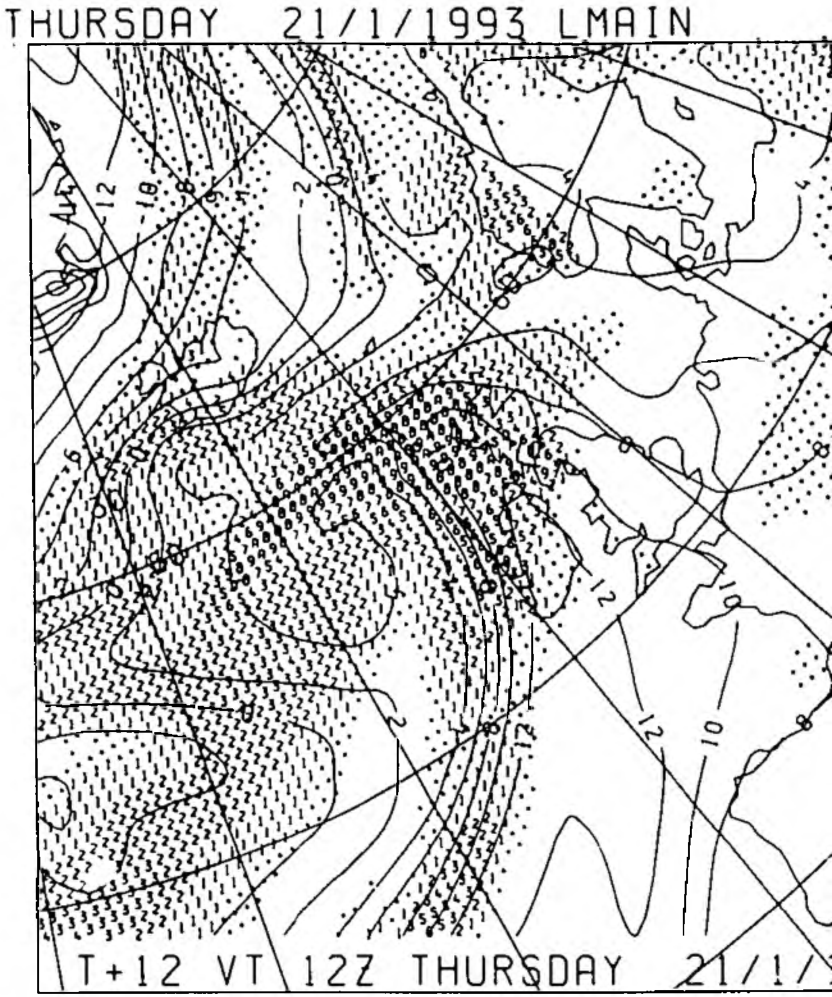
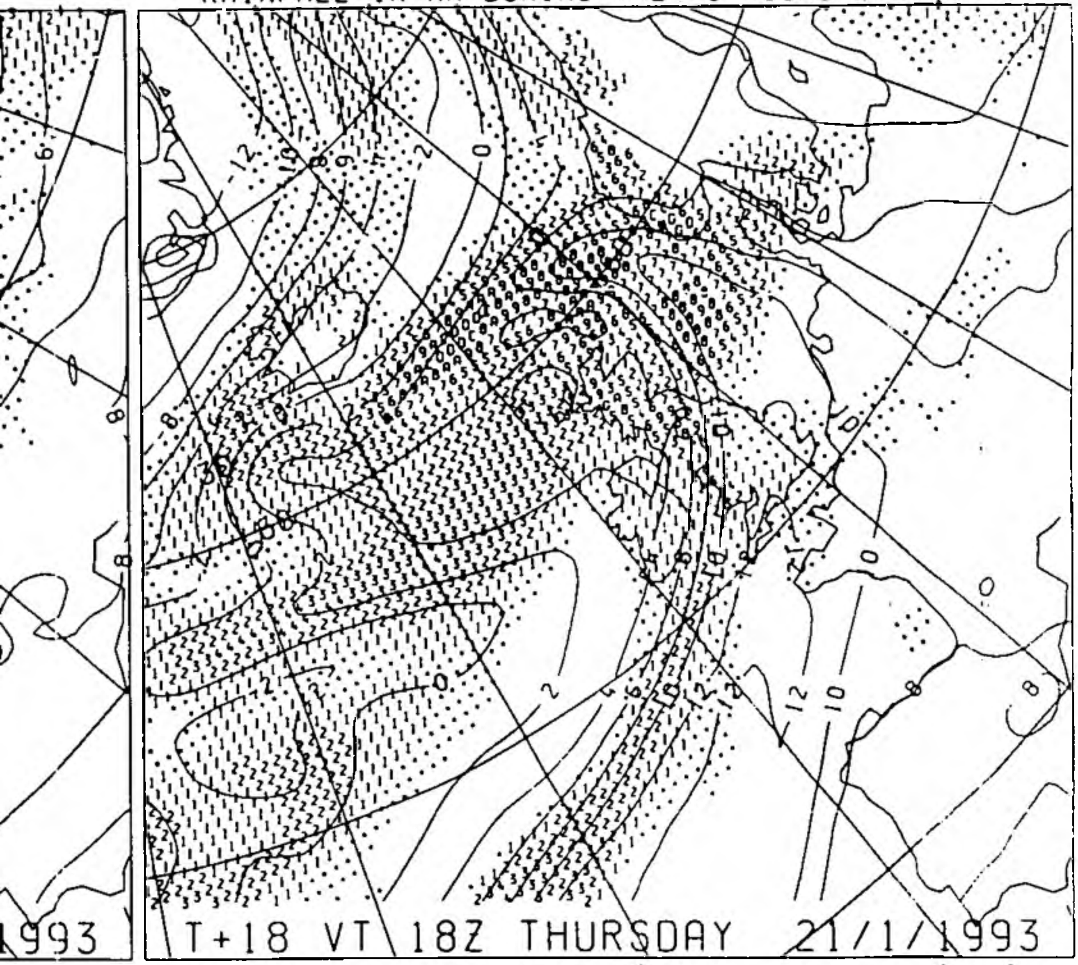


Figure 19

RAINFALL IN MM DURING THE 6 HOURS ENDING AT VT



CRITERIA	WARNING ACTION
COLD FRONTS 1. a. Active cold front expected to become slow-moving as it approaches the area. Development of a wave moving NW across Scotland appears to be particularly favourable, or there may be only small waves running along the front. b. High relative humidity up to 700 mb in the air ahead of the front. c. Gradient wind speed 43 KT or more from a general SW'ly direction (210 to 250 deg probably being the most favourable).	Type 'A' warning for catchments 2 and 4.
2. a. Active cold front, often with small waves, expected to become slow-moving near area. b. Relative humidity as in 1b. c. Gradient wind speed of 35 KT or more from a general SW'ly direction (190 to 250 deg probably being the most favourable but gradient veered more than 250 deg will still probably give heavy rain in catchment 9.	Type 'A' warning for catchments 1, 3, 5, 6, 7 and 9.
3. a. Cold front approaching from a general W'ly, SW'ly or S'ly direction. b. Relative humidity as in 1b. c. Gradient wind direction 150 to 290 deg. d. Gradient wind speed normally 35 KT or more, but 25 to 30 KT may be sufficient if accompanied by pressure falls of the order of 4 mb/3 hr.	Type 'B' warning considered for catchments 11 to 14, depending on frontal orientation and activity, plus likely orographic enhancement. Rarely a Type 'C' warning for catchment 15 may be required.

Figure 20

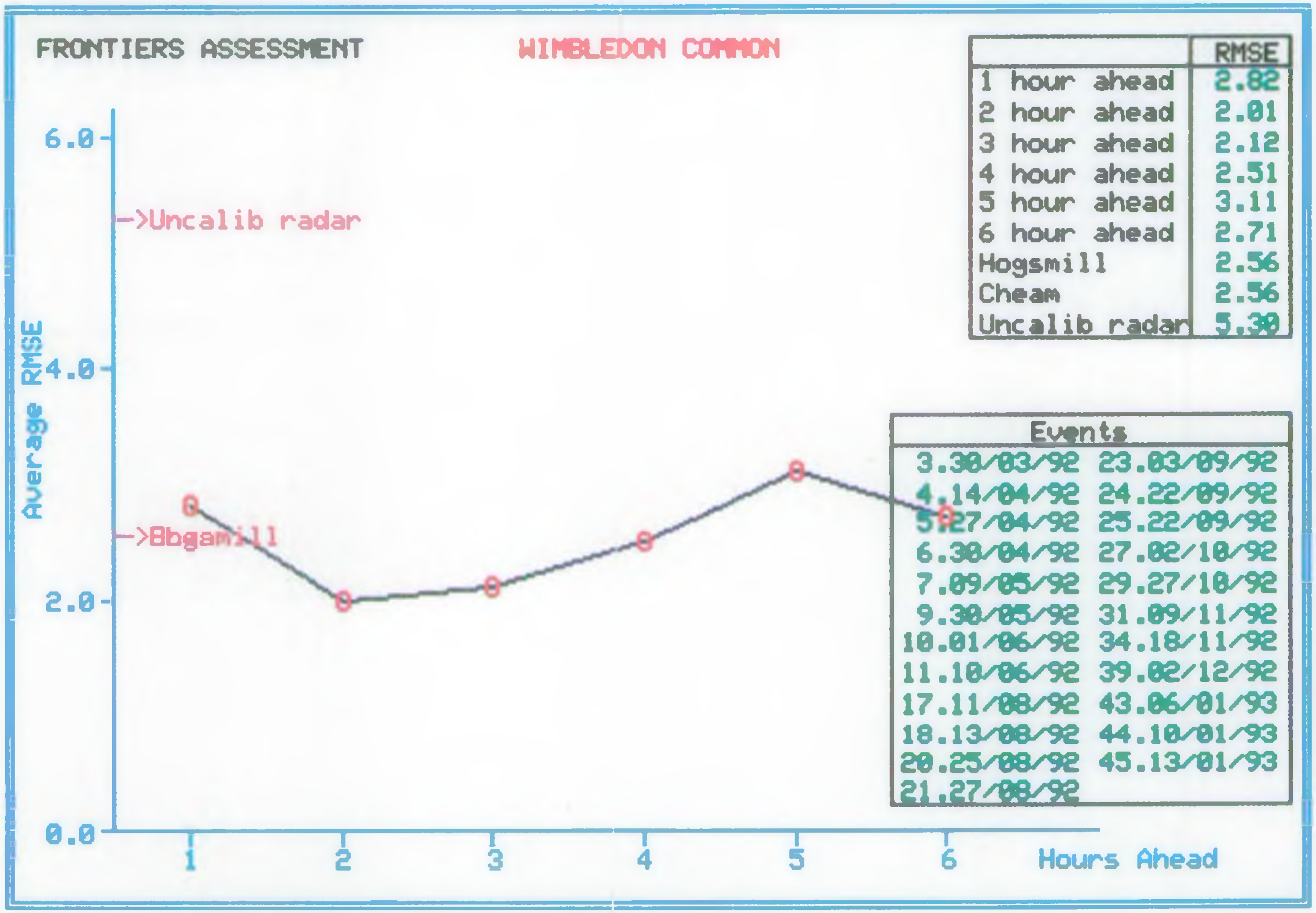


Figure : Average flow RMSE for 23 events at Wimbledon Common using Frontiers Forecasts

Figure 21

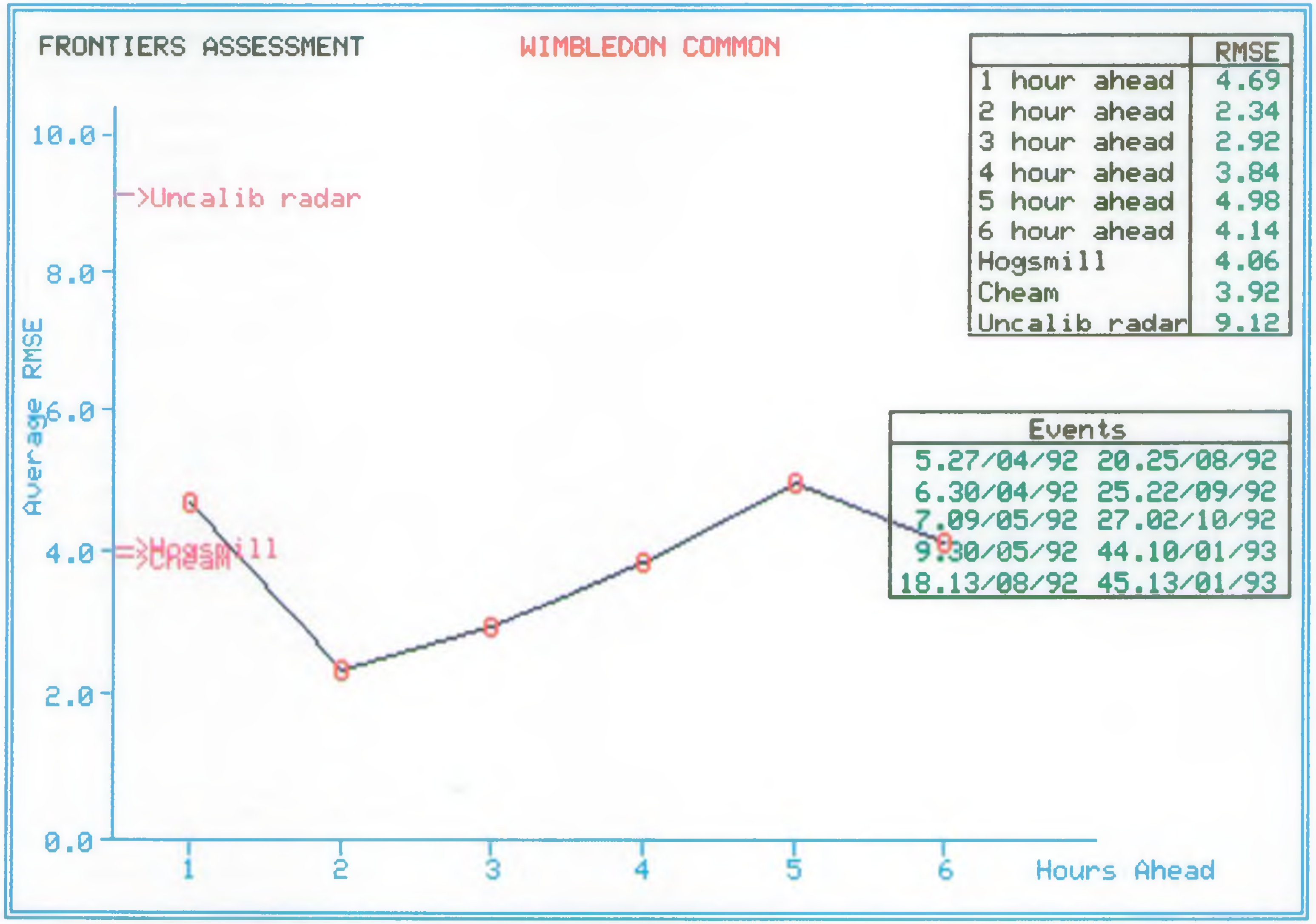


Figure : Average flow RMSE for largest 10 events at Wimbledon Common using Frontiers Forecasts

Figure 22

Figure 23

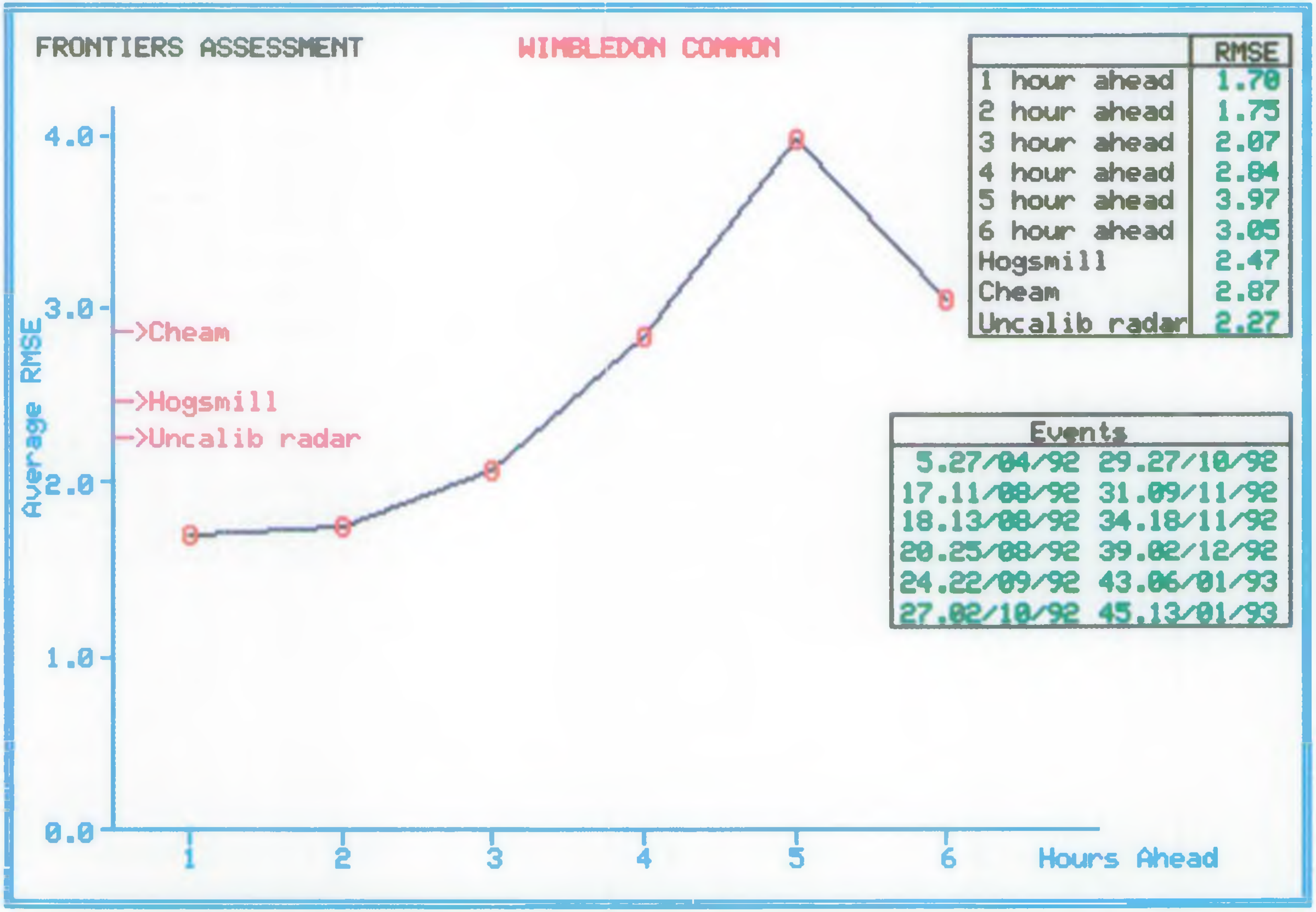


Figure : Average flow RMSE for 12 frontal events at Wimbledon Common using Frontiers Forecasts

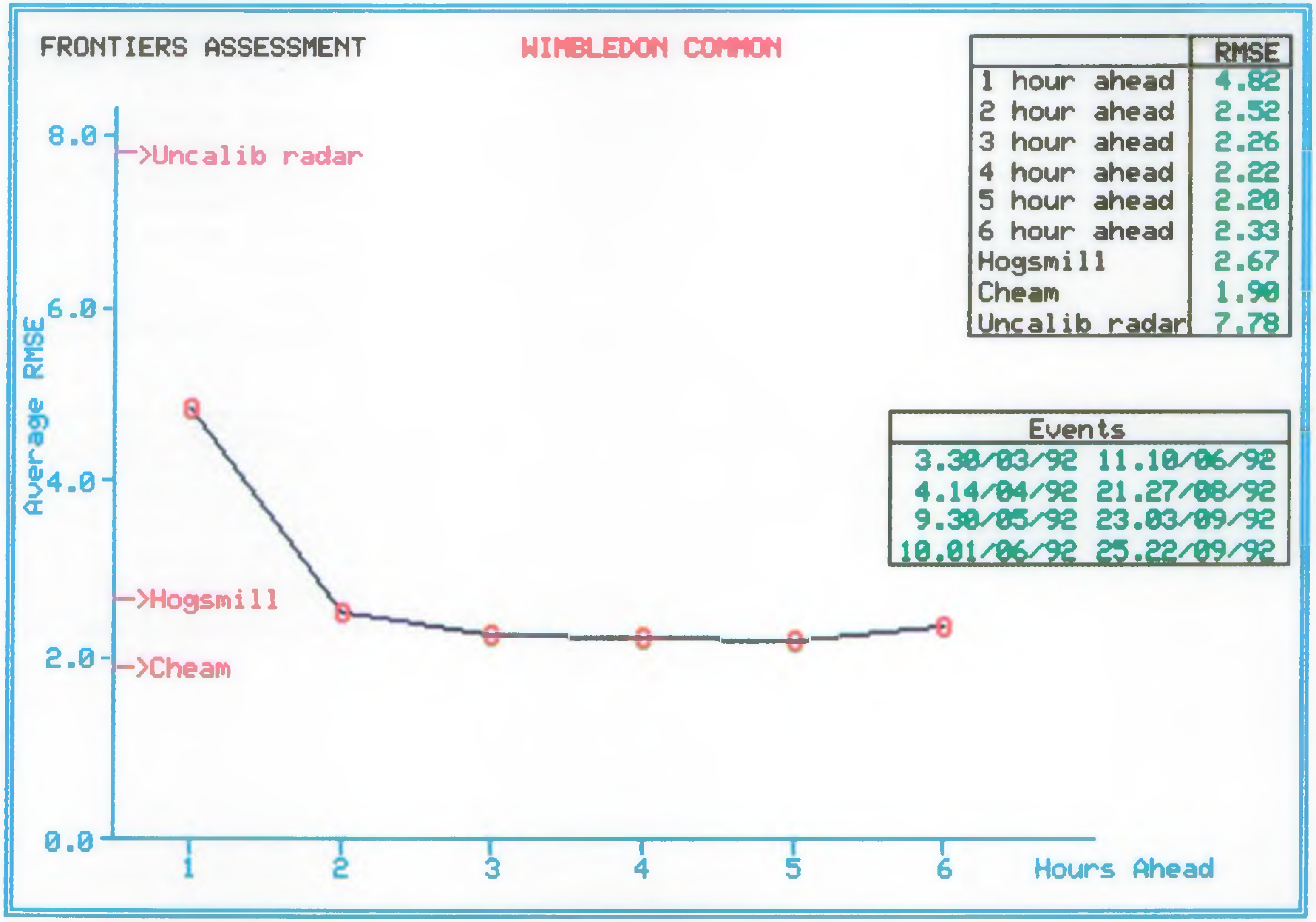


Figure : Average flow RMSE for 8 convective events at Wimbledon Common using Frontiers Forecasts

Figure 24

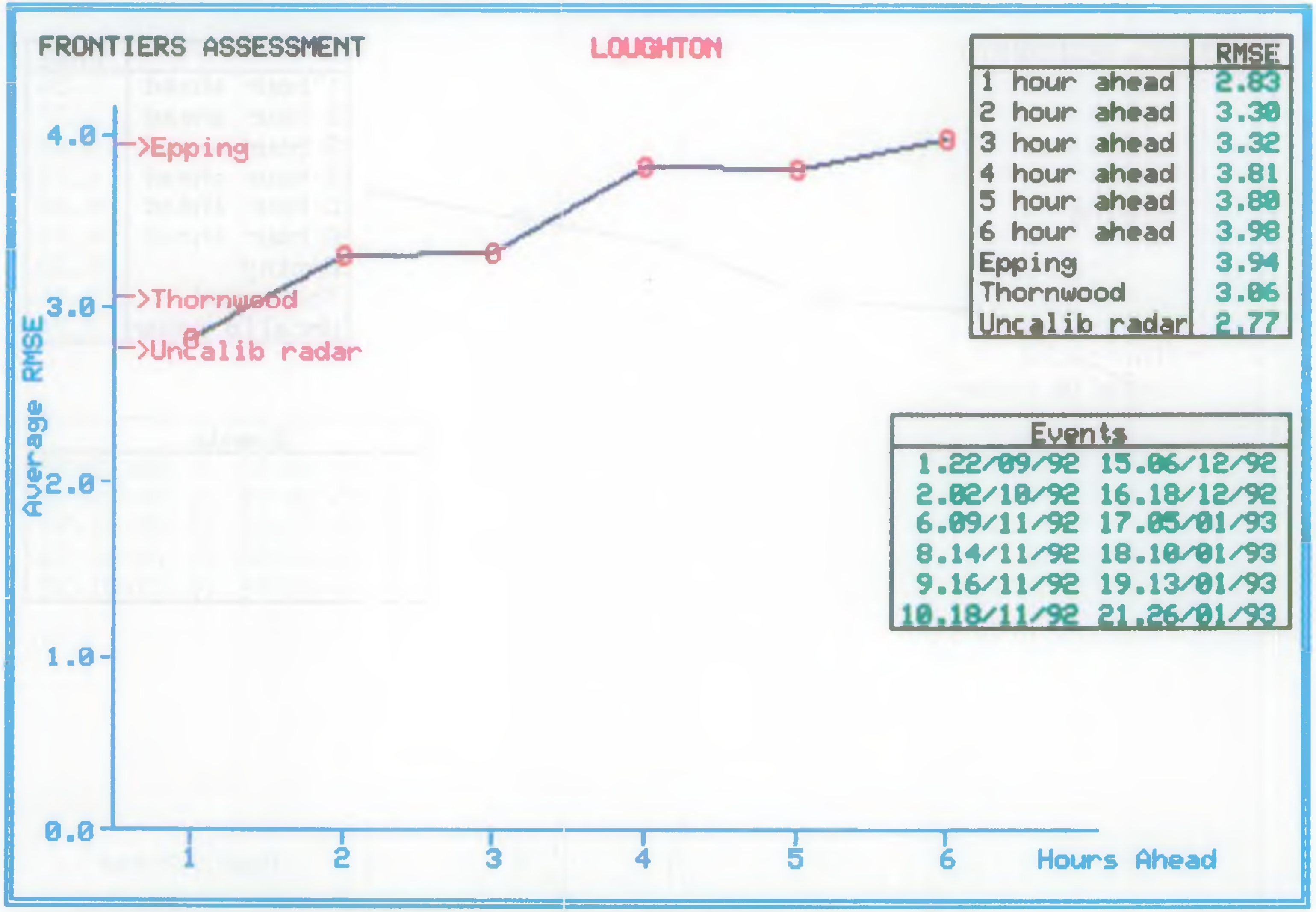


Figure : Average flow RMSE for 12 events at Loughton using Frontiers Forcasts

Figure 25

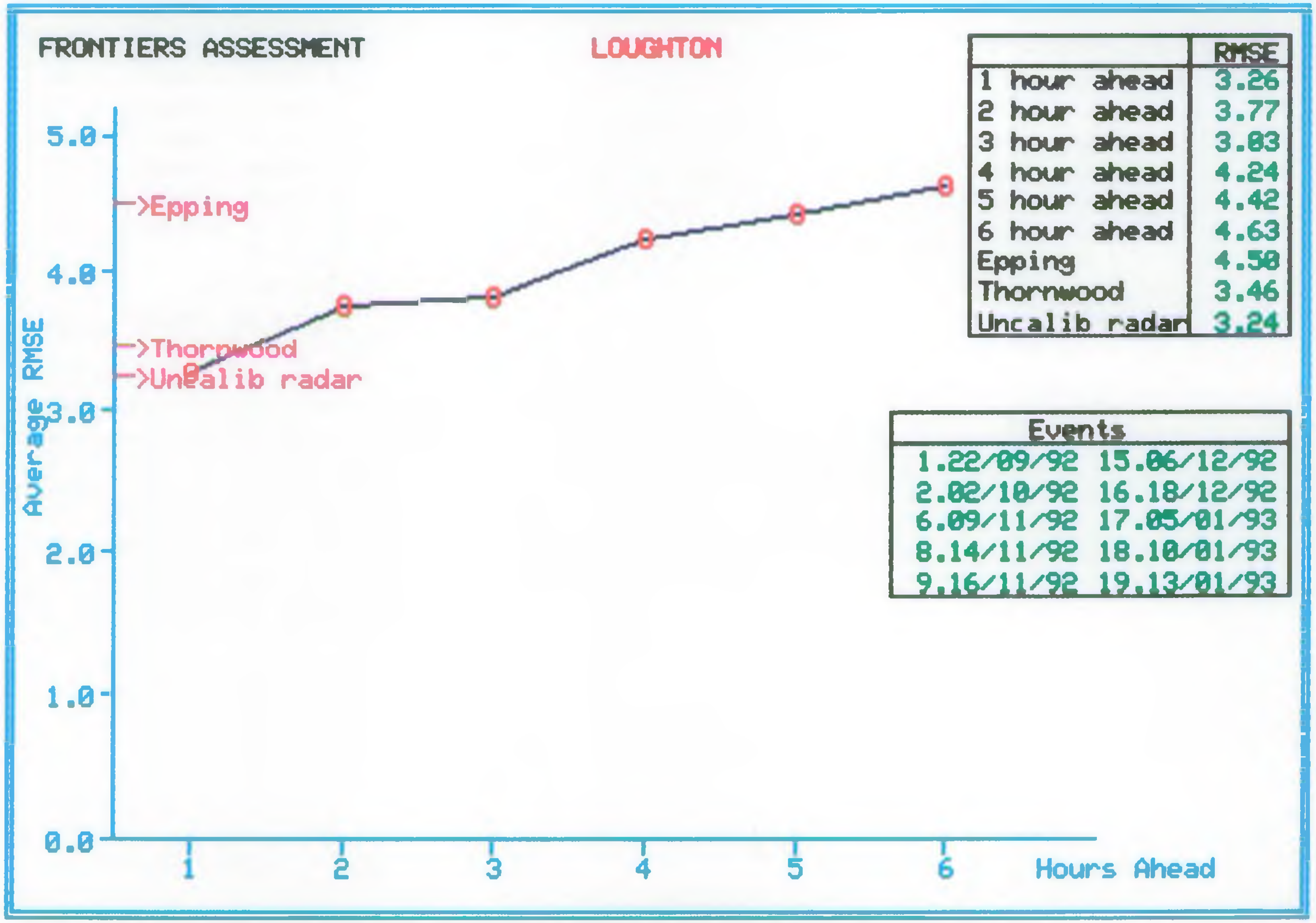


Figure : Average flow RMSE for largest 10 events at Loughton using Frontiers Forecasts

