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Flood estimation for small catchments

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Cover picture: A tributary of the Great Ouse — flood peak of 23rd September 1992

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Executive summary

Accurate estimation of flood parameters on small lowland catchments is known to be difficult. Small (<25 km^2) catchments with good quality data are few in number. Those that do exist tend to be rural, steep, subject to high rainfall and generally impermeable. In practice, the small catchments most frequently encountered within flood estimation problems have the converse characteristics. Thus existing generalised methods are less able to accurately predict floods on relatively permeable, drier, part-urban catchments. The objective of the research described here was to examine the response to rainfall of such catchments and to derive improved flood estimation equations where possible.

A major component of the project was the instrumentation of 15 small catchments in central southern England, chosen so that they possessed particular combinations of catchment characteristics which compensated for deficiencies in the existing catchment set. The report includes a description of the design and installation of the water level recorders used within the study. Nine of the catchments had an urban land cover of 5% or more. A total of 103 rainfall-runoff events were analysed, including at least five from each of the 15 experimental sites.

During the investigation, the Agricultural Development and ADAS Soil & Water Research Centre in Cambridge undertook research on 12 essentially rural small catchments in England and Wales. Information from these two sets of instrumented sites formed a key ingredient and has been analysed by both organisations. Beyond the data already described, recourse was made to the IH flood event archive for 423 events recorded on 46 catchments of less than 25 km^2.

A separate mean annual flood (QBAR) database was compiled, consisting of 87 small catchments, including six of the ADAS experimental sites and three operated by the Department of Agriculture for Northern Ireland.

The investigation determined that existing techniques, although performing reasonably well on small rural catchments, tend to overestimate response times for part-urban catchments. New equations are derived for the estimation of the instantaneous unit hydrograph time-to-peak, Tp(0), and the mean annual flood, QBAR. The Tp(0) estimation equation recommended here can be applied to catchments of any size.

Contents

1 Introduction

A catchment's flood response to rainfall may have to be quantified for a variety of reasons. Among the most common are peak flow and flow volume estimation, flood duration, flood warning and the design of hydraulic structures.

Flood estimation is inherently more difficult on smaller catchments than larger ones. Catchment characteristics, used in the estimation of flood parameters at ungauged sites, are more difficult to extract from smaller catchments; errors that escape detection will have a proportionally greater effect on the final estimate.

Any flood estimation procedure is only as good as the data used in its construction. The relative deficiency of small, lowland, dry, permeable catchments in past analyses has so far meant that accepted procedures are less able to predict flood parameters accurately in such cases.

This report describes strategic research into flood estimation on small catchments (<25 km^2), with a particular emphasis on flood response times.

1.1 Estimation of flood response times

A hydrograph, essentially a graph of flow against time, can be thought of as accommodating a certain volume of water. A unit hydrograph (UH) is understood to include a volume of water which corresponds to a unit depth of net rainfall over the catchment. Each unit hydrograph relates to a specified period, during which the generating rain falls (spatially and temporally) uniformly over the catchment. In general, a T-hour unit hydrograph results from the application of a unit depth of net rainfall to a catchment over a period of T hours. The instantaneous unit hydrograph (IUH) is a theoretical concept which is said to occur when the unit depth of net rainfall is applied to the catchment instantaneously rather than over a finite period. The unit hydrograph is the linchpin within UK rainfall-runoff flood estimation and its accurate construction is essential.

Flood Studies Report

The *Flood Studies Report* (FSR) from the Institute of Hydrology (NERC, 1975) includes recommendations (Vol. I, Ch. 6) on how the 1-hour unit hydrograph may be constructed for an ungauged catchment in a simple triangular form. Estimates of the peak flow (Qp) and time-to-peak flow (Tp) are used to define the apex of the synthetic UH, while the base length is calculated as a function of Tp. Because Qp is calculated as a function of Tp, the requirement to estimate Tp as accurately as possible is heightened. If Tp is in error, the volume of water beneath the UH will not alter, but when the design rainfall is applied, the resulting hydrograph will be inaccurate. An overestimate of Tp will lead to a lower UH Qp value, and to a derived hydrograph that is overly long and subdued. In the FSR rainfall-runoff method, the effect is amplified by the role that Tp also plays in determining the design storm duration.

Where the UH, and hence Tp, cannot be calculated, because of the absence of suitable rainfall and flow data, Tp is usually derived from catchment characteristics via a multiple regression equation. The first Tp estimation equation to be derived (FSR, Vol. I, p. 407) was:

$$\mathrm{Tp}(1) = 46.6\,\mathrm{S1085}^{-0.38}\,(1+\mathrm{URBAN})^{-1.99}\,\mathrm{RSMD}^{-0.4}\,\mathrm{MSL}^{0.14} \qquad [1.1]$$

where the notation Tp(1) emphasises that the estimate refers to a 1-hour UH.

The catchment characteristics are described in detail in the FSR (Vol. I, Ch. 4).

The magnitude and sign of the catchment characteristic exponents in Equation 1.1 give some indication of influences on Tp. A positive exponent will increase the value of Tp (i.e. attenuate the flood response to rainfall) as the magnitude of the characteristic increases. Conversely, a negative exponent has the effect of decreasing the magnitude of Tp (speeding up flood response) as the magnitude of the characteristic increases. The absolute magnitude of the exponent dictates how pronounced the effect is. On this basis, the URBAN characteristic is the most influential and MSL the least. However, this appraisal overlooks the fact that some catchment characteristics typically take a wider range of values than others. The effect of each variable is explained more fully in the following examples.

The longitudinal gradient of the main stream, measured between points 10% and 85% upstream from the gauging point and expressed in units of m/km, is referred to as the

S1085 slope. As the stream gradient increases, $S1085^{-0.38}$ decreases, resulting in a decrease in Tp. The shallowest and steepest gradients for a small catchment within the IH flood event archive are 4 m/km and 180 m/km. The variation in the element of Tp which is due to the effect of S1085 is illustrated by the ratio of $4^{-0.38}$ to $180^{-0.38}$, i.e. 4.24:1.

The fraction of the catchment area under urban land use is defined as URBAN. The term '1+URBAN' is used in place of 'URBAN' to prevent the regression failing when URBAN=0.0 for a completely rural catchment. As a catchment becomes progressively more urbanised, Tp decreases, until at 100% urbanisation this element of Tp has reduced from unity to a minimum of $(1+1)^{-1.99} = 0.25$. The equation indicates that a completely urbanised catchment would return a value of Tp only 25% of that from an equivalent rural catchment.

RSMD, the only climate characteristic in Equation 1.1, is defined as the net 1-day rainfall (mm) of five-year return period. Its magnitude varies throughout the UK between 20 mm and 90 mm so that the term $RMSD^{-0.4}$ is able to vary between 0.3 and 0.165. RSMD is thus only able to affect the magnitude of Tp over a ratio of 1.8:1.

MSL represents the catchment main stream length, the longest stream within the catchment, recorded in km. The exponent of 0.14 indicates a slight increase in Tp as the MSL increases. The extreme values of MSL within the IH flood event archive, 0.15 and 85.0, lead to a variation in Tp of 0.77:1.86 or 1:2.4.

Flood Studies Supplementary Reports

Following publication of the FSR (NERC, 1975), it gradually became clear that the report was being applied in many cases to catchments of a type which had not featured prominently in the FSR data set. According to *Flood Studies Supplementary Report No. 6* (FSSR 6, 1978), only 23 catchments of less than 20 km² had rainfall-runoff data in the relevant FSR data set.

An example of a small catchment that did feature in the FSR is catchment No. 28070, Burbage Brook at Burbage. This 9.1 km² catchment lies within the Peak District, 10 km south-west of Sheffield, on Carboniferous millstone grit. The station altitude of 290 m AOD and average (1941-70) annual rainfall (SAAR) of 985 mm, taken together with the MSL value of 5.00 km and the S1085 of 31.41 m/km, effectively complete the description of this uninhabited, wet, impermeable, rural upland catchment, which was instrumented to meet a specialist requirement.

FSSR 16 (1985), condensed from Boorman (1985), revised the FSR rainfall-runoff model parameter estimation equations but did not specifically address the problem of small catchment flood estimation.

The FSR analysis identified problems in deriving the 1-hour unit hydrograph. If a catchment responds sufficiently fast, so that all parts of it are contributing to outflow within one hour — as many small part-urban catchments do — it is not practical to analyse data from that catchment using a 1-hour data interval to determine a 1-hour UH. An attempt to do so would result in a misshapen UH and consequently an ill-defined Tp. Having recognised this problem, the time-to-peak of the IUH, Tp(0), was adopted in place of Tp within FSSR 16.

An equation linking Tp(0) to the time-to-peak of the T-hour UH is included in FSSR 16:

$$Tp(T) = Tp(0) + T/2 \qquad [1.2]$$

The FSSR 16 equation for estimating IUH time-to-peak, Tp(0), on ungauged catchments is based on the regression result (Boorman, 1985):

$$Tp(0) = 283.0\ S1085^{-0.33}(1+URBAN)^{-2.2}\ SAAR^{-0.54}MSL^{0.23} \qquad [1.3]$$

In addition to three catchment characteristics that feature within the FSR Tp estimation equation, the FSSR 16 equation uses SAAR in place of RSMD.

The context of the project

Out of a total of 210 catchments, FSSR 16 included 48 catchments of less than 25 km² area. However, of those 48, only nine were more than 5% urbanised and only nine had a SOIL index of less than 0.45, equivalent to 100% SOIL type 4. While there are relatively few data available from small, permeable, lowland, part-urban catchments, it is for this type of ungauged catchment that flood estimates appear to be most often required. Some aspects of practical application of the FSR rainfall-runoff method at ungauged sites are discussed by Reed (1987), with permeable small catchments strongly featured. The objective of the project reported here was to improve flood estimation on such catchments.

Data

Fifteen small catchments were instrumented during 1989 and 1990. They are described in detail in Chapter 2 and Appendix 1. The catchments varied in size from 0.9 km² to 22.9 km², spanning a range of geological and land-use types, and all 15 were selected to lie within the 75 km radius limit of the 2 km × 2 km high-definition data recorded by the Chenies weather radar, as seen in Figure 2.1. Other data used in the study are introduced in Chapter 5.

