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Wallingford Water

Floodplain Mapping - Model Study of the River Frome (Gloucestershire)

Hydrological Study

Report EX 3171
August 1995

Wallingford Water

Contract

This report describes the hydrological study carried out by Wallingford Water as part of the "Floodplain Mapping - Model Study of the River Frome" commissioned by the National Rivers Authority - Severn Trent Region. The NRA representative was Mr D Pettifer, and Wallingford Water was represented by Mr TE Parkinson and Mr RJ Millington. The HR job number was RQR 1568. The work was carried out by Miss HA Houghton-Carr (IH) and Mr RJ Millington (HR).

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Approved by R Bettess Rivers Group

Date 7th August 1995

Wallingford Water

Summary

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In September 1993 the National Rivers Authority - Severn Trent Region commissioned Wallingford Water, the joint venture between the Institute of Hydrology and HR Wallingford Ltd, to carry out the "Floodplain Mapping, Model Study of the River Frome (Gloucestershire)" study.

This report gives a detailed description of the hydrological components of the study. The objective of this was to develop calibration and design event hydrological inputs for the computational hydraulic model. All available data were collated and analysed to develop the best possible estimates using the methods of the Flood Studies Report. A routing model was constructed to provide an initial check on the relative timings and magnitudes of the estimates produced, and a physical model study was undertaken to investigate the out-of-bank rating for the gauging station at Ebley Mill. The results of this latter study are presented in Report EX 3170.

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1 Introduction

1.1 Background

In September 1993 the National Rivers Authority - Severn Trent Region (NRA-ST) commissioned Wallingford Water (WW), the joint venture between the Institute of Hydrology and HR Wallingford Ltd, to carry out the "Floodplain Mapping, Model Study of the River Frome (Gloucestershire)" study. The overall objective of the study was to construct and prove a hydraulic model of the River Frome and a small part of its tributary, the Nailsworth Stream, in order to determine the flood plain limits for six design events of specified return periods of between 5 and 150 years.

This report presents the results of the hydrological components of the study, including the derivation of the model inputs and an initial assessment of their validity using a routing model of the Frome catchment.

1.2 Terms of reference

The terms of reference for the overall study are defined in the NRA-ST document "Brief for Report and Advisory Works. Floodplain Mapping - Model Study of the River Frome (Gloucestershire)" of July 1993, the WW proposal to undertake the study of August 1993 and the NRA-ST letter of appointment dated 24 September 1993. The terms of reference for the hydrological study can be summarised as follows:

(a) Identification of suitable calibration events for use both in the hydrological and hydraulic model studies

(b) Construction of a routing model for the Frome catchment to Ebley Mill and calibration by comparison of observed and predicted flows

(c) Construction of a physical model of Ebley Mill gauging station to extend the rating for out-of-bank flows (described in Report EX3170)

(d) Derivation of model inflows using the methods of the Flood Studies Report

(e) Comparison of estimated peak flows at Ebley Mill for design events with those estimated from flood-frequency analysis

2 Approach to the hydrological study

The study requires flood magnitudes of given probability or frequency of occurrence to be estimated in order to identify the flood extent for development control purposes. If sufficiently long records of river flow are available, the flood magnitude-frequency distribution can be estimated directly. However, the majority of sites have little or no data on previous flood flows, and the distribution has to be estimated indirectly.

Since no suitable flood record exists from which to abstract the required information, the design events have been derived using hydrological and hydraulic modelling techniques. The methods of flood estimation adopted were those of the Flood Studies Report (FSR), Reference 1, and Flood Studies Supplementary Reports (FSSRs), Reference 2.

The FSR presents two indirect methods of flood estimation, which have been applied to a large number of catchments throughout the UK:

- The statistical method in which observed flood peaks are treated as random samples from some frequency distribution;

- The rainfall-runoff method in which rainfall is treated as the statistical element and is converted to flow using a deterministic model of catchment response, in this case the unit hydrograph and losses model.

With both methods the various model parameters are related via multiple regression equations to physical and climatic characteristics of the catchment, Table 1, enabling flood estimates to be made at ungauged sites. Such estimates can be improved by using observed data from or near to the site of interest. However, the statistical approach estimates only peak flow, which may suffice for the design of culverts and bridges. For design studies such as this one, where flood routing is involved, the rainfall-runoff method, which synthesises the entire flow hydrograph, is required.

In order to verify the magnitude and relative timings of the inflows derived using the FSR methods, a routing model is also required. This allows the effects of storage and attenuation of the hydrographs to be studied, so that the total hydrograph can be compared with observed flows. The use of a routing model is preferable to the use of the full hydraulic model due to the comparative speed with which a routing model can be constructed. For the purposes of this study, the HR RIBAMAN routing software was used, which includes full Muskingham-Cunge routing, representation of storage ponds, and representation of structures using stage-discharge curves at specified nodes.

The hydrological study required the identification of three calibration events for use throughout the overall study. Following discussion with NRA-ST, the events selected were as follows:

- 18 December 1965
- 30 May 1979
- 5 January 1994

The choice of the December 1965 event reflects that this is the largest event on the Frome for which there are observations. However, the flood predates the installation of the gauge at Ebley Mill and as such there are no available data on the event flows. The 1979 event is the largest event for which flow data are available, whilst the 1994 event, though smaller in magnitude than the others, has continuous level data available at six locations within the catchment, as well as flow data at Ebley Mill.

3 Frome catchment and river system

The Frome catchment extends from the Cotswold escarpment in the east, on the boundary of the Thames and Severn-Trent regions of the NRA, through to the River Severn in the west. A plan of the catchment and river system is shown in Figure 1.

The River Frome rises in the north-east of the catchment, high up on the Cotswold escarpment and flows southwards. After about 10 km the river turns westwards for another 10 km or so, during which it is joined by two tributaries from the north, the Holly Brook and the Toadsmoor Brook. Along much of this stretch the river runs parallel to the now disused Thames and Severn Canal. The river then turns northwards for about 5 km towards Stroud, the largest town in the catchment, and then westwards again to Ebley Mill gauging station. Ebley Mill is the only gauging station in the catchment, and has a catchment area of 198 km^2. Just upstream of Ebley Mill the river is joined by the Nailsworth Stream from the south and the Stroud flood relief channel from the north. The flood relief channel is part of the old Stroudwater Canal and carries the flows from the three remaining northern tributaries, the Randwick Stream, Painswick Stream and Slad Brook.

Downstream of Ebley Mill the river continues in a north-westerly direction for a further 10 km towards its confluence with the River Severn. Along much of this stretch the river runs parallel to the now disused Stroudwater Canal. About 1 km before the confluence, there is a flow diversion into the Gloucester and Sharpness Canal for water supply in the Bristol area. The total catchment area upstream of the Severn is approximately 226 km^2.

The Frome catchment is characterised by steep valley sides sloping down to the river below and small, fast-flowing streams, particularly in the upper reaches. The catchment lies on heavily fissured, oolitic limestone and liassic sandstone bedrock which dips from the Thames basin into the Frome basin. The limestone is thought to act like a sponge, absorbing water until the aquifers are filled; heavy rain may take several days to have an effect, and water lost in the upper reaches may well reappear further downstream. The soils tend to be well-drained and calcareous, with clayey, loamy and stony components. In the downstream part of the catchment some non-calcareous soils are also present.

The catchment is predominantly agricultural in nature, though urban areas account for around 10% of all land use. Bailey, Reference 3, assigned 50% of the catchment to permanent grassland and 15% to temporary grassland, with another 10% to woodland. The remainder is made up of crop-growing areas and open water such as canals and lakes. The Stroud conurbation extends for some distance along the nearby valley bottoms, as does the smaller town of Nailsworth in the south of the catchment. There are also numerous small villages.

Bailey reports that during the late eighteenth and early nineteenth centuries the water resources of the River Frome were heavily utilised, firstly by the then flourishing mill industry in and around Stroud, and secondly by the extensive canal-based transport network. Many of the river and canal beds were lined right up to their source to preserve the water supply for these uses. However, lack of maintenance, associated with the decline of the mills and canals, has caused the clay puddle bed lining to deteriorate, and water can now seep away again. This is said to be an increasingly serious problem in summer.

4 Data collection and processing

Both flood peak and flood event data were available for and used in the study. The flood peak data were available in the form of annual maxima and peaks-over-threshold series. The flood event data typically required for analysis include flow data for the event, recording raingauge data for the storm, daily raingauge data for both the storm and the 5 days preceding it, and estimated soil moisture deficit data at 09:00 on the first day of the event; these data were available in various forms. Some stage data for catchment lag analysis were also available. Finally, physical and climatic characteristics of the catchments were derived from maps to enable no-data estimates of the model parameters to be made using FSR regression equations. The locations of the gauges and stations from which data were obtained are shown in Figure 2. The data collection and processing are described in detail below.

Major floods are known to have occurred during the 1950s, and in 1965 and 1968, but all prior to installation of the gauging station at Ebley Mill. Very little information concerning these events is available, and so it was not possible to incorporate them into the analyses in any way. However, the 1965 event was used as a calibration event, as described in Chapter 11.

4.1 Flow data

Flow data and abstracted flood peak data for Ebley Mill gauging station were obtained from NRA-ST. The flow data were derived from stage data by applying the most recent set of rating equations retrospectively to the entire record (G. Davies, 1993; personal communication):

$Q = 7.7936\,(h + 0.05721)^{1.29024}$ for $h < 0.334$ m
$Q = 20.5842\,(h + 0.074)^{2.42528}$ for $0.334 \leq h < 0.429$ m
$Q = 14.292\,(h + 0.10796)^{2.09351}$ for $0.429 \leq h < 1.600$ m
$Q = -1257.7 + 2532.9\,h - 1654\,h^2 + 365.5\,h^3$ for $1.600 < h$ m

(The final equation was derived from the physical model study undertaken as a part of this study, and described in Report EX 3170).

The record was continuous from January 1969 up to and including the January 1994 event, thus providing 24 complete water years of data for flood frequency analysis.

Events for flood event analysis were selected from examination of the stage charts for Ebley Mill gauging station from 1986 onwards. Two events from 1979, identified previously by NRA-ST, were also included. The annual snow reports published by the Meteorological Office (MO) were referred to in order to check that the events chosen were in snow-free periods. Table 2 lists the dates of the 39 events selected.

4.2 Stage data

Stage data from six continuous level recorders, the details of which are listed in Table 3, were obtained from NRA-ST. The recorders were installed in the catchments between May 1992 and June 1993. Apart from the recorder originally installed at Bowbridge Lock (C3a) which was moved to Thrupp (C3b) in early 1993, the records were continuous up to September 1993. Events for catchment lag analysis were selected from examination of the stage data, and where possible the same events were chosen for each recorder. The requirement was that at least six smooth, single-peaked events were chosen for each recorder. Table 4 lists the dates of the events selected. The outcome was that 10 events were chosen for recorder C1, 8 for recorder C2, and 6 each for recorders C3a, C5 and C6. No events were selected from recorders C3b and C4.

4.3 Rainfall data

The raingauge coverage of the Frome catchment is adequate, and generally better for daily gauges than for recording gauges. For a number of mid-1980s events, only one recording gauge, usually some distance from the catchment, was operational, whereas the daily gauges were spread fairly evenly across the catchment.

The only long-term recording raingauge within the Frome catchment is at Miserden in the north-east of the catchment. There are, however, four long-term recording raingauges nearby at Dowdeswell, Longford and Netheridge, all to the north, and at Kingswood to the south-west. In addition, three new recording raingauges were installed within the catchment during May and June 1993 at Painswick Lodge in the north, at Eastington Park in the east, and at Avening Court in the south. Recording raingauge data corresponding to the selected flood events and catchment lag events were supplied by NRA-ST. Data from the long-term gauges were provided as hourly totals, whilst data from the three new gauges were provided as bucket tip times which were converted to hourly totals. All the recording raingauges were used in the flood event analysis at Ebley Mill, and Table 2 indicates the availability of gauge data for each event. However, for the catchment lag analysis, the recording raingauges used varied between the level recorders. Table 3 shows the raingauges used for each catchment and, on the basis of this, Table 4 indicates the availability of gauge data for each of the events.

Recording raingauge data were also collected for the three events chosen for calibration of the hydraulic model. The dates of the events and the corresponding availability of recording raingauge data are listed in Table 5. For the 1965 event it was necessary to obtain data from Pershore, some distance to the north of the Frome catchment, as none of the other raingauges were operational at that time. 1965 data from Henley-in-Arden, which is even further away, were also provided but were not used.

Daily rainfall data from raingauges within or close to the Frome catchment were obtained from the MO supplied daily rainfall archive at IH, though data from NRA-ST were used to supplement the 1992, 1993 and January 1994 records. The daily gauges are spread fairly evenly across the catchment, with perhaps a slightly higher density to the north and the east.

The rainfall data were used to derive catchment average event rainfalls for the events selected for flood event analysis and catchment lag analysis. The daily rainfall data were used to determine catchment total rainfall, and the autographic raingauge data to provide storm profile information. In addition, the daily rainfall data for the 5 days preceding the start of each of the events selected for flood event analysis were used to calculate the catchment average 5-day antecedent precipitation index API5, used to estimate the likely state of the catchment prior to the storm.

4.4 Soil moisture deficit data

Estimates of soil moisture deficit SMD at the beginning of each event selected for flood event analysis were obtained from the MO. Data from three sites were used: Cheltenham to the north, Cirencester to the south-east and Monmouth to the west on the Welsh side of the River Severn. The data were weighted on the basis of distance from the catchment: Cheltenham and Cirencester were given weights of 0.4, and Monmouth was given a weight of 0.2. The SMDs were used to derive catchment average SMDs for each event, again to enable the state of the catchment prior to the storm to be assessed.

4.5 Catchment characteristics

Catchment characteristics, as listed in Table 1, were abstracted from maps for the Ebley Mill catchment and for the catchments upstream of each of the continuous level recorders. The values were obtained as described in the FSR, and are listed in Table 6.

5 Approach and methodology

The FSR rainfall-runoff method uses a relatively simple, 3-parameter model, known as the unit hydrograph and losses model, to represent the catchment. The three parameters are:

Tp - the time-to-peak of the unit hydrograph which determines how quickly the catchment responds to effective rainfall input;

PR - the percentage runoff which is the ratio of total to effective rainfall i.e. the proportion of the total rainfall input which becomes response runoff in the river;

ANSF - the average non-separated flow or baseflow which represents the flow in the river before the event started.

The unit hydrograph and losses model makes several simplifying assumptions: linearity i.e. that there is a direct proportional relationship between the effective rainfall input and the response runoff; superposition i.e. that successive inputs of effective rainfall produce independent responses which can then be summed to give the total runoff response; time-invariance i.e. that the rainfall-runoff relationship does not change with time; that the effective rainfall input is uniform in both time and space; and finally that the percentage runoff and baseflow are constant through the event.

Further details of unit hydrograph theory and the unit hydrograph and losses model may be found in standard texts, such as Shaw, Reference 4, and Wilson, Reference 5.

5.1 Time-to-peak Tp

The unit hydrograph transforms effective rainfall into response runoff. The T-hour unit hydrograph defines the response of the catchment to unit (10 mm or 1 cm) input of effective rainfall in time T hours. On an ungauged catchment the unit hydrograph is synthesised as a simple triangle of fixed shape, the dimensions of which are controlled by time-to-peak Tp. Time-to-peak therefore has an indirect effect on flood magnitude. Time-to-peak of the instantaneous unit hydrograph Tp(0) is estimated from catchment characteristics using the FSSR16 equation:

$Tp(0) = 283\ S1085^{-0.33}\ (1+URBAN)^{-2.2}\ SAAR^{-0.54}\ MSL^{0.23}$

The instantaneous unit hydrograph assumes an infinitesimally small data interval, but in design flood synthesis the rainfall input will be in block form, each block of duration T hours. Therefore, the time-to-peak of the instantaneous unit hydrograph must be adjusted for this data interval T using the equation:

$Tp(T) = Tp(0) + T/2$

The data interval depends on the size of the catchment and its response time; for most UK catchments, including Ebley Mill, a data interval of 1 hour is suitable.

5.2 Percentage runoff PR

The percentage runoff indicates the proportion of total rainfall which becomes firstly effective rainfall, and then response runoff in the river. The rainfall "losses" include evaporation, transpiration, infiltration to soil moisture stores, and percolation to aquifers to contribute ultimately to baseflow. Percentage runoff is an important parameter with a direct scaling influence on flood magnitude, and the original FSR percentage runoff model was completely revised in FSSR16. The percentage runoff from the natural part of the catchment PR_{RURAL} is estimated in two parts: a "standard" part SPR representing the normal capacity of the catchment to generate runoff, and a "dynamic" part DPR representing the variation in runoff depending on the state of the catchment prior to the storm (DPR_{CWI}) and the storm magnitude itself (DPR_{RAIN}):

$PR_{RURAL} = SPR + DPR_{CWI} + DPR_{RAIN}$

SPR varies between catchments, but is fixed for all storms on a particular catchment. It is estimated from the five soil class fractions abstracted from the WRAP (Winter Rainfall Acceptance Potential) map (FSR I.4.2.3, FSSR7, FSSR17). For chalk catchments underlain entirely by WRAP class 1 permeable soils, SPR will be 10%, whilst for clay catchments underlain by more impermeable WRAP class 5 soils, SPR will be 53%:

$SPR = 10\ SOIL1 + 30\ SOIL2 + 37\ SOIL3 + 47\ SOIL4 + 53\ SOIL5$

DPR varies between storms on a particular catchment. Its components are:

$DPR_{CWI} = 0.25\ (CWI - 125)$

$DPR_{RAIN} = 0.45\ (P - 40)^{0.7}$ for $P > 40$ mm

$DPR_{RAIN} = 0$ for $P \leq 40$ mm

CWI is the catchment wetness index (FSR I.6.4.4) and P is the storm rainfall depth. Hence percentage runoff will be higher when antecedent conditions are wet, and when storm magnitude is large.

The total percentage runoff is estimated by adjusting PR_{RURAL} for the effects of catchment urbanisation:

$PR = PR_{RURAL}\ (1.0 - 0.3\ URBAN) + 70 \times 0.3\ URBAN$

The equation assumes that only 30% of the urban area is impervious and gives 70% runoff, whilst the other 70% of the urban area acts as natural catchment.