Figure 26

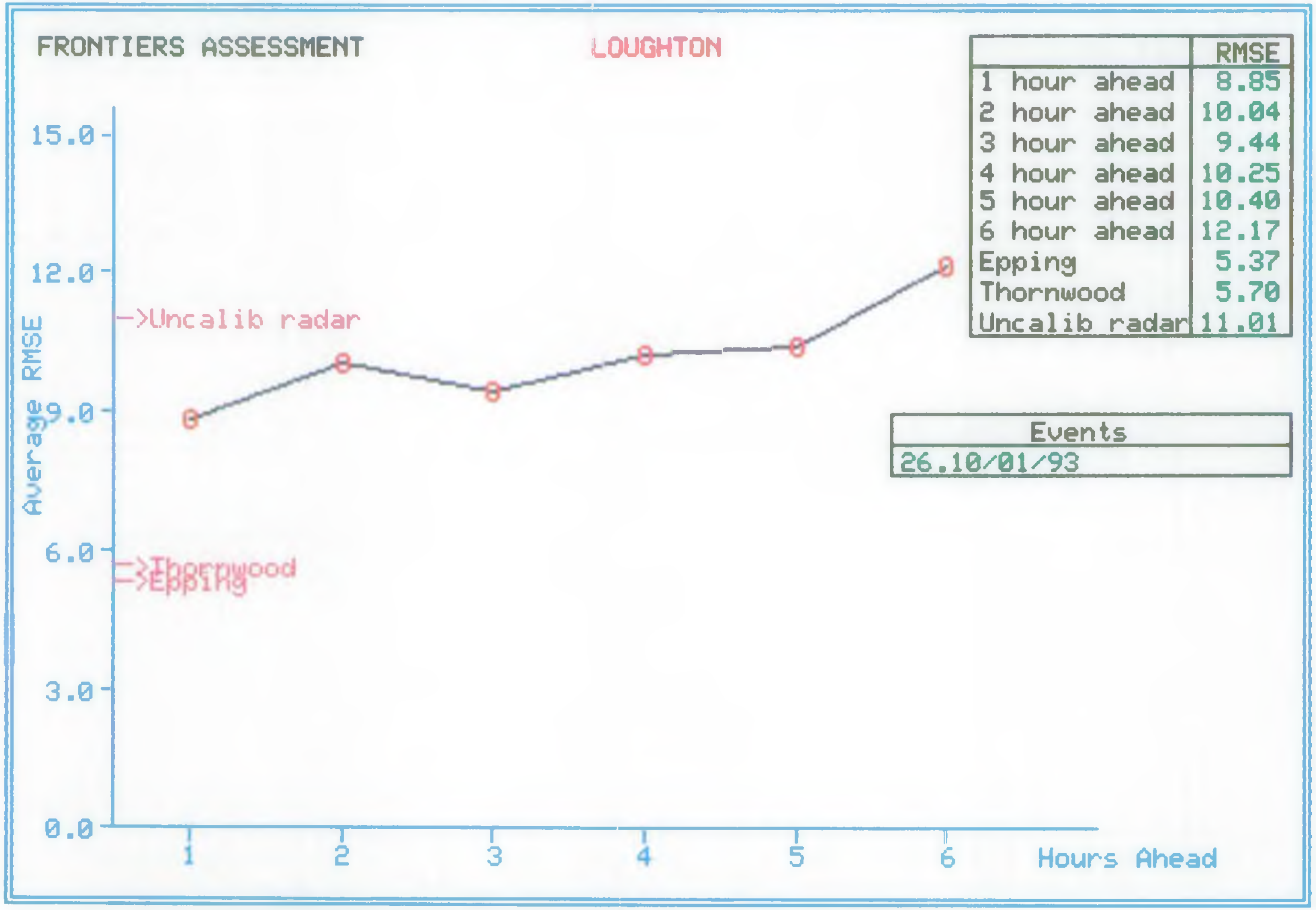


Figure : Average flow RMSE for largest event at Loughton using Frontiers Forecasts

Figure 27

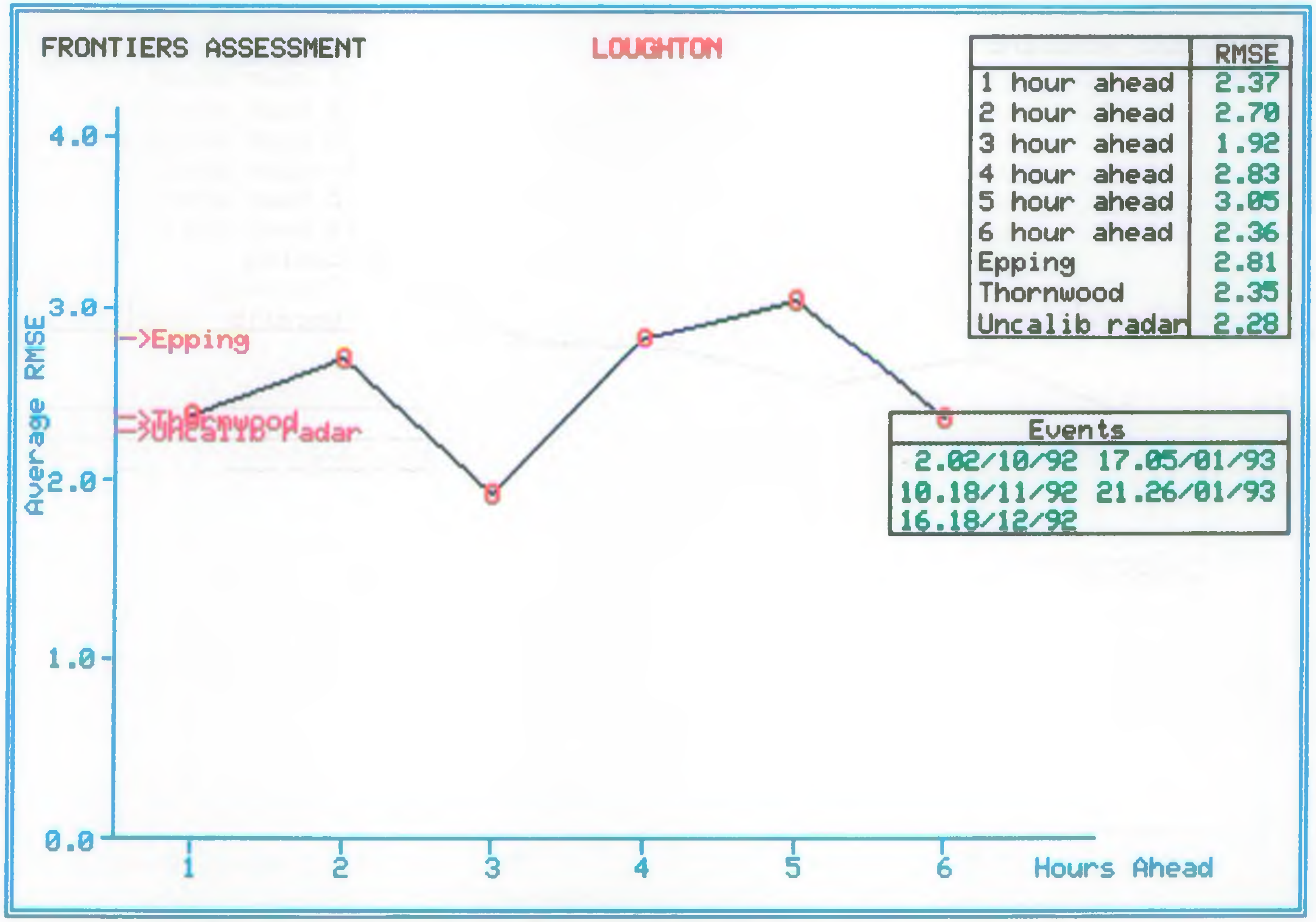


Figure : Average flow RMSE for 5 frontal events at Loughton using Frontiers Forcasts

Figure 28

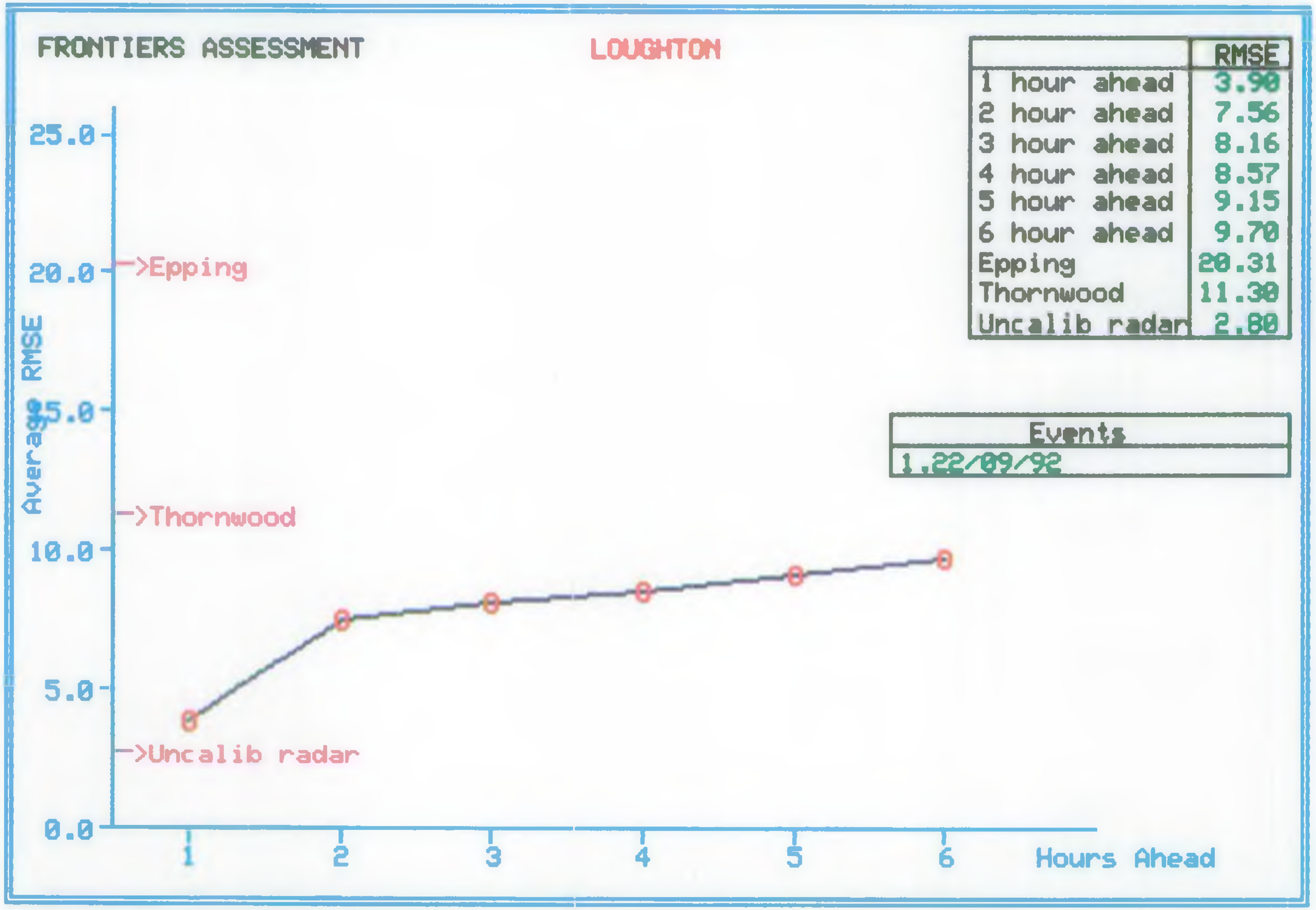
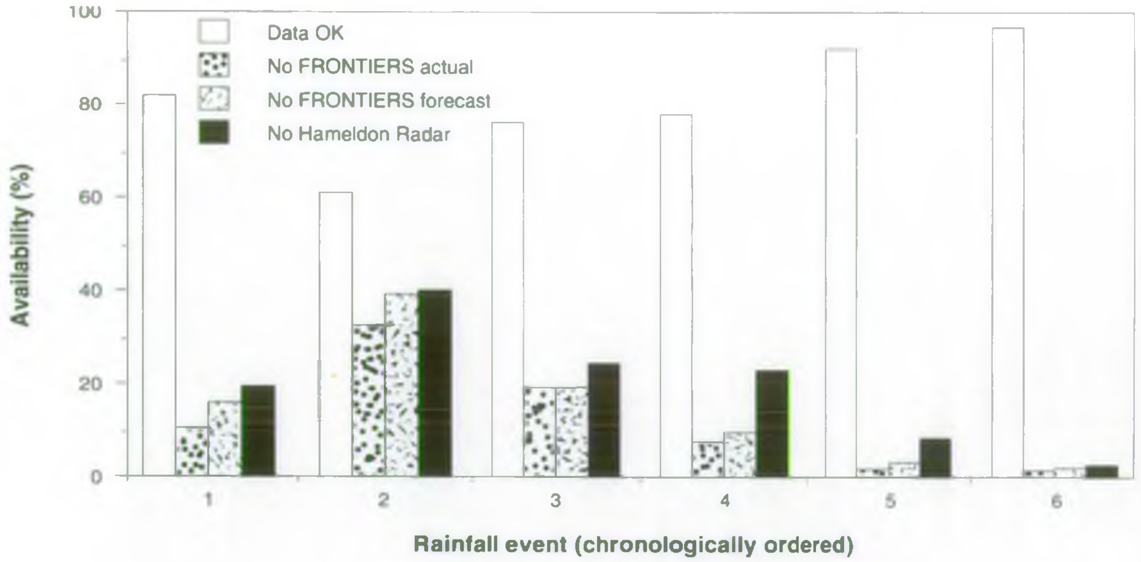
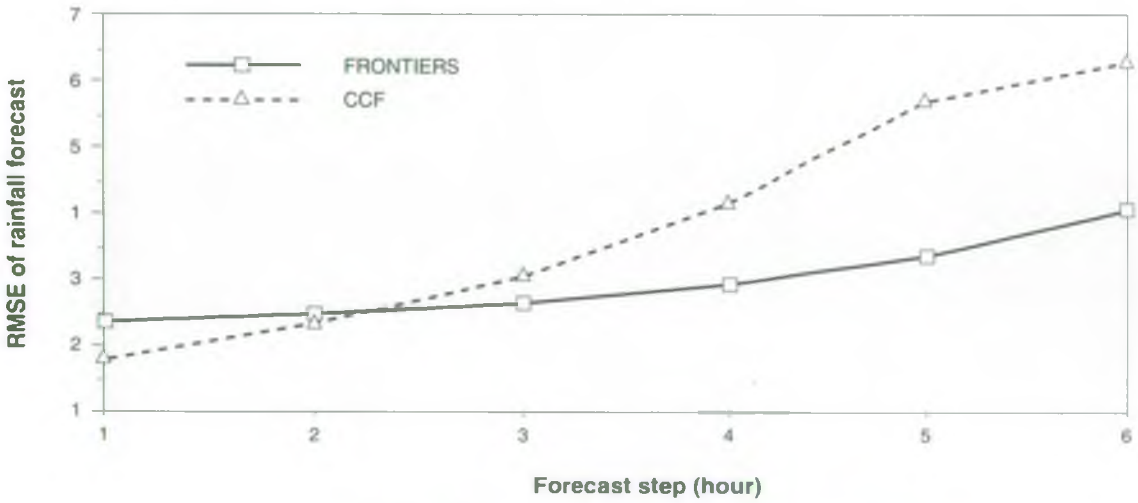


Figure : Average flow RMSE for 1 convective event at Loughton using Frontiers Forcasts

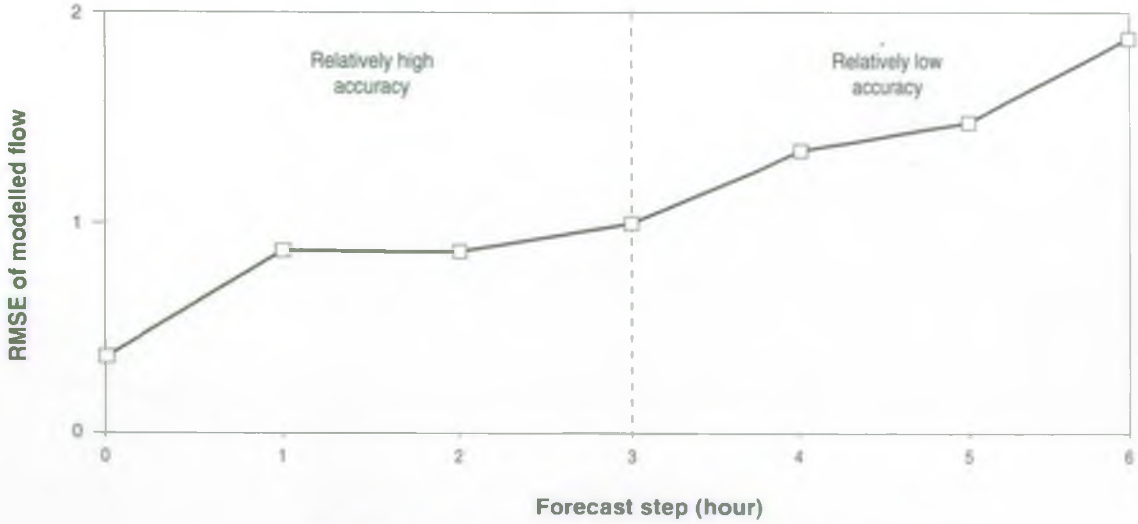
Figure 29



Data availability of FRONTIERS data



Average RMSE comparison between FRONTIERS and CCF



Average RMSE of flow simulation by FRONTIERS forecasts

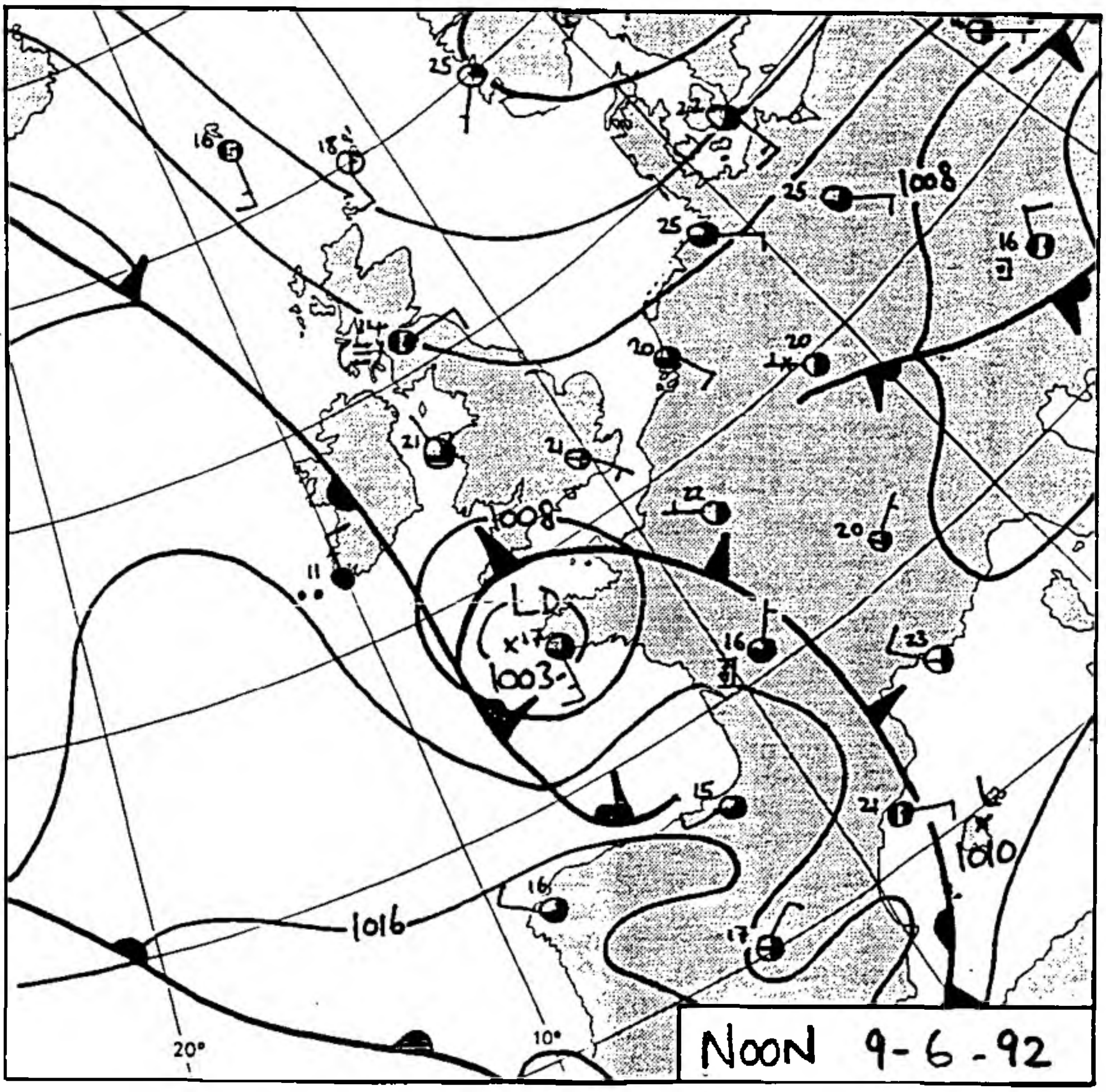
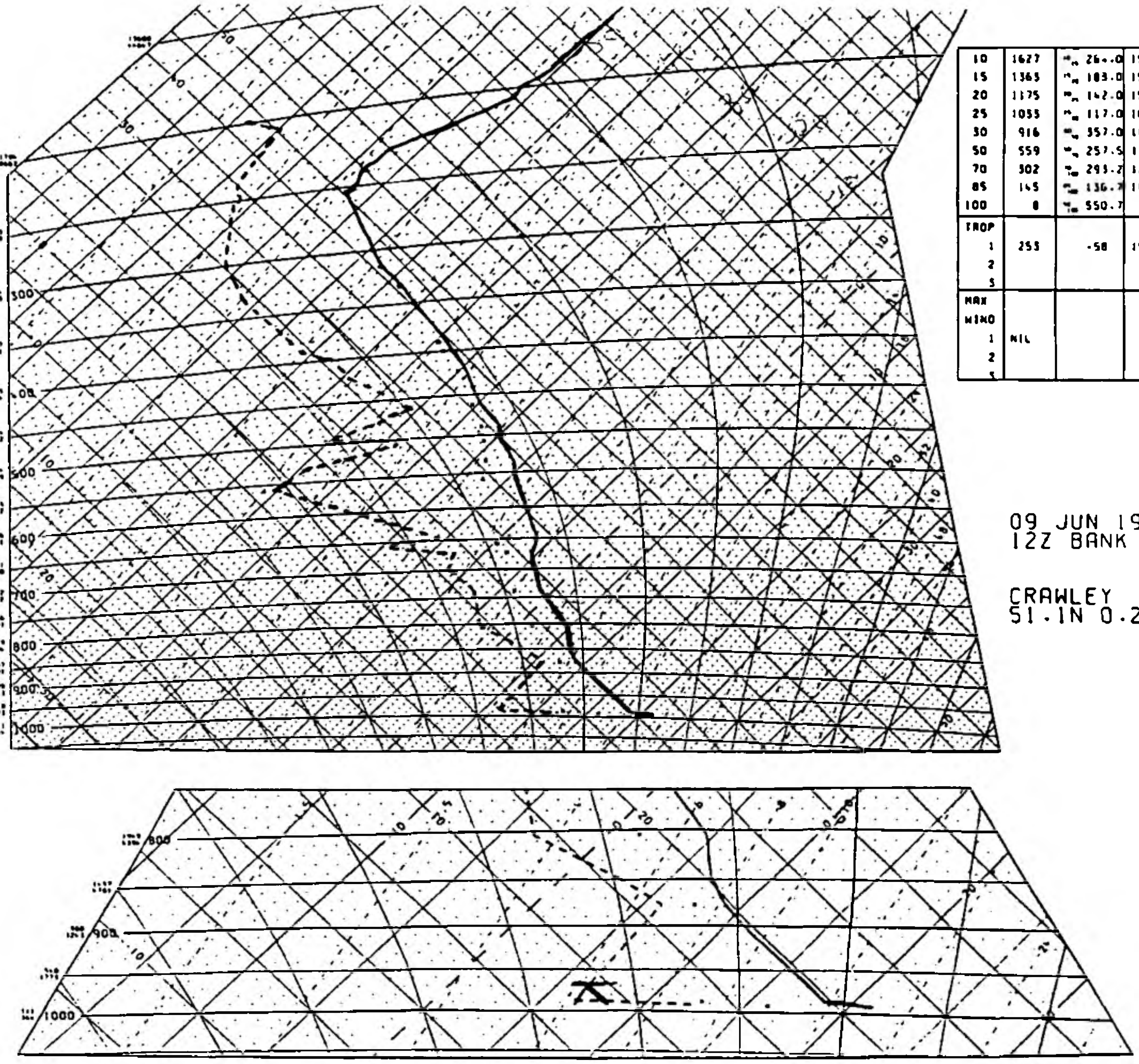


Figure 33



10	1627	264.0	155	10
15	1365	183.0	155	15
20	1175	142.0	150	12
25	1055	117.0	160	21
30	916	357.0	140	31
50	559	257.5	135	19
70	302	293.2	125	10
85	145	136.7	145	5
100	8	550.7		
TROP				
1	253	-58	155	21
2				
3				
MAX WIND				
1	NIL			
2				
3				

Figure 34

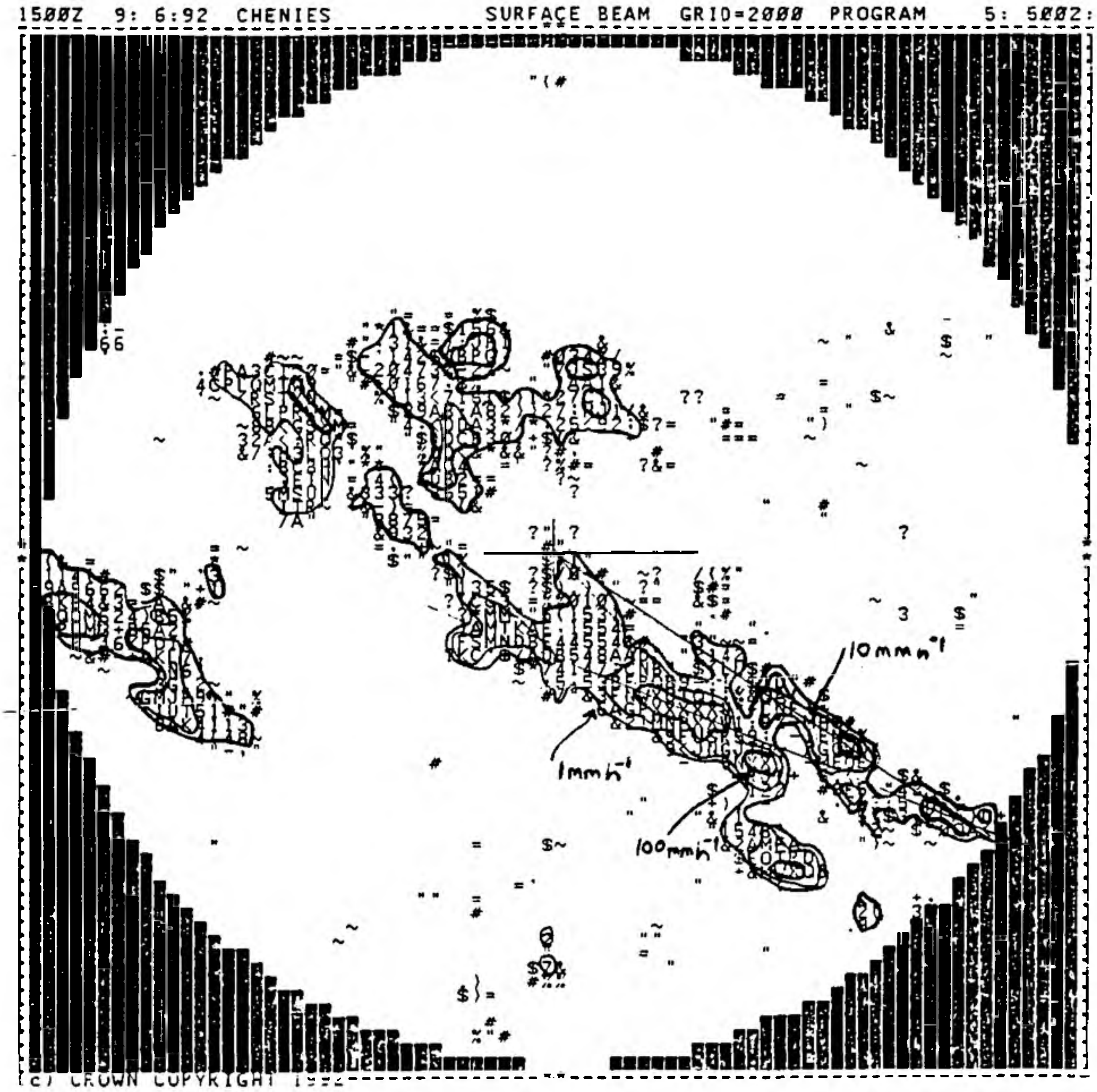
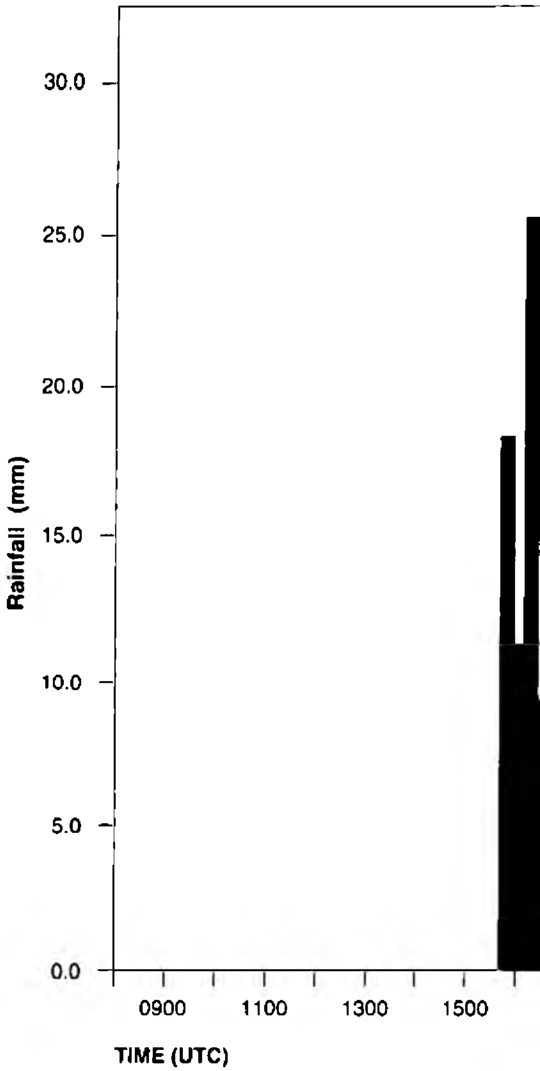