1.2 Estimation of the mean annual flood

Flood Studies Report

The FSR (Vol. I, Section 4.3.10) summarises regression equations linking mean annual flood, QBAR, on an ungauged catchment to a defined number of catchment characteristics. The best known of the several equations is the so-called 6-variable equation:

$$\mathrm{QBAR} = \mathrm{Constant}\ \mathrm{AREA}^{0.94}\ \mathrm{STMFRQ}^{0.27}\ \mathrm{S1085}^{0.16}\ \mathrm{SOIL}^{1.23}\ \mathrm{RSMD}^{1.03}\ (1+\mathrm{LAKE})^{-0.85} \quad [1.4]$$

The constant term depends upon the hydrometric area within which the catchment is located.

Flood Studies Supplementary Reports

Although Equation 1.4 is still in general use, some alternatives have been suggested. FSSR 6 provides QBAR equations for possible use on catchments of less than 20 km²:

$$\mathrm{QBAR} = 0.00066\ \mathrm{AREA}^{0.92}\ \mathrm{SAAR}^{1.22}\ \mathrm{SOIL}^{2.0} \quad [1.5]$$

$$\mathrm{QBAR} = 0.0288\ \mathrm{AREA}^{0.90}\ \mathrm{RSMD}^{1.23}\ \mathrm{SOIL}^{1.77}\ \mathrm{STMFRQ}^{0.23} \quad [1.6]$$

FSSR 5 provided a means of extending QBAR estimation to urbanised catchments, which Equation 1.4 did not deal with. The mechanics of the QBAR adjustment for urbanisation were subsequently amended in FSSR 16.

More recently, Naden & Polarski (1990) formulated a QBAR equation that makes use of digitised stream network data originating from 1:50 000 Ordnance Survey maps. Their equation incorporates the variable NETLEN, which represents the catchment's total stream network length, and represents the effect of urban land use directly:

$$\mathrm{QBAR} = 0.000011\ \mathrm{NETLEN}^{0.73}\ \mathrm{SAAR}^{1.76}\ \mathrm{SOIL}^{0.76}\ (1+\mathrm{URBAN})^{2.00} \quad [1.7]$$

Database

Since the FSR was published, the QBAR database has approximately doubled in size and now holds peaks-over-threshold (POT) information relating to 857 gauging stations and annual maxima for a further 116 stations (Bayliss & Jones, 1993). QBAR data have therefore been calculated for 973 catchments, 98 of which have a catchment area of less than 25 km². Of these, 78 were considered suitable for inclusion within this report. Three Department of Agriculture (Northern Ireland) and six ADAS catchments increased this QBAR database to 87. This dataset is listed in Table 5.5, and the derivation of new estimation equations for QBAR is taken up in Chapter 7.

2 Catchment selection and instrumentation

2.1 Catchment selection

One of the principal objectives of this study was to produce response time estimation procedures using catchment characteristics which are particularly relevant to small catchments. Consequently, perhaps the most important criterion considered when selecting catchments for the study was the need to choose sites which would produce a range of values in each of the characteristics which are thought to influence response times. These characteristics could then be used in regression analyses to produce equations more appropriate to small catchments.

The 15 catchments chosen vary in area between 0.9 and 22.9 km^2, reflecting the sizes of catchments which typically present flood estimation problems. The catchments also span a range of soils, geology and land-use types: the dominant land use in each catchment varies from almost completely rural to heavily urbanised.

All the catchments were selected to lie within the 75 km radius limit of the 2 km × 2 km high-definition rainfall data recorded by the Chenies weather radar (Figure 2.1). This allowed the calculation of five-minute interval catchment average rainfall intensities (described in detail in Chapter 3) and obviated the need to install recording raingauges. Within this 75 km radius, catchments were selected which lie to the west and northwest of London, thus facilitating data collection from the Institute of Hydrology.

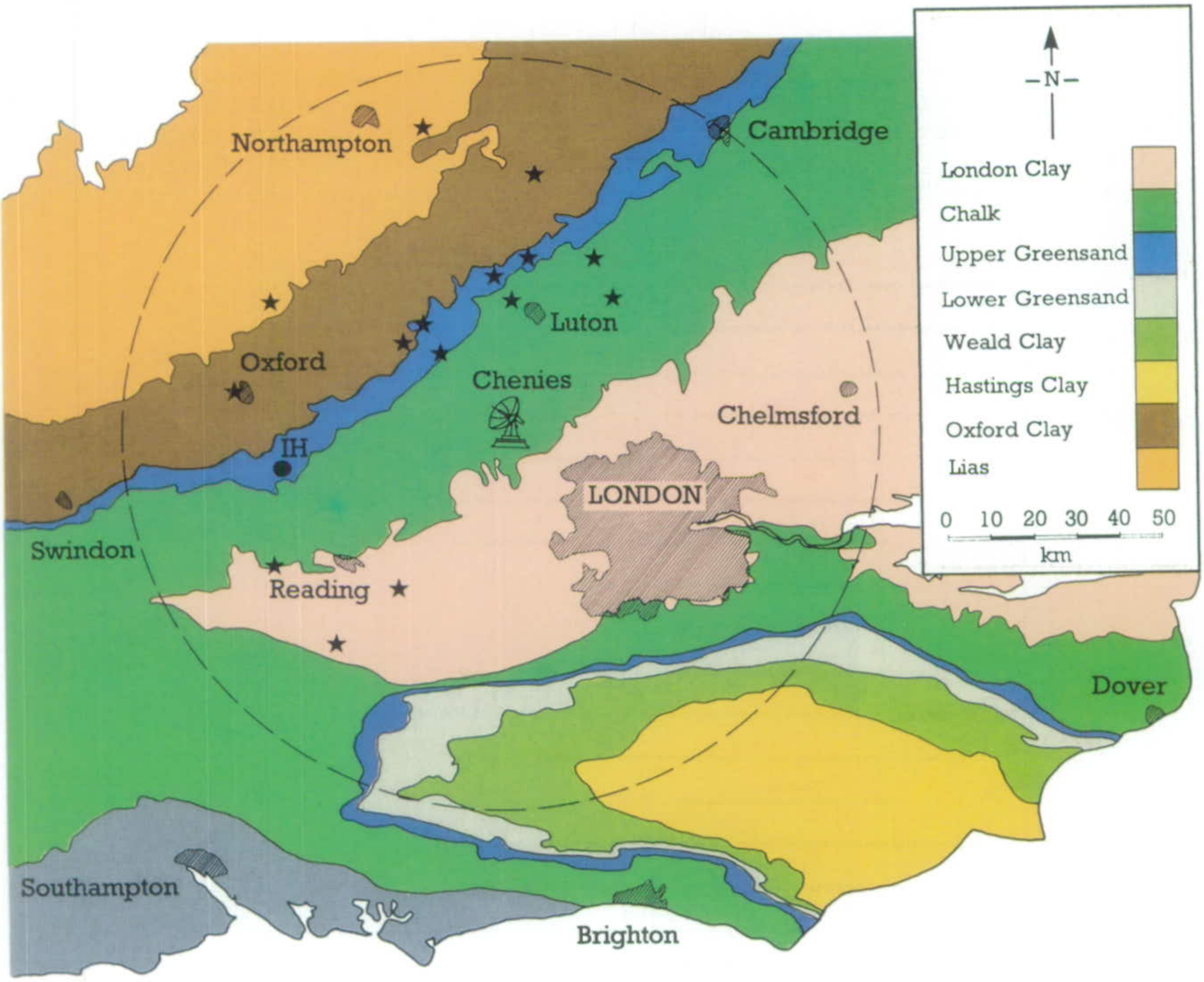

Figure 2.1 *The locations of the 15 water level recording sites*

Selecting a catchment with a suitable site for the installation of the water level recording equipment was also important. In most cases the equipment was secured to road bridges: here the safety of the installation team, and of the staff subsequently collecting the data, had to be considered. A number of sites were rejected because staff would have been put in danger by the speed, frequency and proximity of traffic using the bridge.

Although the equipment was made as vandal-proof as possible (see page 8) the likelihood of the site being vandalised was also taken in to account. The lack of a suitable location for the stilling well to be secured to the bridge also resulted in some sites being rejected. In all, 63 possible sites were inspected before the 15 catchments were finally chosen.

2.2 Catchment instrumentation

The primary function of the instrumentation was to record flood hydrographs as accurately as possible. The time and date of the peak level or flow are used, along with rainfall, in the calculation of a rainfall-runoff lag time (LAG), and the complete flood hydrograph is needed in the computation of the time to peak of the unit hydrograph (Tp). Since the peak level is nearly always coincident with peak flow — and level can be used as a surrogate for flow in the generation of the unit hydrograph (Chapter 6) — then in the context of this study recording the levels was an acceptable alternative to measuring the flows.

The first catchment was instrumented in September 1989; the last installation was completed by March 1990. When sufficient events had been recorded at a given site the equipment was removed. Consequently data collection ceased at four catchments in March 1991, at a further seven in March 1992, and stopped completely at the end of March 1993. Figure 2.2 shows the period of record for each of the 15 catchments.

At each site, water level changes were sensed by a pressure transducer and the information was recorded by a programmable data logger.