5.3 Baseflow ANSF

The baseflow represents the flow in the river before the event started. Baseflow is usually a relatively unimportant parameter as it tends to be small compared with the magnitude of the response runoff hydrograph. It is constant for a catchment and given by the FSSR16 equation:

$$ANSF = \{(33\ (CWI - 125) + 3.0\ SAAR + 5.5) \times 10^{-5}\}\ AREA$$

5.4 Local data

The FSR recommends that where possible model parameter values obtained from regression equations are replaced with or revised using observed values, from either the site of interest or a nearby similar site. In the unit hydrograph and losses model there are essentially three ways in which local data can be used:

- Direct estimation of the model parameters at the subject site from the analysis of observed flood events;
- Estimation of hydrological characteristics which are related to the model parameters from data at the subject site;
- Transfer of information from neighbouring catchments.

All three of these methods were employed in the current study, making full use of all the available data. In particular, Chapter 7 describes the analysis of recorded flood events at Ebley Mill which provided observed values of time-to-peak, standard percentage runoff and baseflow.

For situations where stage data are available but no ratings exists to convert them to flows, a similar approach to flood event analysis provides observed values of catchment lag time LAG. Lag time is the time between the centroid of the total rainfall and the flow peak or centroid of the flow peaks, as illustrated in Figure 3, and is closely related to time-to-peak.

Standard percentage runoff is similarly related to baseflow index BFI. BFI indexes the proportion of the hydrograph that is comprised of baseflow, and ranges from 0.1 for relatively impermeable clay catchments to 0.95 or more for highly permeable chalk catchments, Reference 6. The method yields estimates inferior to those from flood event analysis but, being based on hydrological data, is preferable to the SOIL equation.

Chapter 8 describes catchment lag analysis at six sites in the Frome catchment, as well as the estimation of standard percentage runoff by these methods. Refinement of model parameter values using data from nearby sites is achieved by simply applying the ratio of the observed value to the no-data estimate of the value at the nearby gauged site to the no-data estimate at the ungauged subject site.

6 Flood frequency analysis

Flood frequency analysis, using the IH HYFAP hydrological frequency analysis package, Reference 7, was carried out at Ebley Mill. The flow record at Ebley Mill was continuous from January 1969 to the present, thus providing 24 complete water years of data.

The choice of method for flood frequency analysis depends upon the length of record. The FSR recommends that for record lengths between 10 and 24 years an Extreme Value 1 (EV1) distribution should be fitted to the data, Reference 8, whilst for record lengths greater than 25 years a Generalised Extreme Value (GEV) distribution should be used (FSR I.A.4), Reference 9. The FSR recommendation of fitting by the method of maximum likelihood (MML) has since been superseded by the method of probability-weighted moments (PWM), Reference 10. Boorman *et al.*, Reference 11, found that it was reasonable to fit a GEV distribution to records of 15 or more years in length by PWM, since the likely errors for estimating the T-year flood with a GEV distribution fitted to 15 years of data by PWM were similar or better than by using an EV1 distribution fitted by MML. This conclusion was in line with that of Hosking *et al.*, Reference 12.

A GEV distribution was therefore fitted to the 24-year annual maxima series using PWM. For information, the annual maxima are listed in Table 7. An EV1 distribution was also fitted, again by PWM, for comparison. The plots of discharge against return period are shown in Figure 4.

For return periods of more than twice the record length (i.e. 48 years), the fitted flood frequency curves are shown as dashed lines to emphasise the uncertainties involved in extrapolation. The two curves correspond fairly well up to the 50-year return period, where the GEV distribution tends towards EV3. The data, which are stepped, are best fitted by the EV1 distribution, with no particularly large departures of the data from the line. The ledges in the data might perhaps be explained by overtopping of flood banks and flooding of offline storage progressively further downstream. However, higher level ledges in frequency distributions of flow can be explained simply as a result of sampling effects for small data sets, Reference 13.

It is worth considering how representative this flood frequency curve is. Several major historical floods were reported in the 1950s and 1960s before the gauging station was installed. In their previous hydrological study NRA-ST estimate, using FSR techniques, that an event in December 1965 may have approached 25 m^3/s, whilst another event in July 1968 may have been between 30 m^3/s and 40 m^3/s. The 24-year record at Ebley Mill may be of adequate length for flood frequency analysis, and the data may be better fitted by an EV1 distribution than by an EV3 distribution (the latter almost suggesting an upper limit to flood magnitudes); however, the fitted line does not rise particularly steeply and may be giving a false impression of the true behaviour of the catchment. Clearly, the longer the record, the more likely it is to contain rare floods. Therefore, for comparison, several other flood frequency curves for Ebley Mill were derived using the FSR techniques referred to in Chapter 4. The modelling was done using the IH Micro-FSR software, Reference 14.

In the FSR statistical method, an index flood, called the mean annual flood MAF, is scaled up to the required return period using regional growth curves. On an ungauged catchment, the mean annual flood is estimated using the equation:

$$MAF = \text{Constant}\ AREA^{0.94}\ STMFRQ^{0.27}\ S1085^{0.16}\ SOIL^{1.23}\ RSMD^{1.03}\ (1+LAKE)^{-0.85}$$

The Constant varies with region of the country (FSR I.A.4.1). For Ebley Mill, in hydrometric area 54 and region 4, the value is 0.0213 giving, on substitution of the appropriate catchment characteristics, a mean annual flood of 19.5m^3/s. However, the mean annual flood may also be obtained as the mean of the annual maxima, giving an "observed" value of 11.2 m^3/s, some 40% lower. The region 4 growth curves (FSR I.2.6, FSSR14) were applied to each of these values of mean annual flood, and corresponding flood frequency curves produced. The curves are plotted in Figure 5, together with the EV1 line. The no-data statistical method greatly overestimates the observed curve, but when the observed mean annual flood is substituted in a much better approximation is obtained.

Two other flood frequency curves are shown in Figure 5: the no-data rainfall-runoff method i.e. unit hydrograph and losses model parameters estimated from catchment characteristics, and the statistical method with the observed mean annual flood and an urban-adjusted regional growth curve. The former overestimates the observed curve even more than the no-data statistical method, whilst the latter is a slightly better than when no urban adjustments are made. Urban adjustments in the statistical method are definitely recommended when the urban fraction of the catchment is greater than 0.10, and usually advised for urban fractions greater than about 0.05. Since the catchment to Ebley Mill has an urban fraction of 0.09, urban adjustment to the regional growth curve is certainly appropriate.

It seems possible therefore that the EV1 line, whilst fitting the observed annual maxima series well, may not be representing the long-term behaviour of the catchment, simply because the record does not contain the large floods reported in earlier decades. To investigate this further, an attempt was made to extend the annual maxima series back another 2 years in order to include the large flood of 1968. NRA-ST have given a lower estimate of the July 1968 flood peak as 30.6 m^3/s, and this value was assigned to the 1967 water year. The recorded value of 8.5 m^3/s for May 1969 was assigned to the 1968 water year. GEV and EV1 distributions were again fitted to the now 26-year annual maxima series using PWM, and the plots of discharge against return period are shown in Figure 6. This time the two curves correspond fairly well up to only the 20-year return period, where the GEV distribution tends upwards towards EV2 under the influence of the 1968 peak. In fact, the PWM fitting method tends not to be unduly affected by extreme floods. Although including the estimated peaks for June 1968 and May 1969 has changed the curve from type 3 to type 2, this is because the series now has a larger flood i.e. the absolute value of this flood is less important than the fact that it is significantly larger. Hence uncertainties in the true value of the June 1968 flood should not greatly affect this curve fitting. In summary this evidence suggests that if the estimate of the 1968 flood peak is realistic, and furthermore if it is typical of some of the pre-1969 flood magnitudes, then the flood frequency curves derived from the observed mean annual flood and the region 4 growth curve (either with or without an urban adjustment) may be a better representation of the behaviour of the catchment than the observed curve.

7 Flood event analysis

This chapter describes the flood event analysis undertaken on the catchment to Ebley Mill, in order to obtain some "observed" values for the unit hydrograph and losses model parameters which can be used to replace the no-data estimates at Ebley Mill, and to refine the no-data estimates for ungauged neighbouring catchments. The data requirements for flood event analysis were briefly described in Chapter 5, and Table 2 lists the dates of the events selected.

Figure 7 shows a typical flood event. The hourly flow data are plotted against time for the catchment hydrograph, and hourly rainfall data through the event are plotted as hyetographs from up to four recording raingauges (though more may be used in the analysis) and as a catchment average. The catchment average rainfall was derived from the nearby recording and daily raingauges. Each daily raingauge was weighted according to its location with respect to the catchment, Reference 15. The recording raingauges were weighted in the same way, and then for each gauge, each hour was expressed as a proportion of the total event rainfall at that gauge. For each hour in turn, the weighted proportions at each gauge were summed across all the gauges to yield an average profile. The weighted daily rainfalls were averaged to give a catchment average event total, which was distributed between the hours of the event using the average profile calculated from the recording raingauges, to give the catchment average rainfall profile. In addition, daily rainfalls for the 5 days preceding the start of the event were analysed to give the catchment average 5-day antecedent precipitation index API5. The catchment wetness index CWI at the start of each event was calculated from API5 and the catchment average SMD, and used later in fitting the unit hydrograph and losses model.

The graphical approach adopted in Figure 7 is a useful way of presenting data because it may reveal errors or inconsistencies not apparent from columns of numbers e.g. timing errors between rainfall and flow, discrepancies between recording raingauges, or the possible presence of snow melt. Any one of these things may cause an event to be rejected, and of the 39 original events, 17 were discarded at this stage. Table 8 lists these events, together with the reasons for rejecting them. Non-uniform rainfall across the catchment caused eight events to be rejected, and this was the most common reason. Two events were rejected because the derived catchment rainfall did not match the recorded flow, and another event was rejected later on in the analysis when these data gave a negative lag. A further three events were discarded because they were multi-peaked and too complex for analysis. The last three events all had suspect recording raingauge data.

The FSR unit hydrograph and losses model analysis programs first separate the flow and rainfall, and then derive a smoothed unit hydrograph by the matrix inversion method as described fully in FSR I.6.4. Each of the 22 remaining events was inspected and coded as being of quality suitable for derivation of a unit hydrograph, only suitable for assessing volumes of rainfall and flow i.e. losses only, or of poor quality and not suitable for use in the current study. For full unit hydrograph analysis, smooth single-peaked events are most likely to produce good unit hydrographs, though reasonable ones may sometimes be obtained from double or multi-peaked events. The simple unit hydrograph model may often prove to be an inadequate tool for fitting complex runoff events, where limitations on the input rainfall data often limit the fitting process. In most cases these complex events tend to produce multi-peaked unit hydrographs, making them suitable for estimation of losses only.

Table 9 contains the results of the event analysis in terms of the event details and the derived model parameters. The event details include the storm duration and depth, the peak flow and the catchment lag, and the SMD, API5 and CWI used to determine the antecedent conditions. The derived model parameters include the baseflow, the percentage runoff from which standard percentage runoff values can be abstracted, and the 1-hour unit hydrograph time-to-peak and peak flow Qp. Events where lag values and unit hydrograph parameters are absent are those designated as losses only events.

It is clear that there is some considerable variation in the derived model parameters. Baseflow values range from 1.14 m^3/s to 4.49 m^3/s, percentage runoff values from 0.7% to 7.6% with standard percentage runoff values from -1.27% to 22.26%, and 1-hour time-to-peak values from 2.0 hours to 8.0 hours. The low percentage runoff values, and the low and sometimes negative rural percentage runoff and standard percentage runoff values, though physically meaningless, serve to indicate the dominating influence of the downstream urban areas. Many of the flood peaks are clearly the products of rapid urban runoff from the Stroud conurbation, which reach the gauging station and pass before the rural runoff component has travelled downstream.

It was necessary that these events were split into a group where the flow peak was solely caused by urban runoff, and a group where the entire catchment was believed to be responding, and this was done using the catchment lags. Urban runoff events would be expected to have smaller lags than combined rural and urban runoff events. The mean catchment lag from the 22 flood events was 3.8 hours, and so the 15 events with smaller lags (including the losses only events) were designated as urban runoff events, whilst the 7 events with larger lags were assumed to be the result of runoff from the whole catchment.

This division reduces the variability in the derived model parameters. Considering the combined rural and urban runoff events first: the 1-hour time-to-peak values range from 2.5 hours to 8.0 hours with a mean of 4.6 hours, the standard percentage runoff values range from 0.38% to 9.59% with a mean of 3.67%, and the baseflow values range from 2.16m^3/s to 4.49m^3/s with a mean of 3.15m^3/s. The corresponding mean values for the urban runoff events are: 1.6 hours (some 65% lower), 9.49% (some 158% higher), and 1.57m^3/s (some 50% lower). These results are not unsurprising: urban areas tend to respond more quickly than rural areas, and to have higher runoff and lower baseflow.

Chapter 8 goes on to consider indirect estimation of model parameters through estimation of hydrological characteristics which are related to the model parameters. The results from the flood event analysis are therefore considered further in a wider context in Chapter 9.

8 Estimation of unit hydrograph and losses model parameters by indirect methods

The previous chapter described the usual, direct way of refining the no-data estimates of unit hydrograph and losses model parameters through flood event analysis. This chapter considers alternative approaches which provide indirect ways of obtaining model parameters through estimation of hydrological characteristics which are related to the model parameters, as described briefly in Chapter 4. Unit hydrograph time-to-peak is related to catchment lag LAG, and standard percentage runoff is related to baseflow index BFI.

8.1 Catchment lag analysis

Lag time is the time between the centroid of the total rainfall and the flow peak or the centroid of the flow peaks. Unit hydrograph time-to-peak Tp(0) may be derived from lag time by the equation:

$$Tp(0) = 0.604\ LAG^{1.144}$$

Though catchment lag analysis is usually restricted to situations where only stage data exist, the results of the flood event analysis for Ebley Mill provide details of catchment lags which can be utilised. The main part of this section, however, will be concerned with catchment lag analysis at the six continuous level recorder sites in the Frome catchment.

Lag analysis for Ebley Mill

The results of the flood event analysis at Ebley Mill are shown in Table 9. The event details include the catchment lag which varies, for the entire dataset, from 1.3 hours to 8.4 hours with a mean value of 3.8 hours which corresponds to a time-to-peak Tp(0) of 2.8 hours. The lag values are as variable as the derived model parameters, and indeed it was on the basis of catchment lag that the events were divided into urban runoff events (lag less than 3.8 hours) and events where the entire catchment was thought to be responding (lag greater than 3.8 hours).

This division reduced the variability in the catchment lag values. For the combined rural and urban runoff events, the lag values range from 4.0 hours to 8.4 hours with a mean of 6.1 hours which corresponds to a time-to-peak Tp(0) of 4.7 hours. The mean value for the urban runoff events is 1.5 hours which corresponds to a time-to-peak Tp(0) of 1.0 hours. These results again illustrate the point that urban areas tend to respond more quickly than rural areas.

Lag analysis for continuous level recorders

Table 4 lists the dates of the events selected for catchment lag analysis from the six continuous level recorders. These events chosen were simple, single-peaked events. Several problems were encountered during event selection. In general the record quality was poor, often characterised by apparent jumps in datum level, and by the existence of high peaks and low troughs, both of very short duration.

For each event selected, catchment average rainfalls were derived from the nearby recording and daily raingauges, as described in Chapter 7. The centroid of the rainfall and the time of the stage peak were used to calculate the lag time. However, during analysis several of the flow peaks were found to have no corresponding rainfall, rainfall recorded a day late or rainfall on the correct day but after the flow peak. Though it is acknowledged that the use of an hourly data interval for the rainfall may have reduced the accuracy slightly, there are implications of possible artificial influences or timing errors.

The record from each level recorder is considered in turn in the following sections. Overall the results were inconclusive, with none of the recorders giving particularly meaningful results. In response to concerns about possible datum errors and timing errors, NRA-ST reported that all the recording raingauge data from Avening Court, Eastington Park and Painswick Lodge prior to July 1993 were at BST rather than GMT (P. Davies, 1994; personal communication). This may well account for some, but not all, of the problems encountered; these three gauges are important because of their prominent position within the catchment. However, in view of the general poor quality of the level records, and the satisfactory results from the flood event analysis at Ebley Mill, the catchment lag analysis was not pursued further.

C1 Nailsworth Stream at Dudbridge
The record is continuous from June 1992 to September 1993. The early and late parts of the record are of reasonable quality, but the central part over the 1992-93 Winter period contains several possible datum changes. Although this record covered all the Ebley Mill flood events of 1992 and 1993, only two of these events were of good enough quality to use. Eight further events were selected, seven from 1993 and the other from 1992. The results are listed in Table 10. Four of the ten events gave lag values ranging from 0.25 hours to 2.0 hours, one event gave a lag of zero and another three gave negative lags, possibly indicating timing errors. The remaining two events had no corresponding rainfall.

C2 Stroudwater Canal at Stroud
The record runs from June 1992 to September 1993. The record is quite coarse, indicating few registered changes in water level and making event selection difficult. Again this record covered all the 1992 and 1993 events at Ebley Mill, but only three were of good enough quality to use. An additional five events were selected, four from 1993 and one from 1992. The results are listed in Table 11. Three of the eight events produced lag values ranging from 0.67 hours to 1.5 hours, one event had a lag of zero and three events gave negative lags, again possibly indicating timing errors. The remaining event had no corresponding rainfall.

C3a River Frome at Bowbridge Lock
The record runs from June 1992 to January 1993 when the recorder was moved to Thrupp, a little upstream. However, after mid-September 1992 the record becomes characterised by spikes of constant height and large changes in datum. Of the record prior to this, apart from a single spike comparable with the later ones, the peaks never exceed 44.1m, and this casts doubt on the reliability of the early part of the record as well. Only the minimum of six events were selected, and the results are listed in Table 12. Of these only one gave a lag value, of 3.0 hours. The other five events were characterised by post-event rainfall and even rainfall the next day, but in view of the record quality these results are not surprising.

C3b River Frome at Thrupp
The record is continuous from April 1993, when the recorder was moved from Bowbridge Lock, to September 1993. The record has a lot of high and low spikes, and many of the events were multi-peaked, making selection of single-peaked events difficult. The record does cover all the events in 1993 selected for flood event analysis at Ebley Mill, but none of them were of adequate quality to use. The general quality of the record prevented other events from being selected.