15ØØZ 9: 6:92 CHENIES SURFACE BEAM GRID=2ØØØ PROGRAM 5: 5ØØ2:
10mm h⁻¹
1mm h⁻¹
100mm h⁻¹
(c) CROWN COPYRIGHT

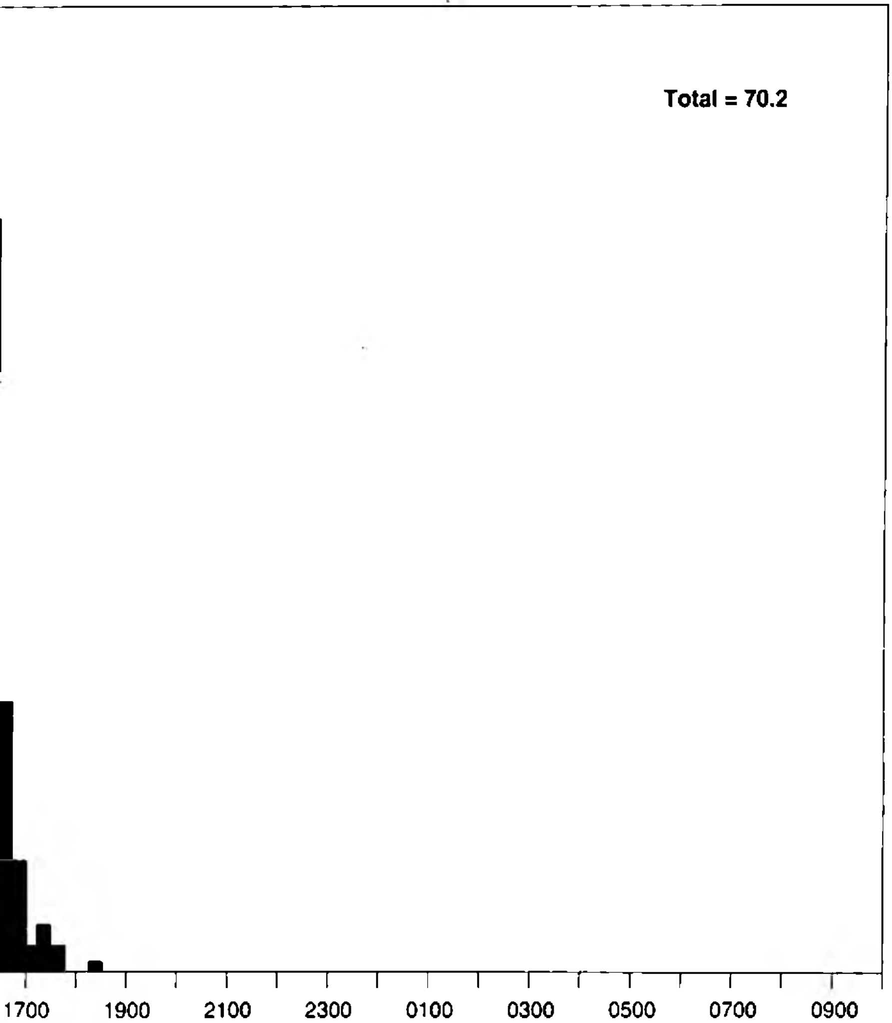
Figure 35

Figure 36

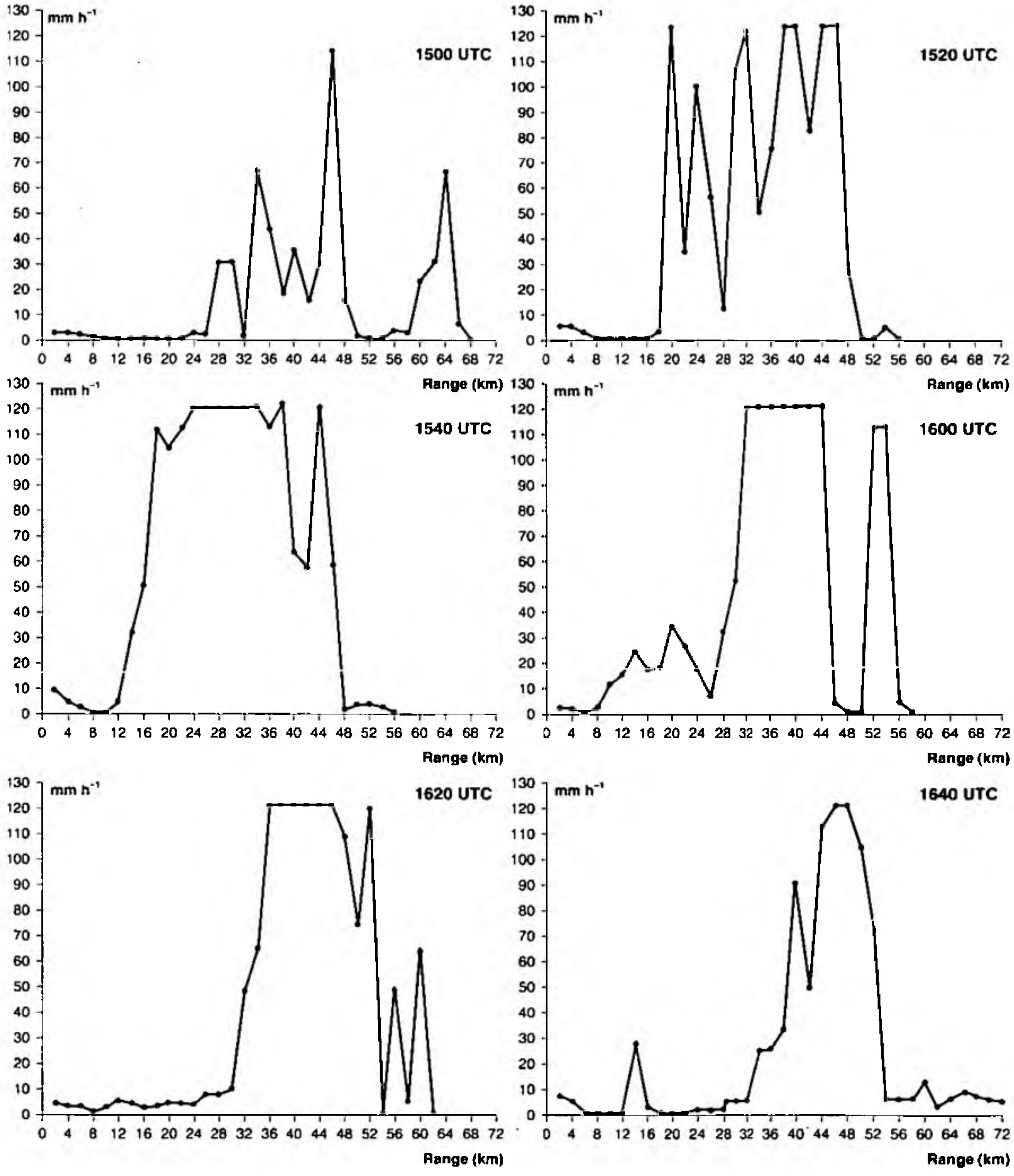
Plot of Telemetred Data
24 hr plot for MO Day of 09/06/92



Outstation : GROVE PARK
Site Id : 0068



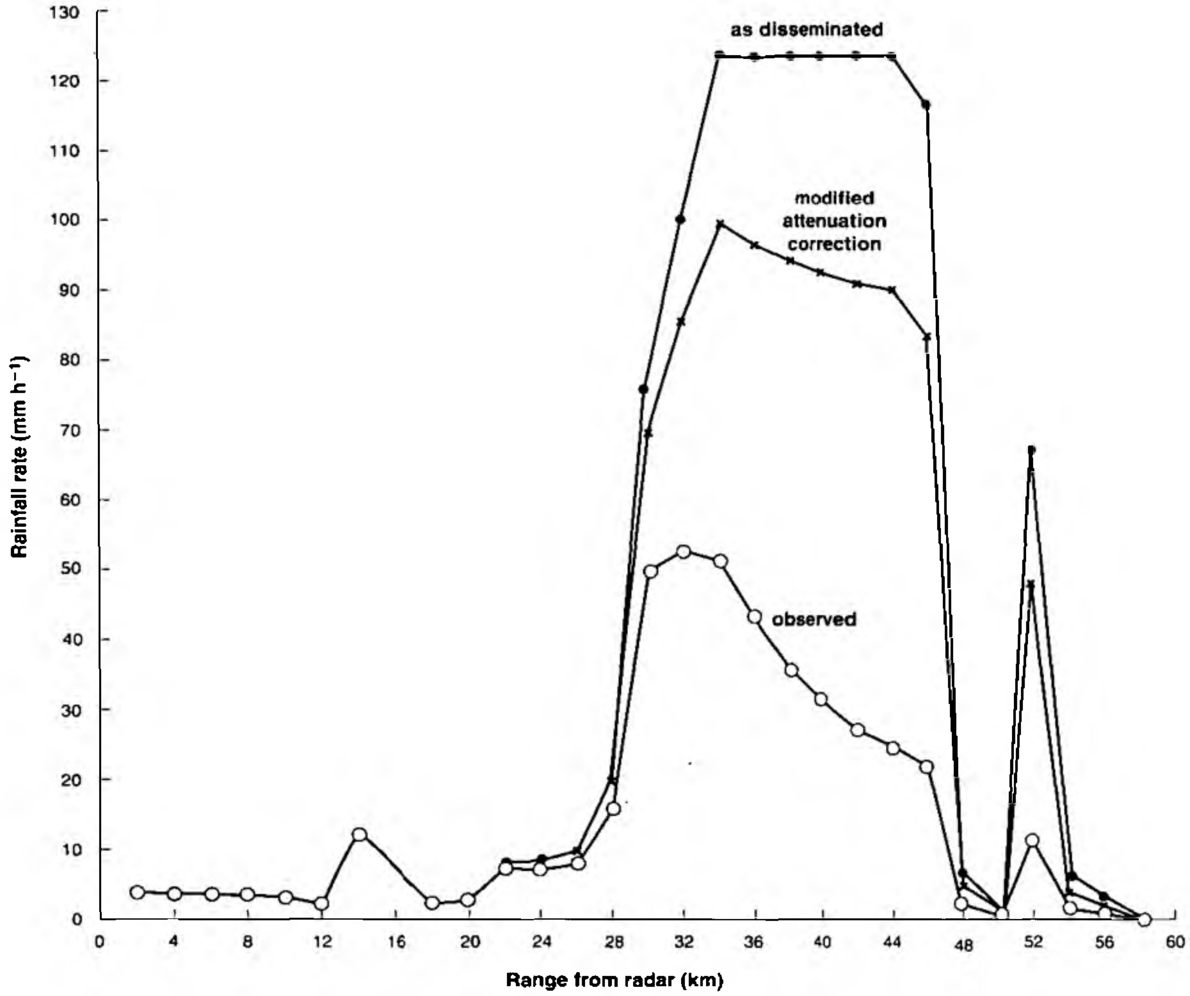
93/375/8



Rainfall rate as disseminated as a function of range from the radar along a radius corresponding to the maximum development between 1500 and 1640 UTC on 9 June 1992

93/3759

Figure 37



Rainfall rate as a function of range from the radar along a radius corresponding to the maximum development at 1615 UTC on 9 June 1992

Figure 38

Ratio of modified (as disseminated) rainfall rate to the observed attenuated rainfall rate as a function of the modified ("true") rainfall rate, raindrop diameter and hail size. Note that the hail size scale is very approximate.

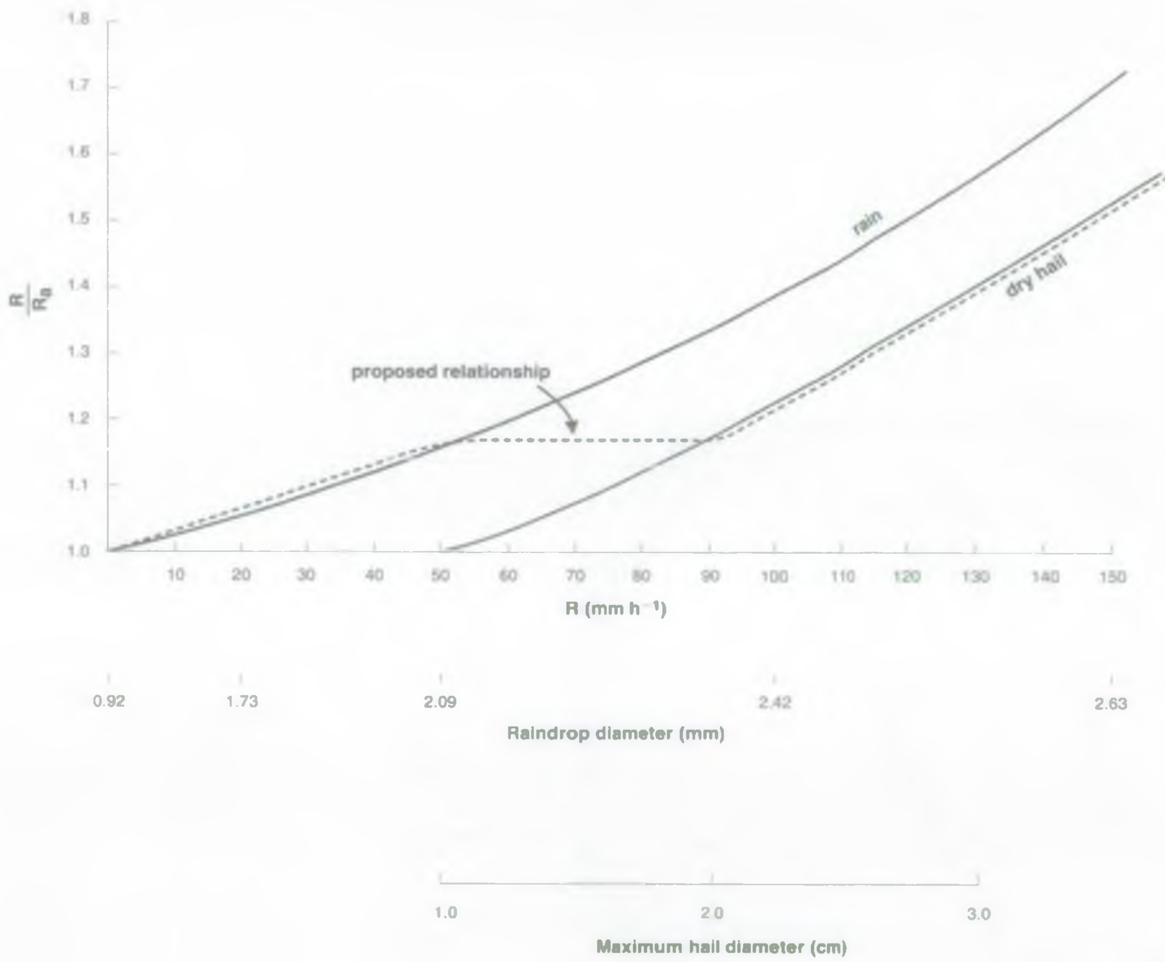
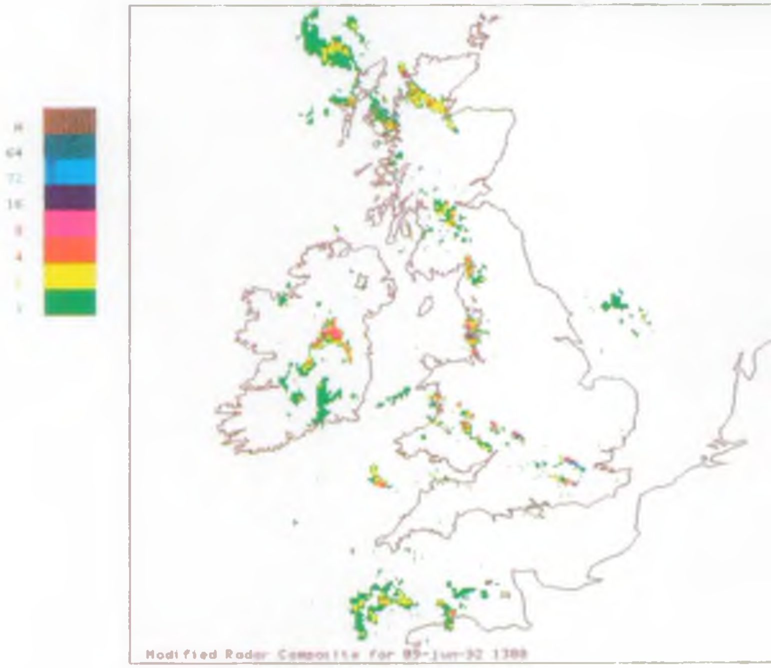
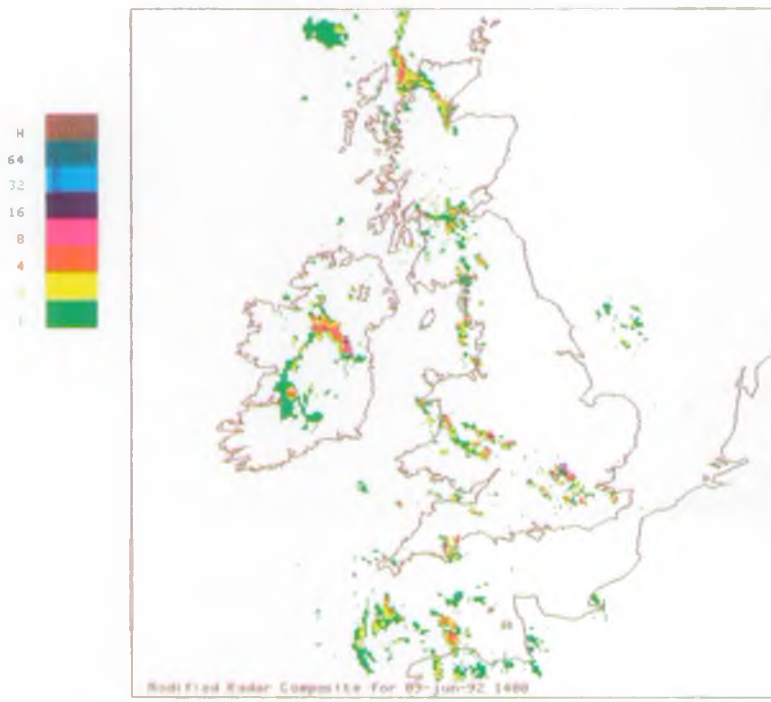
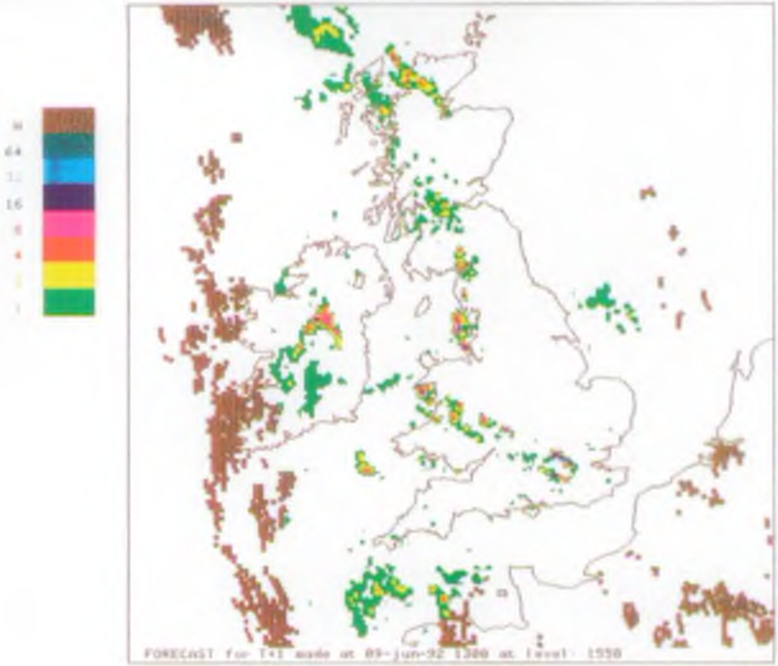


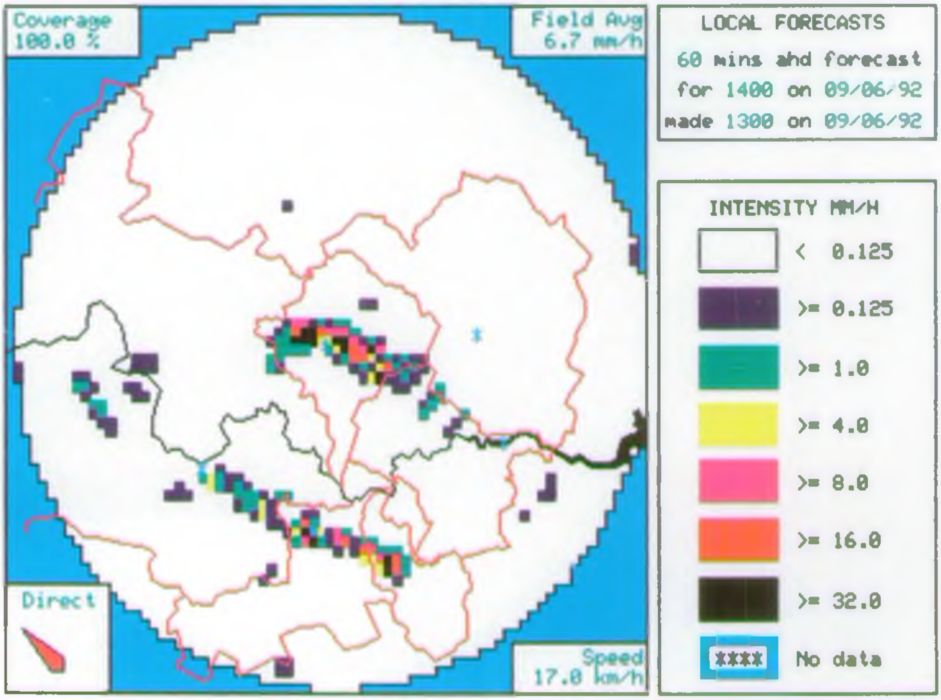
Figure 39


H
64
16
4
Modified Radar Composite for 05-jun-92 1300


H
64
32
16
8
4
1
Modified Radar Composite for 05-jun-92 1400

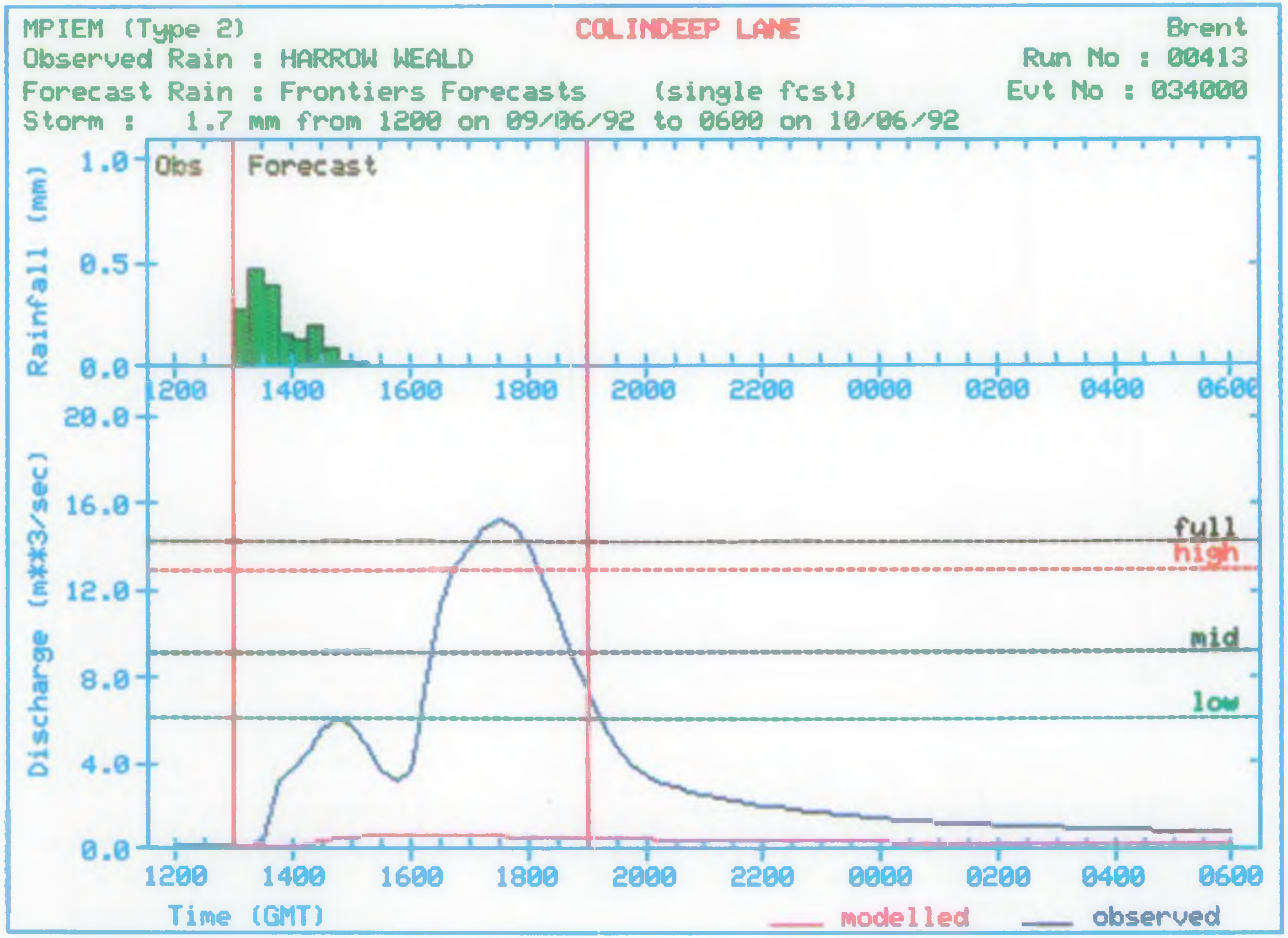


FORECAST for T+1 made at 09-jun-92 1300 at level: 1550



Coverage
100.0 %
Field Avg
6.7 mm/h
Direct
Speed
17.0 km/h
LOCAL FORECASTS
60 mins ahd forecast
for 1400 on 09/06/92
made 1300 on 09/06/92
INTENSITY MM/H
< 0.125
>= 0.125
>= 1.0
>= 4.0
>= 8.0
>= 16.0
>= 32.0
**** No data