Water level measurement

Pressure transducers have the advantages that they do not necessarily require a stilling well, they are relatively easy to install, and they require less maintenance than a conventional float and counter-weight instrument. The pressure transducers used in this study were from the PDCR830 Series manufactured by Druck. These are general purpose depth sensors which are supplied with their own

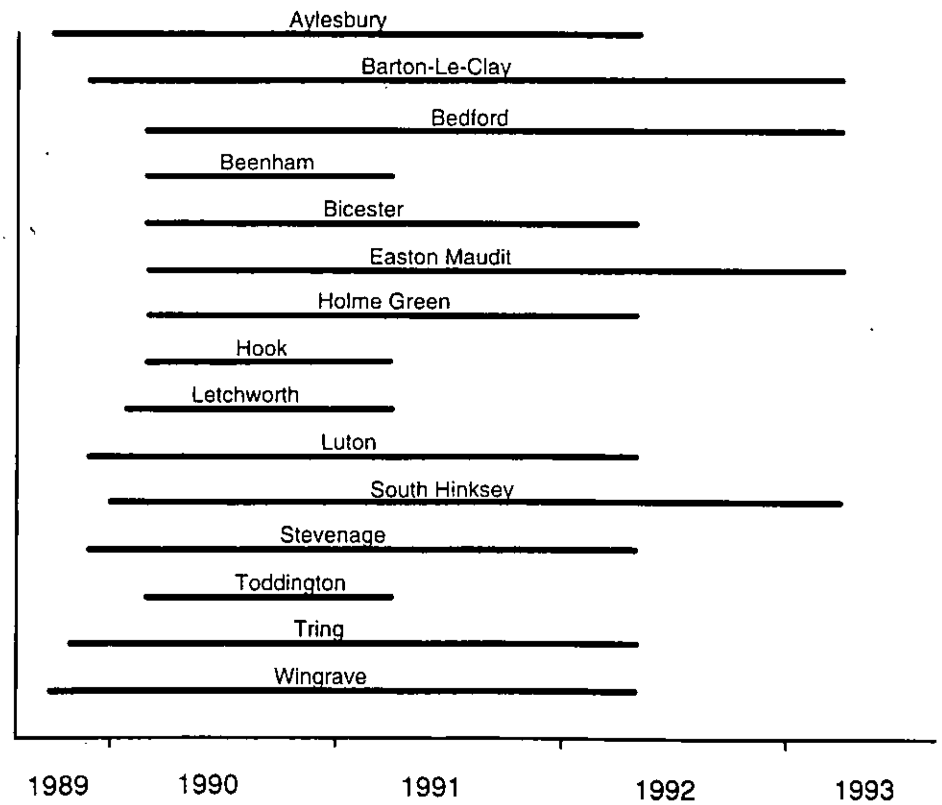

Figure 2.2 *Water level data — record lengths*

vented cable to balance to the atmosphere. The instrument range is 0-70 millibars, which is approximately equivalent to a range of 0-725 mm in depth, but the transducer was over-pressured to alter the scale to 0-7 metres.

Pressure transducers are often unreliable when monitoring absolute values, relative to a fixed datum, with the recorded value gradually departing or 'drifting' from the true value. For the purposes of this study, as long as there was no serious drift during the flood event itself, this would not matter since the absolute values themselves were less important than the relative change. However, in order to monitor transducer performance, stage boards were installed at 13 sites and read during each site visit. At the other two sites, Bicester and Tring, installing stage boards in the narrow concrete channel adjacent to the sites might have led to accumulation of debris against the board during high flows, increasing the risk of the channel or culvert being blocked. Here a 'dipflash' was used to measure the distance from a fixed datum to the water surface during each site visit (Smart *et al.*, 1977). These values were compared with the transducer data in the same way as the readings from the stage boards.

Although the transducers were positioned inside the stilling well (see page 8), at a height which placed them above any sediment lying on the stream bed, siltation did occur within stilling wells after floods at some sites. The transducers were removed and cleaned where silt was observed to have accumulated and as much material as possible was removed from inside the stilling well. However, even where silt was seen to have adhered to the transducer, this appeared to have had little effect on the instrument's accuracy. The most serious scenario affecting the instrument's reliability seemed to be cold dry spells of weather when temperatures went below freezing and water levels were very low. During these conditions the recorded data could be spurious, perhaps as the result of water freezing on the transducer diaphragm. At the onset of warmer weather the logged levels often returned to more acceptable values, but in some cases the equipment had to be replaced.

In general the pressure transducers performed well, with less than 5% data loss at most sites. Drift of the order of 10 - 20 mm over a month was observed at many sites, but this appeared to be evenly distributed in time and was unlikely to have been significant over the duration of an event. The largest discrepancies occurred at sites where the head of water being measured was small, or the stream was ephemeral. At sites where a reasonable depth of water was present all year round, the transducer was accurate both in absolute and relative terms.

Data logging

Each pressure transducer was linked to a Campbell Scientific CR10 logger, programmed to record water levels more frequently during flood events than during the intervening periods. This was achieved by incorporating a user-defined rise in water level or 'trip' in the logger software. For the majority of sites the trip was activated only if water levels rose at least 20 mm in 30 minutes or less, but for two sites, Easton Maudit and Bedford, the trip was reduced to 10 mm in 30 minutes or less after a number of small events appeared to have been missed. Once the trip had been activated, the logger switched to an event-logging mode where data were recorded more frequently.

The event-logging mode began with water levels being recorded at one-minute intervals. This frequency of recording continued while the criteria for the trip were still satisfied. When these criteria were no longer fulfilled, logging at one-minute intervals continued for a further 30 minutes and then ceased. Typically this meant that the rising limb, the peak and the early part of the recession limb were defined by one-minute data. However, if the hydrograph did not have a steep rising limb, then sometimes levels ceased to be recorded at one-minute intervals before the flood peak had been reached. On the cessation of one-minute logging, levels were recorded every five minutes for one hour and then every 15 minutes for a further 90 minutes. Logging at short time intervals for long periods is possible, but there is obviously a need to balance this against the speed at which the logger storage becomes filled. In the majority of cases this frequency of logging produced an accurate definition of the flood hydrograph without recording superfluous data, thereby reducing the frequency of data collection visits necessary.

As well as recording water levels specifically during a flood event, the logger was programmed to record water levels on the hour, together with the depths and times of the maximum and the minimum level during the preceding hour. This not only provided useful level information outside event-logging periods, but the maximum values also accurately determined the time of the flood peak in cases where one-minute logging had ceased before the peak had occurred.

Stilling wells

At all sites except Tring and Bicester, a 300 mm diameter PVC stilling well was used to house the pressure transducer and logger. The length of the stilling well was governed by the need to have safe and easy access to the instruments and by the requirement to keep the logger above the highest water level likely to occur. Whilst complying with these conditions it was also important to make the installation as unobtrusive as possible.

The transducer was secured near the bottom of a length of angle-section, which in turn was fixed to the inside of the stilling well. The angle-section was easily removed to enable the transducer to be cleaned, adjusted, or replaced. Locating the logger on shelving near the top of the PVC stilling well kept it dry and protected the equipment from vandalism. A padlocked bar was passed through the stilling well and its steel cap to prevent unauthorised access.

However at the Luton site, a few weeks after installation the padlock was smashed and the instruments were damaged. Since the padlocks appeared to be the weak point they were replaced at all sites, after some alterations to the bar, by special wheel bolts used to secure alloy wheels on motor vehicles (Figure 2.3). The presence of a British Waterways gauge at Tring allowed the transducer to be secured inside a conventional gauging hut.

At Bicester there was a risk that the 300 mm diameter stilling well would cause too great an obstruction at the entrance to the culvert, so a smaller diameter steel tube was used to house the transducer and cable, with the logger in the 'cut off' stilling well (Plate 2.1).

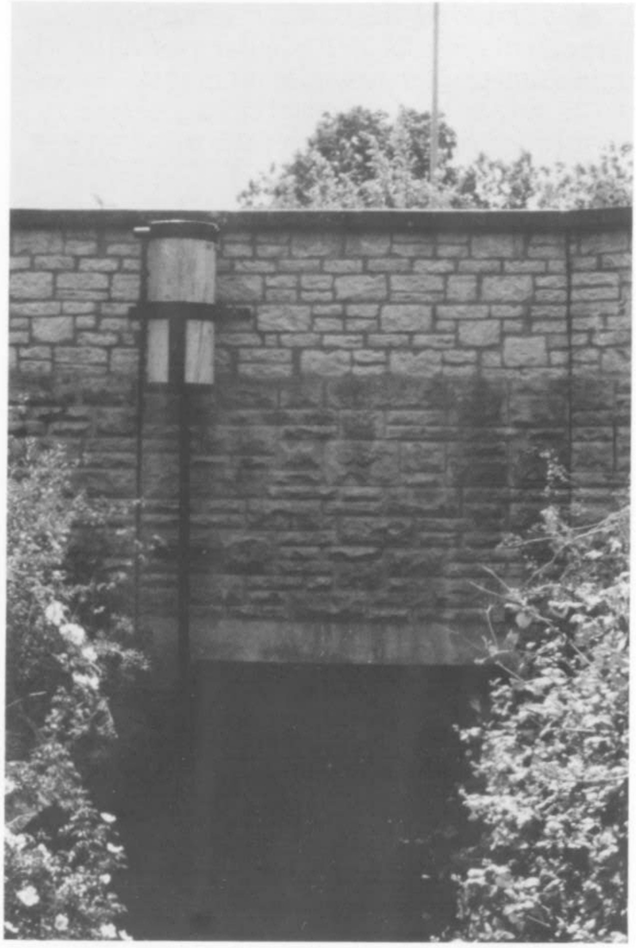

Plate 2.1 *Small-diameter pipe used to minimise obstruction to the flow, Bicester*

Installation

In the majority of cases the stilling wells were secured to road bridges owned by the County Council, since these provided easy access to the site for data collection and routine maintenance. Authorisation to install the recorders was also obtained from the National Rivers Authority.

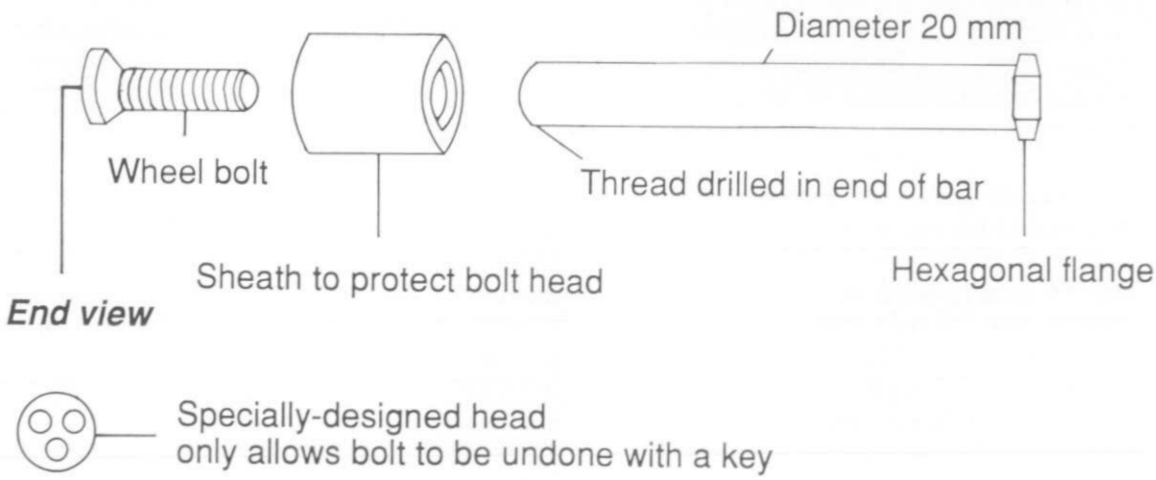

Figure 2.3 *Locking bar with special wheel bolt to reduce vandalism*

When positioning the stilling well and pressure transducer, account had to be taken of the need to record the full range of levels likely to occur, without obstructing the flow in a way which could increase the risk of flooding upstream. This was usually achieved by positioning the stilling well away from the culvert aperture, or between apertures (Plate 2.2) at sites with two or more culverts. Where possible, the stilling well was sited on the upstream side of the culvert or bridge. If the culvert surcharged, the hydrograph would not then be truncated as it might have been on the downstream side.