C4 River Frome at Golden Valley
The record runs from June to September 1993, covering less than 3 months. Most of the record appears to be on a recession, making it difficult to select events. Only one of the 1993 flood events at Ebley Mill was contained in this period, and it was not of adequate quality to use. Further event selection was restricted by the quality and length of the record.

C5 Nailsworth Stream at Egypt Mill
The record is continuous from May to September 1993, covering 4 months. Particular problematic features are deep troughs which frequently occur

immediately before peaks, making the peaks unusable. Five of the 1993 Ebley Mill events were contained in this record, though only one was of a good enough quality to use. However, a further five events were eventually selected, and the results are listed in Table 13. Two of the events gave positive lags, of 0.5 hours and 1.25 hours, one had zero lag, two had negative lags, and the remaining event had no corresponding rainfall.

C6 Painswick Stream at Stroud

This was another 4 month record, continuous from May to September 1993. This level recorder had the best record of the six with few spikes, no obvious datum errors and smooth peaks and troughs of variable stages, usually rising sharply with gentle recessions. Five of the 1993 events selected for flood event analysis at Ebley Mill were present; three were usable and a further three were selected to make the total up to the minimum of six. The results are listed in Table 14. Three of the events gave lag values ranging from 0.5 hours to 2.5 hours, one event gave a negative lag, possibly indicating a timing error, and the remaining two events had no corresponding rainfall.

8.2 Estimation of standard percentage runoff through baseflow index

Standard percentage runoff is related to baseflow index BFI. BFI is the ratio of the baseflow to the total flow in the observed flow hydrograph. Standard percentage runoff may be derived from BFI by the equation:

$$SPR = 72.0 - 66.5\ BFI$$

There are two sources of BFI information available for input into the above equation. The Hydrometric Register and Statistics 1986-90 contains BFI values for many catchments, Reference 16. The published value for the Frome at Ebley Mill is 0.86, which yields a standard percentage runoff of 15%. The other source is provided from the results of recent MAFF-funded research to develop a more detailed classification of soil types, known as HOST (Hydrology Of Soil Types), Reference 17. The ultimate aim is to replace the 5-class WRAP map. Interpretation for percentage runoff estimation has yet to be finalised, but Boorman has supplied details of the HOST classes covering the Frome catchment together with provisional estimates of BFI applicable to each class. A recent revision of the HOST system has renumbered many of the classes, and so the class numbers are omitted from this report to ensure that they cannot be misapplied in the period until the HOST system is fully launched. The derived BFI is 0.73, which yields a standard percentage runoff of 23%, some 50% higher than the estimate obtained from the published value of BFI.

The next chapter considers the results from this chapter, together with the flood event analysis results from Chapter 7, in order to come up with the best estimates of the unit hydrograph and losses model parameters at Ebley Mill.

9 Discussion

This chapter brings together the results from the flood event analysis at Ebley Mill, described in Chapter 7, and the results from the alternative approaches to unit hydrograph and losses model parameter estimation, described in Chapter 8. These values are compared with the no-data values derived from catchment characteristics using regression equations. Table 15 shows the results for Ebley Mill from the various methods in tabular form.

Considering time-to-peak Tp(0) first, the flood event analysis and catchment lag analysis give very similar results to each other, but very different results from the no-data estimate. The 'observed' time-to-peak for the combined rural and urban components of the catchment is around 44% lower than the value derived from catchment characteristics.

For the standard percentage runoff, the values obtained from the SOIL equation and from the published value of BFI agree well, but the value obtained from BFI derived from HOST is around 60% higher. However, the results from the flood event analysis suggest that the 'observed' standard percentage runoff is in fact lower than that derived from catchment characteristics; for the combined rural and urban components of the catchment some 75% lower which is an enormous correction. These results are in line with Gurnell & Midgley, Reference 18, who state the requirement for a standard percentage runoff of less than 10% for WRAP class 1-dominated catchments in southern England.

A similar pattern of results are obtained for the baseflow. The catchment characteristic method again overestimates the 'observed' catchment baseflow, by a little over 30%.

Following considerable debate on the accuracy of the various FSR methods, a study was undertaken to investigate the performance of the rainfall-runoff method by comparison of observed and modelled flood frequency curves, Reference 11. The rainfall-runoff method with model parameters estimated from catchment characteristics has a tendency to overestimate, particularly on WRAP class 1 catchments, as was most clearly illustrated in Figure 5. The results obtained from the analyses carried out for this study show that the no-data estimates of the model parameters are somewhat erroneous, and serve to illustrate the importance of incorporating local data whenever possible.

At this point it is also convenient to discuss a concern raised by NRA-ST regarding the effects of heavy rainfall and/or snow melt if the catchment were frozen. The concerns seem unfounded if observations by Gurnell & Midgley, Reference 18, are considered; they were worried that on their WRAP class 1 catchment, runoff might occur before thawing made the surface permeable enough to accept the rainfall, but evidence from an observed event suggested that the runoff was still substantially less than 10%

10 Derivation of model parameters

The objective of the hydrological study was to provide inflows to the hydraulic model. These inflows would be either from observed events for the purposes of model calibration, or from design events for the flood plain mapping study.

The limits of the hydraulic model divided the Frome catchment naturally into six subcatchments: Upper Frome, Toadsmoor Brook, Slad Brook, Painswick Stream, Randwick Stream and Nailsworth Stream, as illustrated in the schematic plan in Figure 8. The remaining four areas were modelled as diffuse lateral inflows, with their hydrographs based on that from Nailsworth Stream, considered the most similar from the six mentioned above. The catchment characteristics abstracted for each of the six subcatchments are listed in Table 16, together with the characteristics for the Frome catchment to its outfall at the River Severn.

Table 17 lists the no-data estimates of the unit hydrograph and losses model parameters for Ebley Mill, the six subcatchments and the catchment to the Severn. The "observed" values for Ebley Mill are also included. Refinement of model parameter values using data from nearby sites is done by simply applying the ratio of the observed value to the no-data estimate of the value at the gauged site to the no-data estimate at the ungauged site.

For the Upper Frome, Toadsmoor Brook, Painswick Stream and Randwick Stream this was a straightforward procedure. These four subcatchments were regarded as having combined rural and urban responses. The appropriate ratios related the observed parameter values for the entire Ebley Mill catchment to the no-data parameter values. For example for time-to-peak the ratio is:

$Tp(0)obs_{rural/urban}$ / $Tp(0)\ ccs$

which works out as 0.56 (i.e. $Tp(0)obs_{rural/urban}$ of 4.1 hours / Tp(0)ccs of 7.3 hours). Corresponding ratios were applied for standard percentage runoff and baseflow, and the "observed" values for the subcatchments are also listed in Table 17.

For the Slad Brook and the Nailsworth Stream the situation was more complicated. These two subcatchments each had a fairly large rural area with an urban area concentrated at the outfall, and it was felt necessary to model the rural response and the urban response separately. The subcatchments were split into rural areas and urban areas, each with appropriate urban fractions, as shown in Table 18. The rural part of each catchment was modelled as above for the other four subcatchments. The urban part was modelled in the same way but applying the appropriate urban ratio, except for time-to-peak where the value was fixed at 1.0 hours. For example for standard percentage runoff the ratio is:

$SPRobs_{urban}$ / SPRccs

which works out as 0.66 (i.e. $SPRobs_{urban}$ of 9.5% / SPRccs of 14.3%). Fixing the time-to-peak values at 1.0 hours was forced by the requirement for a sub-hourly data interval for some of the smaller subcatchments. After consideration of the various catchment sizes and response times and the "working" data interval of 1 hour, a compromise of 0.5 hours was reached for the remainder of the modelling. The two hydrographs produced for each subcatchment were added together to give total catchment hydrograph.

The four diffuse lateral inflows were modelled from the rural and urban hydrographs for Nailsworth Stream. Table 18 indicates the rural and urban areas in each of these catchments, and the multiplying factors listed in Table 19 are simply the ratios of the corresponding areas. For example the Lower Frome has 23.44/45.83 times the rural hydrograph for the Nailsworth Stream, and 4.96/2.27 times the urban hydrograph for the Nailsworth Stream. Again the two hydrographs produced for each subcatchment were added together to give the total catchment hydrograph.

11 Derivation of event inflows

The previous chapter described finalisation of the unit hydrograph and losses model parameters for each of the six subcatchments, and the way in which inflows for each of the diffuse lateral inflow subcatchments were to be derived. Inflow events were derived for calibration of the hydraulic model, and for the ultimate objective of the study to determine flood plain limits for various return period design flood events. This chapter describes the derivation of the calibration and design event inflow hydrographs, which were then used for input to the RIBAMAN routing model in order to assess their suitability.

11.1 Calibration events

Three events were chosen for the purposes of calibrating the hydrological and hydraulic models, as described in Chapter 2. Catchment average rainfalls were derived for the entire catchment to the Severn, for each of the events, as described in Chapter 7. The daily rainfall data for the 5 days preceding the start of each event were analysed to give the catchment average API5, and this was combined with the observed catchment SMD to give the observed pre-event CWI. Table 20 lists the storm details and antecedent conditions for each event.

These storm and antecedent inputs were combined with the unit hydrograph and losses models for each of the six subcatchments to produce the calibration event inflows. The four diffuse lateral inflows were derived as described in Chapter 10. Figures 9, 10 and 11 show the ten inflows for each of the calibration events.

11.2 Design events

Design flood estimates for return periods of 5, 10, 25, 50, 100 and 150 years were required to fulfil the model study objectives. The conventional FSR package of design inputs was assumed i.e. a design CWI (related to SAAR), a T-year design rainfall depth (where T is the return period), a bell-shaped temporal storm profile (the 75% Winter profile), and the standard FSR rainfall statistics. The storm duration was estimated from time-to-peak and again SAAR. The design inputs were derived for the entire catchment to the Severn, and the storm details and antecedent conditions for each event are listed in Table 21. It can be seen that the only variable is the rainfall depth; the storm duration and profile and the CWI remain fixed.

In the same way as for the calibration events, these storm and antecedent inputs were combined with the unit hydrograph and losses models for each of the six subcatchments to produce the design event inflows, and the four diffuse lateral inflows were derived as described earlier.

12 RIBAMAN modelling

In order to verify the predicted inflows a simplified routing model of the River Frome was built using the HR RIBAMAN software. This model was used to check hydrograph shape and peak flow predicted at Ebley Mill gauging station.

12.1 Model construction

The model extended from the upstream model boundary at Whitehall Bridge on the River Frome, and from Egypt Mill on the Nailsworth Stream, to the Ebley Mill gauging station. A stretch of the Dudbridge relief channel was also included. The model consisted of almost 70 nodes, and the schematisation of this is shown in Figures 12, 13 and 14. Five types of unit were used in the model, and these and the data required for them are outlined below in more detail.

Non-routing reach
Non-routing reaches are used to transfer a flood hydrograph from one model node to another without imposing any attenuation or delay, so that the outflow hydrograph is identical to the inflow hydrograph. They are generally used as a means of combining hydrographs from different branches of the model.

Routing reach
A hydrograph input to the upstream end of a routing reach is routed downstream using the variable parameter Muskingham-Cunge method. The method requires information on the reach length, kinematic wave speed and attenuation parameter. The last two of these can be derived by the package from a representation of channel and floodplain geometry given to RIBAMAN, and this was the method used for the Frome model. Average channel properties for each of the routing reaches were derived from a consideration of the available section data for the reach, and these were then input into RIBAMAN.

On-line storage ponds, off-line storage ponds, diversions
These last three reach types can all be considered as similar in terms of the data required by the package. Though strictly intended to model storage ponds, they can also be used to model structures, either directly as a weir or a sluice, or using a rating curve. For the purposes of modelling the flow splits and structures in the Frome model, data on each structure to be modelled was input into a spreadsheet and a rating for each derived using standard flow equations. Values for the coefficients of discharge for these equations were derived from an inspection of the structures and experience in other studies of likely values for them. These ratings were then applied within the model to represent the structures.

12.2 Model verification

The purpose of the RIBAMAN model was to assess the output hydrographs from the FSR models of the Frome catchment, prior to modelling them within the hydraulic model. As such, the RIBAMAN model could only provide an indication of the validity of the FSR results, since the routing model and the full hydrodynamic model are unlikely to behave identically. A simplified approach to the model verification was therefore adopted. This was based on adjusting RIBAMAN model parameters within acceptable limits, and comparing the predicted and recorded hydrographs at Ebley Mill.

Two events were used for this purpose, the May 1979 and the January 1994. The December 1965 event was not used since no estimate of flows at Ebley Mill was available. The parameters adjusted were the coefficient of discharge used in the calculation of the structure and diversion ratings (Cd), and the wave speed curves for the routing reaches (c). No adjustment was made to the attenuation parameter since the method is relatively insensitive to changes in this, Reference 19. The adjustments made were an arbitrary ± 20% for both of these parameters, so that four tests were run for each event in addition to that with the default reach parameters. The results of these tests are shown in Figures 15 and 16.

From the results of these tests it can be seen that the default set of parameters, indicated by the green line on the two plots, gives a peak flow at Ebley Mill which is around 4 m^3/s higher than that observed for the May 1979 event. This translates as an error of c.20% For the 1994 event, the error is smaller, being c.17%. It can also be seen that the routing model is insensitive to changes in the wave speed curve, but significant changes in the peak discharge are obtained by modifying the discharge coefficient. The lack of sensitivity to wave speed is thought primarily to be a function of the steepness of the river.

The other main feature of the performance of the FSR and RIBAMAN models is the inability to predict the raised baseflow component of the hydrograph which occurs after the peak of the event has passed. This is presumably a function of water entering into storage unrepresented in either model, in particular groundwater.

Despite reservations over the quality of the hydrological inflows predicted it was decided, in consultation with NRA-ST, to use these inflows in the hydraulic model. The main reason for this was that the total inflow produced a reasonable estimate of peak discharge at Ebley Mill, and that this was conservative in terms of the peak flow. In particular it was anticipated that the full hydrodynamic model, which models floodplain storage and performance of structures more accurately, would produce a further reduction in the peak flow at Ebley, possibly also associated with an increase in the length of time the hydrograph took to peak. This was subsequently proved to be the case.

12.3 Design events

It was originally proposed to use the RIBAMAN model to produce an estimate of the peak flows for each of the design events at Ebley prior to modelling them with the full hydrodynamic model. However, due to the relative timings of the hydrological and hydraulic phases of the study, it was decided to run these events only on the full hydrodynamic model, due to the perceived greater accuracy attributable to the results from this model. As such, they were not simulated on the routing model.

Chapter 6 describes the flood frequency analyses performed for Ebley Mill gauging station. In Figure 5, the EV1 flood frequency curve from 24 years of observed data was compared with the curves derived from various FSR methods. However, the EV1 curve may not represent the long-term behaviour of the catchment because it does not contain the large floods reported in the 1950s and 1960s, before the gauging station was installed. Figure 6 shows the EV2 curve fitted to an extended annual maxima series which contains the estimated peak value for large flood of 1968, and the shape of the curve is strongly influenced by the 1968 peak. Assuming that the estimate of the 1968 flood peak is realistic, and that the 1968 flood peak is typical of some of the pre-1969 flood magnitudes, then the FSR flood frequency curves derived from the observed mean annual flood and the region 4 growth curve may be a better representation of the behaviour of the catchment than the EV1 curve derived from 24 years of observed data.

Following derivation of the design event inflows for each of the Frome subcatchments, and routing of these combined flow hydrographs down to Ebley Mill, a flood frequency curve was drawn up from the flood peaks generated at Ebley Mill gauging station. This curve is shown on Figure 17, together with the EV1 curve from 24 years of annual maxima, the EV2 curve from 26 years of annual maxima, and the "best estimate" curve derived using the Ebley Mill unit hydrograph and losses model parameters presented in Table 17. Also shown is the curve derived from the observed mean annual flood and the region 4 growth curve.

The EV1 curve has the flattest line, whilst the curve from the unit hydrograph and losses model has the steepest line. The line for the mean annual flood and region 4 growth curve is slightly beneath the EV2 curve; there is good agreement on curve shape, but the position of EV2 curve implies a slightly higher mean annual flood. The curve from the routed flows fits between the curve from the unit hydrograph and losses model, and the EV2 curve. The routed flows produce a less steep curve than direct use of the unit hydrograph and losses model does, because of the attenuation effects associated with the routing. However, the steepness of the curve from the routed flows compared to the EV2 curve and the curve from the mean annual flood and region 4 growth curve needs resolving.

Also shown on Figure 17 is the curve from the mean annual flood and region 6/7 growth curve, and this corresponds more closely with the curve from the routed flows; the agreement on curve shape is reasonable, but the position of the curve from routed flows implies a higher index flood. Regional growth curves represent the average behaviour of catchments within that particular region, and it is appropriate to use the region 6/7 growth curve because the Frome catchment is right on the boundary of regions 4 and region 6, and it might be that the properties of the Frome catchment are more similar to catchments in region 6 than to catchments in region 4. FSSR14 also states that regions 4 to 8 show increasingly similar behaviour with increasing return period, and identifies these regions as together comprising a major region.

Several conclusions can therefore be drawn from this. Firstly, the 24 years of observed flow data, from which the EV1 curve was derived, appear to be not wholly representative of the catchment. Inclusion of the estimated 1968 flood peak caused the curve to steepen, and if the 1968 flood is typical of large floods on the catchment, then the derived EV2 curve may be a better representation of the true flood frequency curve of the catchment. The EV2 curve corresponds fairly closely with the FSR curve derived from the observed mean annual flood and the region 4 growth curve. The curve derived from the routed flows has a higher mean annual flood, but otherwise is of similar shape to the EV2 curve. This would be expected if large floods are missing from the observed record from which the mean annual flood was derived. The curve from the routed flows corresponds fairly closely, particularly at higher return periods, with the FSR curve derived from the observed mean annual flood and the region 6/7 growth curve. This suggests that the Frome catchment may be more like catchments in the neighbouring Thames basin, than catchments in the rest of the Severn region in its behaviour.