Figure 40



Forecast analysis using PERC & PERI

Figure 41a

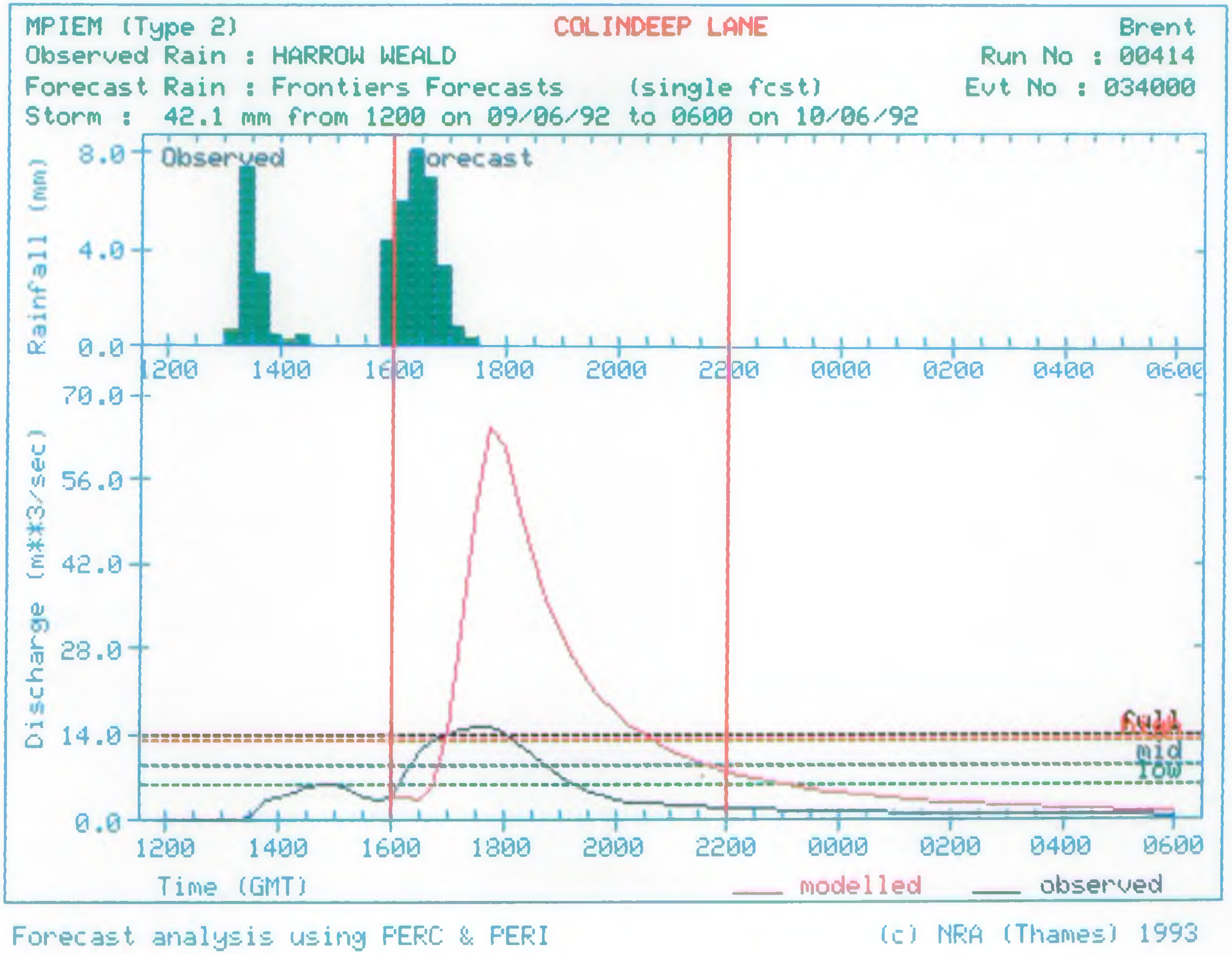
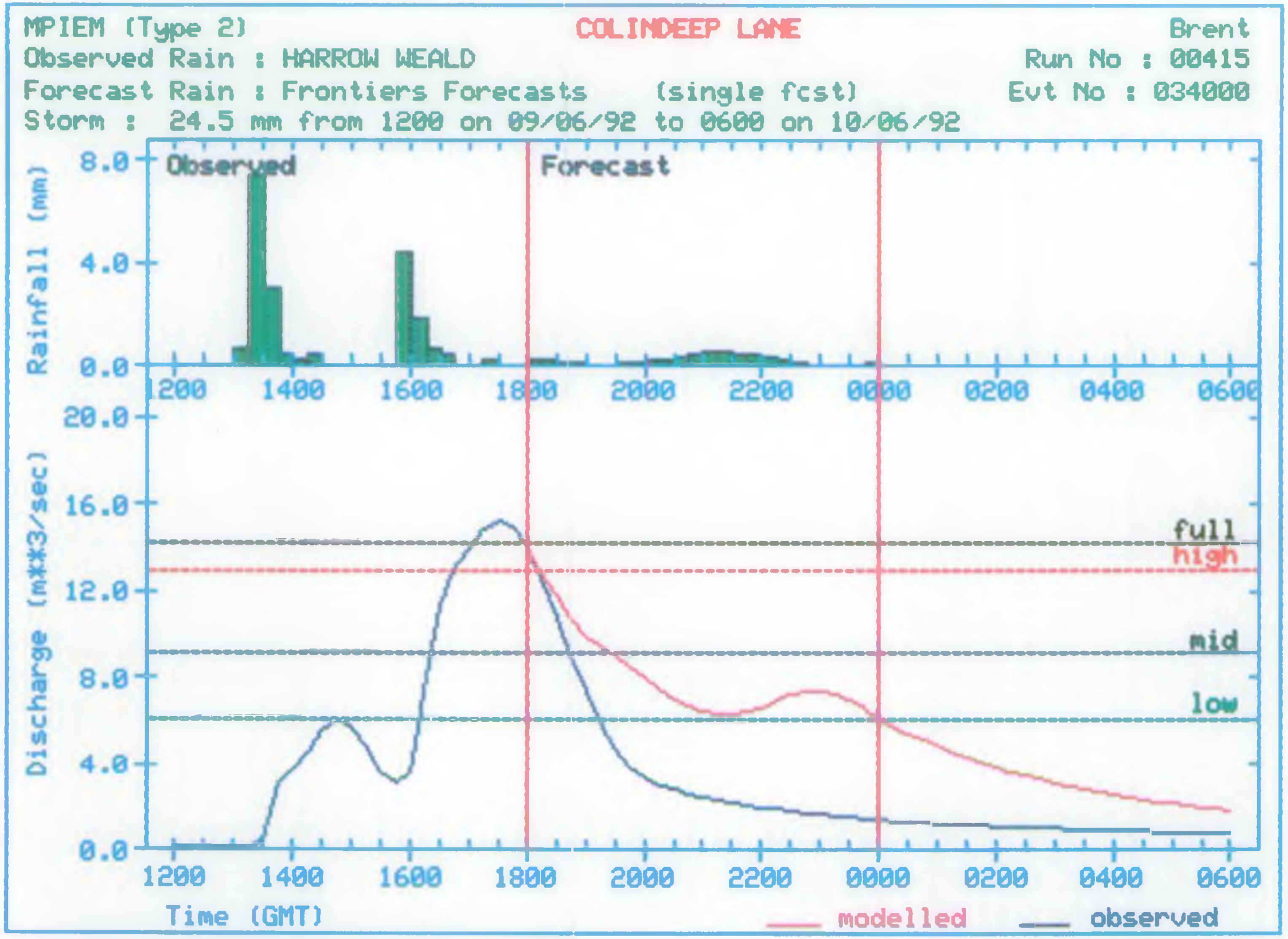

MPIEM (Type 2)
COLINDEEP LANE
Brent
Observed Rain : HARROW WEALD
Run No : 00414
Forecast Rain : Frontiers Forecasts (single fcst)
Evt No : 034000
Storm : 42.1 mm from 1200 on 09/06/92 to 0600 on 10/06/92
Rainfall (mm)
8.0
4.0
0.0
Observed
Forecast
1200 1400 1600 1800 2000 2200 0000 0200 0400 0600
Discharge (m**3/sec)
70.0
56.0
42.0
28.0
14.0
0.0
full
mid
low
Time (GMT)
modelled
observed
Forecast analysis using PERC & PERI
(c) NRA (Thames) 1993

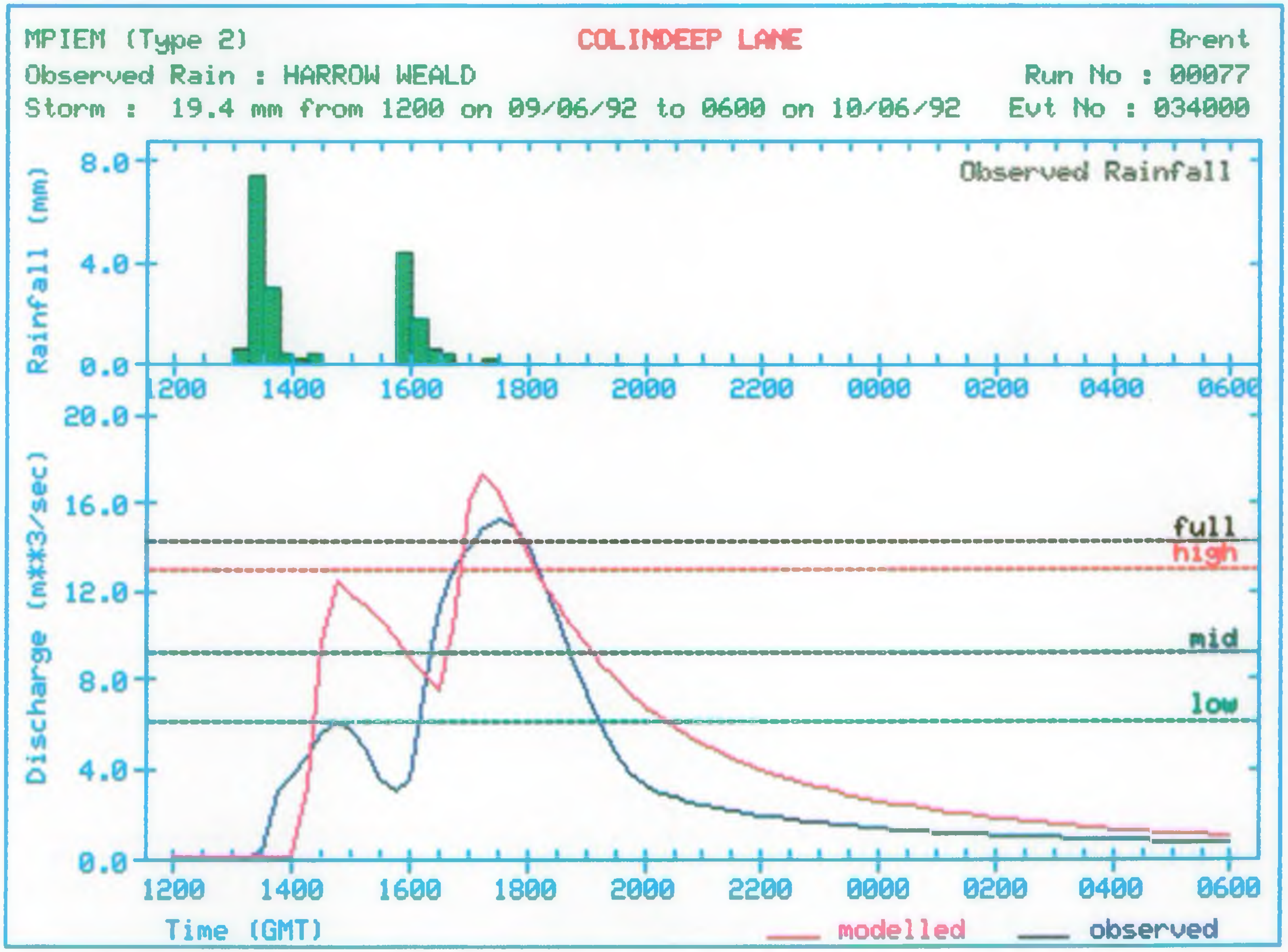
Figure 41b



Forecast analysis using PERC & PERI

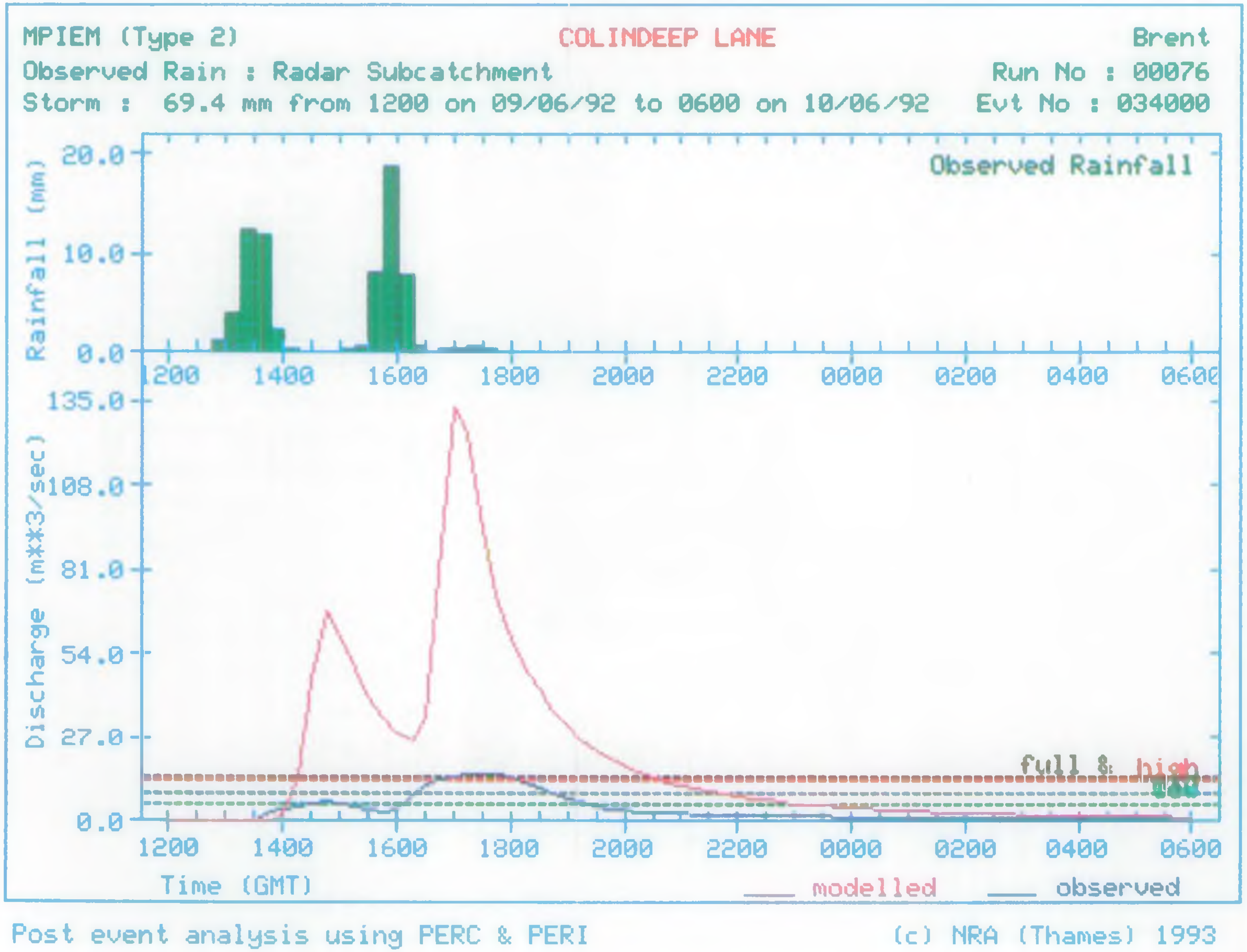
(c) NRA (Thames) 1993

Figure 41c



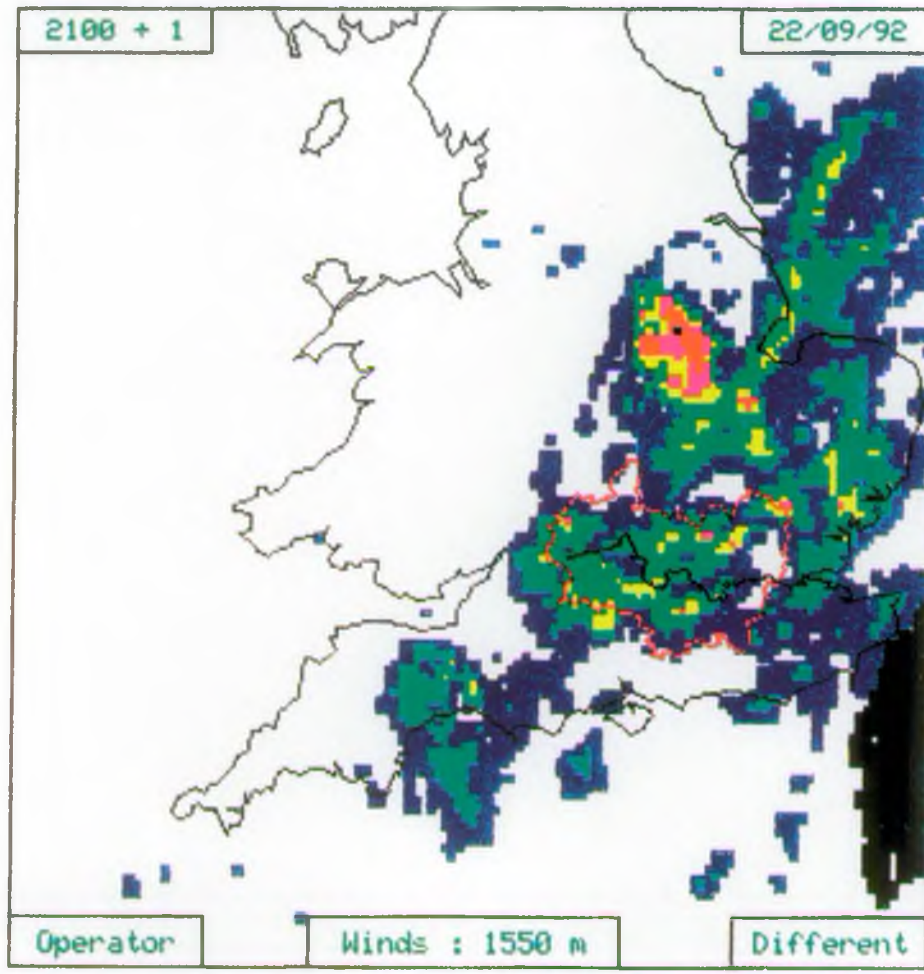
Post event analysis using PERC & PERI

Figure 41d



MPIEM (Type 2)
COLINDEEP LANE
Brent
Observed Rain : Radar Subcatchment
Run No : 00076
Storm : 69.4 mm from 1200 on 09/06/92 to 0600 on 10/06/92
Evt No : 034000
Observed Rainfall
Rainfall (mm)
20.0
10.0
0.0
135.0
108.0
81.0
54.0
27.0
0.0
Discharge (m**3/sec)
1200 1400 1600 1800 2000 2200 0000 0200 0400 0600
full & high
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1993

Figure 41e



(c)

FRONTIERS FORECASTS

1 hr ahead forecast
for 2200 on 22/09/92
made 2100 on 22/09/92

INTENSITY MM/H

< 0.13	>= 8.0
>= 0.13	>= 16.0
>= 1.0	>= 32.0
>= 4.0	Satall.

LATEST DATA AVAILABLE

1 hr ahd - 1430 05/10/92
2 hr ahd - 1530 05/10/92
3 hr ahd - 1630 05/10/92
4 hr ahd - 1730 05/10/92
5 hr ahd - 1830 05/10/92
6 hr ahd - 1930 05/10/92

NRA - Thames Region 1992

Figure 42a

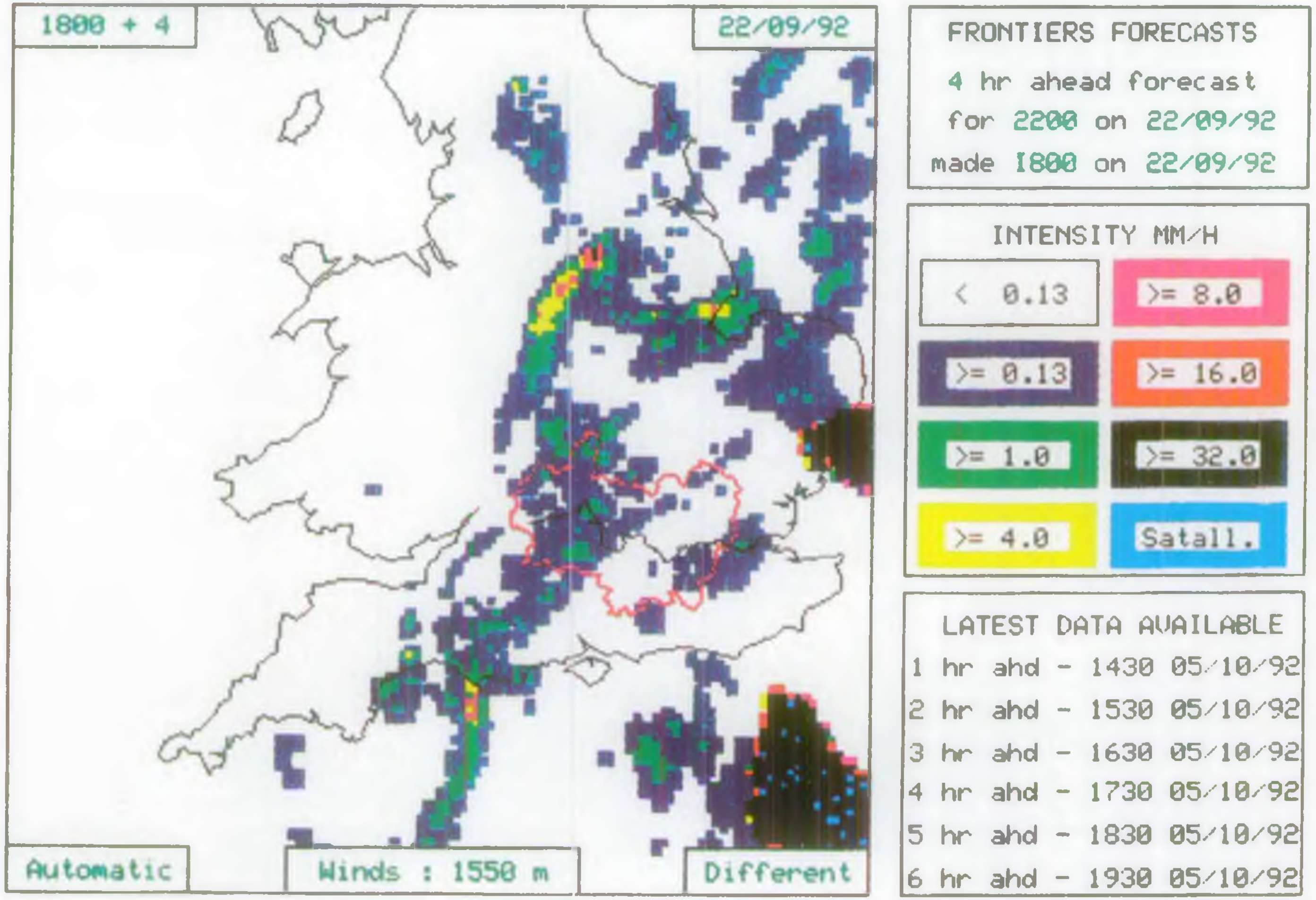
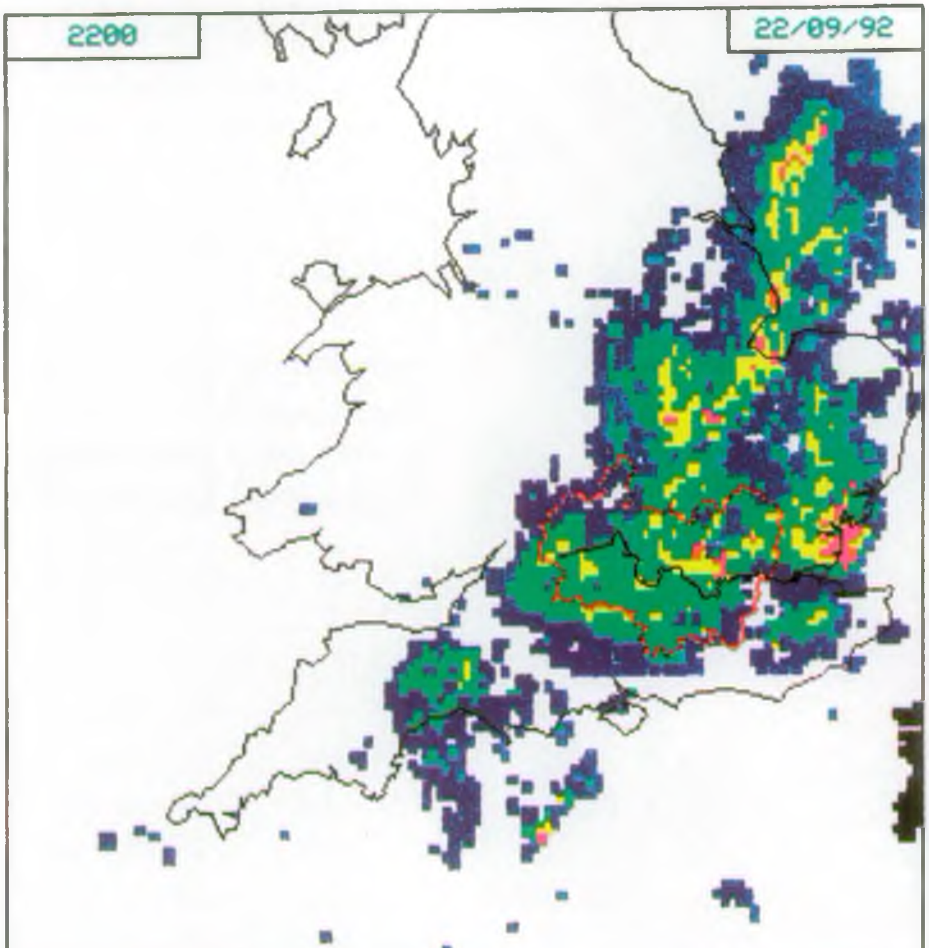
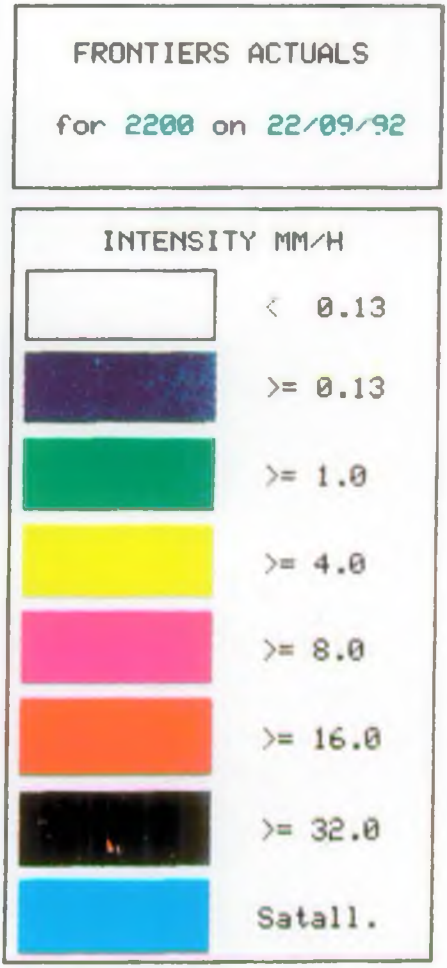

1800 + 4
22/09/92
Automatic
Winds : 1550 m
Different
FRONTIERS FORECASTS
4 hr ahead forecast
for 2200 on 22/09/92
made 1800 on 22/09/92
INTENSITY MM/H
< 0.13
>= 8.0
>= 0.13
>= 16.0
>= 1.0
>= 32.0
>= 4.0
Satall.
LATEST DATA AVAILABLE
1 hr ahd - 1430 05/10/92
2 hr ahd - 1530 05/10/92
3 hr ahd - 1630 05/10/92
4 hr ahd - 1730 05/10/92
5 hr ahd - 1830 05/10/92
6 hr ahd - 1930 05/10/92