Plate 2.2 *Stilling well positioned between twin culverts, Wingrave*

Once the location of the stilling well had been selected relative to the channel, the PVC well was rested on, or pushed into, the stream bed. The top was held in position by wrapping two semi-circular bands around the well and then securing it to the bridge. If the well could not be pushed into the bed, or was particularly long, then a second fixing point was often needed. Several methods for attaching the bands to the bridge have been used: they are described in detail by Marshall (1989). At the request of bridge owners, all securing bolts were resin-bonded rather than self-expanding, to minimise the stress on the brickwork or concrete. Where possible, bridge rails were used to secure the well (Plate 2.3), obviating the need to drill into the structure.

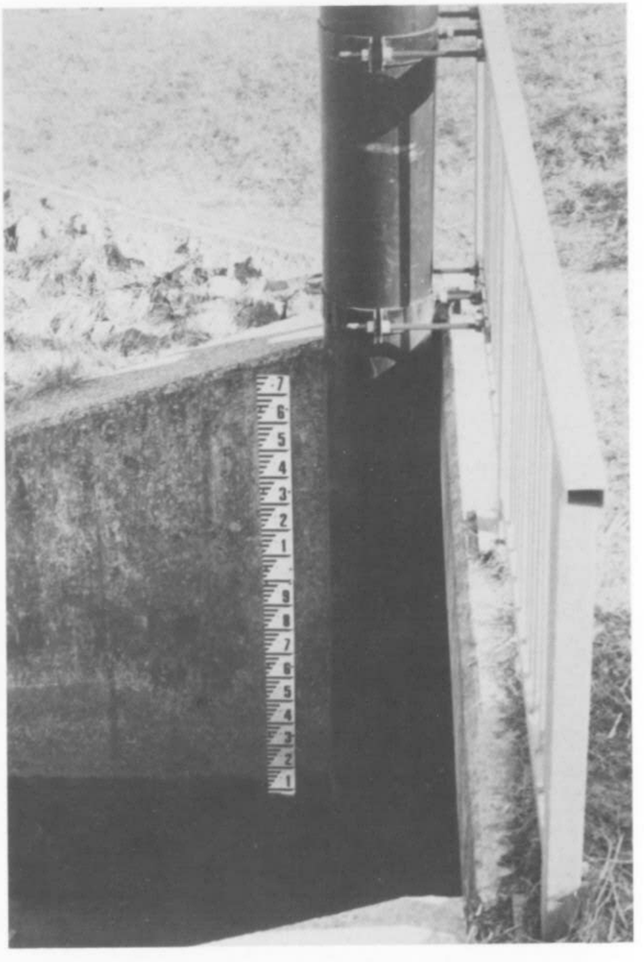

Plate 2.3 *Bridge rails used to secure top of stilling well, Stevenage*

Data collection

Given the frequency of logging described, the Campbell loggers had sufficient storage space to hold 62 days of data. However, to minimise the loss of data in the case of equipment failure, each site was visited approximately monthly.

A key pad was used to communicate with the data logger (Plate 2.4) in order to check the internal clock and battery state, examine the stored data, label the data prior to transfer to the storage module and implement logger software modifications. After marking the end of the data with a label, the data were copied to an SM192 storage module and, on returning to the office,

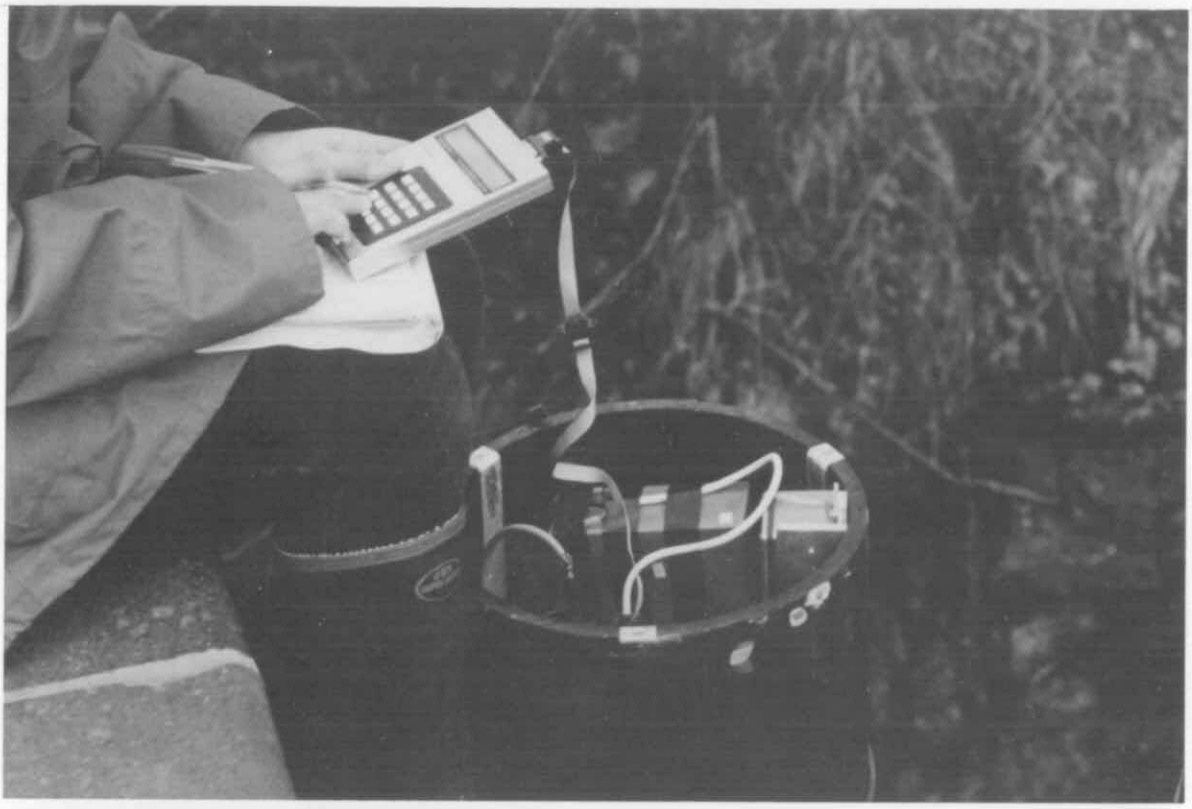

Plate 2.4 *Communicating with a logger using a key pad*

to an IBM PS/2 via an SC532 interface using Campbell software. A copy of the data remained on the logger and storage module until such time as the stores became full, thereby providing the security of a temporary 'backup' for downloaded data. Figure 2.4 summarises the water level data collation procedure.

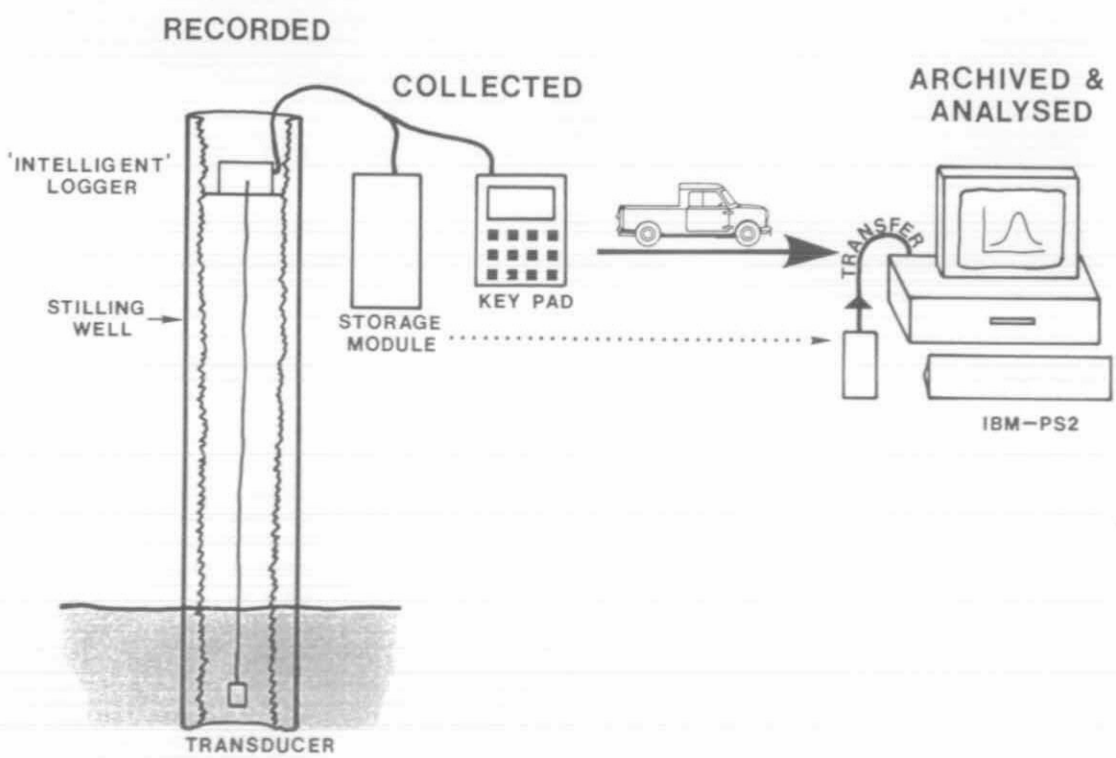

Figure 2.4 *Diagrammatic representation of water level data collation*

Costs

Using a generalised estimation procedure to calculate response times will never be as good as instrumenting the problem catchment and observing the response to rainfall. An important aspect of this study was to demonstrate that good results can be achieved with low-cost instrumentation installed over a relatively short period.

The 1993 sensor and logger cost for each site, including software, was approximately £1500 including VAT (pressure transducer £250; logger £1250). Pressure transducers can be secured in the required location in a number of ways without using stilling wells. They were used in this instance because the IH workshop had developed a way of housing the logger and transducer inside the well, which protected the equipment from the weather and from vandalism. The stilling wells cost approximately £60 per metre (including VAT), with caps, brackets, shelving and locking system costing an additional £90 per site.