In summary, a fairly narrow band can be defined which indicates the most likely position of the true flood frequency curve for the Frome at Ebley Mill. This band has a width of about 3 m^3/s at the low (5-year) return period end, and widens to about 8 m^3/s at 150-years return period. This band is higher than the flood frequency curve derived from 24 years of observed data, which is thought to be lacking some large floods, such as those reported in the 1950s and 1960s before the gauging station was installed. The flood frequency curve derived from the routed design events forms the upper limit of the band, hence errs on the conservative side. Further data collection and analysis may be able to narrow this band.

13 Conclusions

This review of the hydrology of the Frome catchment has made use of all available data to develop the best possible estimates of the design flood inflows required by the hydraulic model. The FSR rainfall-runoff method, whereby rainfall is converted to flow using the unit hydrograph and losses model of catchment response, was used for the hydrological modelling because it synthesises the entire flow hydrograph, which is required in cases such as this, where flood routing is involved.

The three model parameters are related via multiple regression equations to physical and climatic characteristics of the catchment, enabling flood estimates to be made at ungauged sites. However, the FSR recommends that where possible such no-data estimates are refined using observed data from, or near to, the site of interest, and the current study considered various ways of doing this.

Firstly, the model parameters for the catchment to Ebley Mill were estimated directly by analysis of observed flood events. The derived model parameters showed considerable variation, indicating the dominating influence of the downstream urban areas, and making it necessary to divide the flood events into a group where the flow peak was caused by urban runoff, and a group where the entire catchment was believed to be responding. This separation was done on the basis of mean catchment lag time, and reduced the variability in the derived model parameters. The unit hydrograph time-to-peak was some 44% lower than the value estimated from catchment characteristics, whilst the standard percentage runoff was some 75% lower than the value derived from catchment characteristics. Similarly the catchment characteristics method overestimated the baseflow by around 30%

In another approach, hydrological characteristics which are related to the model parameters were estimated. The catchment lag analysis at Ebley Mill gave time-to-peak values which agreed closely with those derived by flood event analysis. Lag analysis from the continuous level recorders in the catchment gave inconclusive results. Standard percentage runoff derived from BFI was similar to the value derived from catchment characteristics, whilst the value derived from the new HOST classification was some 60% higher.

The model parameter values derived from the rainfall-runoff analysis were taken as the best estimate of the true values for the Frome catchment. This information was transferred to the each of the six subcatchments making up the Frome catchment by simply applying the ratio of the observed value to the no-data estimate of the value at Ebley Mill to the no-data estimate for the particular subcatchment. This was straightforward for four of the subcatchments, where the observed value used was that from the events showing a combined rural and urban response, but more complicated for the Slad Brook and Nailsworth Stream which both have a fairly large rural area with an urban area concentrated at the catchment outfall. For these catchments it was necessary to model the rural and urban responses separately, with the rural parts modelled in the same way as for the other four subcatchments, and the urban parts modelled in the corresponding way, but where the observed value used was that from the events resulting solely from urban runoff. Four remaining areas were modelled as diffuse lateral inflows, with their hydrographs modelled on those for the Nailsworth Stream subcatchment.

Inflow hydrographs were derived for calibration of the hydraulic model, and for the ultimate objective of the study to determine flood plain limits for various return period design flood events. The predicted calibration event inflow hydrographs were verified using a RIBAMAN routing model of the River Frome, and checking the shapes and peak flows of the routed hydrographs at Ebley Mill. The main feature apparent from the routing was the inability of the FSR model to simulate the raised baseflow component of the hydrograph which occurs after the event has passed. This baseflow is interpreted as water entering into storage unrepresented in the model e.g. groundwater. However, the routed inflows produced reasonable estimates of peak discharge at Ebley Mill, which were conservative in terms of the peak flow.

The full hydrodynamic model, which models flood plain storage and performance of structures more accurately, produced a further reduction in peak flow at Ebley Mill, possibly also associated with an increase in the length of time the hydrograph took to peak. The design events were run only with the full hydrodynamic model, due to the greater perceived accuracy attributable to the results from this model.

The 24 years of observed flow data at Ebley Mill appear to be not wholly representative of the catchment as the record does not contain any of the major floods reported in the 1950s and 1960s before the gauging station was installed. The flood frequency curve fitted to the annual maxima steepens significantly, from EV1 to EV2, when the estimated 1968 flood peak is included. If the 1968 flood is typical of large floods on the catchment, then this EV2 curve may be a better representation of the true flood frequency curve of the catchment. The flood frequency curve derived from the routed design events has a higher mean annual flood, but otherwise is of similar gradient to the EV2 curve. This would be expected if large floods are missing from the observed record from which the mean annual flood was derived.

A fairly narrow band can be defined which indicates the most likely position of the true flood frequency curve for the Frome at Ebley Mill. This band has a width of about 3 m^3/s at the low (5-year) return period end, and widens to about 8 m^3/s at 150-years return period. The flood frequency curve derived from the routed flows forms the upper limit of this band, and it may be possible to narrow the band by further data collection and analysis.

14 References

1 Natural Environment Research Council 1975. Flood Studies Report. NERC, London.

2 Institute of Hydrology 1977-1988. Flood Studies Supplementary Reports 1-18. Wallingford.

3 Bailey, R.P. 1991. An investigation into the water resources of the River Frome near Stroud. MSc dissertation.

4 Shaw, E.M. 1993. Hydrology in Practice (3rd edition). Van Nostrand Reinhold (International) Co. Ltd., London.

5 Wilson, E.M. 1990. Engineering Hydrology (4th edition). Macmillan, London.

6 Gustard, A., Bullock, A. & Dixon, J.M. 1992. Low flow estimation in the United Kingdom. Institute of Hydrology Report No. 108, Wallingford.

7 Institute of Hydrology 1991. Hydrological Frequency Analysis Package (HYFAP) Operation Manual. Wallingford.

8 Gumbel, E.J. 1941. The return period of flood flows. Annals of Mathematical Statistics 12(2), 163-190.

9 Jenkinson, A.F. 1955. The frequency distribution of the annual maximum (or minimum) of meteorological elements. Quart. J. Roy. Met. Soc. 81, 158-171.

10 Greenwood, J.A., Landwehr, J.M., Matalas, N.C. & Wallis, J.R. 1979. Probability-weighted moments: definition and relation to parameters of distributions expressible in inverse form. Wat. Res. Res. 15(5), 1049-1054.

11 Boorman, D.B., Acreman, M.C. & Packman, J.C. 1990. A review of design flood estimation using the FSR rainfall-runoff method. Institute of Hydrology Report No. 111, Wallingford.

12 Hosking, J.R.M., Wallis, J.R. & Wood, E.F. 1985. Estimation of the generalised extreme value distribution by the method of probability-weighted moments. Technometrics 27(3), 251-261.

13 Naden, P.S. & McCartney, M.P. 1991. Direct estimation of flood depth. Report to MAFF, Institute of Hydrology, Wallingford.

14 Institute of Hydrology 1992. Micro-FSR Operation Manual. Wallingford.

15 Jones, S.B. 1983. The estimation of catchment average point rainfall profiles. Institute of Hydrology Report No. 87, Wallingford.

16 Institute of Hydrology / British Geological Survey 1993. Hydrometric Register and Statistics 1986-90. Wallingford.

17 Boorman. D.B., Hollis, J. & Lilly, A. 1991. The production of the Hydrology Of Soil Types (HOST) dataset. BHS 3rd Nat. Hydrol. Symp., Southampton, 6.7-6.13.

18 Gurnell, A.M. & Midgley, P. 1987. Refining the estimation of percentage runoff in catchments with extreme hydrogeological conditions. BHS 1st Nat. Hydrol. Symp., Hull, 3.1-3.12.

19 Hydraulics Research Ltd 1987. RBM-DOGGS User Manual. Wallingford.

Tables

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Table 1 Definition of catchment characteristics

Catchment Characteristic	Units	Description
AREA	km^2	Catchment area
STMFRQ	junctions km^{-2}	Stream frequency i.e. number of natural stream junctions per km^2 catchment area
MSL	km	Mainstream length
S1085	m km^{-1}	10-85% channel slope
LAKE	-	Lake index i.e. fraction of catchment draining through a significant lake/reservoir
URBAN	-	Urban index i.e. fraction of catchment in urban development
SOIL	-	Soil index i.e. the weighted sum of the individual soil class fractions SOIL1 to SOIL5 from WRAP (Winter Rainfall Acceptance Potential) map.
SAAR	mm	Standard annual average rainfall for period 1941-70
RSMD	mm	1-day catchment rainfall of 5-year return period less effective mean soil moisture deficit
M5-2D	mm	2-day rainfall of 5-year return period
r	-	Jenkinson's r i.e. the ratio of M5-60min to M5-2D
SMDBAR	mm	Effective mean soil moisture deficit

Table 2 Events selected for flood event analysis with recording raingauge availability

Event date	Recording raingauges							
	Miserden	Dowdeswell	Longford	Netheridge	Kingswood	Painswick	Eastington	Avening
30 May 1979					Y			
28 Dec 1979					Y			
24 Mar 1986		Y						
02 Apr 1986		Y						
28 May 1986		Y						
30 Jul 1986		Y						
25 Aug 1986		Y						
13 Sep 1986		Y						
20 Oct 1986		Y						
04 Apr 1987		Y						
05 Jun 1987		Y						
08 Jun 1987		Y						
19 Jun 1987		Y						
22 Aug 1987		Y						
12 Sep 1987								
19 Nov 1987		Y						
30 Dec 1987		Y						
18 Aug 1988	Y	Y	Y	Y	Y			

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Table 2 Continued

Event date	Recording raingauges							
	Miserden	Dowdeswell	Longford	Netheridge	Kingswood	Painswick	Eastington	Avening
01 Sep 1988	Y	Y	Y	Y				
16 Sep 1988	Y	Y	Y	Y	Y			
18 Oct 1988	Y	Y	Y	Y	Y			
06 Mar 1988	Y	Y	Y	Y	Y			
23 May 1989		Y	Y	Y	Y			
24 May 1989		Y	Y	Y	Y			
07 Jul 1989	Y	Y	Y	Y	Y			
16 Sep 1989	Y	Y	Y	Y	Y			
08 Nov 1989	Y	Y	Y	Y	Y			
21 Jun 1990	Y	Y	Y		Y			
30 Sep 1990	Y	Y	Y	Y	Y			
30 Apr 1991	Y	Y	Y	Y	Y			
31 Jul 1991	Y	Y	Y	Y	Y			
01 Jun 1992	Y	Y	Y		Y			
03 Apr 1993	Y	Y	Y		Y			
05 Apr 1993	Y	Y	Y		Y			
10 May 1993	Y	Y	Y		Y			
26 May 1993	Y	Y	Y		Y			
11 Jun 1993	Y	Y	Y		Y	Y		Y
14 Jun 1993	Y	Y	Y		Y	Y		Y
09 Jul 1993	Y	Y	Y		Y	Y	Y	Y

Table 3 Details of continuous level recorders

Continuous level recorders	Reference	Record start	Recording raingauges							
			Miserden	Dowdeswell	Longford	Netheridge	Kingswood	Painswick	Eastington	Avening
Nailsworth Stream at Dudbridge	C1	June 1992	Y							Y
Stroudwater Canal at Stroud	C2	June 1992	Y		Y					
River Frome at Bowbridge Lock	C3a	June 1992 - Jan 1993	Y					Y		
River Frome at Thrupp	C3b	April 1993	Y							
River Frome at Golden Valley	C4	June 1993	Y				Y			Y
Nailsworth Stream at Egypt Mill	C5	May 1993								
Painswick Stream at Stroud	C6	May 1993	Y					Y		

Table 4 Events selected for catchment lag analysis with recording raingauge availability

Event date	Continuous level recorders											
	C1	C2	C3a	C3b	C4	C5	C6	Miserden	Longford	Kingswood	Painswick	Avening
26 Jun 1992	Y							Y		Y		
29 Jun 1992			Y					Y	Y			
01 Jul 1992		Y						Y	Y	Y		
20/21 Jul 1992		Y	Y					Y	Y	Y		
26 Jul 1992	Y							Y	Y	Y		
08 Aug 1992			Y					Y	Y			
21 Aug 1992			Y					Y	Y			
31 Aug 1992			Y					Y	Y			
16 Sep 1992			Y					Y	Y			
05 Apr 1993	Y							Y		Y		
12 Apr 1993	Y							Y		Y		
9/10 May 1993	Y	Y						Y	Y	Y		
26 May 1993							Y	Y				
10 Jun 1993		Y					Y	Y	Y	Y	Y	Y
11 Jun 1993	Y						Y	Y	Y	Y	Y	Y
14 Jun 1993	Y	Y				Y	Y	Y	Y	Y	Y	Y
09 Jul 1993	Y	Y					Y	Y	Y	Y	Y	Y
19 Jul 1993	Y	Y				Y	Y	Y	Y	Y	Y	Y
30 Jul 1993	Y	Y					Y	Y	Y	Y	Y	Y

Table 4 Continued

Event date	Continuous level recorders												
	C1	C2	C3a	C3b	C4	C5	C6	Miserden	Longford	Kingswood	Painswic k	Avening
22 Aug 1993						Y		Y		Y		Y
03 Sep 1993							Y	Y		Y	Y	
08 Sep						Y		Y		Y		Y
08 Sep 1993						Y		Y		Y		Y
09 Sep 1993						Y		Y		Y		Y

Table 5 Calibration events with recording raingauge availability

Date of peak	Recording raingauges								
	Miserden	Dowdeswell	Longford	Netheridge	Kingswood	Painswick	Eastington	Avening	Pershore
18 Dec 1965									Y
30 May 1979					Y				
05 Jan 1994	Y	Y	Y		Y	Y		Y	

Table 6 Catchment characteristics for Ebley Mill and continuous level recorders

Catchment characteristic	Ebley Mill	C1	C2	C3a	C3b	C4	C5	C6
AREA (km^2)	198.0	62.6	48.7	79.5	78.4	56.4	48.1	31.0
STMFRQ (Junctions km^{-2})	1.54	-	-	-	-	-	-	-
MSL (km)	27.29	12.32	11.70	21.96	21.26	15.27	6.38	11.70
S1085 (m km^{-1})	6.0	6.7	11.6	6.0	7.0	8.0	9.8	11.6
LAKE	0.004	-	-	-	-	-	-	-
URBAN	0.092	0.087	0.080	0.063	0.061	0.024	0.063	0.058
SOIL	0.19	0.22	0.15	0.20	0.19	0.19	0.24	0.15
SAAR (mm)	851	838	880	845	844	846	834	889
RSMD (mm)	29.1	-	-	-	-	-	-	-
M5-2D (mm)	52.8	-	-	-	-	-	-	-
r	0.357	-	-	-	-	-	-	-
SMDBAR (mm)	9.97	-	-	-	-	-	-	-

Table 7 Ebley Mill annual maxima

Year	Peak flow (m^3/s)
1969	7.000
1970	13.350
1971	8.600
1972	13.034
1973	11.893
1974	9.122
1975	10.523
19786	10.857
1977	8.426
1978	19.358
1979	17.500
1980	8.000
1981	10.857
1982	13.495
1983	12.387
1984	10.000
1985	12.002
1986	10.750
1987	11.784
1988	7.300
1989	12.892
1990	5.271
1991	8.717
1992	14.926

Table 8 Events rejected from flood event analysis

Event date	Reason for rejection
02 Apr 1986	Non-uniform rainfall
28 May 1986	Non-uniform rainfall
19 Jun 1987	Complex event
22 Aug 1987	Rainfall does not match flow
12 Sep 1987	No recording raingauge data
18 Aug 1988	Non-uniform rainfall
16 Sep 1988	Rainfall does not match flow
06 Mar 1989	Non-uniform rainfall
23 May 1989	Non-uniform rainfall
24 May 1989	Non-uniform rainfall
07 Jul 1989	Non-uniform rainfall
16 Sep 1989	Complex event
29 Sep 1990	Complex event
01 Jul 1992	Negative lag
11 Jun 1993	Zero lag/suspect recording raingauge data
14 Jun 1993	Non-uniform rainfall/suspect recording raingauge data
09 Jul 1993	Suspect recording raingauge data

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Table 9 Results of flood event analysis

Event date	Rainfall depth mm	Storm duration hr	Peak flow m^3s^{-1}	LAG hr	ANSF m^3s^{-1}	SMD mm	API 5 mm	CWI mm	PR %	PR_{RURAL} %	DPR_{RAIN} %	DPR_{CWI} %	SPR %	Tp(1) hr	Qp m^3/s	Urban event
May 79	39.4	12	19.18	5.8	4.34	2.9	5.7	127.8	7.6	5.83	0.00	0.55	5.13	4.5	32	N
Dec 79	59.2	23	16.99	8.4	2.16	0.0	2.2	127.2	6.3	4.49	3.56	0.28	0.38	3.5	29	N
Mar 86	15.3	8	4.52	4.0	3.02	6.0	2.5	121.5	2.3	0.38	0.00	-0.88	1.25	3.5	28	N
Jul 86	15.5	13	3.56	-	2.17	91.8	4.3	35.4	1.8	-0.14	0.00	-22.40	22.26	-	-	Y
Aug 86	42.5	12	7.25	-	1.50	73.2	2.9	54.7	2.4	0.48	0.86	-17.58	17.20	-	-	Y
Sep 86	17.9	11	2.35	1.3	1.40	59.2	0.3	66.1	0.7	-1.27	0.00	-14.73	13.46	2.0	66	Y
Oct 86	22.8	6	3.51	1.8	1.25	76.4	2.9	51.5	0.9	-1.06	0.00	-18.38	17.31	2.0	66	Y
Apr 87	26.0	15	9.31	6.5	4.49	0.0	3.1	128.1	4.7	2.85	0.00	0.78	2.07	5.5	27	N
Jun 87	23.9	8	4.82	-	2.29	60.7	6.9	71.2	1.7	-0.24	0.00	-13.45	13.21	-	-	Y
Jun 87	12.9	11	3.23	5.3	2.19	46.6	7.7	86.1	1.8	-0.14	0.00	-9.73	9.59	5.0	25	N
Nov 87	29.0	11	10.75	5.7	3.78	0.2	1.3	126.1	5.4	3.57	0.00	0.70	3.29	8.0	33	N
Dec 87	8.3	3	4.06	2.4	3.00	0.0	6.2	131.2	2.2	0.28	0.00	1.55	-1.27	3.0	42	Y
Aug 88	21.1	9	3.10	2.8	1.29	66.5	7.6	66.1	1.2	-0.75	0.00	-14.73	13.97	2.0	46	Y
Oct 88	21.3	7	5.04	-	1.83	35.7	2.7	92.0	1.8	-0.14	0.00	-8.25	8.11	-	-	Y
Nov 89	28.0	17	4.75	3.0	1.54	57.7	1.2	68.5	2.4	0.48	0.00	-14.13	14.61	3.0	30	Y
Jun 90	14.2	9	2.51	3.1	1.14	95.8	5.4	34.6	1.3	-0.65	0.00	-22.60	21.95	2.0	40	Y
Apr 91	30.4	26	3.52	6.8	2.10	19.0	0.9	106.9	1.4	-0.55	0.00	4.53	3.98	2.5	27	N
Jul 91	24.5	9	3.44	2.6	1.32	46.3	0.8	79.5	1.1	-0.86	0.00	-11.38	10.52	3.0	54	Y
Apr 93	12.6	8	2.76	2.9	1.95	13.9	3.8	114.9	0.9	-1.06	0.00	-2.53	1.46	3.0	40	Y
Apr 93	15.0	7	3.95	2.3	2.07	5.8	6.7	125.9	1.5	-0.44	0.00	0.23	-0.67	3.0	40	Y
May 93	10.7	5	3.33	1.7	2.01	27.0	2.8	100.8	1.0	-0.96	0.00	-6.05	5.09	2.5	60	Y
May 93	17.2	5	4.20	2.8	1.90	22.2	2.2	105.0	1.5	-0.44	0.00	-5.00	4.56	3.5	50	Y
Average values				3.8	2.22				2.4	0.44			8.52	3.5	41	
Averages from urban events only				1.5	1.57				1.3	0.35			9.49	1.6	30	
Averages from events only rural/urban				6.1	3.15				4.2	2.35			3.67	4.6	29	