Figure 42b

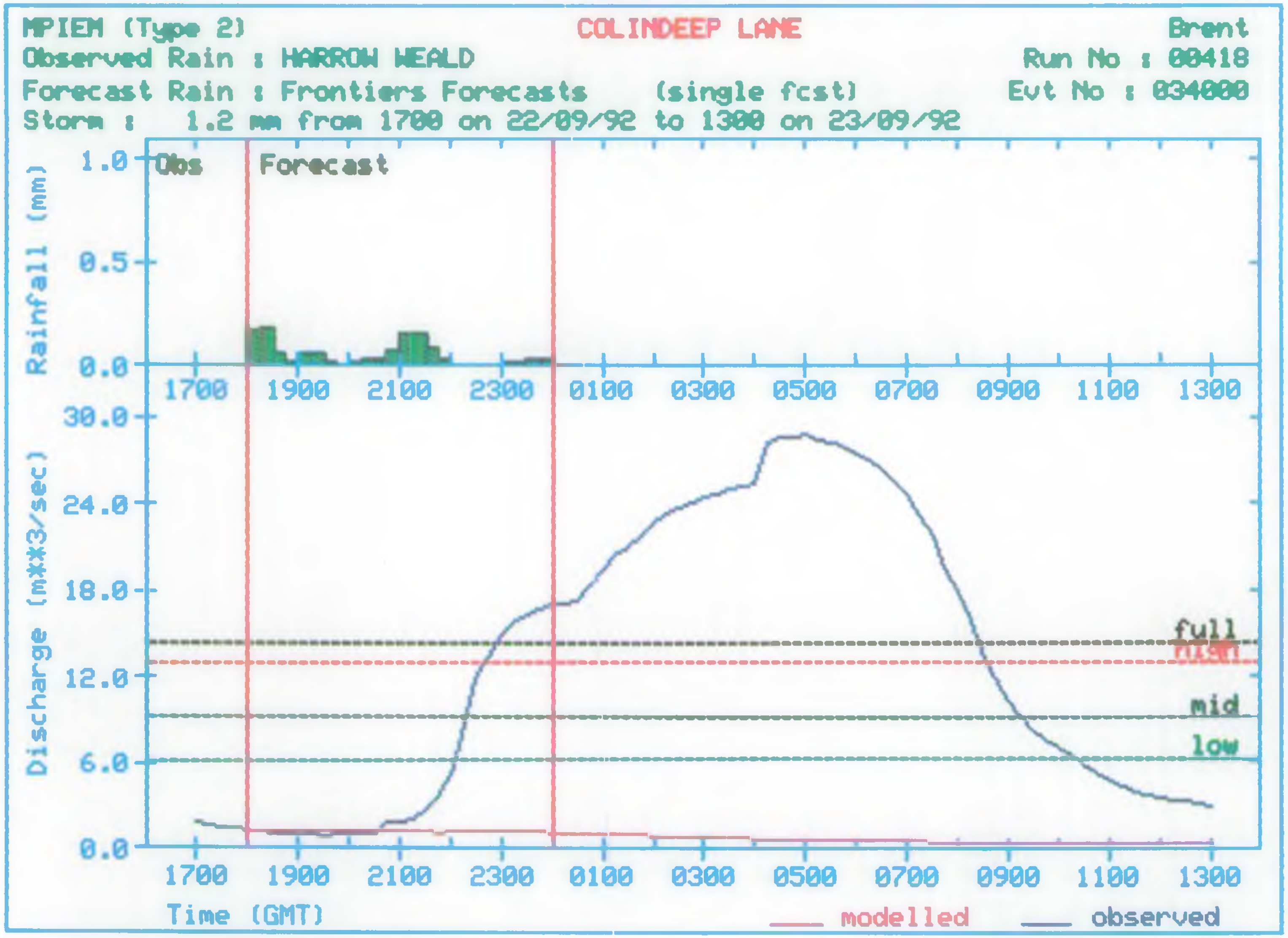


(c)



NRA - Thames Region 1992

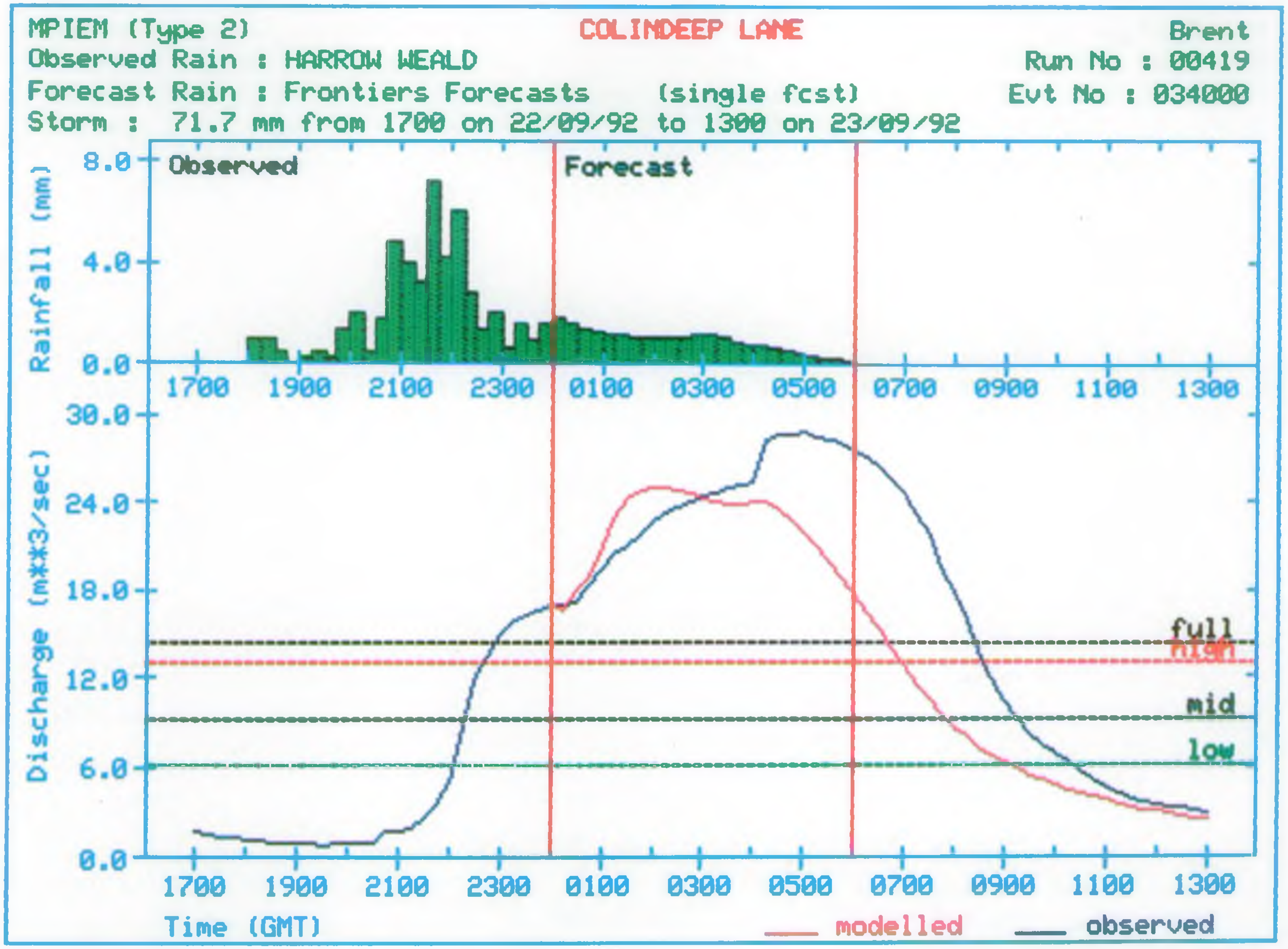
Figure 42c



Forecast analysis using PERC & PERI

(c) NRA (Thames) 1993

Figure 43a



Forecast analysis using PERC & PERI

Figure 43b

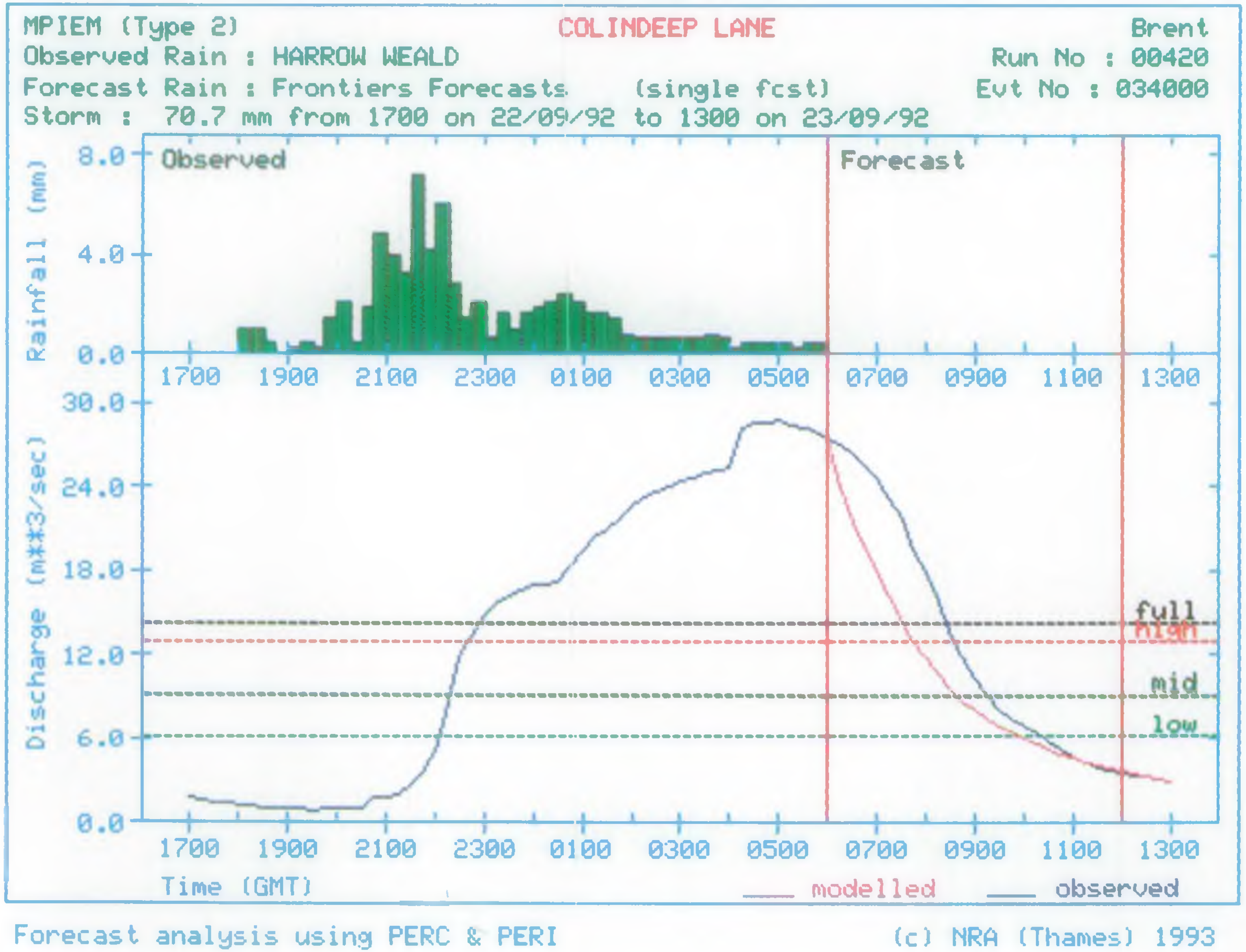

MPIEM (Type 2)
COLINDEEP LANE
Brent
Observed Rain : HARROW WEALD
Run No : 00420
Forecast Rain : Frontiers Forecasts (single fcst)
Evt No : 034000
Storm : 70.7 mm from 1700 on 22/09/92 to 1300 on 23/09/92
Observed
Forecast
Rainfall (mm)
8.0
4.0
0.0
30.0
24.0
18.0
12.0
6.0
0.0
Discharge (m**3/sec)
1700 1900 2100 2300 0100 0300 0500 0700 0900 1100 1300
full
high
mid
low
Time (GMT)
modelled
observed
Forecast analysis using PERC & PERI
(c) NRA (Thames) 1993

Figure 43c

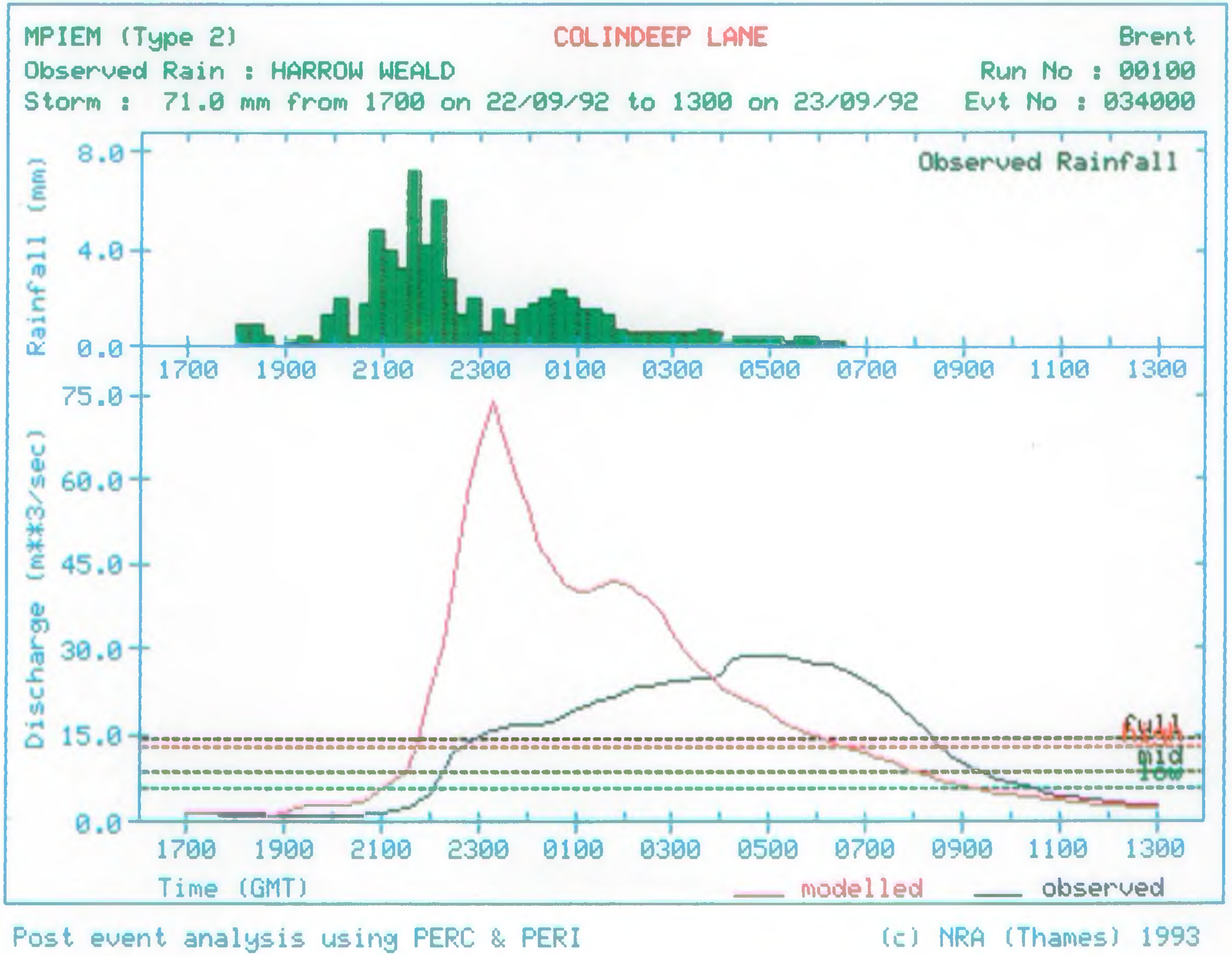
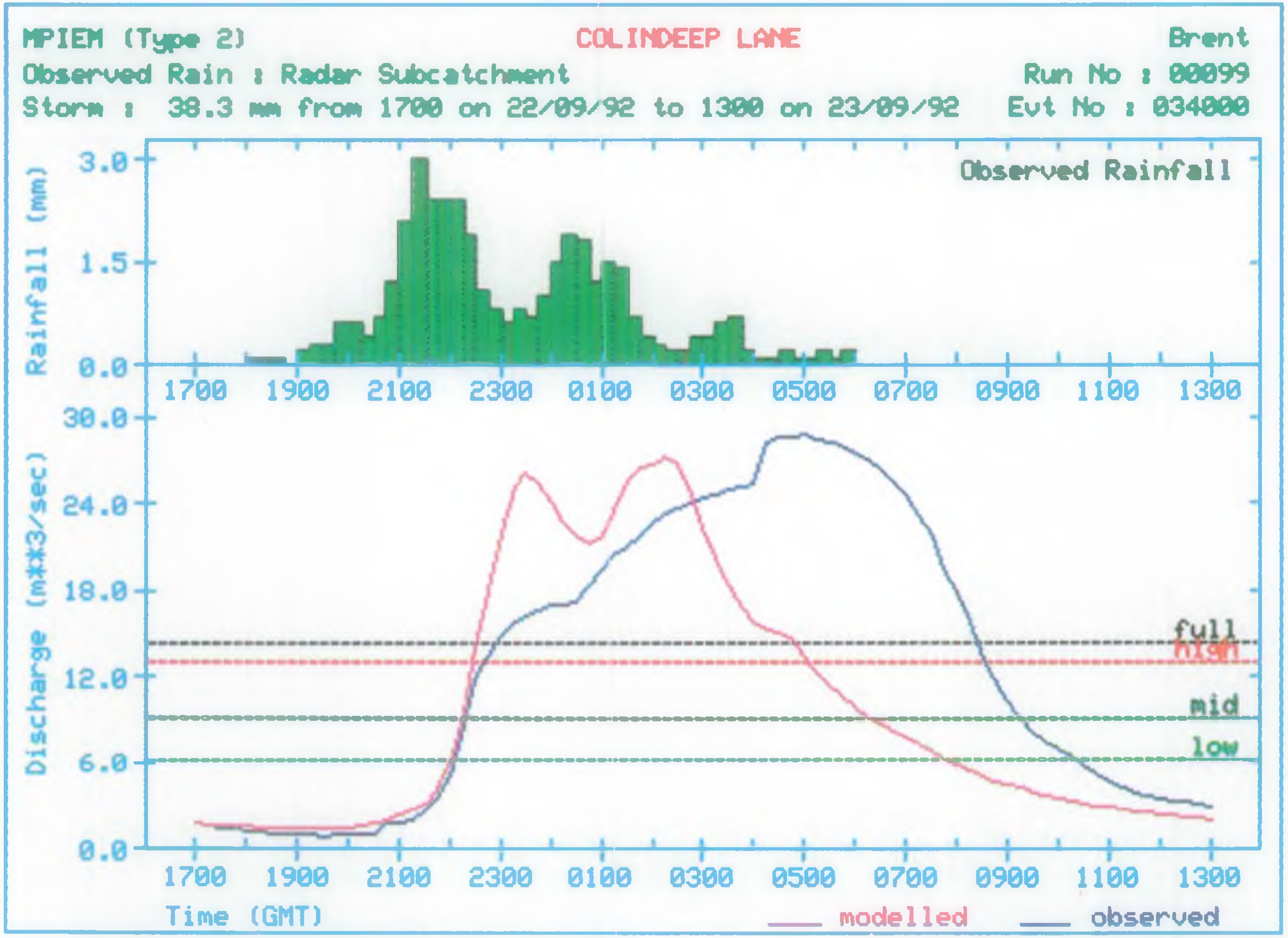
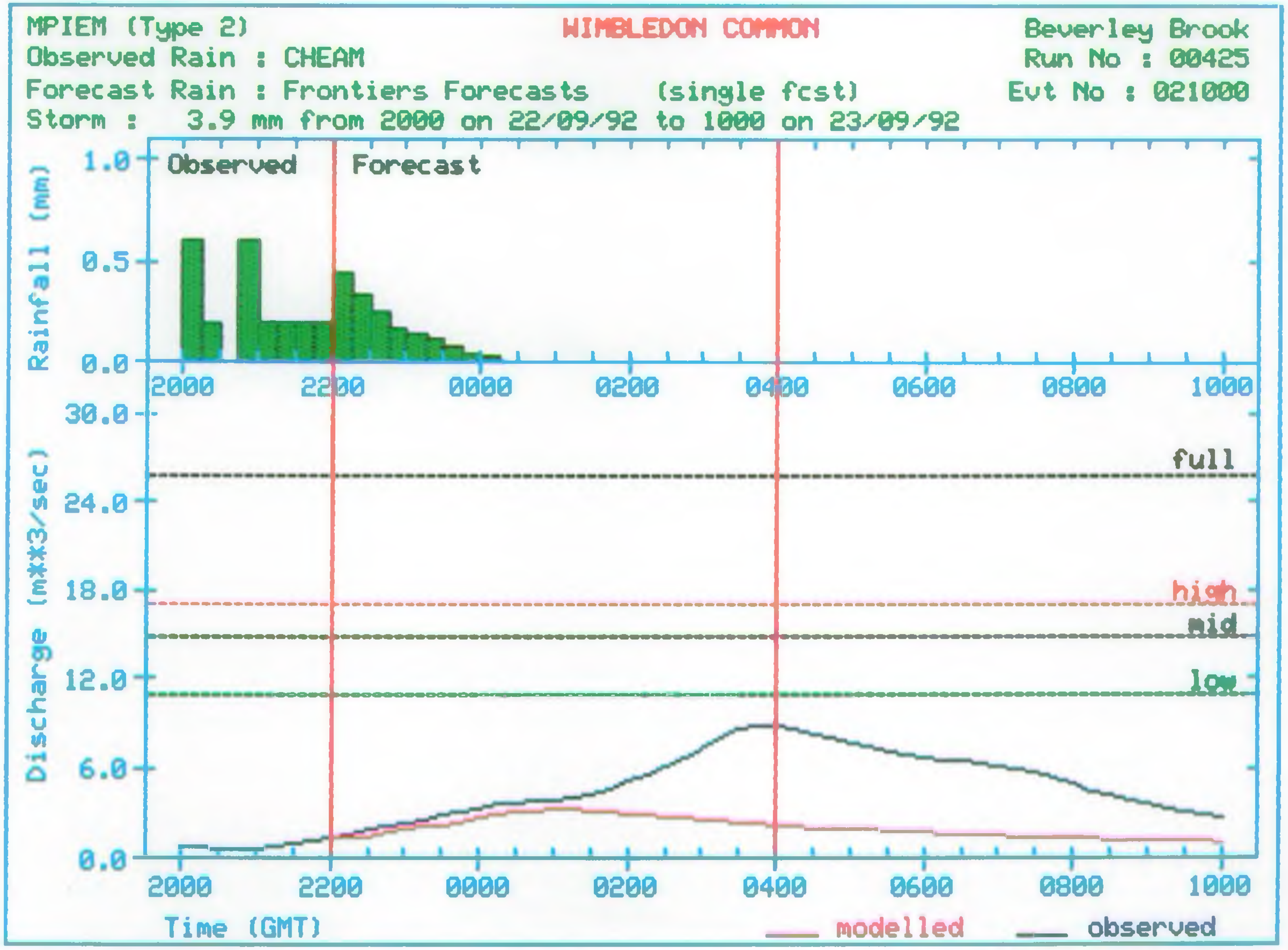

MPIEM (Type 2)
COLINDEEP LANE
Brent
Observed Rain : HARROW WEALD
Run No : 00100
Storm : 71.0 mm from 1700 on 22/09/92 to 1300 on 23/09/92
Evt No : 034000
Observed Rainfall
Rainfall (mm)
8.0
4.0
0.0
1700
1900
2100
2300
0100
0300
0500
0700
0900
1100
1300
Discharge (m**3/sec)
75.0
60.0
45.0
30.0
15.0
0.0
full
mid
low
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1993