To service the 15 sites in this study, two key pads (£250 each) and two storage modules (£500 each) were purchased. All prices are given as a guide only.

3 Rainfall measurement

3.1 The Chenies weather radar

The Chenies weather radar was set up by a consortium consisting of the Ministry of Agriculture, Fisheries and Food (MAFF), the Meteorological Office and the National Rivers Authority (NRA). The radar is situated on the Chilterns — a chalk downland to the northwest of London (see Figure 2.1). The tower is 15 m high (Plate 3.1) and the site, approximately 140 m AOD, is at OS grid reference TQ 016 999. The adjacent building houses a PDP 11 computer on which incoming data are processed for transmission to the Met. Office, the NRA and the London Weather Centre.

The radar revolves 1.2 times per minute, completing four revolutions at reducing angles of elevation, between 4.5° and 0.5°, within each five-minute period. Rainfall intensity data (mm h^{-1}), received from all four elevations over a five-minute period, are gridded at two different spatial definitions: within a 76 km radius of the radar the grid size is 2 km × 2 km, while a coarser 5 km × 5 km grid is constructed out to a 210 km radius. Both the 2 km and 5 km grids are computed at five-minute intervals. The 15 catchments instrumented were all located within 76 km of the Chenies radar and consequently only the 2 km × 2 km gridded data were used for rainfall analysis.

Plate 3.1 *Chenies weather radar*

The derived data grids are not centred on the Chenies radar, but coincide with the National Grid. Grid reference TL 020000, one of the locations where the corners of four cells of both grid sizes meet, is a convenient point of reference: the 2 km grid square containing the Chenies transmitter is defined by TQ 000980 and TL 020000, while the corresponding 5 km grid square is defined by SU 970950 and TL 020000. The catchment maps in Appendix 1 illustrate the 2 km × 2 km grid squares that are relevant to each instrumented catchment: each catchment made use of radar data from between 2 and 12 cells. Table 3.1 lists the fraction of each individual 4 km^2 cell required to assemble the gridded rainfall data into catchment average values.

3.2 The use of uncalibrated radar data

Calibrating weather radar data is a complex exercise and has been the subject of several studies (e.g. Moore *et al.*, 1989a; 1989 b; 1991). Most hydrological applications require absolute rather than relative rainfall intensities, and it is then necessary to use calibrated data. However, uncalibrated radar data can be used to determine temporal parameters of a rainfall event, provided that no significant change in the calibration factor occurs during the event. The duration, time of peak intensity, centroid and profile of a rainfall event were determined from uncalibrated data within this study.

Comparisons between radar data and ADAS recording raingauge data from two locations, North Weald (TL 496043) and Conington (TL 333670), have shown good temporal agreement. The centroids of five rainfall events at each of these two sites, calculated from both data types, were found to differ in their geometric means by only five and six minutes respectively.

3.3 Evaluation of catchment temporal rainfall profile

Once a catchment boundary had been superimposed on the 2 km × 2 km radar grid, it was possible to determine the fraction of the catchment lying within each 4 km^2 cell (see Table 3.1). Catchment average values of uncalibrated radar rainfall intensity were

Table 3.1 *Location of catchment 2 km × 2 km radar cells (with fractional weights)*

Catchment	Grid reference of south-west corner of cells relevant to catchment			
Aylesbury	SP8210 (0.286)	SP8212 (0.253)	SP8410 (0.250)	SP8412 (0.211)
Barton-Le-Clay	TL0830 (0.928)	TL0828 (0.067)	TL0832 (0.005)	
Bedford	TL0844 (0.174)	TL0846 (0.151)	TL0642 (0.148)	TL0644 (0.137)
	TL0842 (0.115)	TL1044 (0.090)	TL1048 (0.066)	TL0646 (0.060)
	TL1046 (0.023)	TL0848 (0.022)	TL0640 (0.009)	TL1042 (0.005)
Beenham	SU5668 (0.793)	SU5468 (0.105)	SU5868 (0.102)	
Bicester	SP5822 (0.610)	SP5824 (0.390)		
Easton Maudit	SP8656 (0.251)	SP8654 (0.170)	SP8856 (0.140)	SP8454 (0.128)
	SP8456 (0.123)	SP8658 (0.107)	SP8858 (0.043)	SP8854 (0.033)
	SP8254 (0.005)			
Holme Green	SU8464 (0.359)	SU8266 (0.252)	SU8466 (0.245)	SU8264 (0.120)
	SU8664 (0.018)	SU8468 (0.005)	SU8462 (0.001)	
Hook	SU7054 (0.584)	SU7254 (0.297)	SU7052 (0.119)	
Letchworth	TL2232 (0.388)	TL2032 (0.300)	TL2230 (0.154)	TL2030 (0.072)
	TL2234 (0.050)	TL2034 (0.036)		
Luton	TL0220 (0.370)	TL0222 (0.209)	TL0020 (0.202)	TL0422 (0.176)
	TL0420 (0.028)	TL0218 (0.015)		
South Hinksey	SP4802 (0.685)	SP5002 (0.286)	SP5004 (0.029)	
Stevenage	TL2624 (0.534)	TL2622 (0.329)	TL2424 (0.101)	TL2626 (0.035)
	TL2426 (0.001)			
Toddington	TL0028 (0.937)	TL0228 (0.061)	TL0026 (0.002)	
Tring	SP9210 (0.253)	SP9008 (0.246)	SP9010 (0.221)	SP8808 (0.142)
	SP9212 (0.090)	SP9208 (0.043)	SP8810 (0.005)	
Wingrave	SP8818 (0.475)	SP8816 (0.221)	SP8618 (0.158)	SP9018 (0.125)
	SP8616 (0.016)	SP9016 (0.005)		

calculated at five-minute intervals using a weighted area approach and were then used to compute the temporal centroid of the rainfall event. Figure 3.1 illustrates a storm which occurred over the Wingrave catchment on 20th December 1989. The centroid was calculated from the instantaneous rainfall intensity data represented in the figure by the discrete five-minute interval ordinates. The centroid of this event was computed to occur at 18.54 GMT.

The use of rainfall radar data eliminated the need to instrument the 15 research catchments with recording raingauges, effectively halving the instrumentation cost. At the same time it provided an enhanced spatial appreciation of the rainfall, especially on the larger catchments.

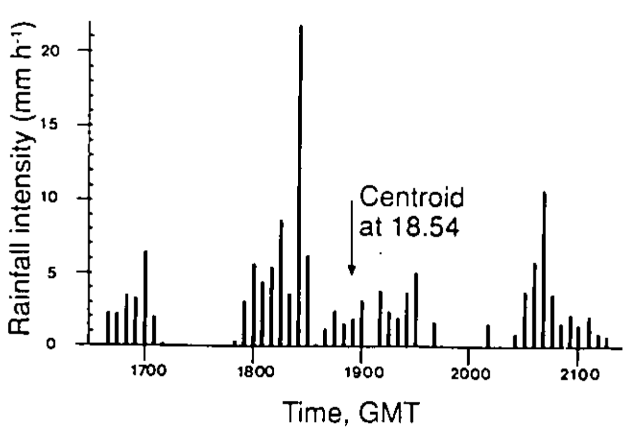

Figure 3.1 *Instantaneous uncalibrated five-minute interval catchment average rainfall for the event at Wingrave on 20th December 1989*

4 Catchment characteristics for primary dataset

4.1 Introduction

The FSR and its supplementary reports identified a number of catchment characteristics which could be used to estimate Tp and QBAR on ungauged catchments. The way in which some of these characteristics were calculated for the purposes of this study differed in some respects to the definitions described in the FSR, largely to take account of the smaller catchment size. One new map-based characteristic (FOREST) was defined: it represents the fraction of the catchment occupied by woodland.

A hydrologically-appropriate digital terrain model (DTM) has been developed at the Institute of Hydrology from digitally-held rivers and contours taken from Ordnance Survey 1:50 000 maps. DTM-generated valley bottoms are forced to coincide with mapped rivers; gridded elevations are then produced using multiple transects and curve-fitting procedures (Morris & Flavin, 1990). The completion of the DTM for much of the United Kingdom has allowed the calculation of characteristics using gridded elevation data. This has meant that some catchment attributes previously derived from Ordnance Survey maps, and new characteristics too time-consuming to produce from maps, could be derived automatically from the DTM.

4.2 Map-based characteristics

To estimate Tp(0), Boorman (1985) recommends an equation which uses S1085, URBAN, SAAR and MSL. Values of these characteristics, along with AREA, SOIL and FOREST, were calculated for the 15 catchments and these are given in Table 4.1. The calculation of these variables is described in detail in the FSR (Vol I, Chapter 4), but a brief summary of their derivation is given here, since in some instances there is a degree of departure from the FSR procedures.

Table 4.1 *Map-based catchment characteristics*

Catchment	AREA (km^2)	URBAN	MSL (km)	S1085 (m/km)	SAAR (mm)	SOIL	FOREST
Aylesbury	1.74	0.631	1.900	6.34	629	0.450	0.020
Barton-Le-Clay	2.27	0.004	2.250	7.70	612	0.150	0.010
Bedford	22.92	0.040	9.550	1.33	550	0.426	0.060
Beenham	3.40	0.020	2.350	13.30	700	0.450	0.420
Bicester	1.46	0.652	0.700	8.00	655	0.150	0.003
Easton Maudit	15.76	0.017	5.800	6.44	621	0.410	0.170
Holme Green	9.81	0.154	4.150	11.57	671	0.414	0.390
Hook	2.49	0.084	1.725	7.73	725	0.450	0.190
Letchworth	8.52	0.845	0.925	7.21	575	0.344	0.030
Luton	9.05	0.630	0.680	0.98	675	0.150	0.030
South Hinksey	1.49	0.005	2.200	29.39	650	0.400	0.060
Stevenage	4.14	0.492	1.300	8.21	638	0.300	0.030
Toddington	0.88	0.384	1.100	31.51	645	0.450	0.006
Tring	8.92	0.118	0.425	18.82	729	0.150	0.240
Wingrave	5.85	0.004	2.100	6.35	654	0.450	0.050

AREA
Catchment boundaries were drawn on Ordnance Survey (OS) 1:25 000 maps (Pathfinder Series) with the aid of catchment surveys and drainage authority plans. Reference to surface water drainage plans was particularly important in urban areas in order to define the effective boundary accurately. The boundaries were digitised, and the catchment area calculated from watershed coordinates recorded to the nearest 100 m.