Table 10 Results of catchment lag analysis for C1

Event Date	Time of flow peak	Time of rainfall centroid	Lag(hr)
26 Jun 1992	15.15	-	-
26 Jul 1992	21.30	21.30	0.00
05 Apr 1993	06.45	04.50	2.00
12 Apr 1993	12.45	13.45	-1.00
09 May 1993	01.30	00.30	1.00
11 Jun 1993	18.45	18.00	0.75
14 Jun 1993	15.45	16.30	-0.75
09 Jul 1993	08.00	07.45	0.25
19 Jul 1993	13.00	14.20	-1.33
30 Jul 1993	16.00	-	-

Table 11 Results of catchment lag analysis for C2

Event Date	Time of flow peak	Time of rainfall centroid	Lag(hr)
01 Jul 1992	04.00	05.00	-1.00
21 Jul 1993	03.45	02.20	1.50
10 May 1993	01.00	00.20	0.67
10 Jun 1993	14.30	15.20	-0.83
14 Jun 1993	18.15	18.15	0.00
09 Jul 1993	06.45	08.30	-1.75
19 Jul 1993	13.30	-	-
30 Jul 1993	16.30	15.30	1.00

Table 12 Results of catchment lag analysis for C3a

Event Date	Time of flow peak	Time of rainfall centroid	Lag(hr)
29 Jun 1992	10.30	-	-
20 Jul 1992	15.45	12.40	3.00
08 Aug 1992	21.30	-	-
21 Aug 1992	10.45	-	-
31 Aug 1992	17.30	-	-
16 Sep 1992	15.15	-	-

Table 13 Results of catchment lag analysis for C5

Event Date	Time of flow peak	Time of rainfall centroid	Lag(hr)
14 Jun 1993	16.10	16.30	-0.33
19 Jul 1993	13.15	14.20	-1.00
22 Aug 1993	22.45	22.45	0.00
08 Sep 1993	08.30	07.15	1.25
08 Sep 1993	17.30	-	-
09 Sep 1993	04.30	03.30	1.00

Table 14 Results of catchment lag analysis for C6

Event Date	Time of flow peak	Time of rainfall centroid	Lag(hr)
10 Jun 1993	14.15	15.20	-1.00
11 Jun 1993	20.15	17.40	2.50
14 Jun 1993	18.15	16.40	1.50
19 Jul 1993	13.15	-	-
30 Jul 1993	16.00	15.30	0.50
03 Sep 1993	01.15	-	-

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Table 15 Estimation of unit hydrograph and losses model parameters by different methods

Method	Time-to-peak Tp(0) (hr)	Standard percentage runoff SPR (%)	Baseflow ANSF (m^3s^{-1})
Catchment characteristics	7.3	14.3	4.80
Flood event analysis	3.0 4.1 rural/urban 1.1 urban	8.5 3.7 rural/urban 9.5 urban	2.22 3.15 rural/urban 1.57 urban
LAG from flood event analysis	2.8 4.7 rural/urban 1.0 urban	-	-
BFI from flow	-	14.8	-
BFI from HOST	-	23.4	-

Table 16 Catchment characteristics for subcatchments

Catchment characteristic	Frome to Severn	Upper Frome	Toadsmoor Valley	Painswick Stream	Randwick Stream	Slad Brook	Nailsworth Stream
AREA (km^2)	226.4	51.7	9.2	32.1	3.9	16.2	48.1
MSL (km)	37.11	13.46	5.49	11.70	2.79	7.56	6.38
S1085 ($m\ km^{-1}$)	5.5	7.5	25.5	11.6	30.1	14.8	9.8
URBAN	0.098	0.019	0.089	0.058	0.380	0.076	0.063
SOIL1	0.85	0.9	1.0	1.0	1.0	1.0	0.65
SOIL2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SOIL3	0.15	0.1	0.0	0.0	0.0	0.0	0.35
SOIL4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SOIL5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SOIL	0.19	0.17	0.15	0.15	0.15	0.15	0.24
SAAR (mm)	855	854	843	889	874	863	834

Table 17 Refinement of unit hydrograph and losses model parameters for subcatchments

Catchment	Tp(0)ccs (hr)	Tp(0)obs (hr)	SPRccs (%)	SPRobs (%)	ANSF ccs (m^3/s)	ANSFobs (m^3/s)
Ebley Mill	7.30	4.10 rural/urban 1.10 urban	14.3	3.7 rural/urban 9.5 urban	4.80	3.15 rural urban 1.57 urban
Upper Frome	6.62	3.72	12.7	3.3	1.25	0.82
Toadsmoor Valley	4.75	2.67	19.5	5.1	0.22	0.14
Painswick Stream	4.99	2.80	10.0	2.6	0.82	0.54
Randwick Stream	1.48	0.83	10.0	2.6	0.10	0.07
Slad Brook	4.81	2.70 rural/urban 1.00 urban	10.0	2.6 rural/urban 6.6 urban	0.30	0.20 rural/urban 0.03 urban
Nailsworth Stream	5.06	2.84 rural/urban 1.00 urban	19.5	5.1 rural/urban 13.0 urban	1.07	0.70 rural/urban 0.02 urban
Frome to Severn	7.84	4.40	14.1	3.6	5.47	3.60

Table 18 ***Division of rural and urban areas for Slad Brook, Nailsworth Stream and diffuse lateral inflow subcatchments***

Areas and associated urban fractions	Slad Brook	Nailsworth Stream	Upper Middle Frome	Lower Middle Frome	Lower Nailsworth	Lower Frome
Total area (km^2)	16.15	48.10	12.90	9.50	14.50	28.40
URBAN	0.076	0.063	-	-	-	-
Rural/urban area (km^2)	12.31	45.83	11.15	6.48	11.13	23.44
URBAN	0.001	0.029	-	-	-	-
Urban area (km^2)	3.84	2.27	1.75	2.97	3.37	4.96
URBAN	0.700	0.700	-	-	-	-

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Table 19 Multiplying factors to apply to Nailsworth stream hydrographs for diffuse lateral inflow subcatchments

Catchment	Multiplying factors to apply to Nailsworth Stream hydrographs	
	Rural/urban hydrograph	Urban hydrograph
Upper Middle Frome	0.2433	0.7709
Lower Middle Frome	0.1414	1.3084
Lower Nailsworth	0.2429	1.4846
Lower Frome	0.5115	2.1850

Table 20 Details of calibration events

Date	Rainfall depth (mm)	Storm duration (hr)	SMD (mm)	API5 (mm)	CWI (mm)
18 Dec 1965	85.8	120	0.14	2.14	127.0
30 May 1979	41.0	72	4.43	9.28	129.9
05 Jan 1994	20.9	72	0.29	11.26	136.0

Table 21   Details of design events

Return period	Rainfall depth (mm)	Storm duration (hr)	CWI (mm)
5 year	35.7	8.5	120.7
10 year	42.4	8.5	120.7
25 year	50.6	8.5	120.7
50 year	58.1	8.5	120.7
100 year	65.2	8.5	120.7
150 year	69.9	8.5	120.7

Wallingford Water

Figures

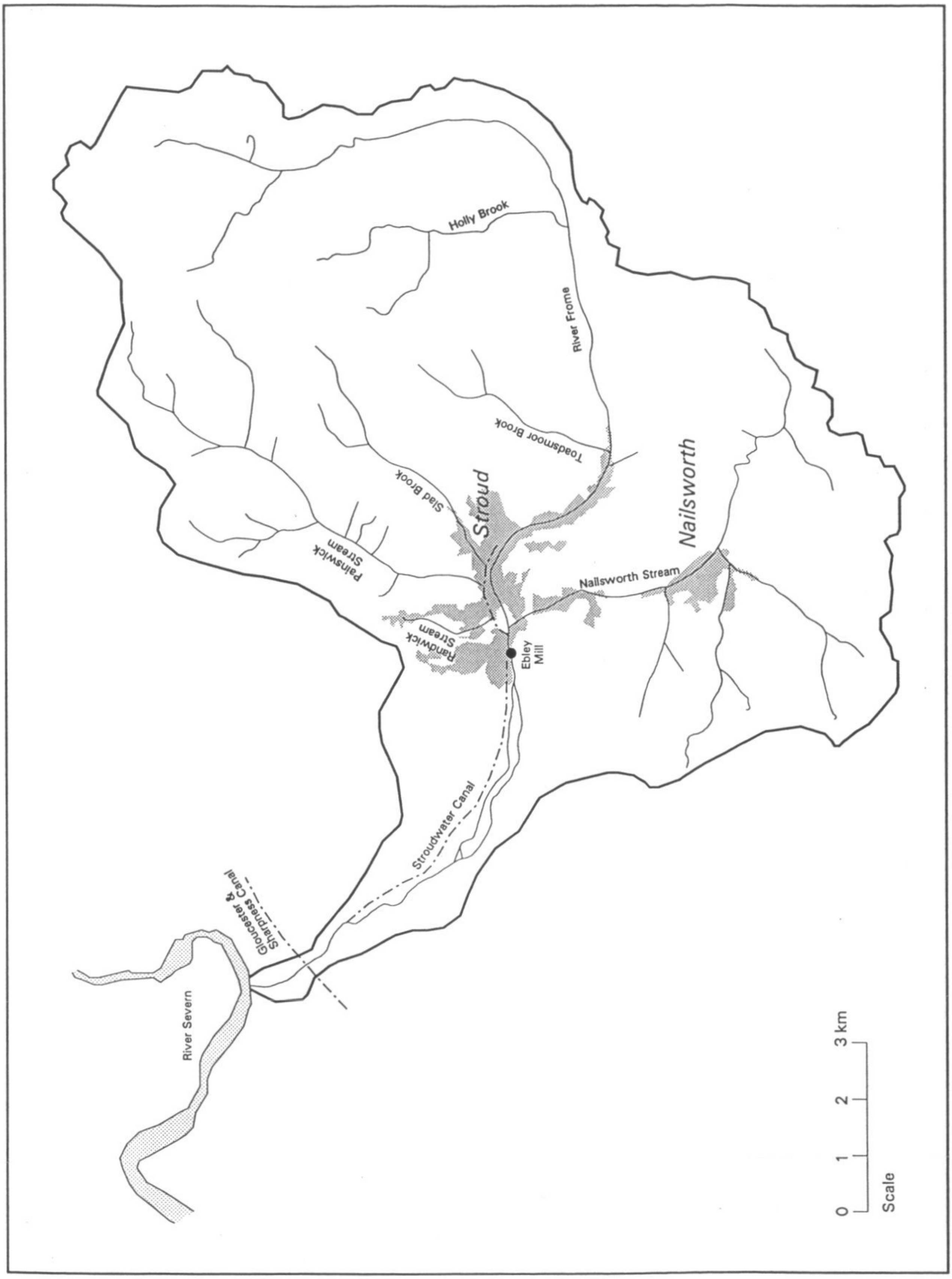

Figure 1 Frome catchment and river system

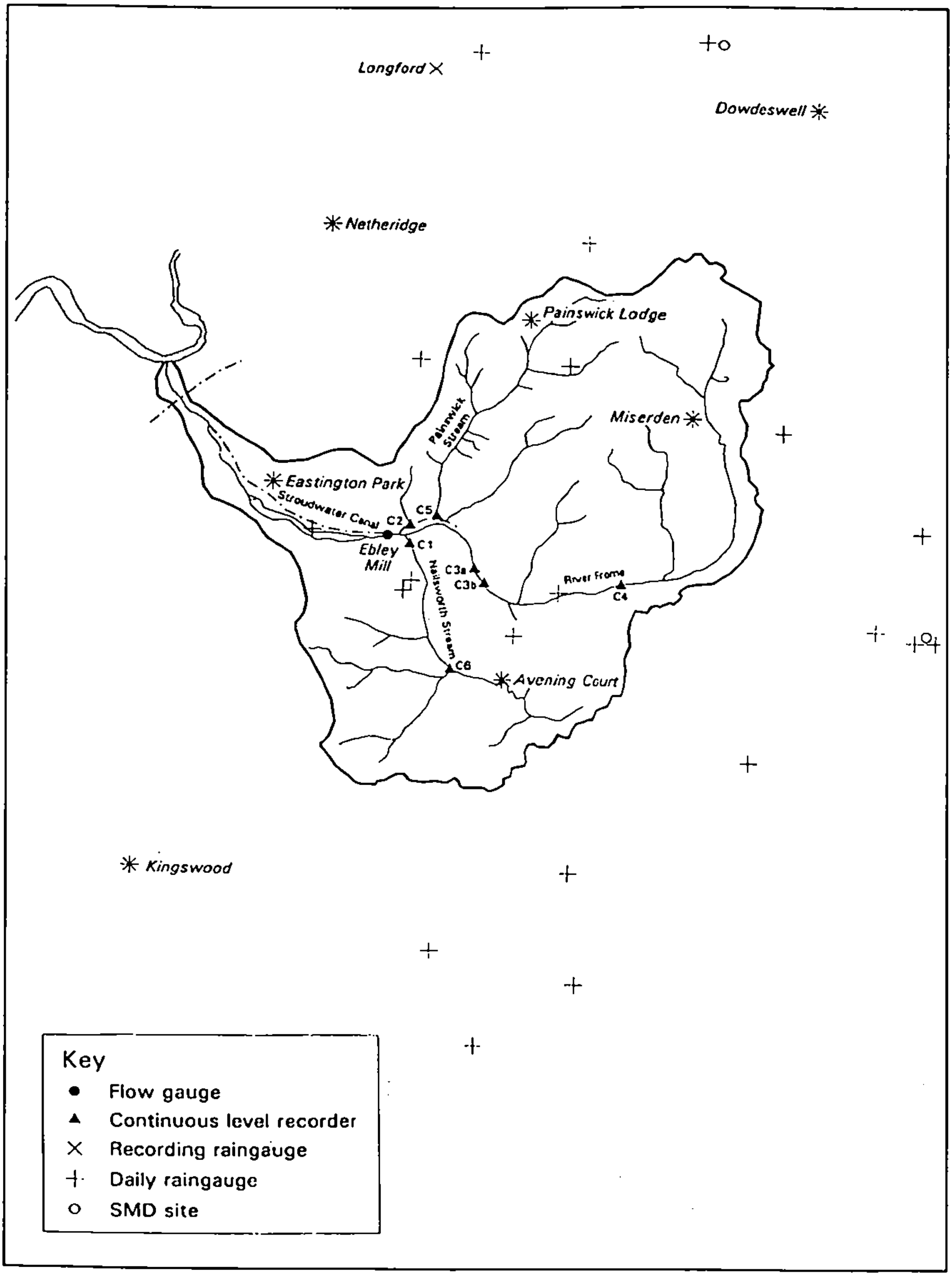

Figure 2 Locations of flow gauging stations and meteorological sites in the Frome basin