Figure 43d



Post event analysis using PERC & PERI

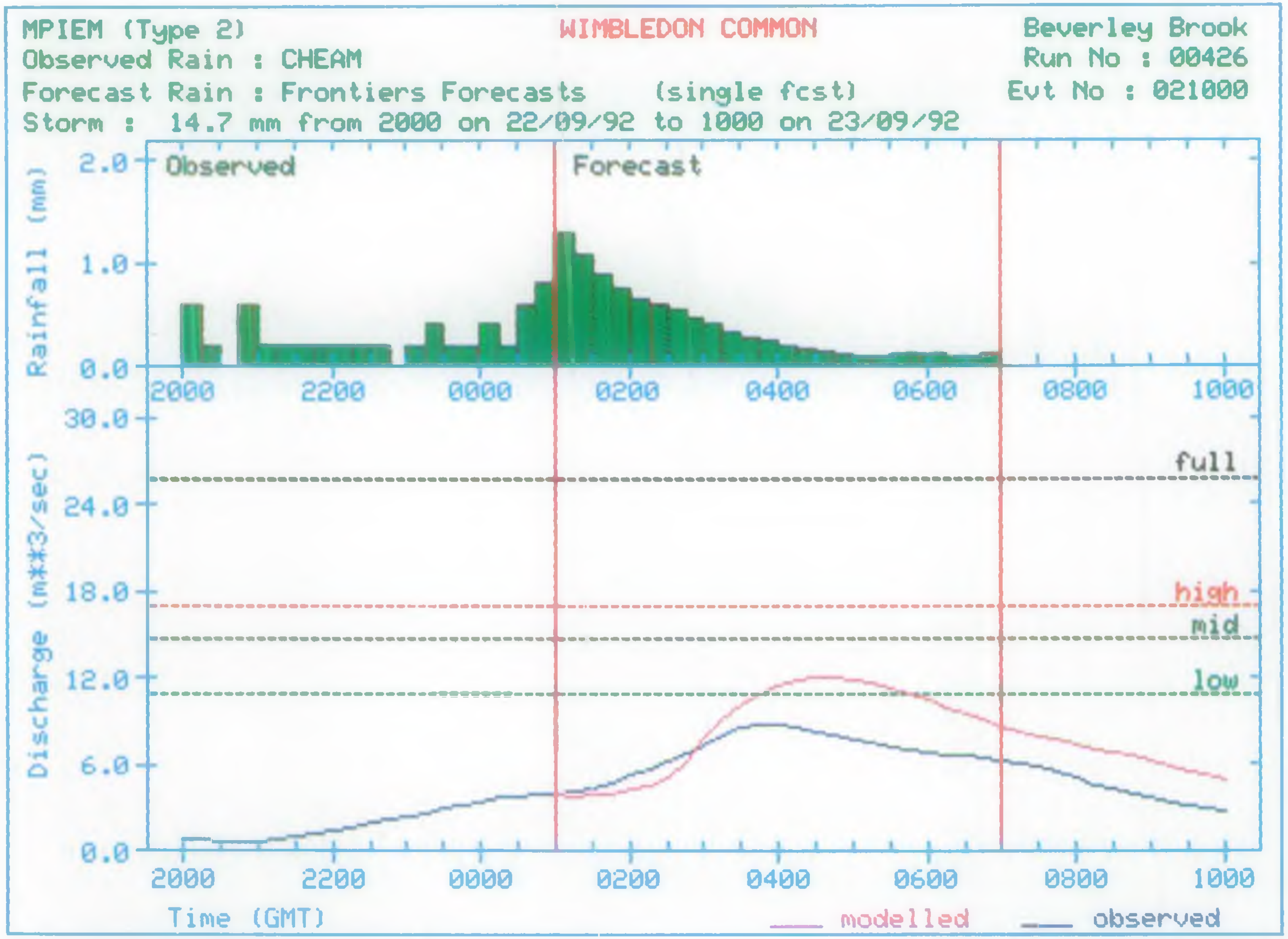
Figure 43e



Forecast analysis using PERC & PERI

(c) NRA (Thames) 1993

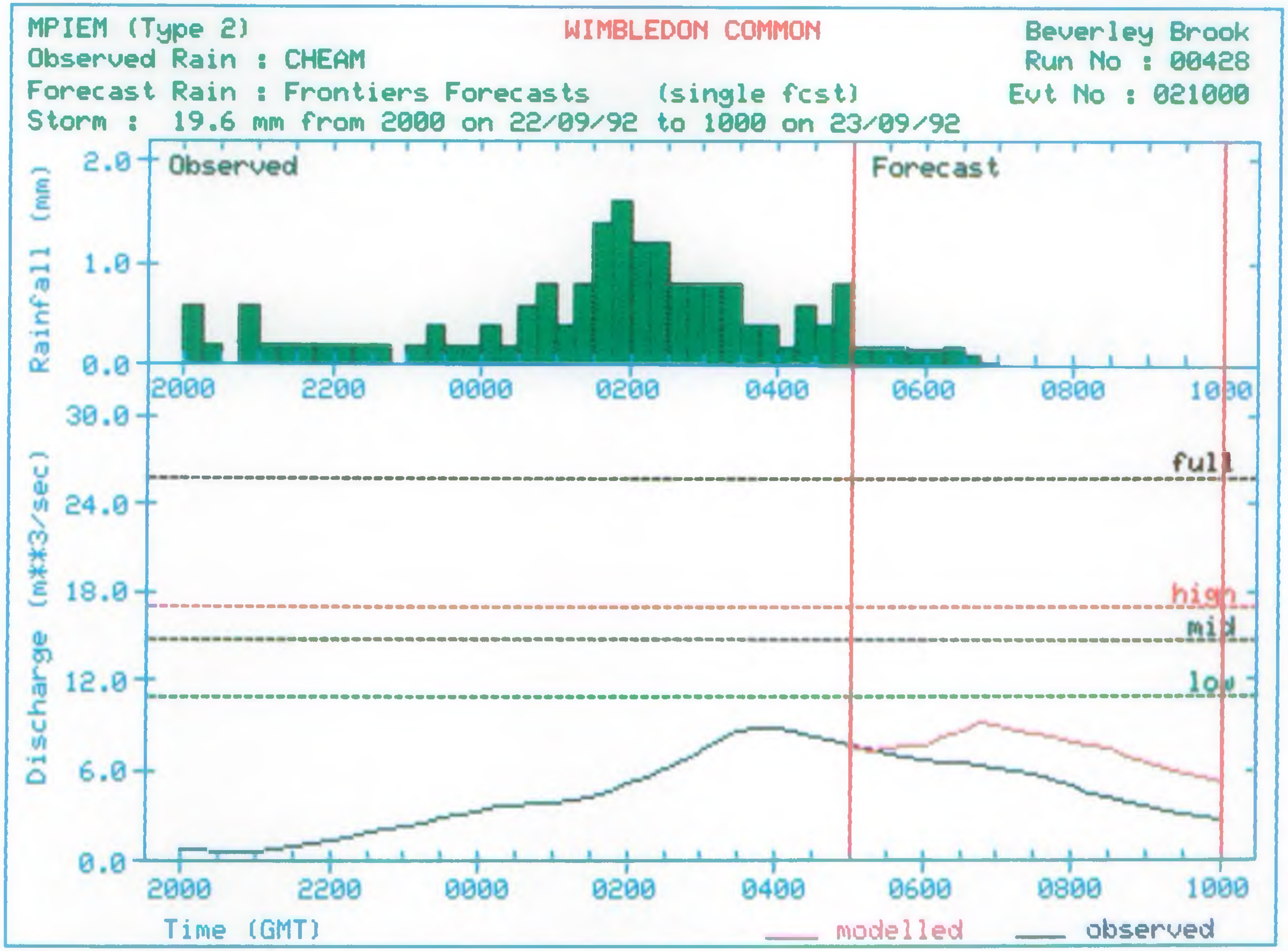
Figure 44a



Forecast analysis using PERC & PERI

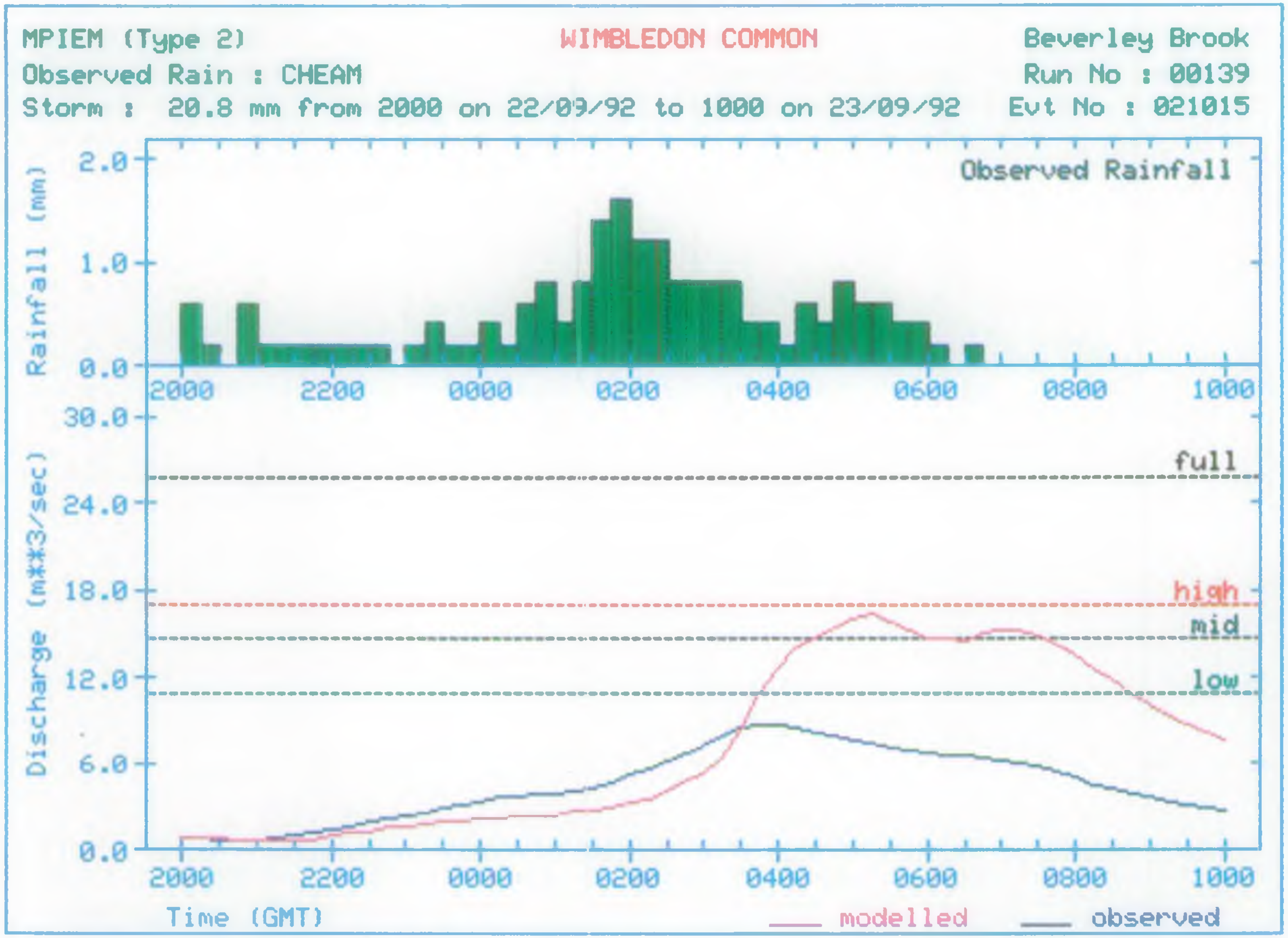
(c) NRA (Thames) 1993

Figure 44b



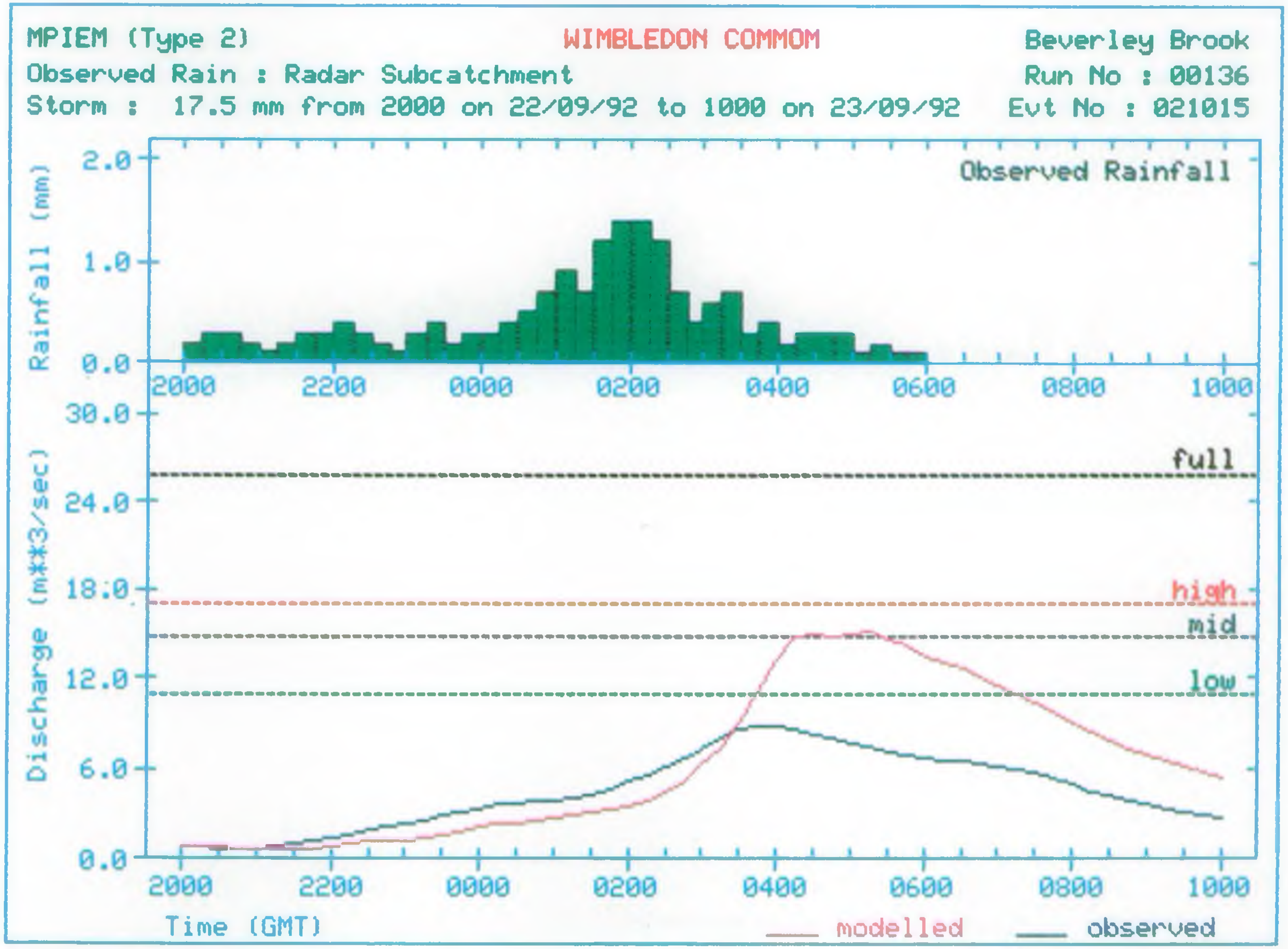
Forecast analysis using PERC & PERI

Figure 44c



Post event analysis using PERC & PERI

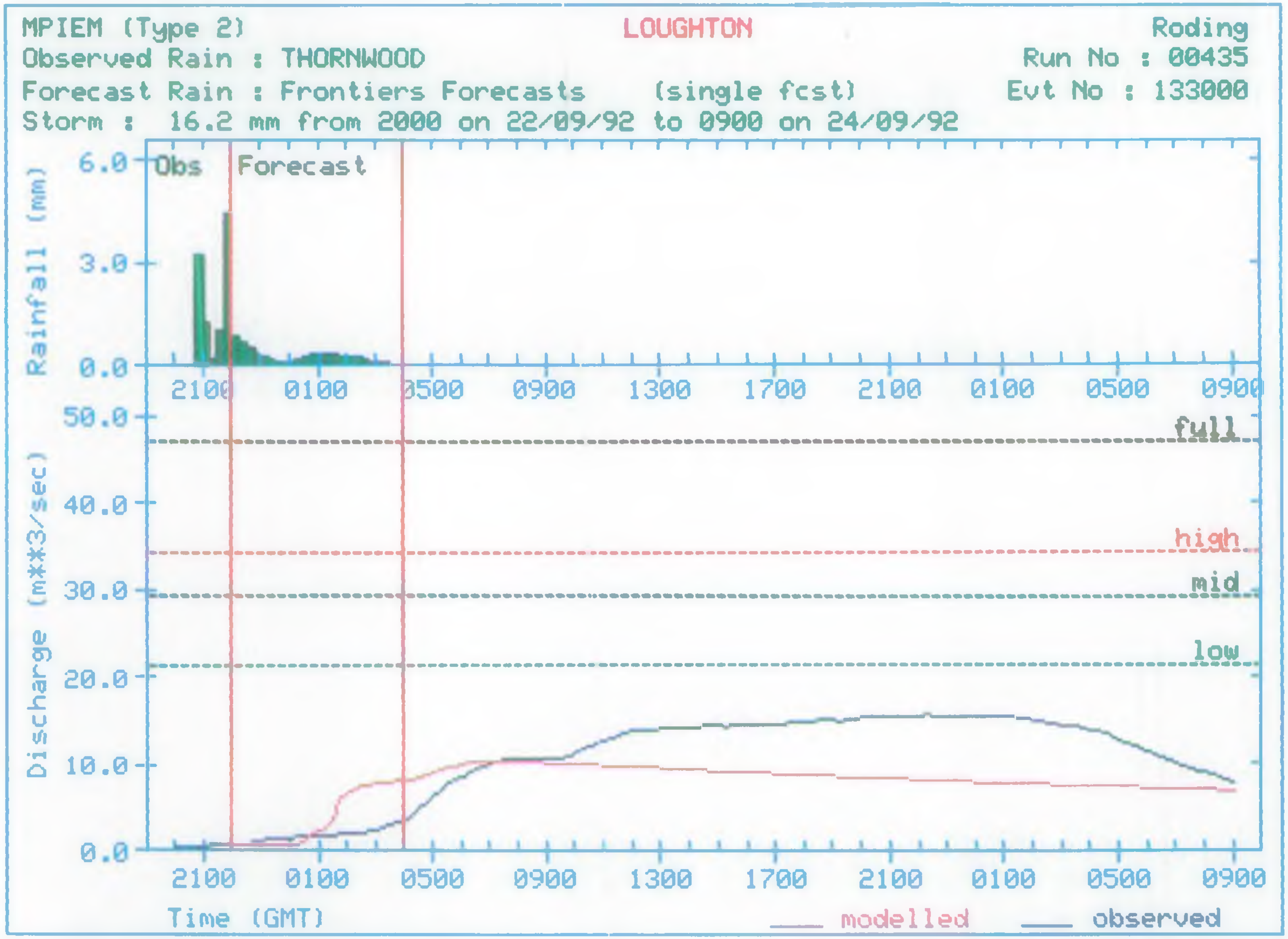
Figure 44d



Post event analysis using PERC & PERI

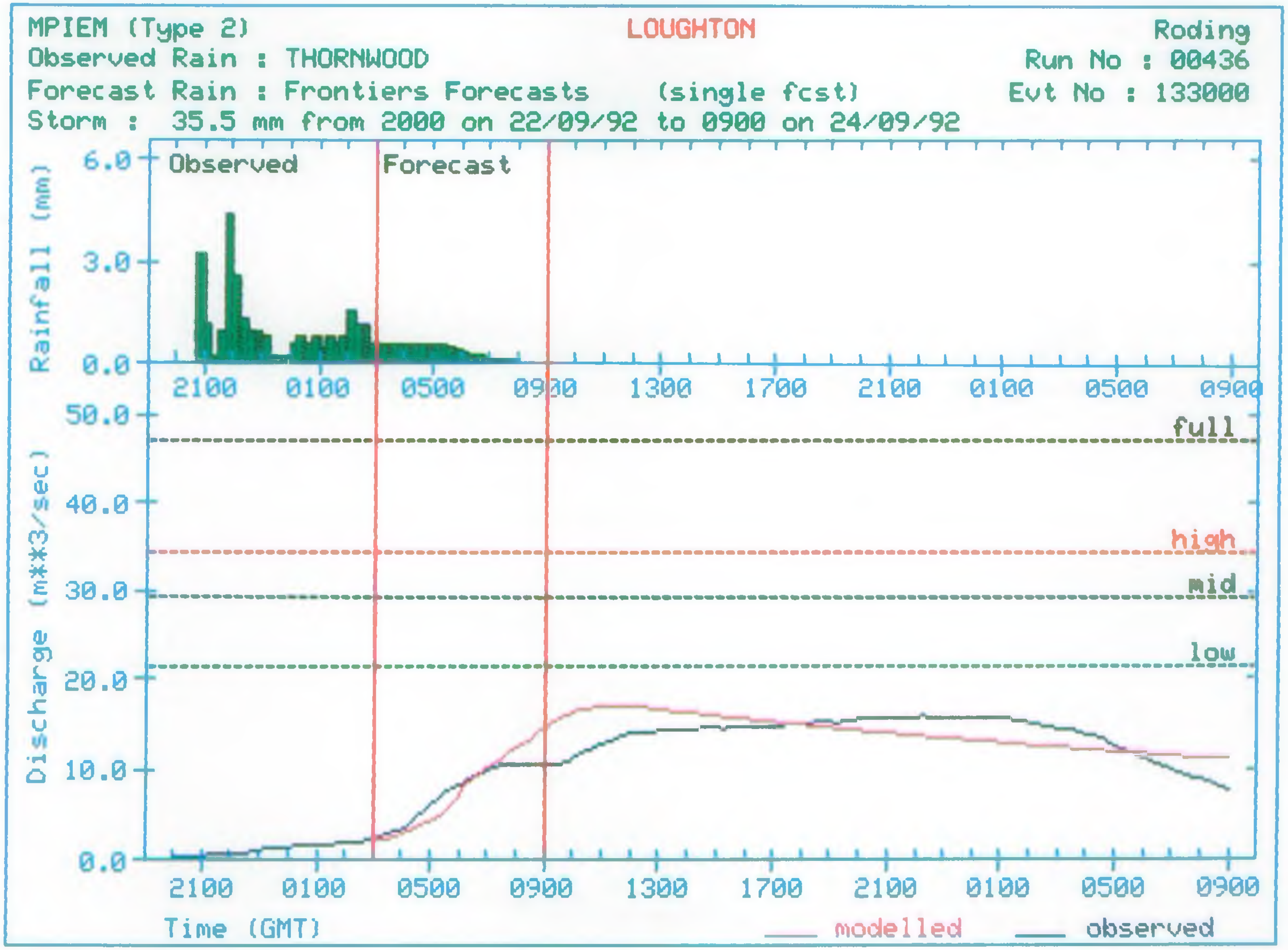
(c) NRA (Thames) 1993

Figure 44e



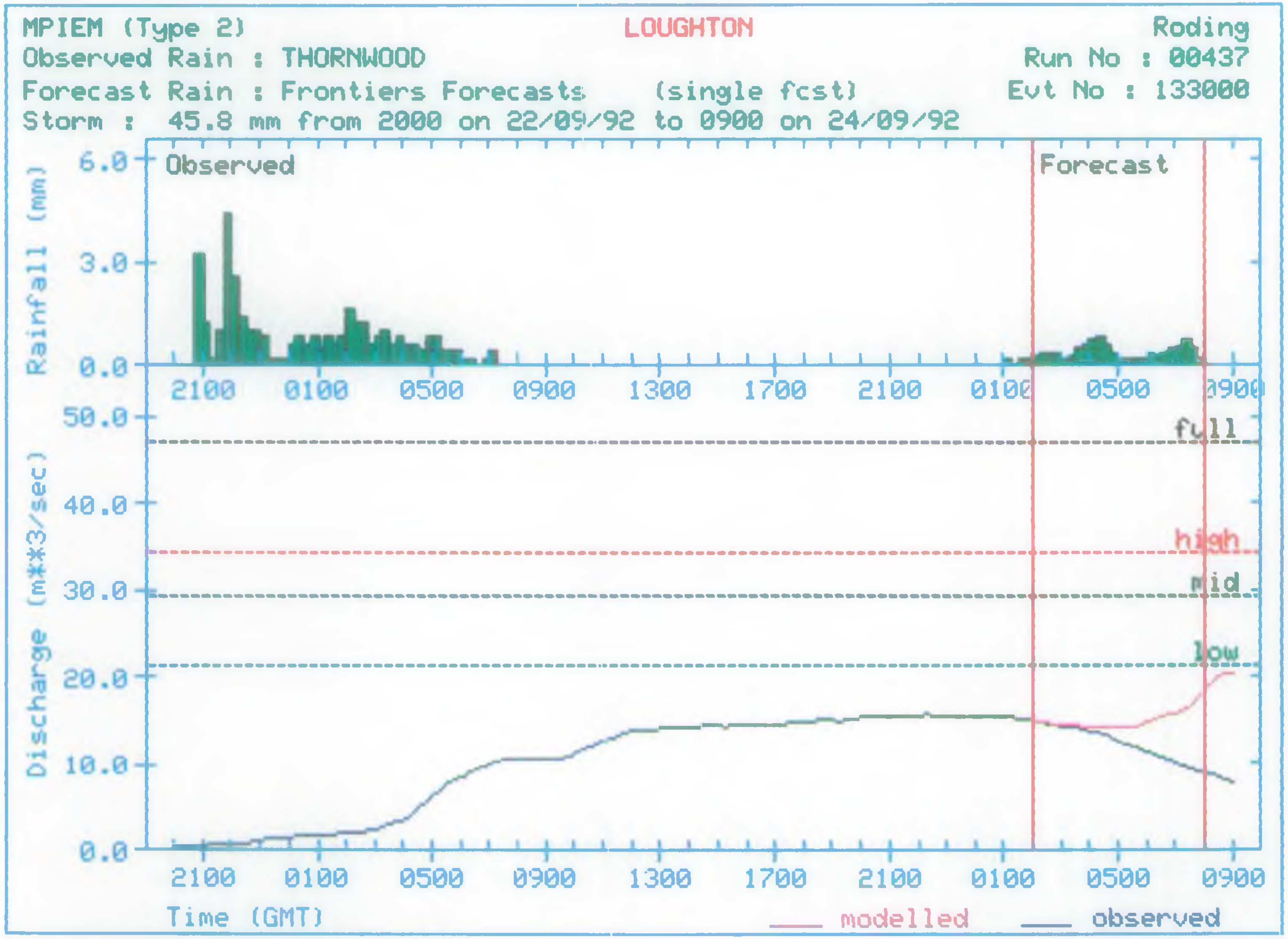
Forecast analysis using PERC & PERI

Figure 45a



Forecast analysis using PERC & PERI

Figure45b



Forecast analysis using PERC & PERI

Figure 45c

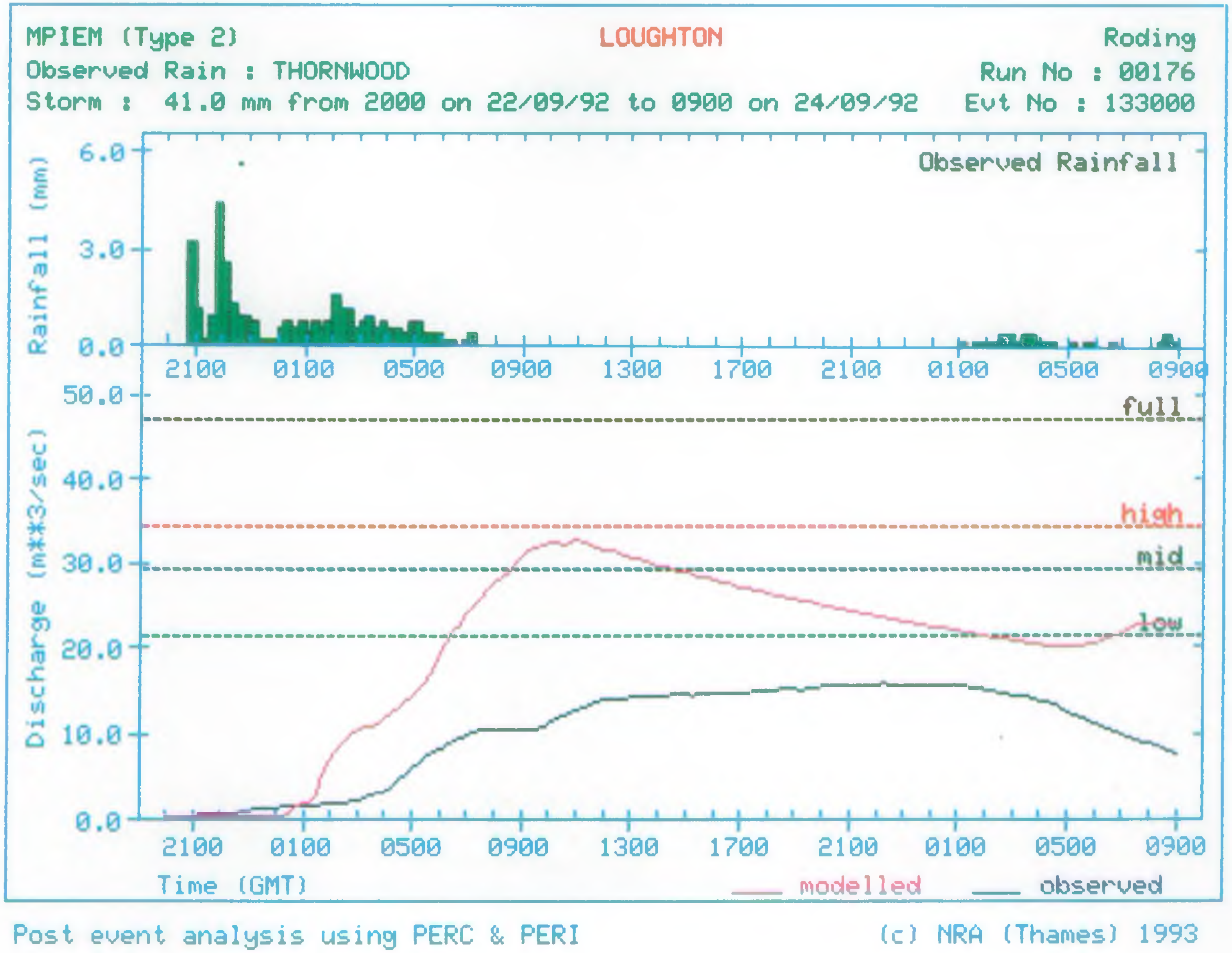
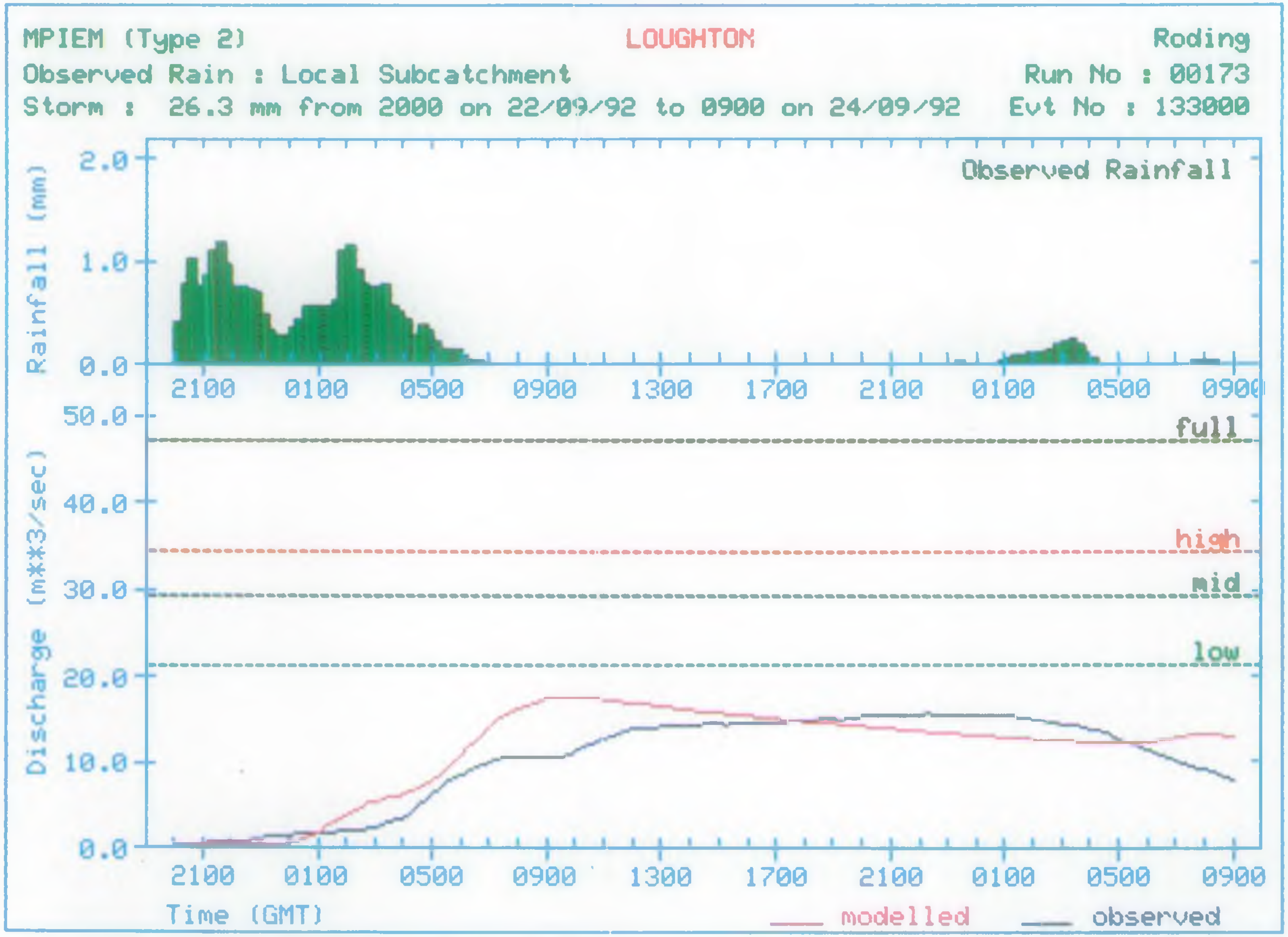
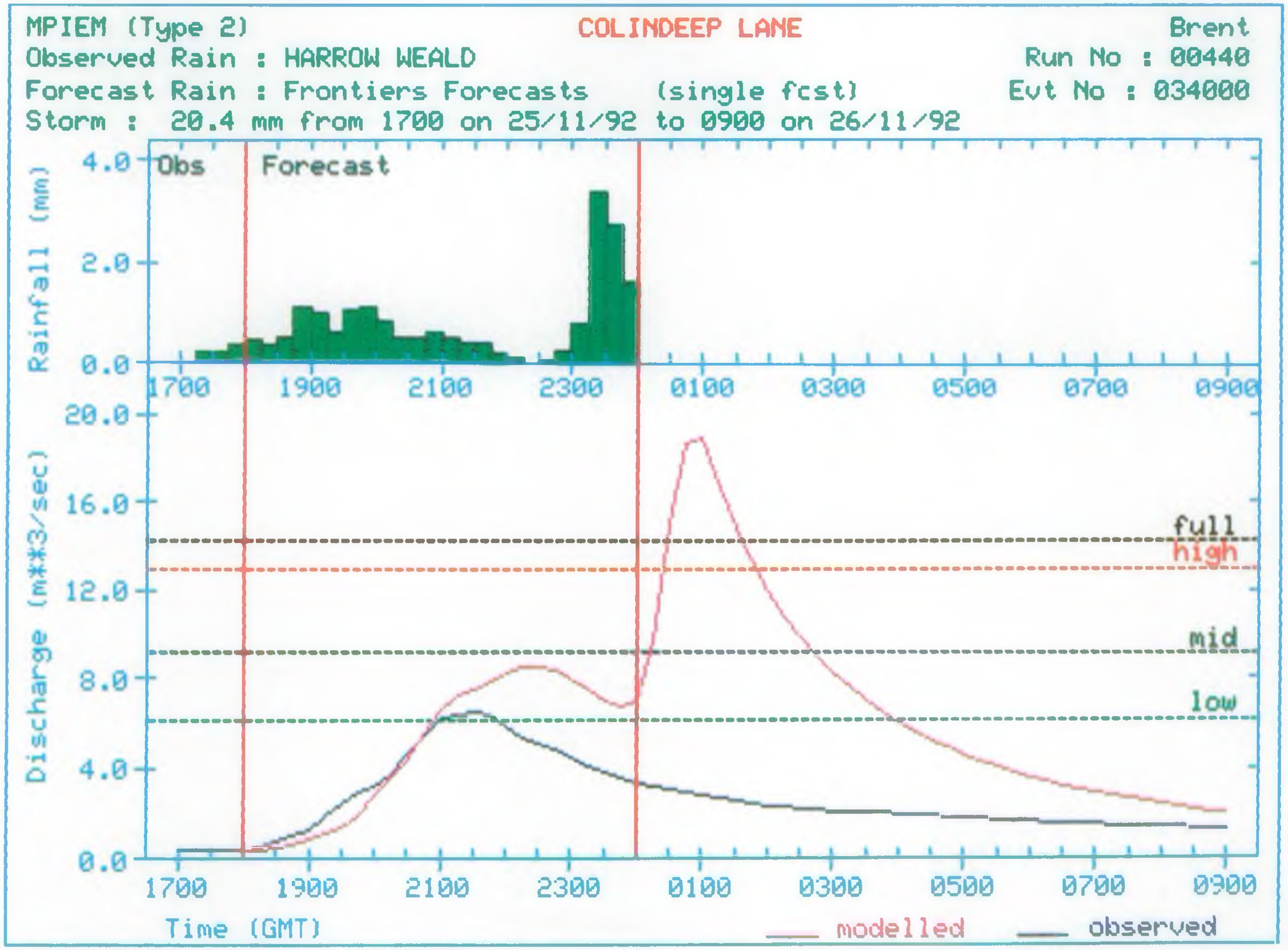