URBAN
The fraction of each catchment given over to urban development was obtained from the OS Pathfinder Series, updated where necessary by catchment surveys. Urban areas are represented at a level of detail at this scale (1:25 000) which is more appropriate to small catchments than the 1:50 000 maps more commonly used. Although no attempt was made to remove residential gardens from the urban fraction, larger non-urban areas, such as recreation and sports fields, cemeteries and allotments, were excluded.

MSL and S1085
Main stream length (MSL) is defined as the longest stream in the catchment, as shown on the OS 1:25 000 map. S1085 is the gradient of the longest stream between points 10% and 85% upstream of the catchment outlet. Both of these were computed using the FSR defined procedures.

SAAR
The Standard Average Annual Rainfall was derived manually by overlaying the catchment boundary on the Met. Office map of average annual rainfall for the period 1941-70. A weighted area method was used to calculate a catchment average value.

SOIL
An overlay of the catchment boundary was placed on the FSR map of Winter Rain Acceptance Potential (NERC, 1975, Vol V, I.4.18(S), revised 1978; FSSR 7) and the fraction of the catchment in each of the five classes was calculated. From this the SOIL index was calculated according to the formula given in the FSR (Vol I, Section 4.2.6).

FOREST
The fraction of the catchment shown as woodland or forest was not one of the catchment characteristics considered for the estimation of Tp in the FSR or supplementary reports. However, it was calculated here, since afforestation is known to have an effect on catchment response (e.g. Robinson *et al.*, 1991): the 'green areas' on the OS 1:25 000 Pathfinder Series gave an estimate of forest area.

4.3 DTM-based characteristics

Comparison of catchment areas

A prerequisite for the production of catchment characteristics is a precise definition of the catchment boundary. By selecting the nearest 50 m × 50 m DTM grid point to each recording site, the catchment boundaries were defined from automatically-derived drainage paths (Morris & Heerdegen, 1988). Before using these boundaries to derive catchment characteristics, a comparison was undertaken between the drainage areas produced by the DTM (DTMAREA) and those considered to be the 'true' areas.

Figure 4.1 indicates that there is good agreement between the two approaches, except for the four catchments indicated: Barton-Le-Clay, Bicester, Luton and Tring. Any catchment which is not defined by topography alone is likely to have a DTM-derived area unrepresentative of the true catchment. Bicester, Luton and Tring are all partly urbanised, generating surface water drainage which does not conform to the topographic boundary: this accounts for the differences shown. The Tring site is unusual in that the stream being gauged is taken under a canal in a culvert just upstream of the water level recorder (see the catchment map in Appendix 1). The high canal embankment means that the topography dictates that the DTM-derived boundary is very small. In addition an open channel, which discharges into the canal, intercepts most of the surface water drainage from the north-west part of Tring, thereby excluding an area which would be included by referring to elevation data alone. Although Barton-Le-Clay is a rural catchment, the flat terrain means that much of the boundary is determined by agricultural drainage rather than topography. Such difficulties are likely to occur in flat or very small catchments. Since the catchments defined by the DTM were thought to be unrepresentative, further DTM-derived characteristics have not been computed for these four cases.

Stream network and slope

The 'blue lines' on OS maps, even at a scale of 1:25 000, often do not depict the full extent of the stream network: indeed, ephemeral streams may not be shown at all. Although OS surveyors

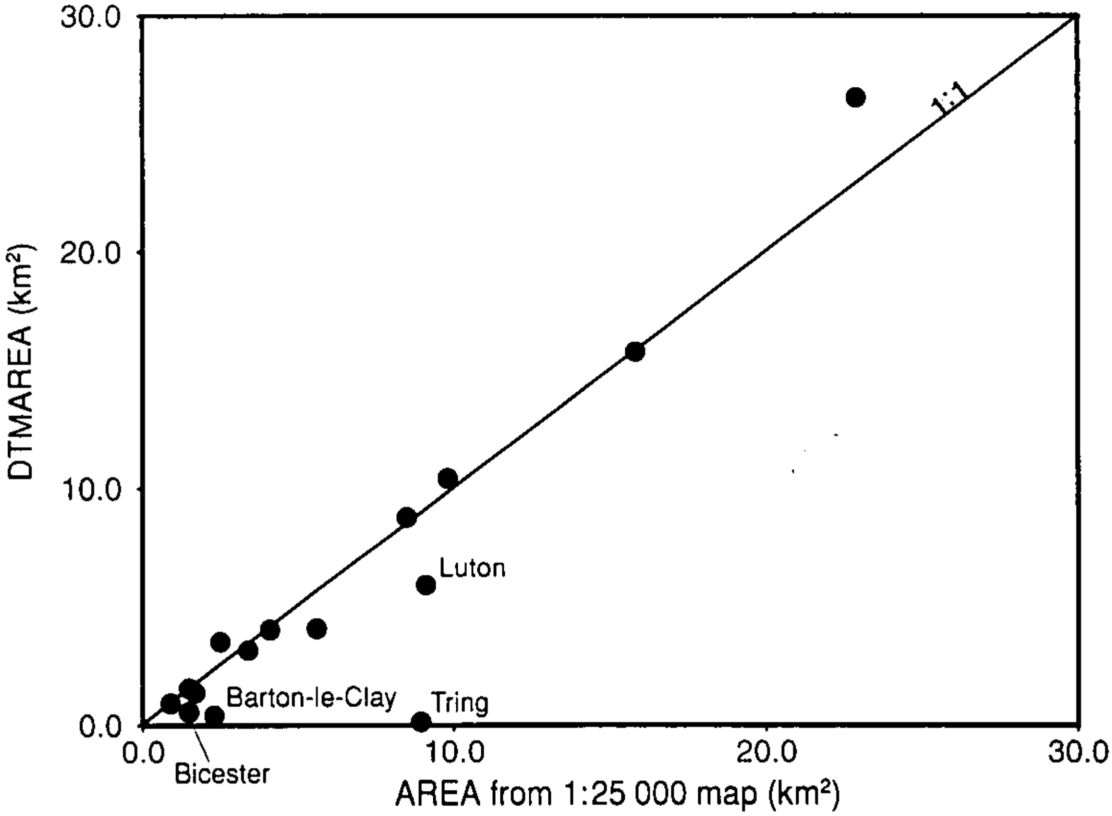

Figure 4.1 *Comparison of drainage areas*

have guidelines showing the criteria which need to be met for a watercourse to be shown on a map as a blue line, inevitably there is a degree of subjectivity. Comparisons of stream networks from 1:25 000 maps with those extracted from aerial photographs (Lloyd, 1991), and validated by field surveys, showed that the map network often underestimated the contributing network that exists for much of the year, in particular during flood events.

Since the DTM holds the number of 50 m × 50 m squares draining to each point, a stream network can be generated based on a threshold of contributing area. All flow paths exceeding the threshold are designated part of the stream network and therefore the choice of threshold determines the extent of the network. Figure 4.2 illustrates how, for each catchment, the total length of the network varies when the contributing area threshold is changed. Although the curves are steep when the threshold is small, indicating that small variations in threshold give rise to large variations in network length, the network length becomes relatively stable when the threshold is greater than 5.0 hectares (20 grid squares).

Stream networks were generated at several sites using a range of thresholds and compared with the networks derived from aerial photographs and catchment surveys. Figure 4.3 shows how, for the Wingrave catchment, a threshold of 7.5 hectares generated DTM flow paths which provided an acceptable representation of the observed stream network. For this study, a threshold of 7.5 hectares was eventually chosen as standard, since it produced flow paths which were also representative of the network at the other sites.

In the same way that MSL and S1085 were calculated using the longest catchment stream on the 1:25000 OS map (Section 4.2), these two characteristics were also calculated using the longest flow path within the DTM-derived network. Figure 4.4 illustrates how the main stream lengths (DTMMSL) are greater than the map-based values, particularly in partly urbanised catchments. In urban areas, streams tend not to appear on OS maps until they have emerged from culverted sections. Where these culverts are long, this can result in a significantly reduced value of MSL. With the exception of Hook, the catchments named on Figure 4.4 are all heavily urbanised. Figure 4.5 compares main channel slope data calculated from OS maps with those computed from the DTM. Although DTM-derived MSL data are systematically greater than those calculated from maps, the

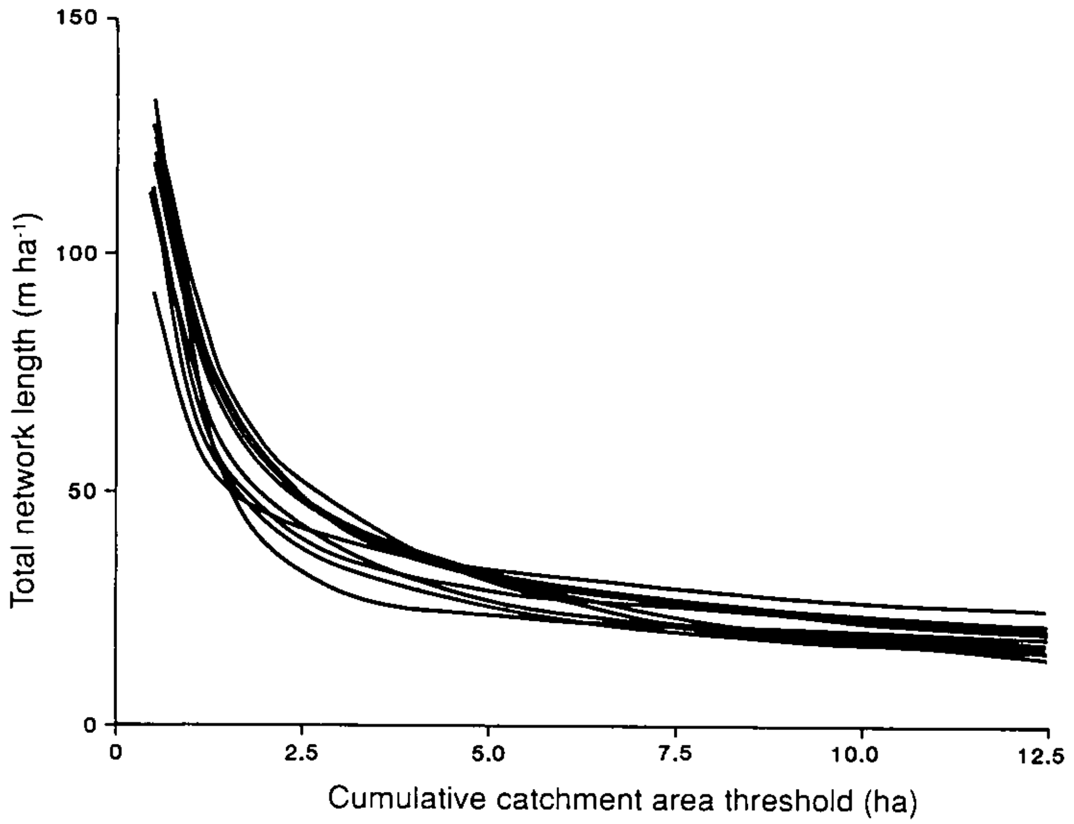

Figure 4.2 *Variation in stream length with changes in contributing area threshold*