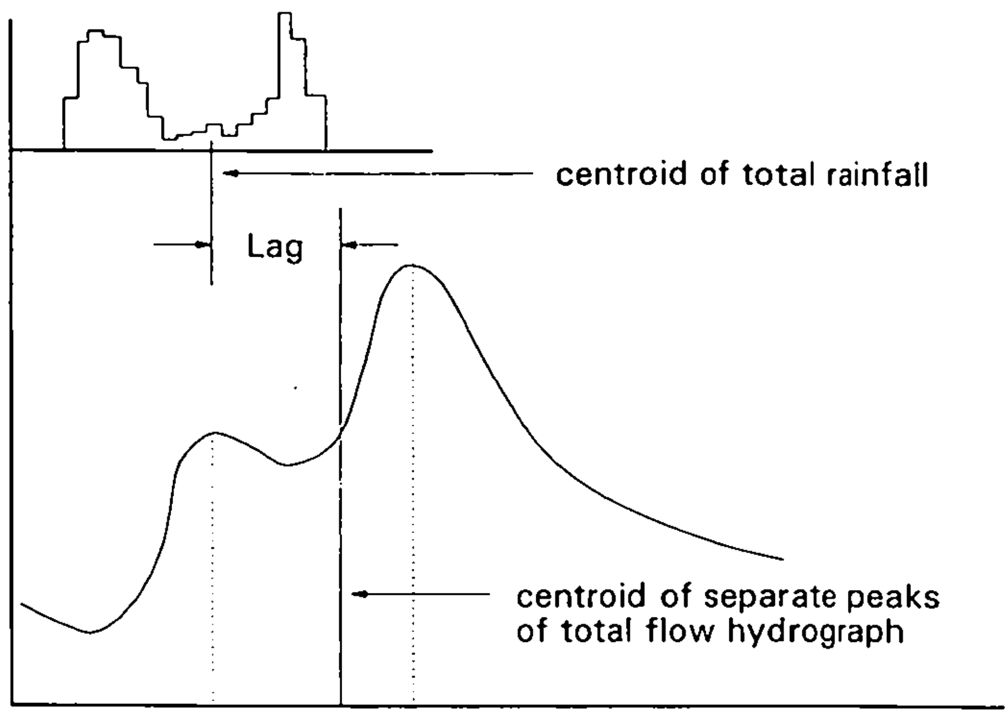

Figure 3 Definition of catchment lag

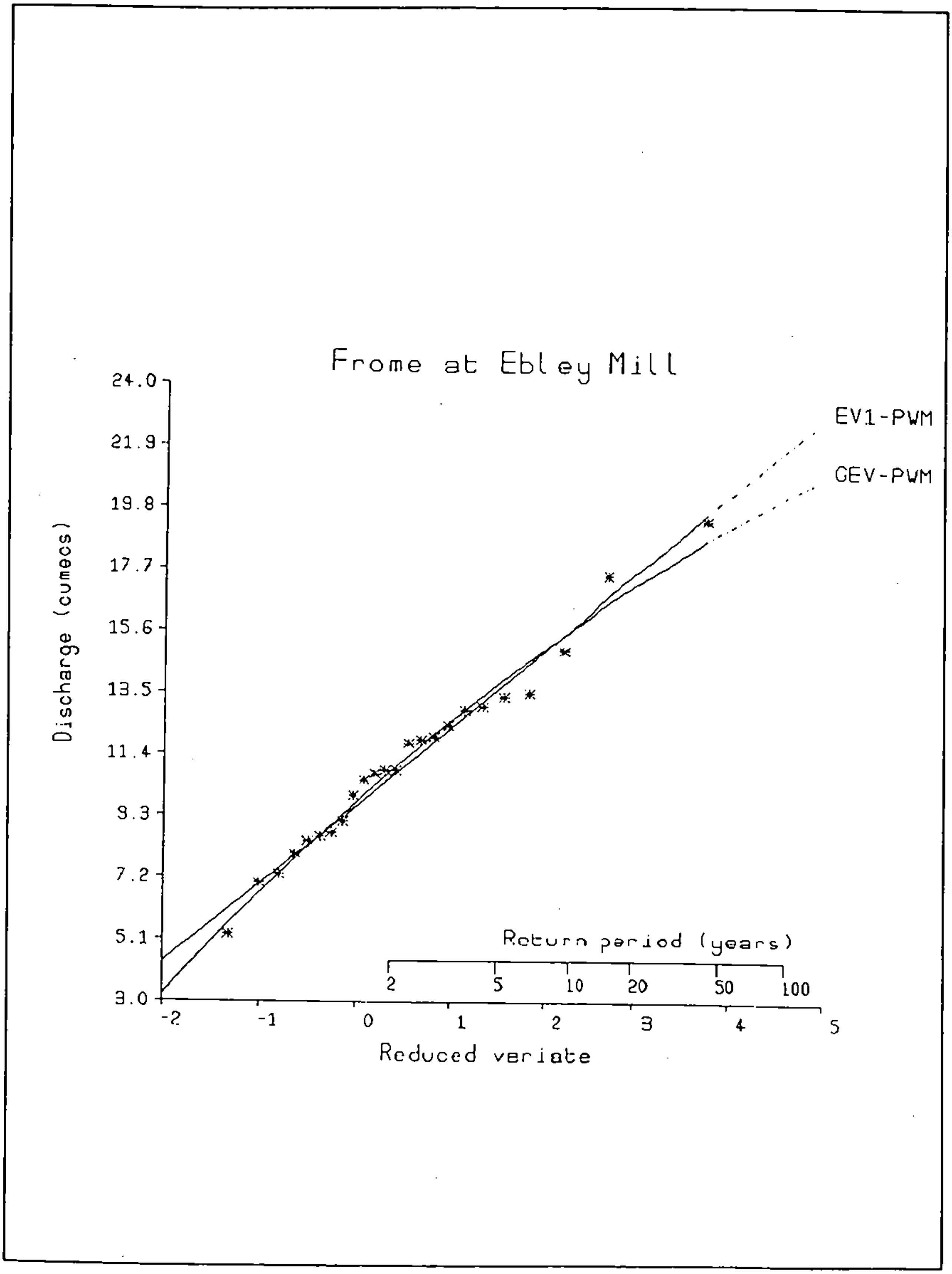

Figure 4 Flood frequency plots for Ebley Mill (based on 24 years of data)