MPIEM (Type 2)
LOUGHTON
Roding
Observed Rain : THORNWOOD
Run No : 00176
Storm : 41.0 mm from 2000 on 22/09/92 to 0900 on 24/09/92
Evt No : 133000
Observed Rainfall
Rainfall (mm)
6.0
3.0
0.0
2100 0100 0500 0900 1300 1700 2100 0100 0500 0900
Discharge (m**3/sec)
50.0
40.0
30.0
20.0
10.0
0.0
full
high
mid
low
2100 0100 0500 0900 1300 1700 2100 0100 0500 0900
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1993

Figure 45d



Post event analysis using PERC & PERI

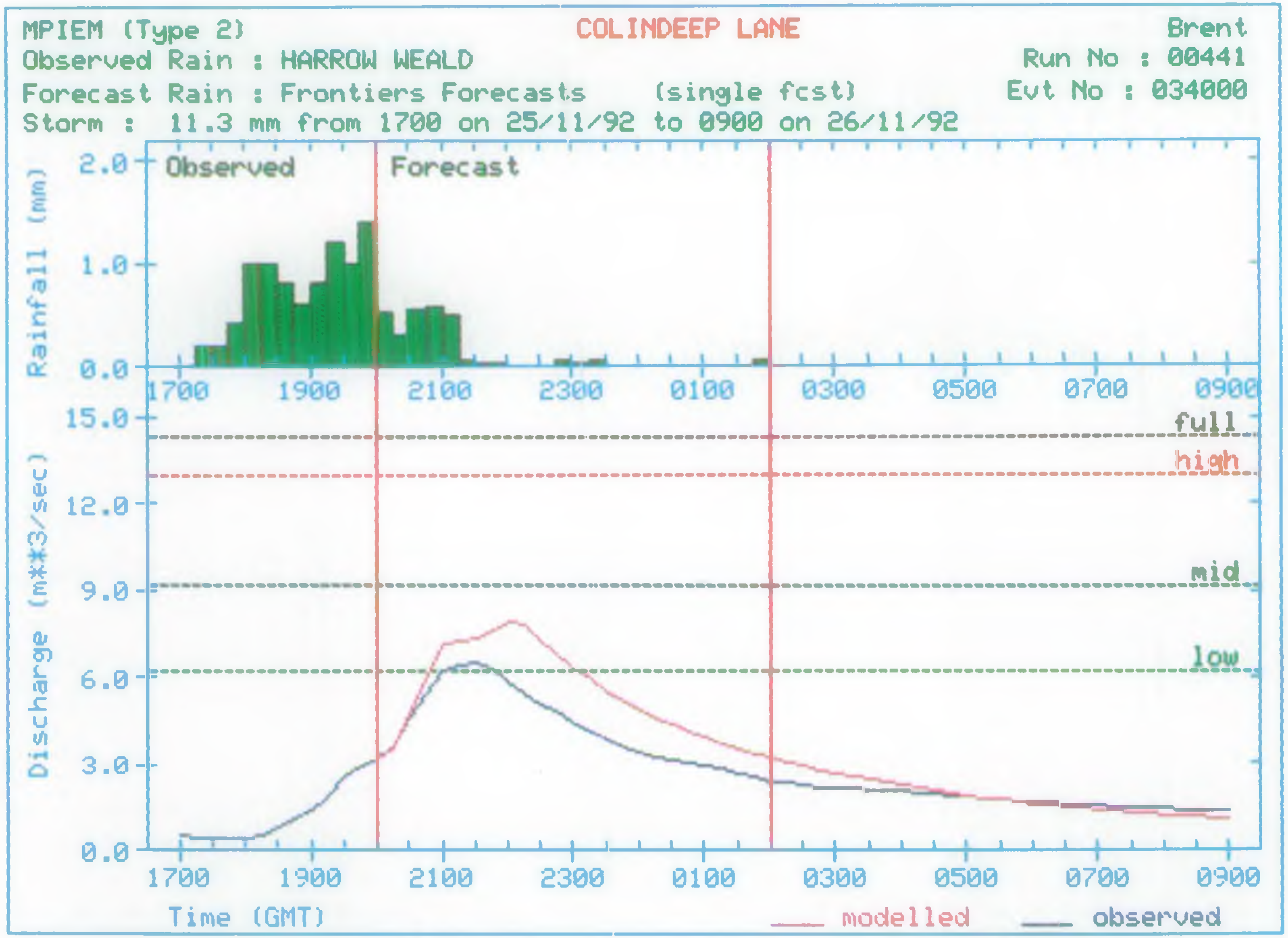
Figure 45e



Forecast analysis using PERC & PERI

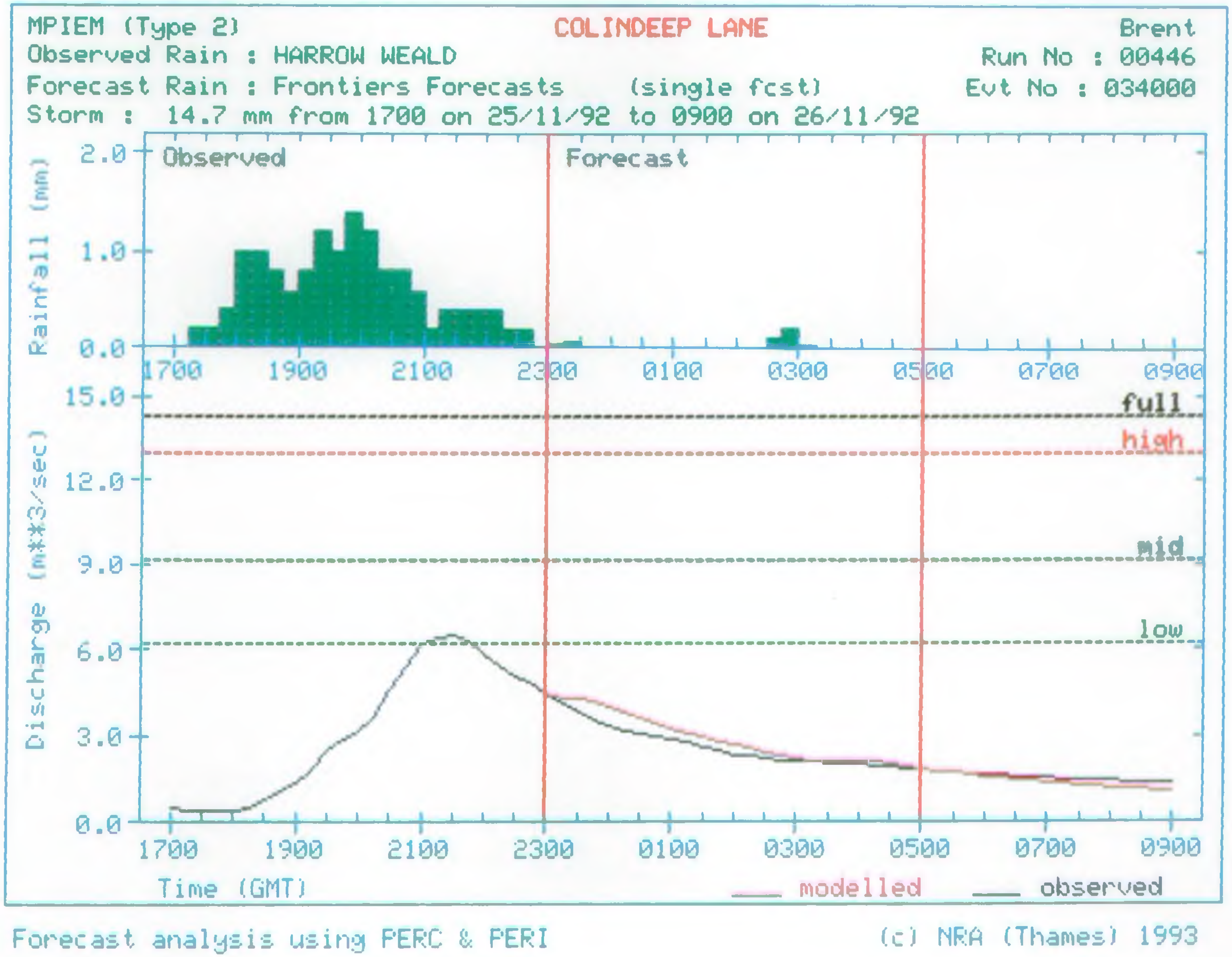
(c) NRA (Thames) 1993

Figure 46a



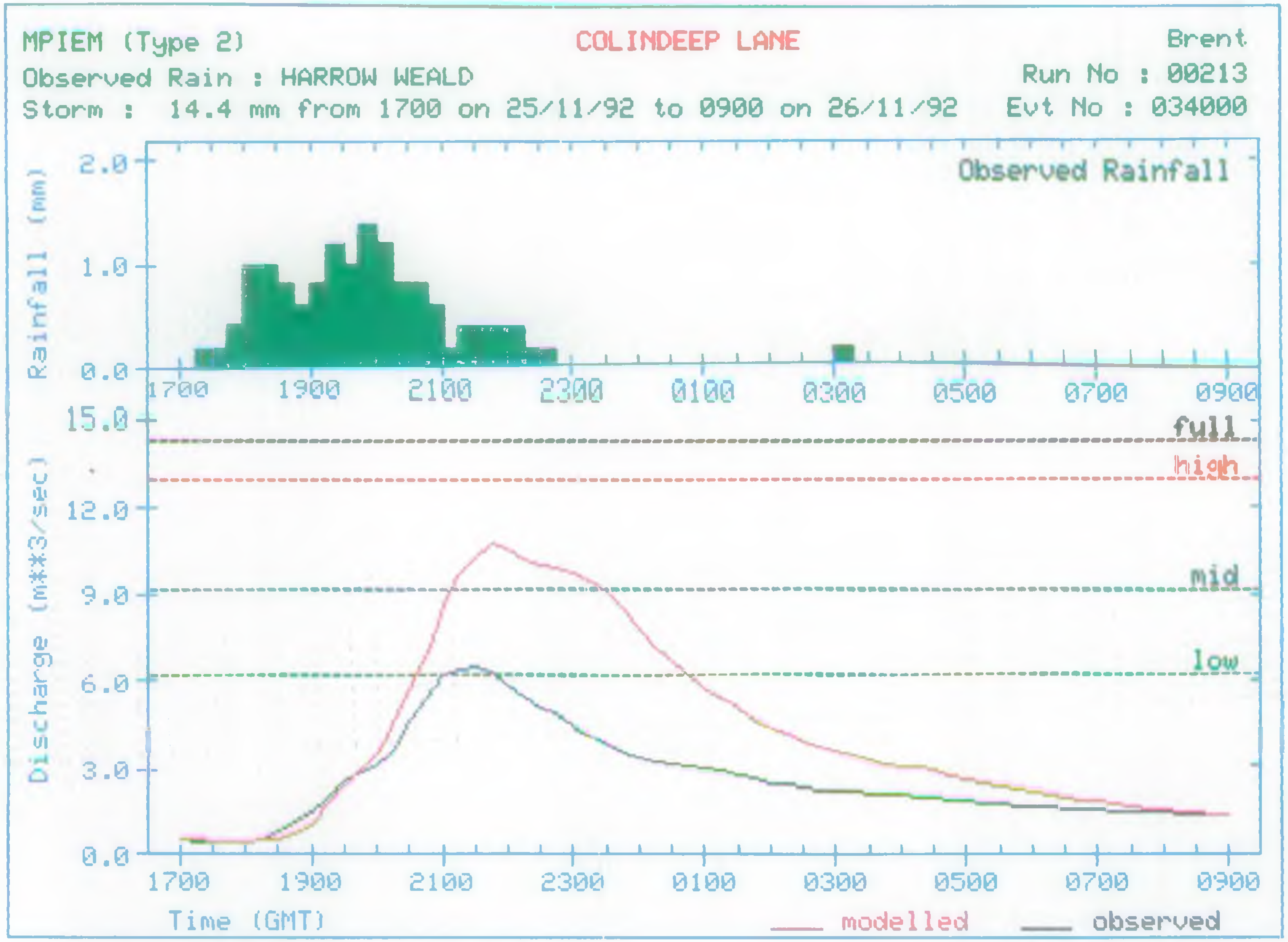
Forecast analysis using PERC & PERI

Figure 46b



MPIEM (Type 2)
COLINDEEP LANE
Brent
Observed Rain : HARROW WEALD
Run No : 00446
Forecast Rain : Frontiers Forecasts (single fcst)
Evt No : 034000
Storm : 14.7 mm from 1700 on 25/11/92 to 0900 on 26/11/92
Observed
Forecast
Rainfall (mm)
2.0
1.0
0.0
1700 1900 2100 2300 0100 0300 0500 0700 0900
15.0
12.0
9.0
6.0
3.0
0.0
full
high
mid
low
Discharge (m**3/sec)
Time (GMT)
modelled
observed
Forecast analysis using PERC & PERI
(c) NRA (Thames) 1993

Figure 46c



Post event analysis using PERC & PERI

(c) NRA (Thames) 1993

Figure 46d

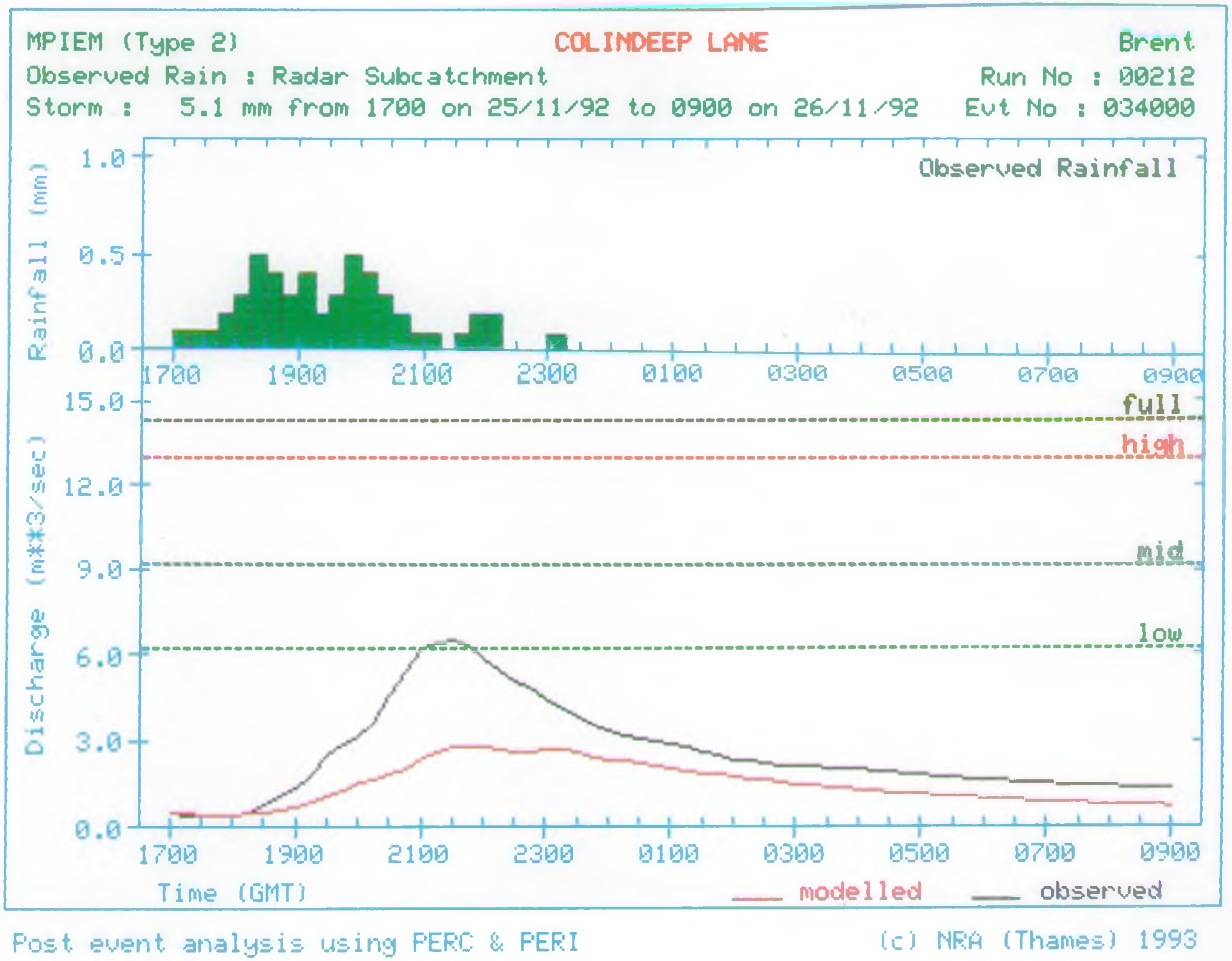
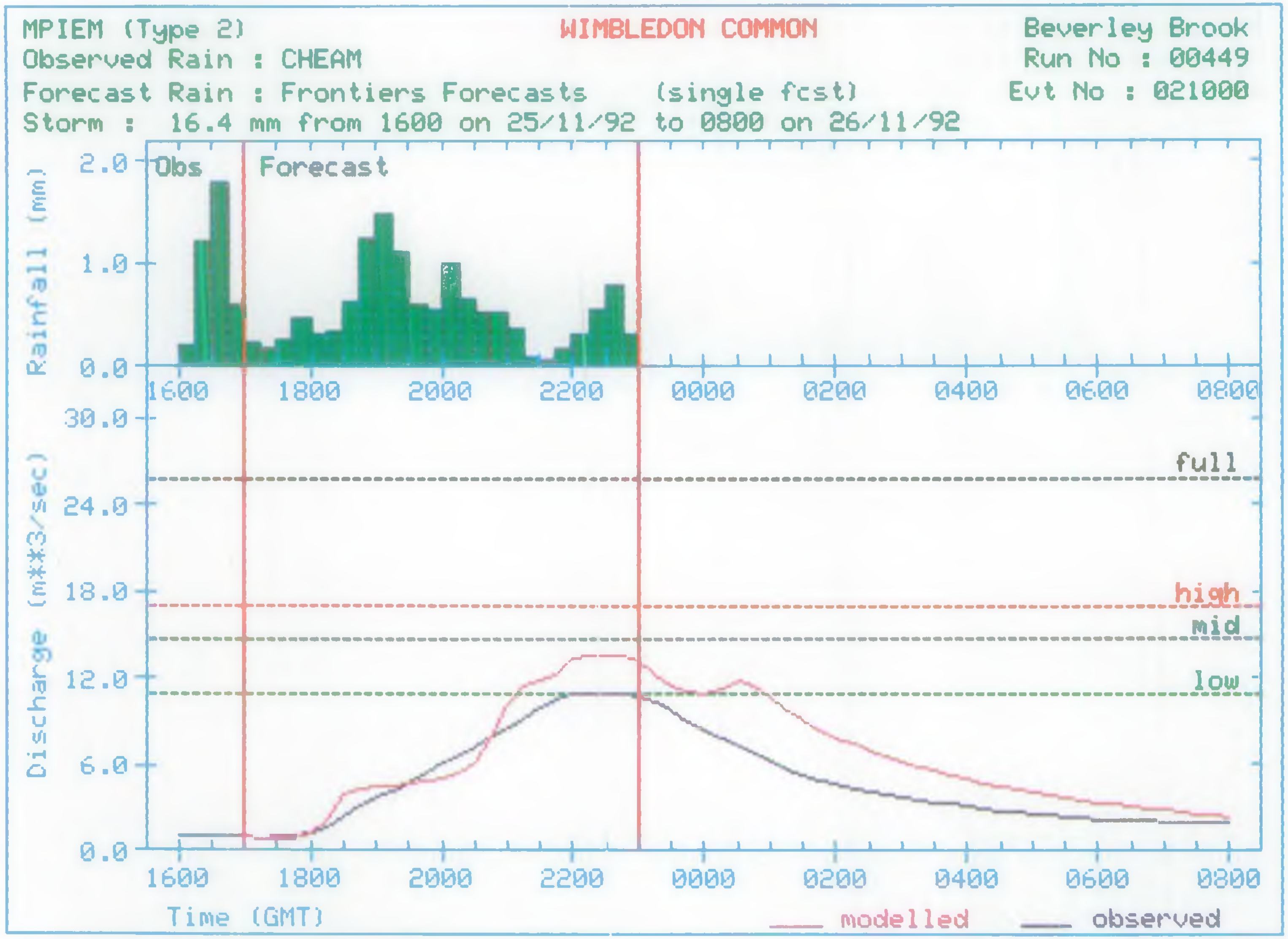
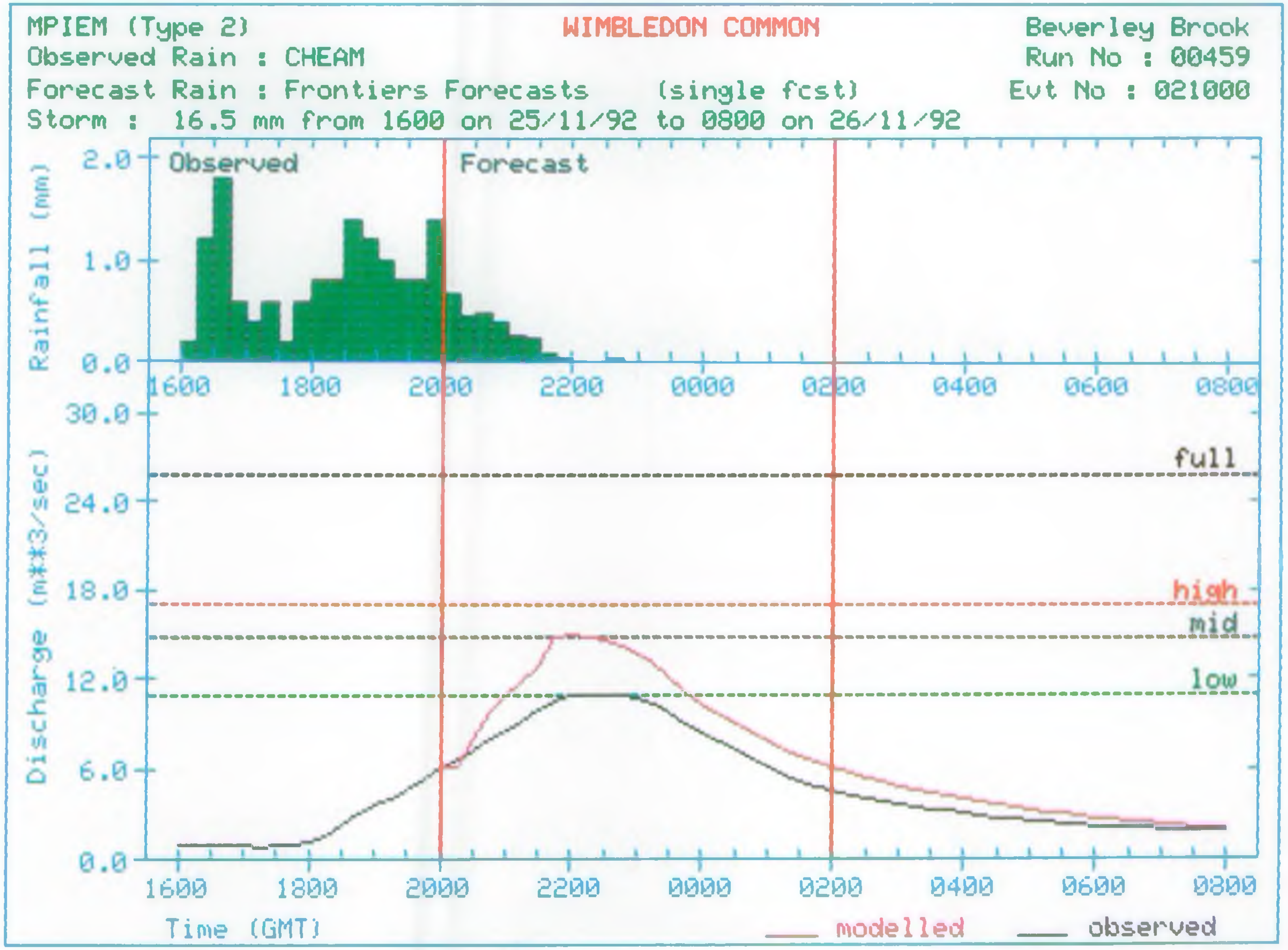

MPIEM (Type 2)
COLINDEEP LANE
Brent
Observed Rain : Radar Subcatchment
Run No : 00212
Storm : 5.1 mm from 1700 on 25/11/92 to 0900 on 26/11/92
Evt No : 034000
Observed Rainfall
Rainfall (mm)
1.0
0.5
0.0
1700
1900
2100
2300
0100
0300
0500
0700
0900
Discharge (m**3/sec)
15.0
12.0
9.0
6.0
3.0
0.0
full
high
mid
low
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1993