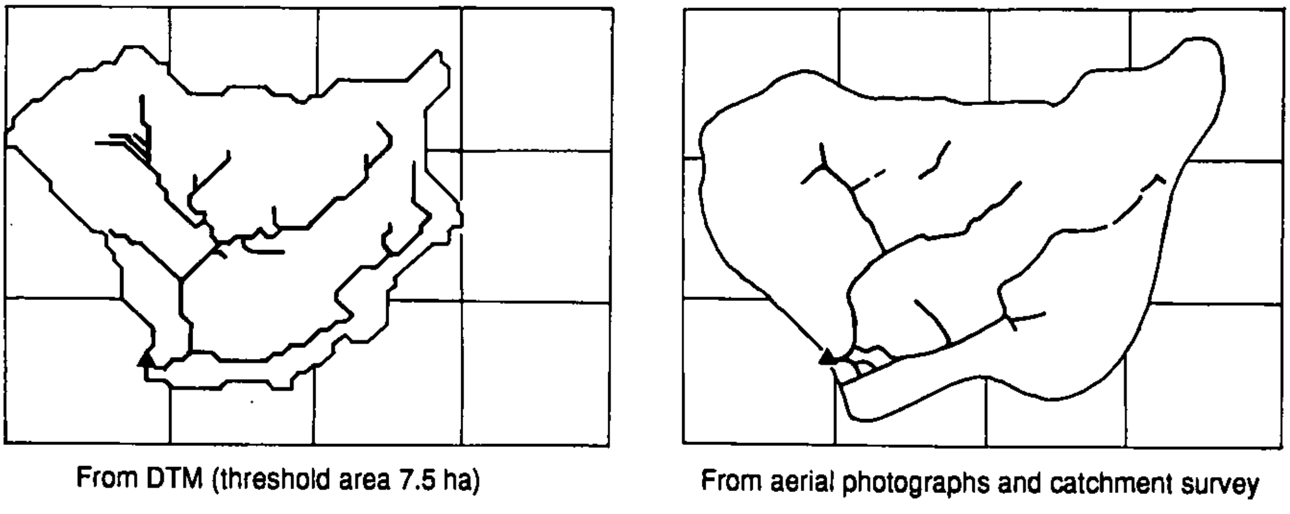

Figure 4.3 Comparison of stream networks, Wingrave catchment

two sets of S1085 values are in broad agreement.

Two other catchment characteristics were produced directly from the DTM-derived stream network: the number of stream sources or network magnitude (DTMMAG), and the total network length (DTMLEN). Both of these characteristics describe the density of the flow paths produced by the chosen threshold (7.5 hectares).

The slope characteristics, mean river slope (DTMRIVS) and mean land slope (DTMLANS) were also calculated. DTMRIVS was computed using those grid point elevations which were designated part of the DTM-derived stream network, whereas DTMLANS was derived from all remaining grid points in the catchment (i.e. those *not* designated part of the network). These two slope characteristics in particular would have been exceedingly time-consuming to calculate from OS maps.

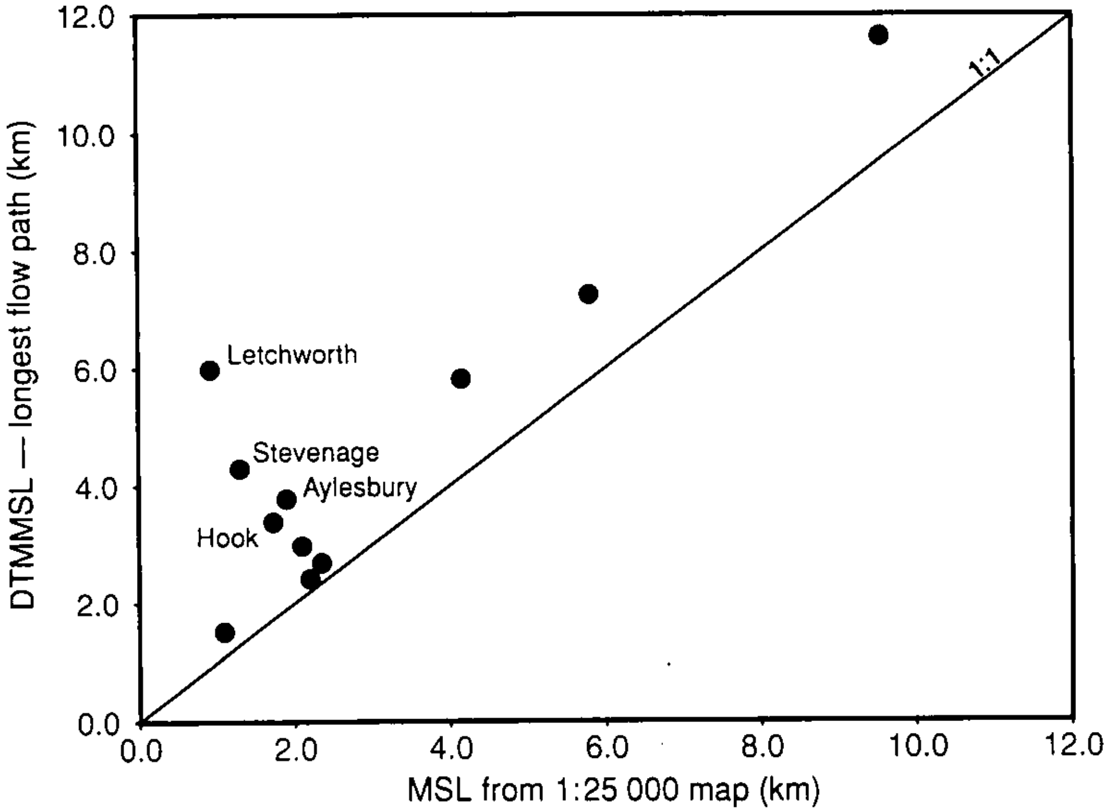

Figure 4.4 *Comparison of main stream lengths*

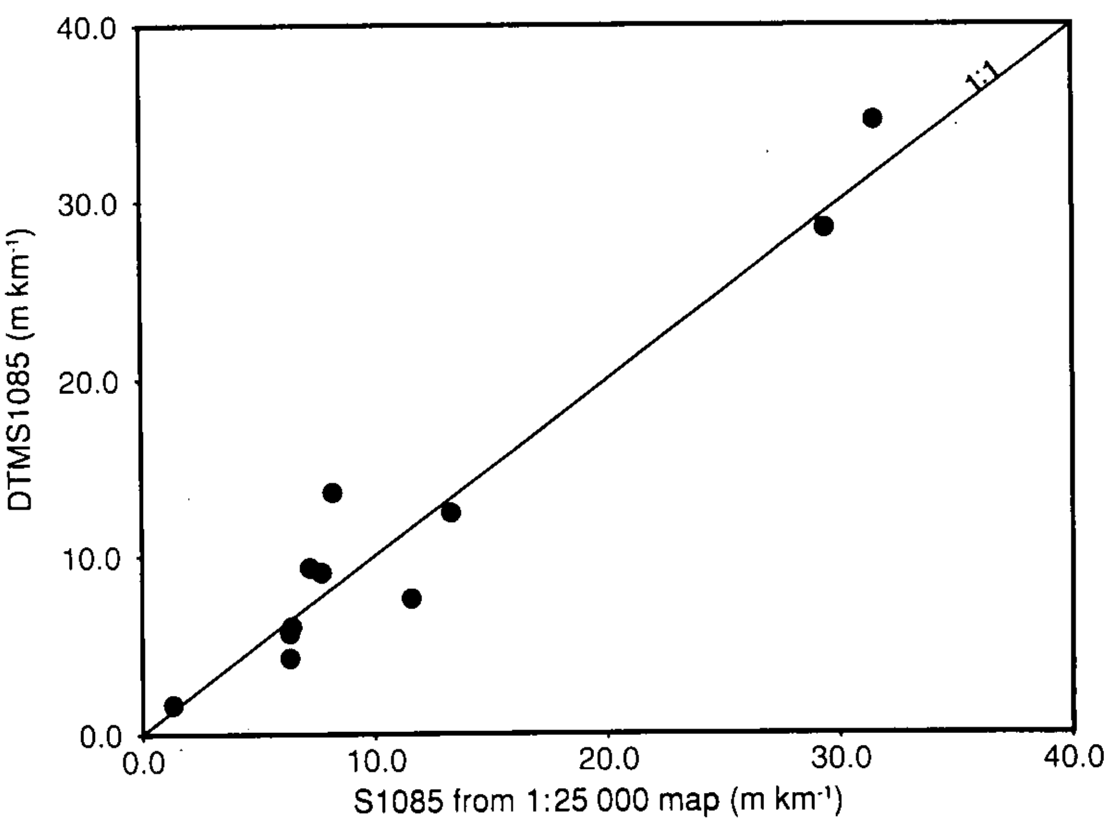

Figure 4.5 *Comparison of main channel slopes*

The altitude of the catchment outlet (DTMALT) and the mean altitude of the catchment (DTMMALT) were also computed: these two characteristics are included as the last two columns in the list of DTM catchment characteristics in Table 4.2.