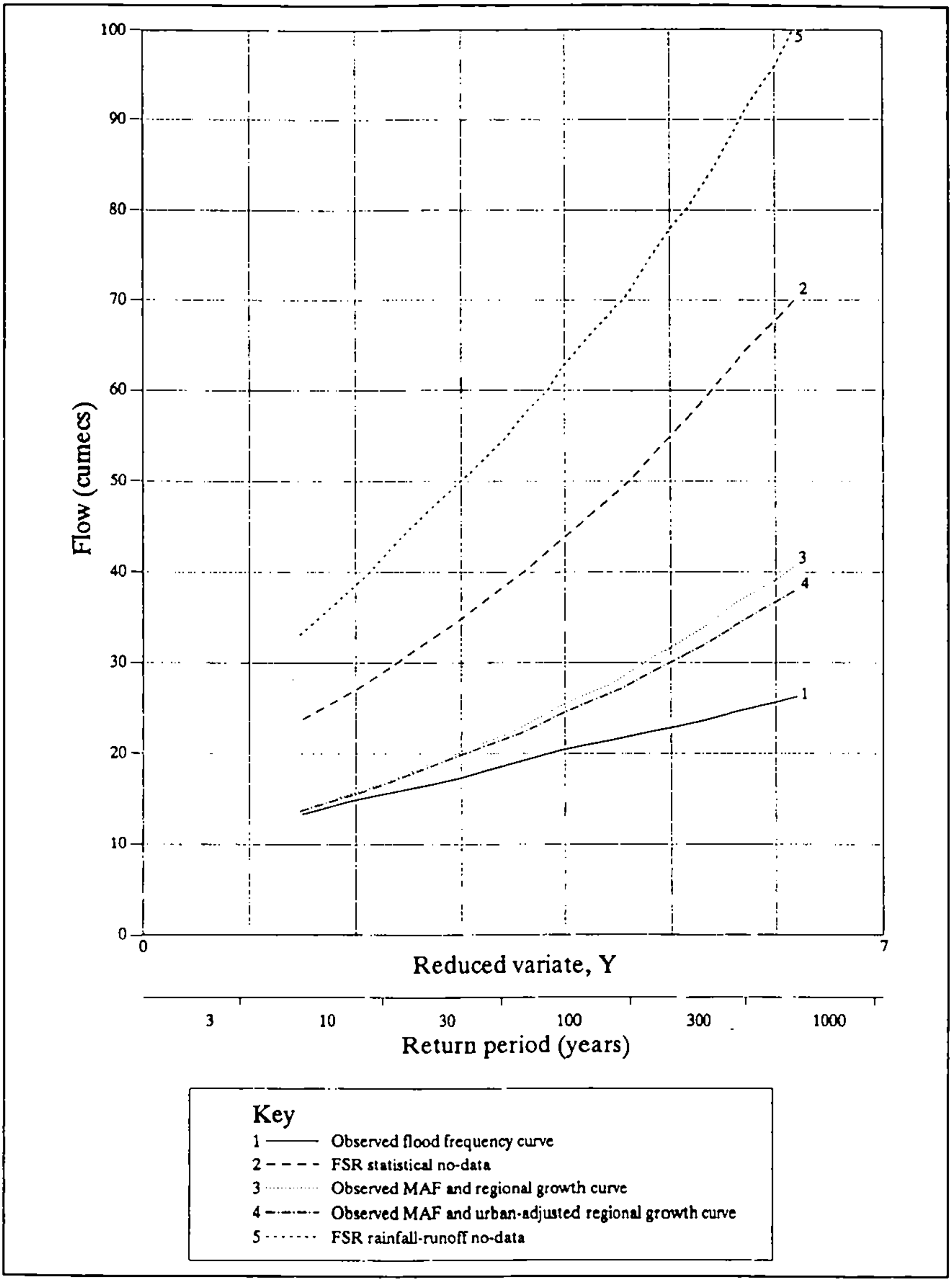

Figure 5 Flood frequency plots for Ebley Mill from various methods

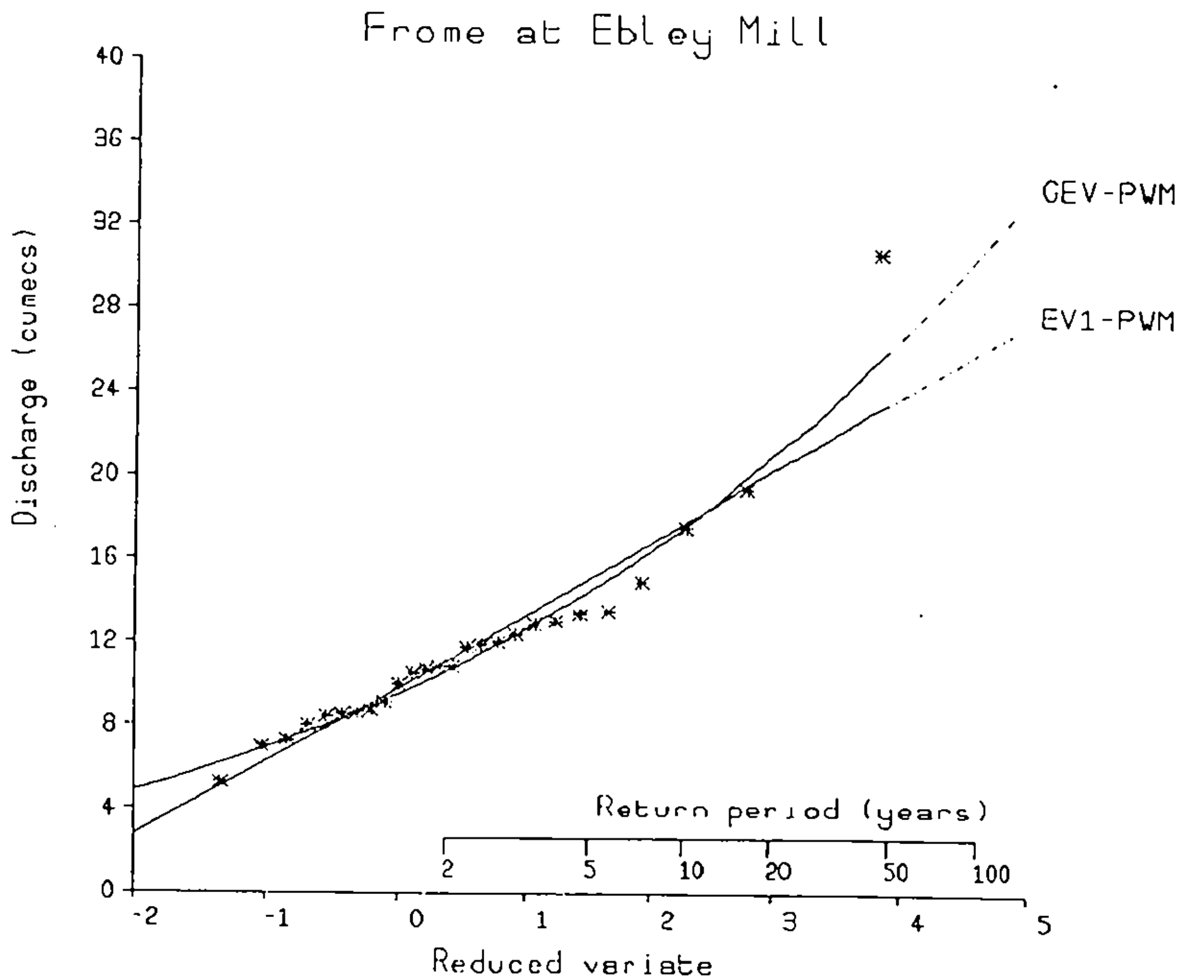

Figure 6 **Flood frequency plots for Ebley Mill (based on 26 years of data)**

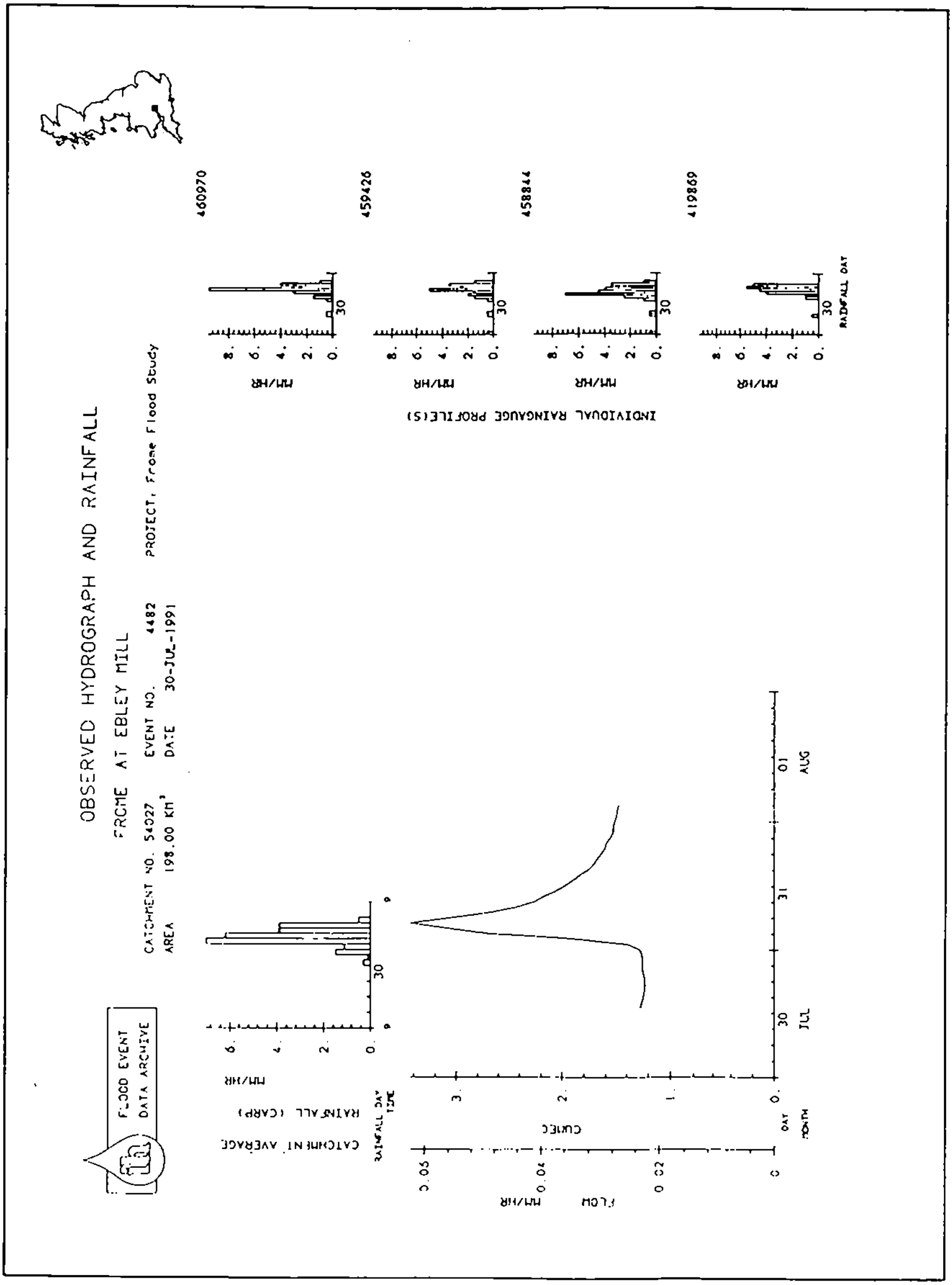

Figure 7 Typical flood event at Ebley Mill

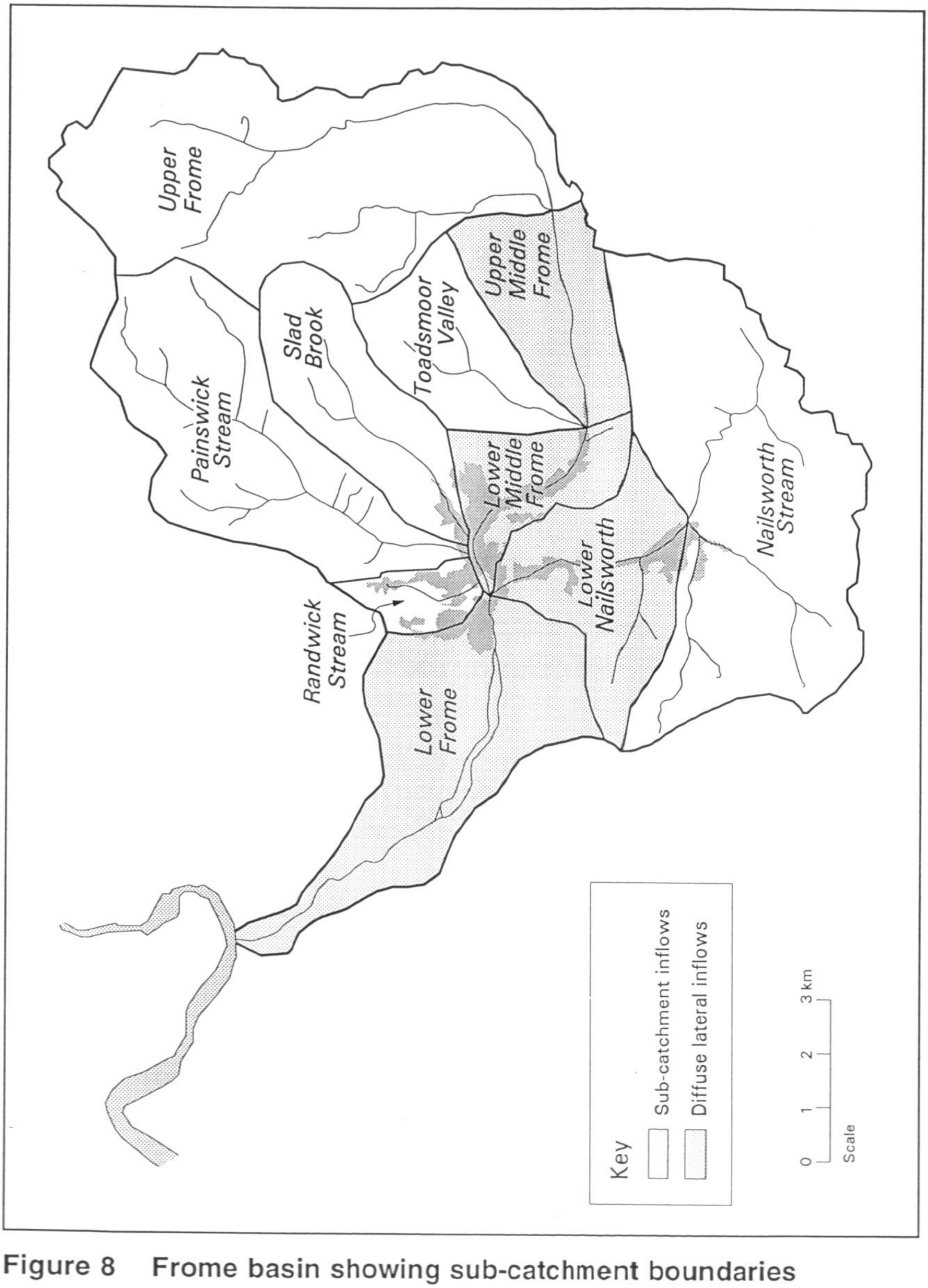

Figure 8 Frome basin showing sub-catchment boundaries

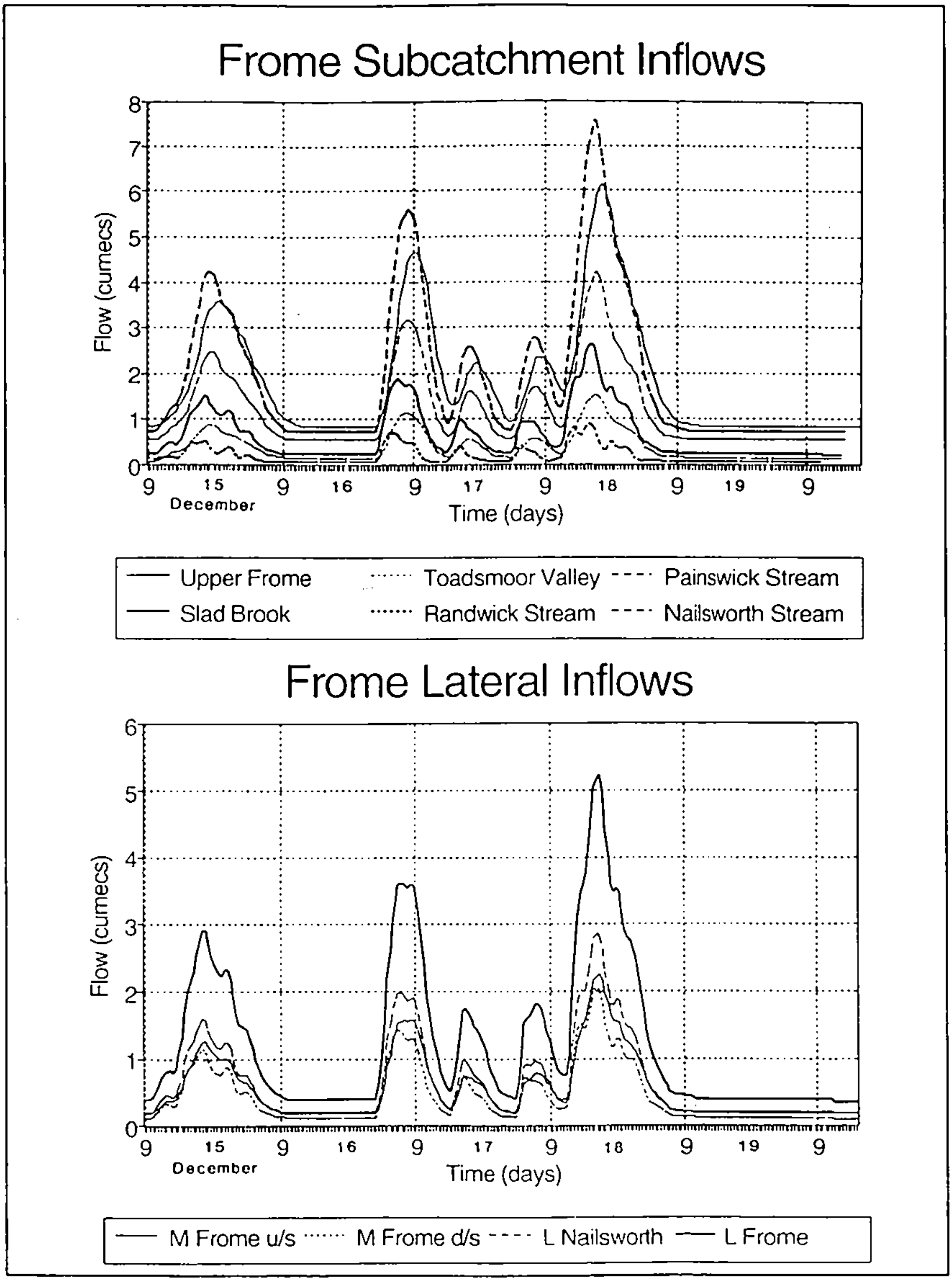

Figure 9 1965 calibration event inflows

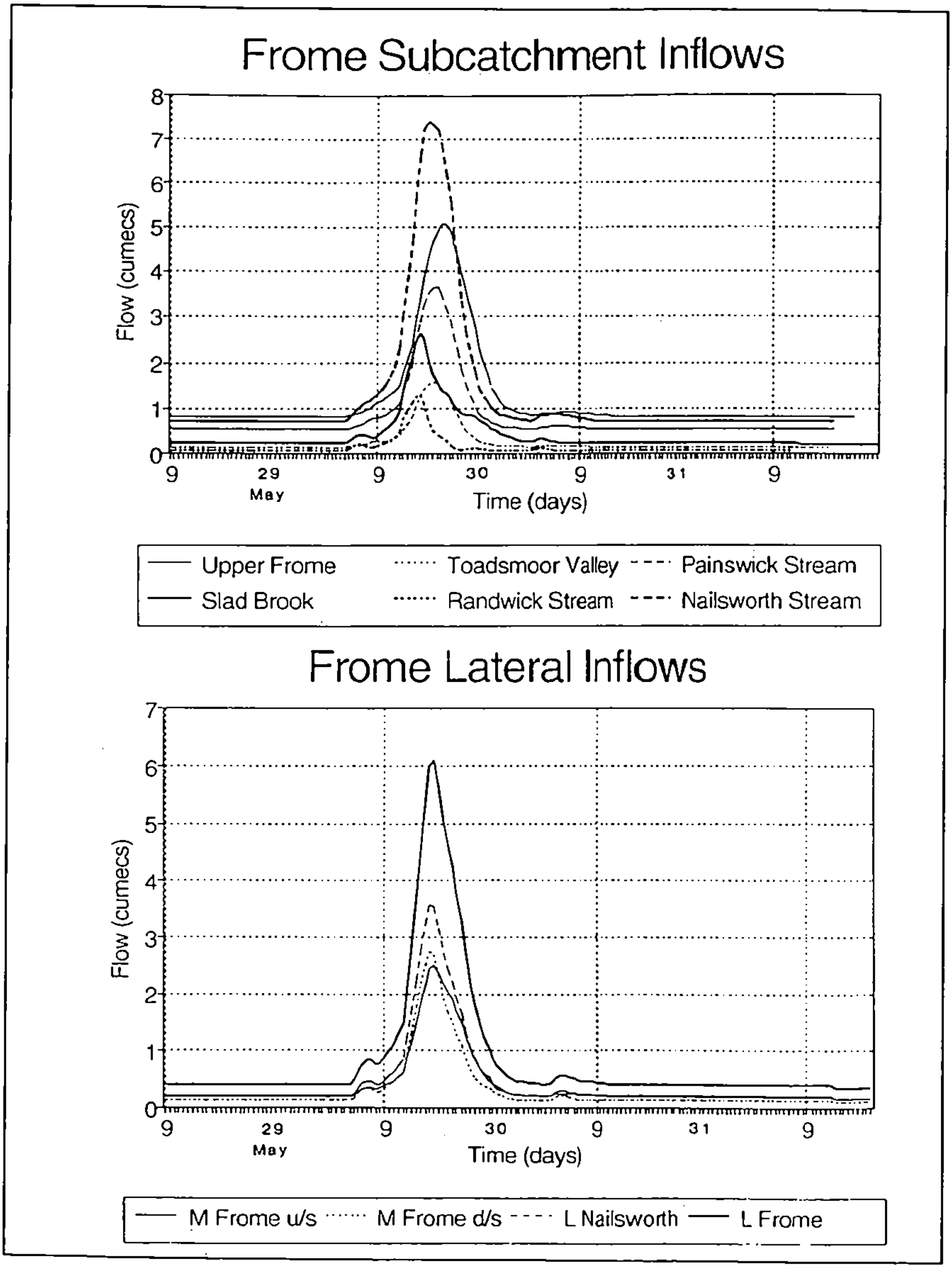

Figure 10 1979 calibration event inflows

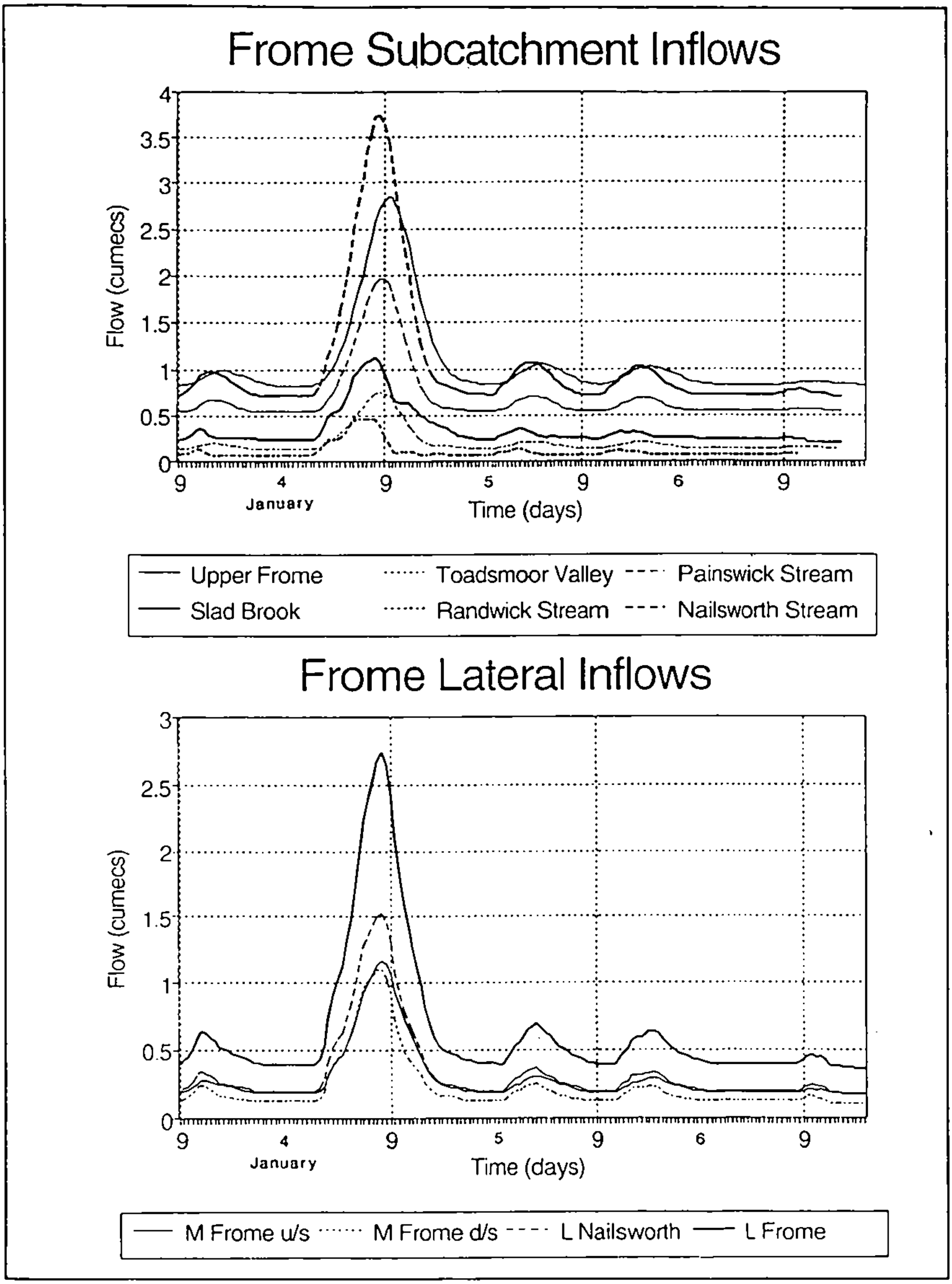

Figure 11 1994 calibration event inflows