Figure 46e



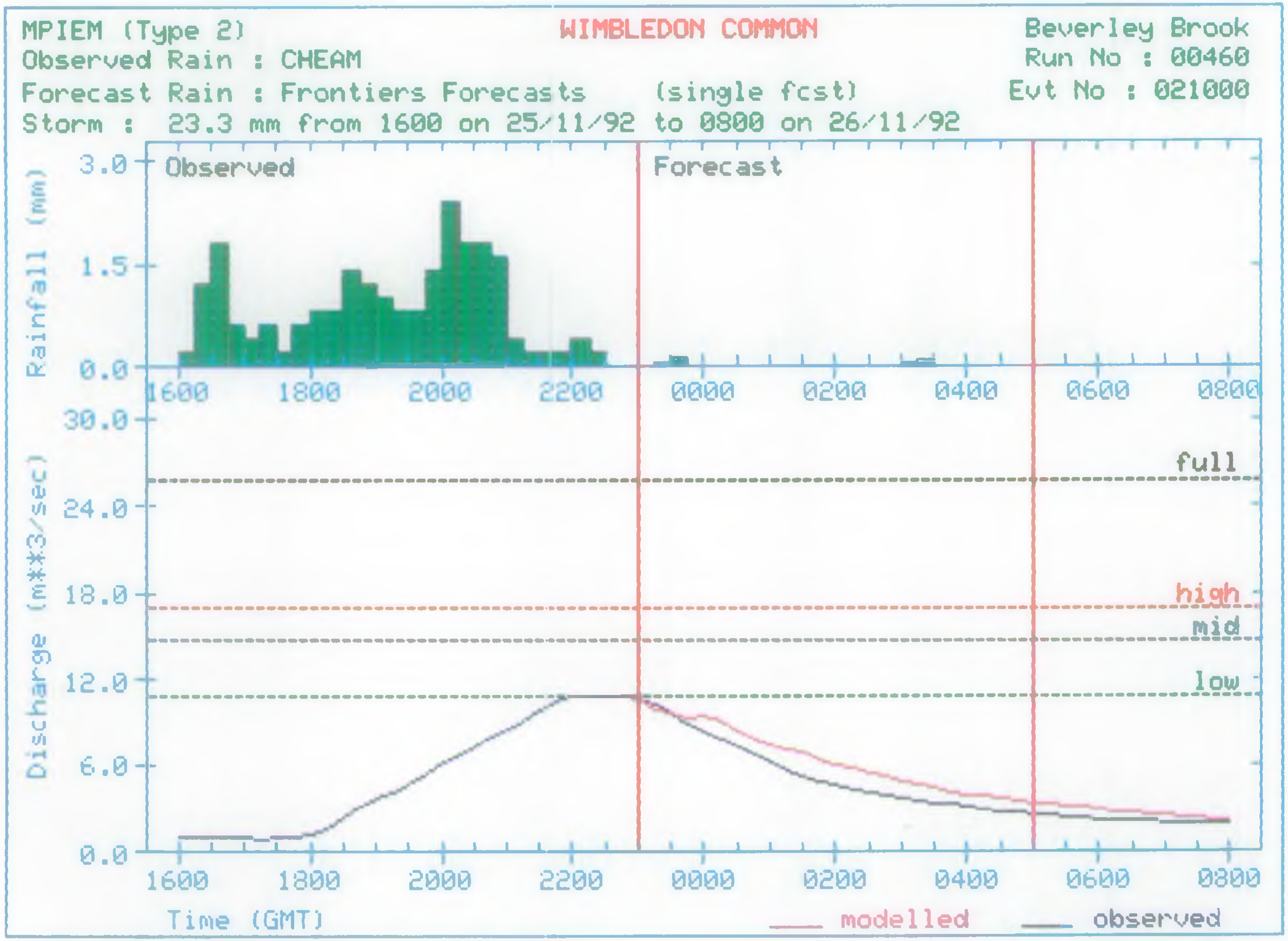
Forecast analysis using PERC & PERI

Figure 47a



Forecast analysis using PERC & PERI

Figure 47b



Forecast analysis using PERC & PERI

Figure 47c

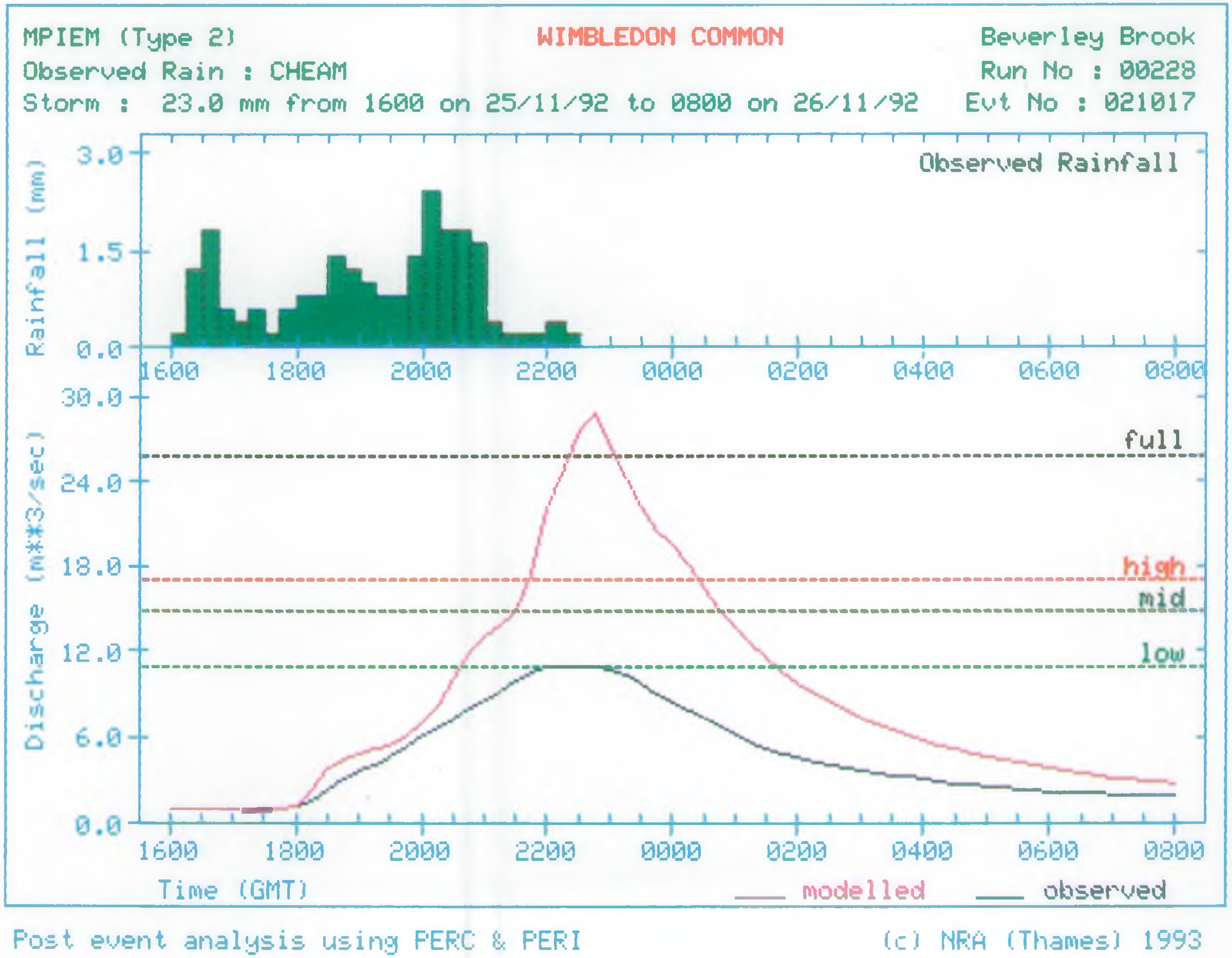
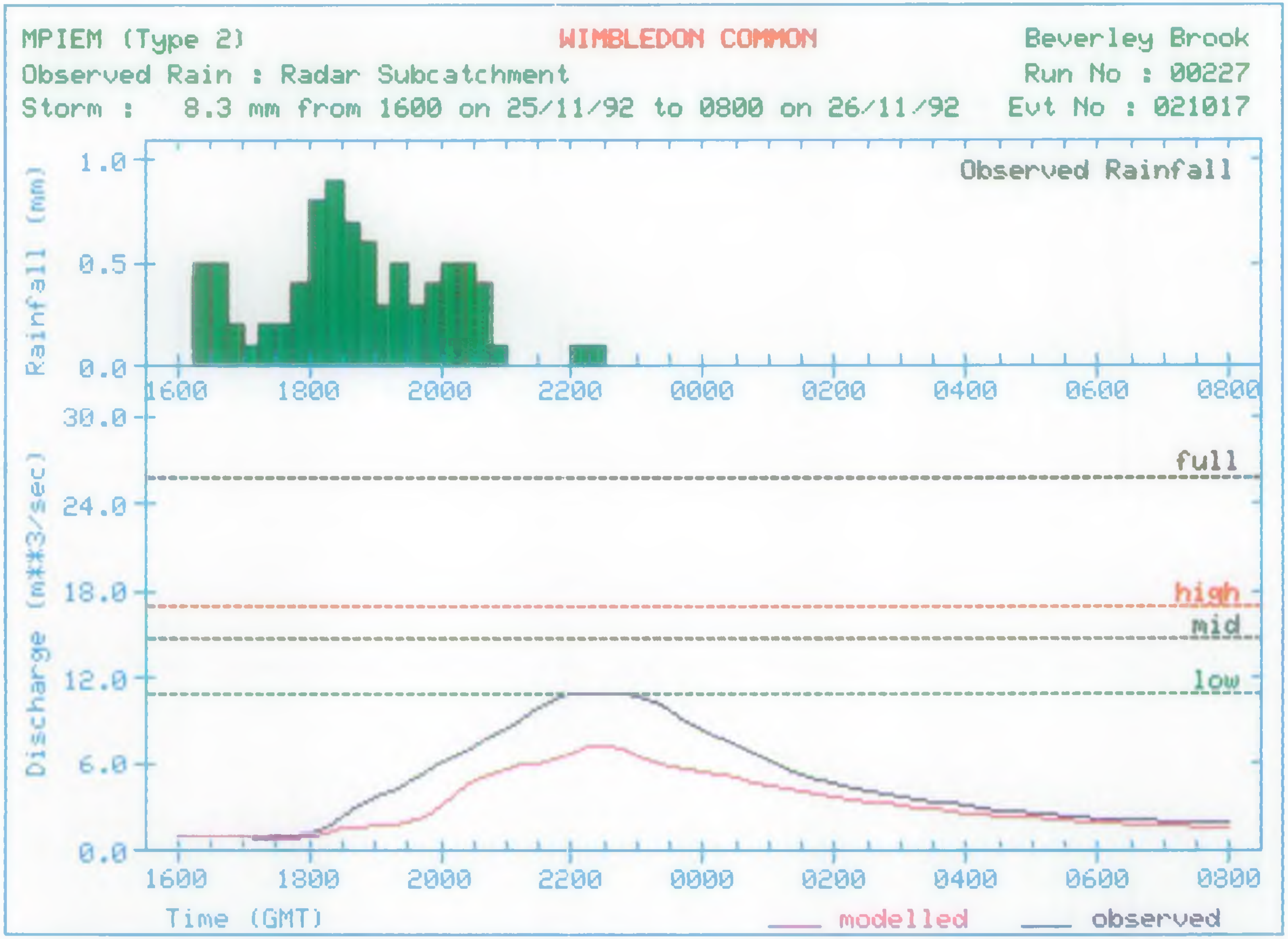
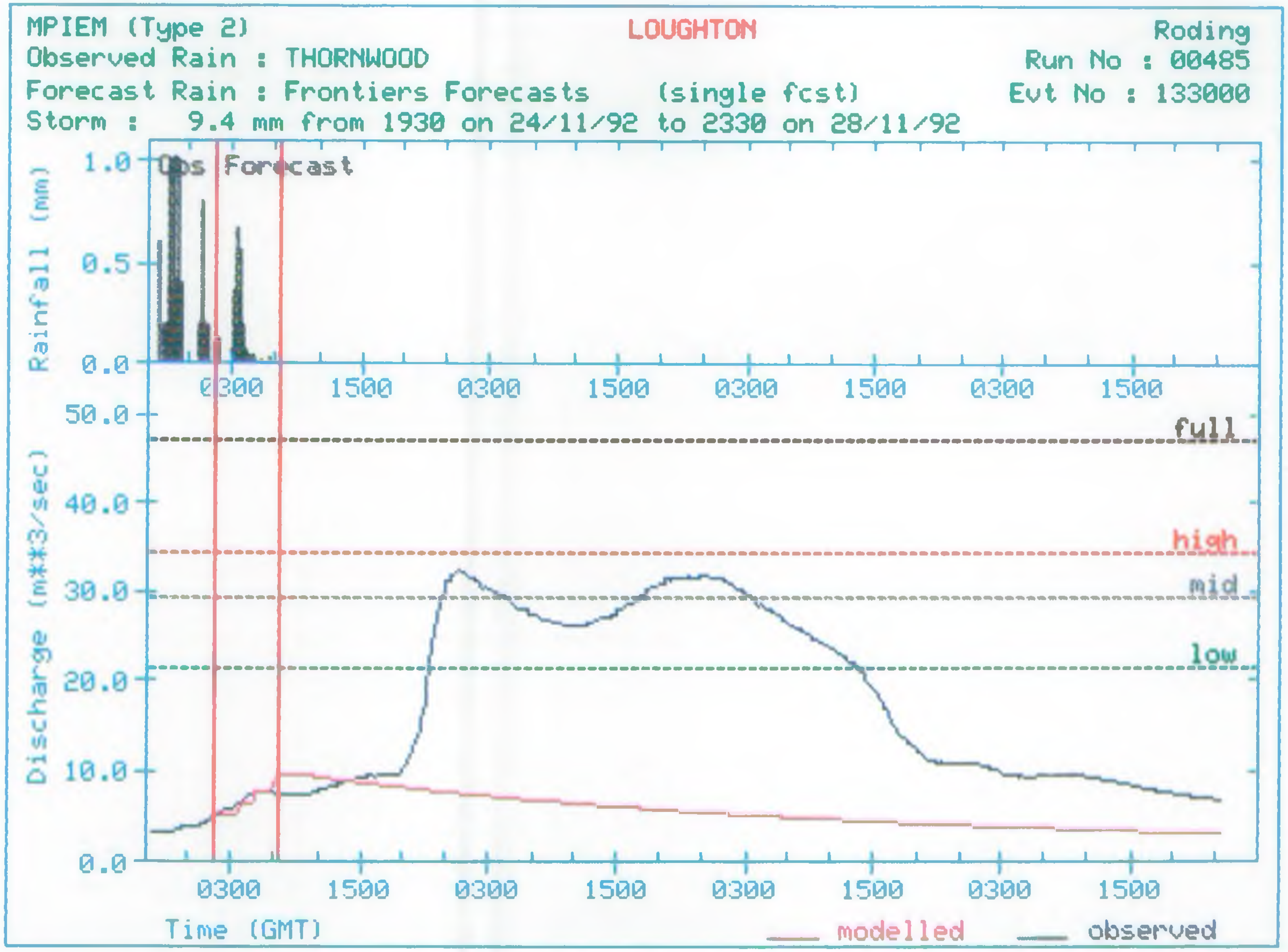

MPIEM (Type 2)
WIMBLEDON COMMON
Beverley Brook
Observed Rain : CHEAM
Run No : 00228
Storm : 23.0 mm from 1600 on 25/11/92 to 0800 on 26/11/92
Evt No : 021017
Observed Rainfall
Rainfall (mm)
3.0
1.5
0.0
1600
1800
2000
2200
0000
0200
0400
0600
0800
Discharge (m**3/sec)
30.0
24.0
18.0
12.0
6.0
0.0
full
high
mid
low
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1993

Figure 47d



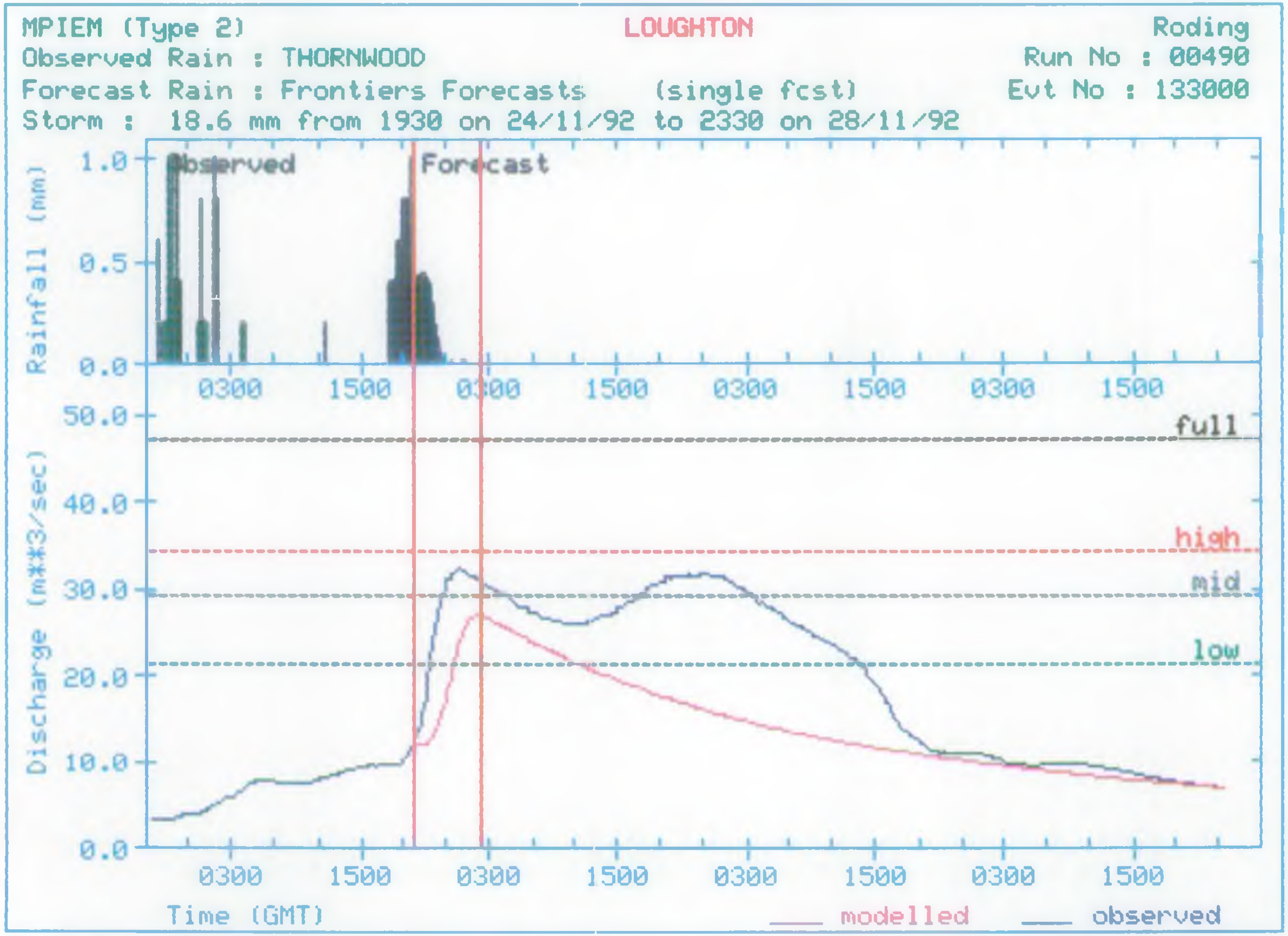
Post event analysis using PERC & PERI

Figure 47e



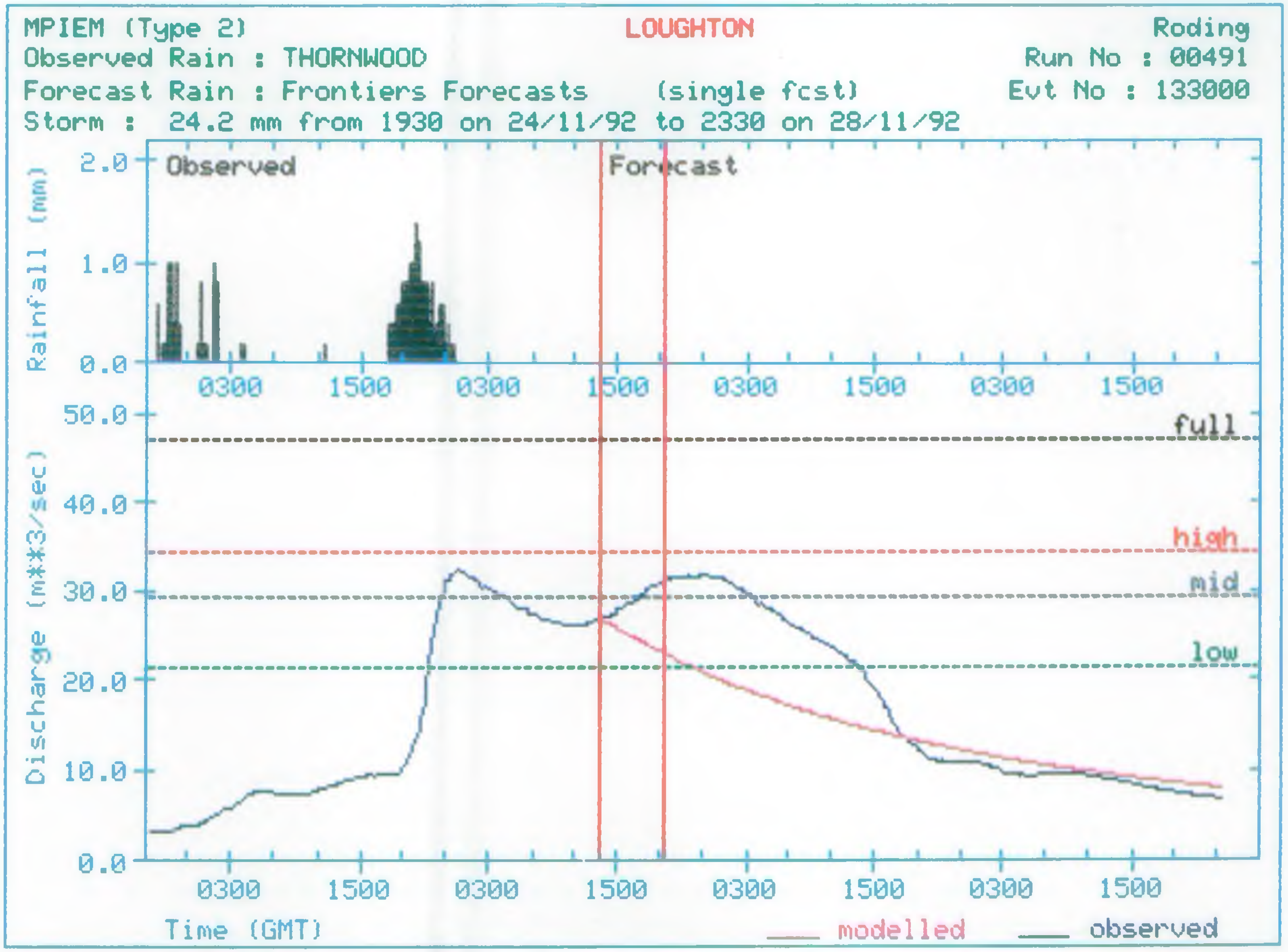
Forecast analysis using PERC & FERI

Figure 48a



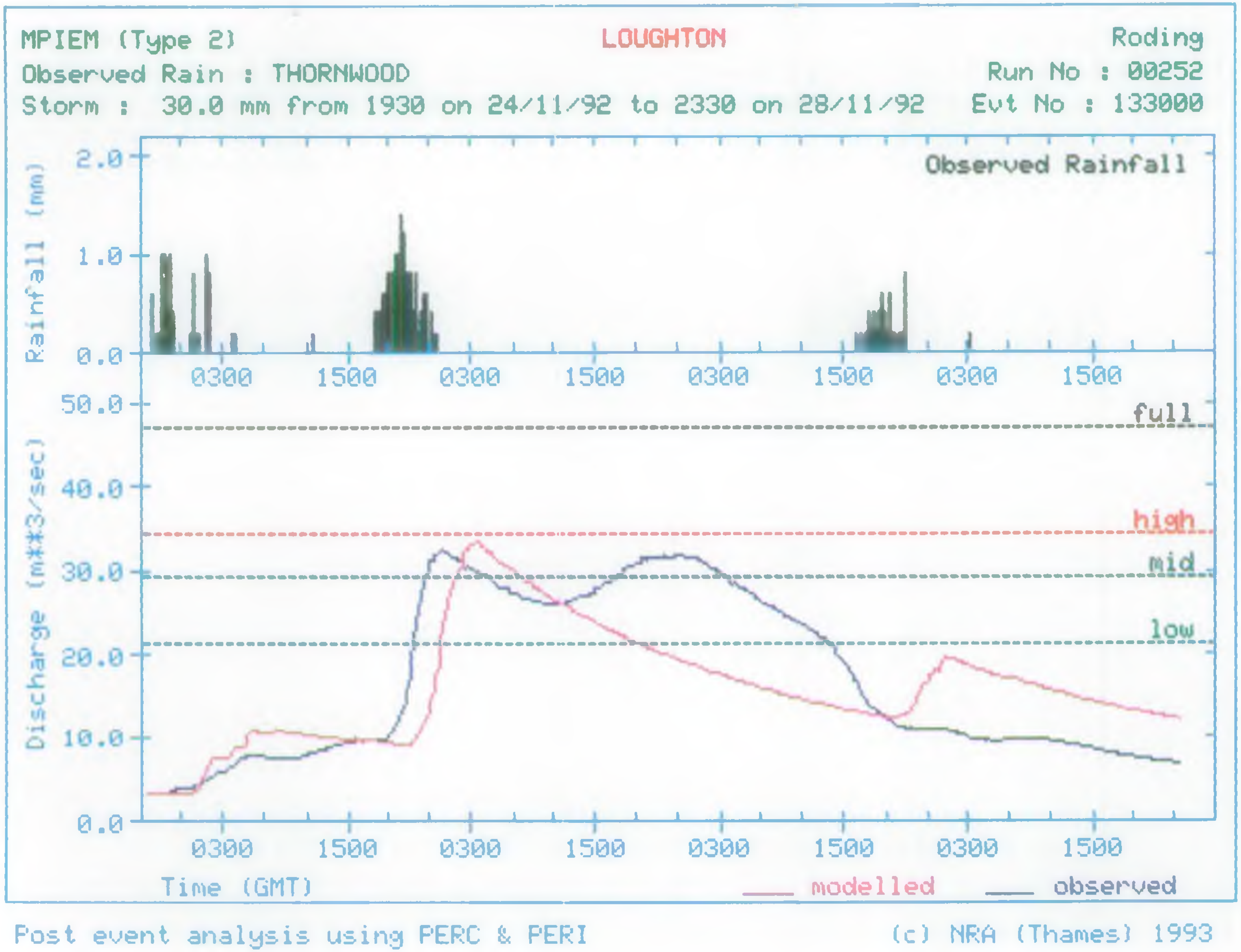
Forecast analysis using PERC & PERI

Figure 48b



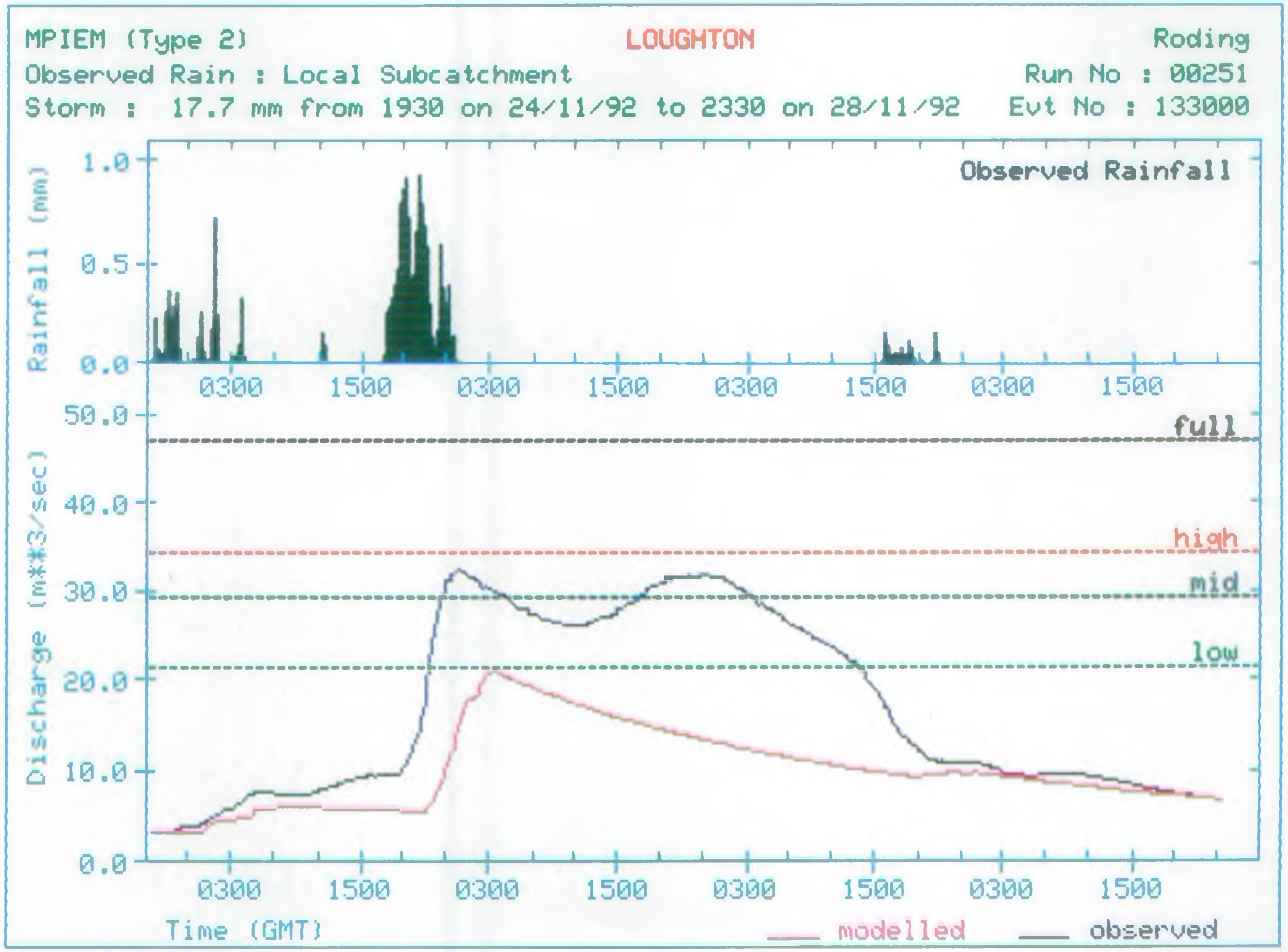
Forecast analysis using PERC & PERI

Figure 48c



MPIEM (Type 2)
LOUGHTON
Roding
Observed Rain : THORNWOOD
Run No : 00252
Storm : 30.0 mm from 1930 on 24/11/92 to 2330 on 28/11/92
Evt No : 133000
Observed Rainfall
Rainfall (mm)
2.0
1.0
0.0
0300 1500 0300 1500 0300 1500 0300 1500
Discharge (m**3/sec)
50.0
40.0
30.0
20.0
10.0
0.0
full
high
mid
low
0300 1500 0300 1500 0300 1500 0300 1500
Time (GMT)
modelled
observed
Post event analysis using PERC & PERI
(c) NRA (Thames) 1993

Figure 48d



Post event analysis using PERC & PERI

Figure 48e