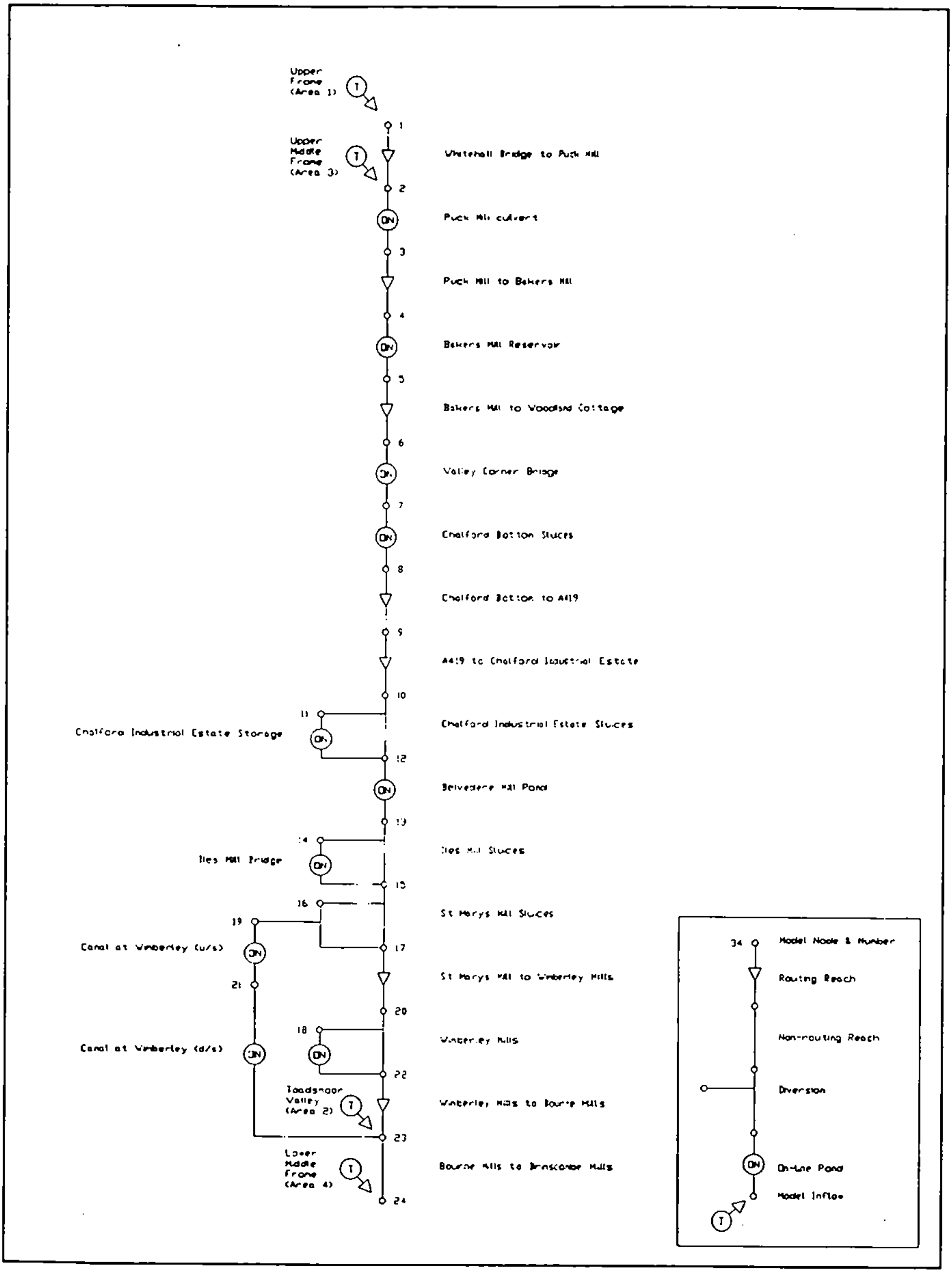

Figure 12 RIBAMAN schematic - Whitehall Bridge to Brimscombe Port

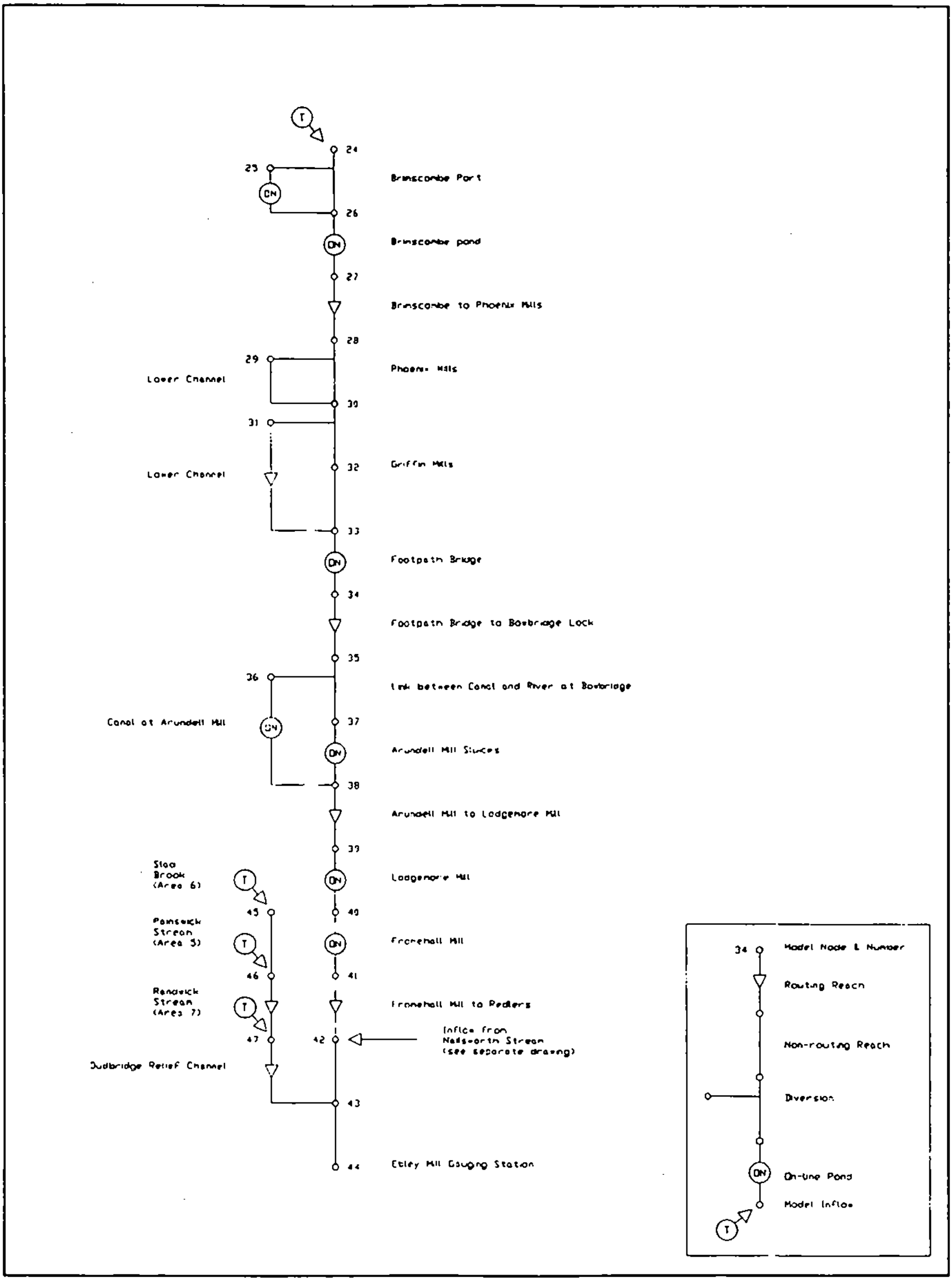

Figure 13 RIBAMAN schematic - Brimscombe Port to Ebley Mill

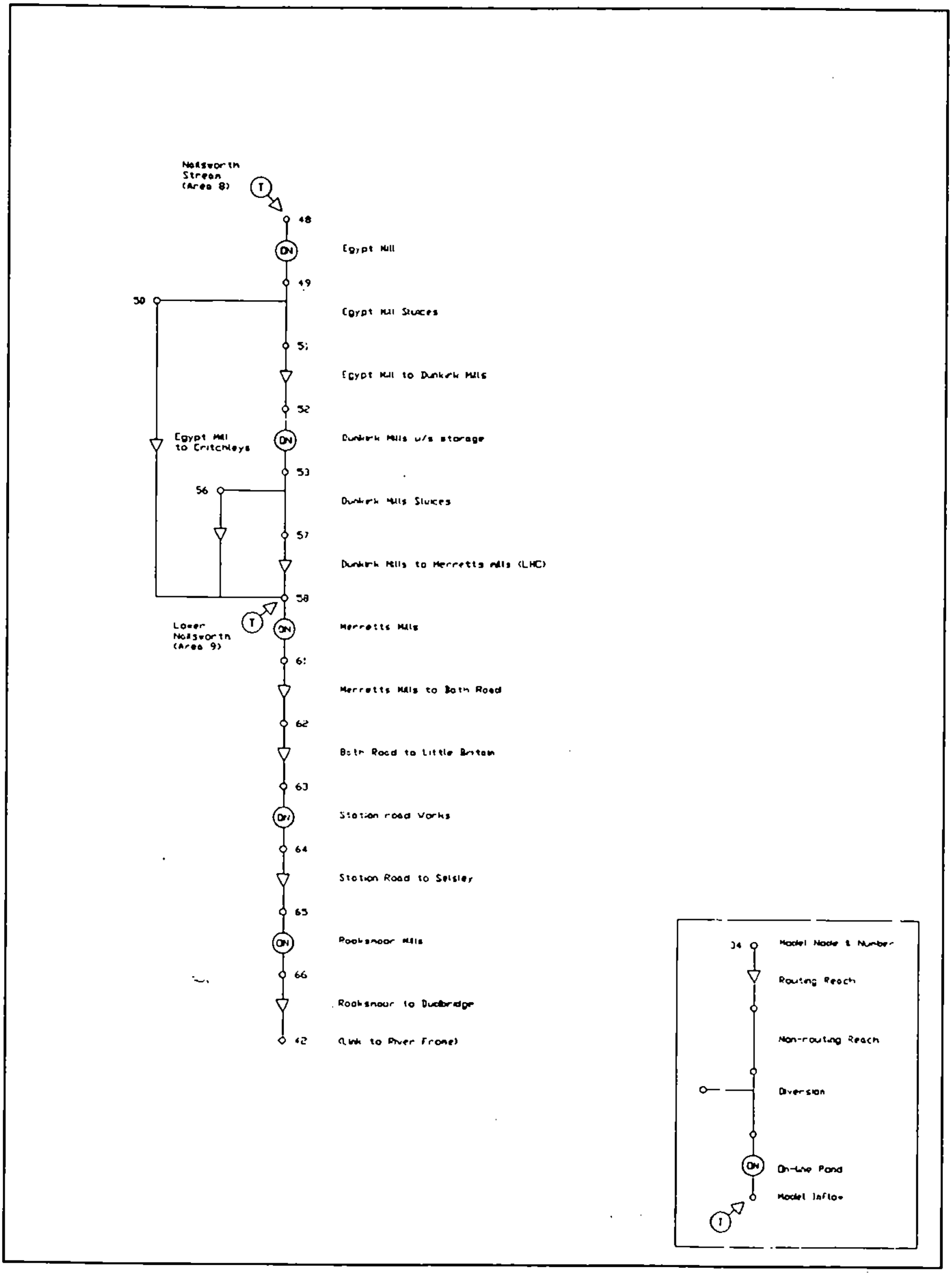

Figure 14 RIBAMAN schematic - Nailsworth Stream

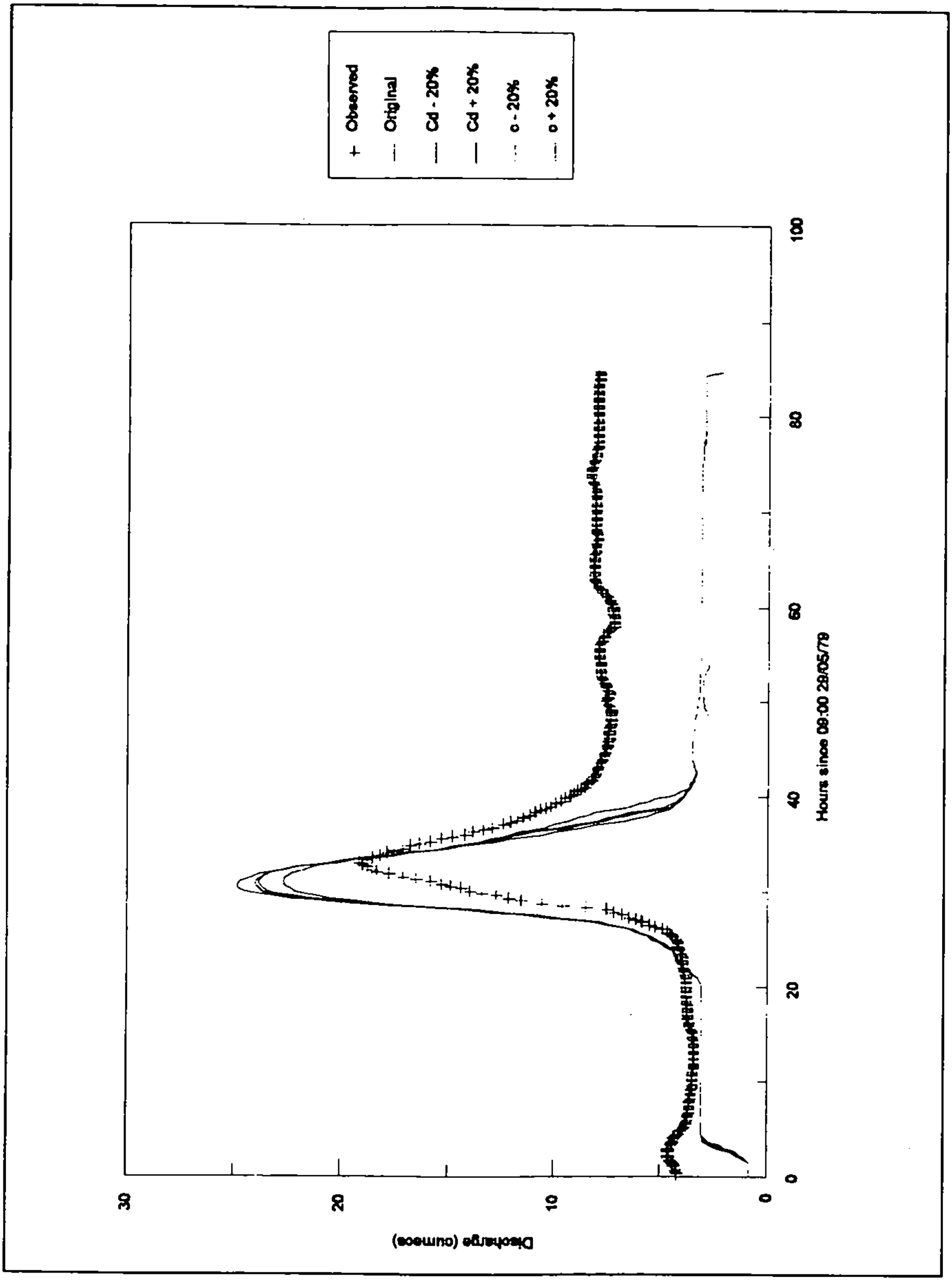

Figure 15 RIBAMAN results at Ebley Mill - May 1979 calibration event

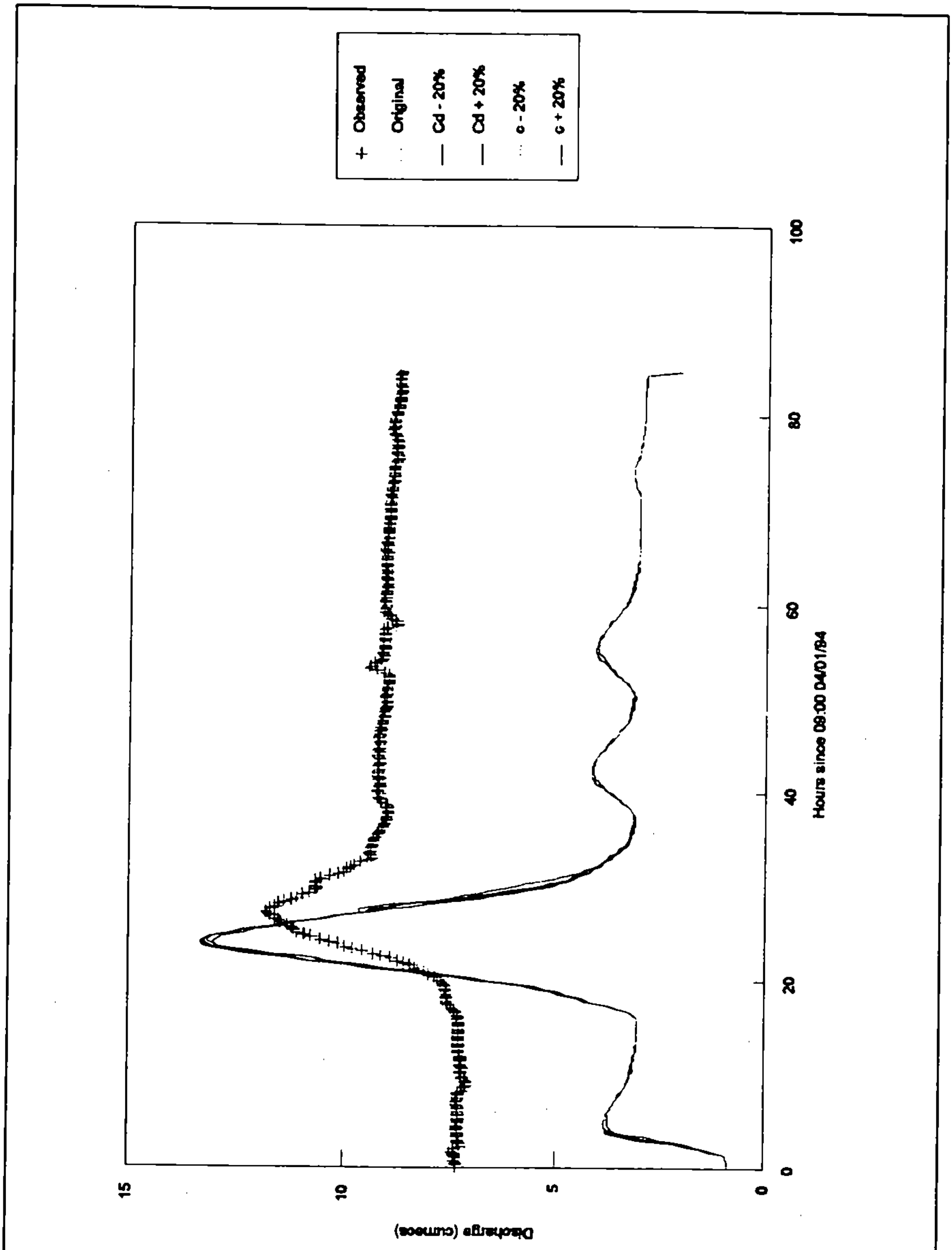

Figure 16 RIBAMAN results at Ebley Mill - January 1994 calibration event

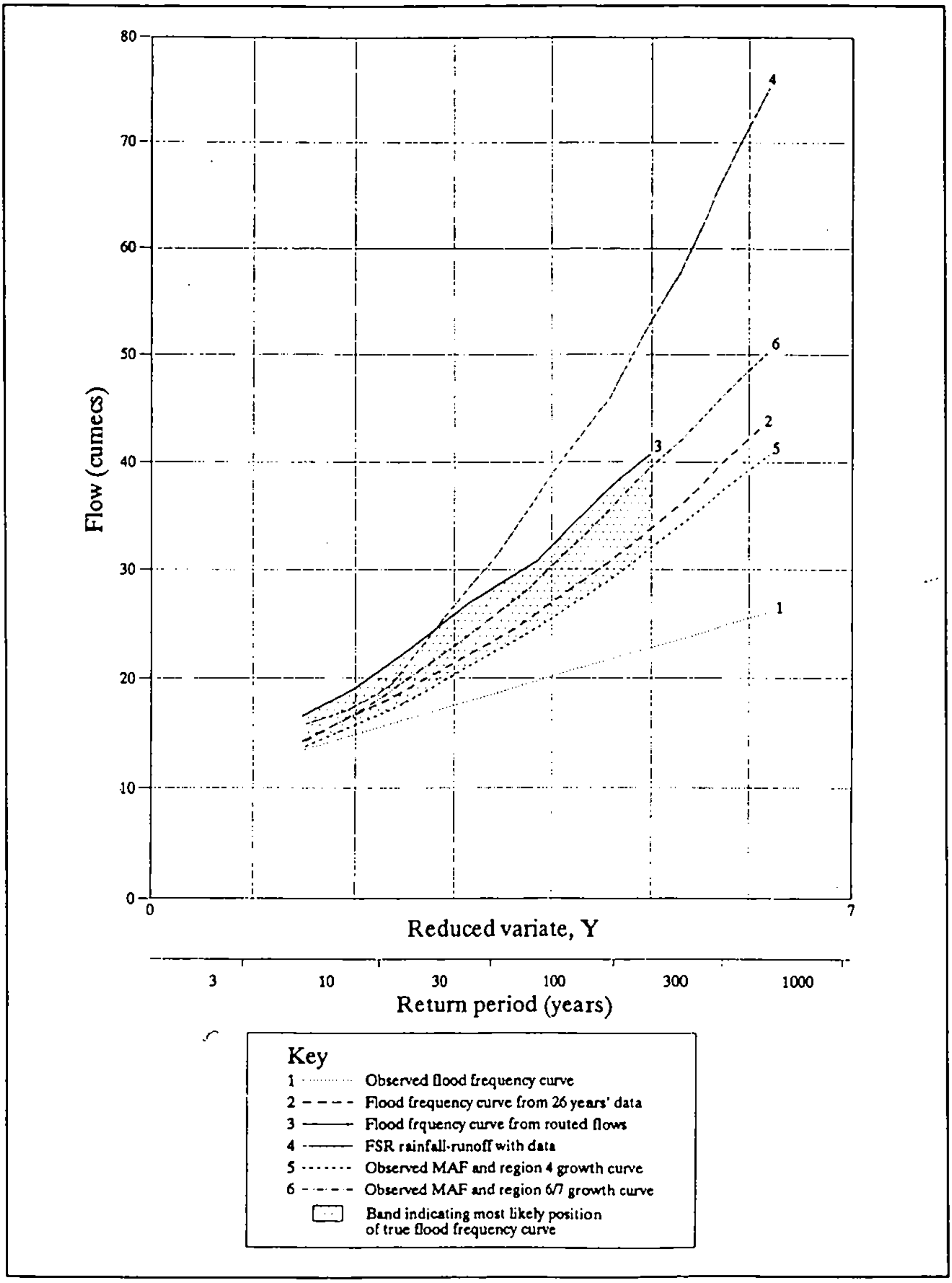

Figure 17 Comparison of flood frequency plots for Ebley Mill