Table 4.2 *DTM-based catchment characteristics (11 catchments only)*

Catchment	DTM-AREA (km^2)	DTM-MSL (km)	DTM-S1085 (m/km)	DTM-MAG	DTM-LEN (km)	DTM-RIVS (m/km)	DTM-LANS (m/km)	DTM-ALT (m AOD)	DTM-MALT (m AOD)
Aylesbury	1.365	3.776	5.660	3	4.238	6.109	14.166	83.4	96.281
Bedford	26.547	11.625	1.660	102	109.213	8.377	18.241	22.3	39.363
Beenham	3.160	2.693	12.450	9	6.440	20.320	43.117	85.5	111.086
Easton Maudit	15.782	7.254	6.016	54	35.027	13.802	25.816	66.4	93.633
Holme Green	10.417	5.823	7.597	35	27.952	13.985	26.949	53.9	80.459
Hook	3.507	3.392	9.080	12	7.351	14.156	27.726	63.1	85.502
Letchworth	8.795	5.987	9.364	31	23.241	16.153	28.890	59.2	90.931
South Hinksey	1.557	2.423	28.487	2	3.297	28.807	74.622	61.2	113.550
Stevenage	4.020	4.295	13.661	9	10.406	16.864	34.663	77.4	107.109
Toddington	0.927	1.519	34.557	3	2.052	38.777	48.674	96.1	135.371
Wingrave	4.080	2.976	4.254	14	9.827	12.486	33.262	83.8	99.227

5 Summary of other datasets

5.1 ADAS catchments

The ADAS Soil & Water Research Centre, based at Cambridge, also undertook research on small catchment response times during the period of this investigation. As part of the collaboration between the two organisations, mean response times and catchment characteristics were exchanged.

The map-based characteristics for the nine ADAS catchments are listed in Table 5.1, along with their mean response times. The DTM-based characteristics described in Section 4.3 were also computed (at IH) for these catchments and are presented in Table 5.2 (page 22). Merging the 15 IH and nine ADAS catchments produced a larger and more diverse dataset.

5.2 Small catchments in the flood event archive

The IH flood event archive includes 48 small catchments (<25 km^2) with LAG and Tp data (defined in section 6.1). The majority of characteristics used for these catchments were taken directly from the archive, but all MSL and S1085 values were recalculated using Second Series Ordnance Survey 1:25 000 maps (Pathfinder or Outdoor Leisure), thus ensuring consistency with those calculated for the IH and ADAS instrumented catchments.

Characteristics for the flood event archive catchments are presented in Table 5.3 on page 23, along with the geometric mean LAG and Tp(0) times.

Table 5.1 *Map-based catchment characteristics and mean response times, ADAS catchments*

Catchment	AREA *(km²)*	URBAN	MSL *(km)*	S1085 *(m/km)*	SAAR *(mm)*	SOIL	FOREST	LAG Geometric mean *(hours)*	Tp(0) Geometric mean *(hours)*
Cliftonthorpe SK357189	1.120	0.000	1.330	12.65	714	0.375	0.010	2.47	2.13
Drayton DT2 SP162550	5.470	0.026	3.020	13.79	619	0.450	0.024	4.41	3.89
Lower Smisby SK353182	2.600	0.031	2.170	13.85	714	0.380	0.010	2.97	3.08
North Weald TL494036	1.600	0.000	1.640	13.88	650	0.425	0.500	4.01	4.20
Pwllpeiran SN811786	1.801	0.000	3.250	24.24	1727	0.500	0.190	3.31	3.17
Redesdale RD2 NY832960	4.490	0.000	3.000	50.66	940	0.473	0.040	2.74	2.78
Redesdale RD3 NY825957	1.901	0.000	2.020	45.49	940	0.475	0.000	2.26	2.49
Trawsgoed SN675732	2.321	0.000	2.750	80.00	1199	0.413	0.210	1.51	1.45
Upper Smisby SK342188	1.160	0.000	0.716	16.97	714	0.375	0.020	2.34	2.45

Table 5.2 *DTM-based catchment characteristics, ADAS catchments*

Catchment	DTM-AREA (km^2)	DTM-MSL (km)	DTM-S1085 (m/km)	DTM-MAG	DTM-LEN (km)	DTM-RIVS (m/km)	DTM-LANS (m/km)	DTM-MALT (m AOD)
Cliftonthorpe SK35701895	1.122	1.428	20.271	3	1.669	20.494	40.446	168.773
Drayton DT2 SP16205495	4.747	3.464	15.628	16	10.561	16.774	39.053	67.753
Lower Smisby SK35401820	2.470	2.593	13.861	8	5.024	19.107	38.850	159.598
North Weald TL49500360	1.492	1.569	16.788	9	2.814	21.688	25.072	103.167
Pwllpeiran SN81107860	2.000	2.660	20.905	8	4.409	33.830	79.547	531.709
Redesdale RD2 NY83209595	4.127	2.726	40.498	13	11.516	49.483	65.486	291.898
Redesdale RD3 NY82459575	1.727	1.831	41.121	7	4.287	62.428	70.708	310.022
Trawsgoed SN67507315	1.882	2.061	81.955	7	4.021	88.651	202.866	163.786
Upper Smisby SK34301880	1.130	1.186	21.309	4	1.990	22.492	35.490	168.277

5.3 Urban catchments in the flood event archive

The IH flood event archive, updated since Boorman (1985), includes Tp data and characteristics for 36 catchments which have an urban fraction of at least 0.05. In order to maximise the number of catchments satisfying these criteria, no restriction was placed on catchment size. Characteristics and mean Tp(0) data for these catchments are presented in Table 5.4 (p. 24).

Nine of the 15 IH catchments have an urban element of at least 5% and they were added to the dataset, making 45 urbanised catchments altogether.

5.4 Small catchments in the peak flows database

Institute of Hydrology Report 121 (Bayliss & Jones, 1993) lists mean annual flood (QBAR) data for 973 gauged catchments in the UK. Map-based catchment characteristics were available for 78 of the 98 catchments whose areas are less than 25 km². Flood data for three further catchments were contributed from the Department of Agriculture for Northern Ireland (DANI), and QBAR data were derived for six of the ADAS catchments, making 87 catchments in all. Catchment characteristics for these catchments, along with their QBAR values, are listed in Table 5.5 on pages 25-26.

Table 5.3 *Catchment characteristics and geometric mean response times for small catchments in the flood event archive*

Station	AREA (km^2)	MSL (km)	S1085 (m/km)	URBAN	SAAR (mm)	SOIL	LAG (h)	Tp(0) (h)
25003	11.40	5.54	37.79	0.00	2027.	0.50	3.0	3.4
25019	14.80	8.59	10.86	0.00	858.	0.48	6.6	3.9
25810	0.04	0.16	48.78	0.00	1995.	0.50	2.7	1.7
27051	8.10	4.27	29.35	0.00	866.	0.45	4.0	2.9
28033	8.00	5.30	39.25	0.00	1363.	0.50	3.6	2.1
28070	9.10	5.00	31.41	0.00	985.	0.48	3.5	2.1
31023	4.40	2.31	12.70	0.00	647.	0.45	3.5	3.8
32801	6.81	3.10	9.68	0.00	646.	0.45	4.8	3.9
38007	21.40	6.09	6.35	0.29	611.	0.37	3.4	3.1
39017	18.60	7.30	5.48	0.00	650.	0.45	9.9	8.7
39813	12.69	4.63	8.35	0.18	843.	0.45	6.9	5.8
39814	4.50	1.09	4.89	0.77	832.	0.45	1.7	1.4
39830	10.00	5.28	9.44	0.64	678.	0.22	2.7	2.7
39831	7.00	1.68	10.40	0.41	684.	0.20	1.4	1.0
41028	24.00	9.92	4.92	0.01	847.	0.45	8.5	8.0
41801	3.52	3.60	19.81	0.40	777.	0.45	3.9	3.1
46005	21.50	12.09	22.94	0.00	1987.	0.50	3.9	3.2
46802	14.20	4.71	15.85	0.00	1921.	0.50	4.1	2.1
46805	5.90	2.68	114.76	0.00	2145.	0.50	2.3	1.6
47013	16.20	5.35	12.46	0.00	1760.	0.50	5.0	3.6
48005	19.10	7.15	12.12	0.06	1107.	0.30	3.9	3.7
48009	22.70	13.20	16.87	0.00	1622.	0.46	8.6	9.4
49003	21.70	6.68	12.77	0.00	1714.	0.50	6.3	4.9
51002	20.80	10.60	34.09	0.00	1443.	0.32	5.0	3.9
52016	15.70	3.22	18.43	0.00	969.	0.38	4.6	3.9
52020	16.40	6.66	13.71	0.01	1020.	0.42	4.0	2.9
54022	8.70	4.58	67.00	0.00	2249.	0.50	3.2	1.8
54090	0.89	2.99	109.50	0.00	2257.	0.50	2.3	0.8
55008	10.55	7.32	36.30	0.00	2395.	0.50	2.7	1.7
55034	3.13	4.21	27.60	0.00	2410.	0.50	2.7	1.0
65801	11.40	4.50	54.22	0.00	3596.	0.50	4.2	2.7
67003	20.20	6.70	13.30	0.00	1300.	0.50	6.1	4.7
67010	13.10	5.87	10.90	0.00	2051.	0.47	3.2	2.5
68010	18.40	6.10	7.80	0.24	784.	0.45	5.7	3.5
68014	5.40	3.30	6.00	0.00	752.	0.45	3.7	2.3
69019	24.90	9.90	12.50	0.34	950.	0.42	2.6	1.8
69034	3.10	2.40	94.40	0.00	1475.	0.50	2.3	1.2
69802	13.00	4.55	88.79	0.00	1550.	0.50	3.6	3.2
71003	10.40	5.10	41.57	0.00	1786.	0.50	3.5	2.4
71804	24.90	7.00	30.90	0.00	1856.	0.50	1.8	1.6
72820	0.71	0.80	166.70	0.00	1634.	0.50	3.0	1.2
73007	23.60	10.80	21.75	0.00	2194.	0.50	4.6	3.4
73803	20.70	9.82	13.43	0.00	1507.	0.33	10.1	9.4
76011	1.50	1.66	24.10	0.00	1163.	0.50	3.1	1.7
76805	4.10	3.06	11.76	0.00	1508.	0.50	2.9	1.2
84002	12.40	7.20	30.55	0.00	2232.	0.50	3.0	2.4

Table 5.4 *Catchment characteristics and geometric mean response times for urban catchments in the flood event archive*

Station	AREA (km^2)	MSL (km)	S1085 (m/km)	SAAR (mm)	URBAN	SOIL	Tp(0) (h)
19001	369.0	42.0	5.81	914	0.11	0.46	6.47
19002	43.8	17.9	5.06	1062	0.07	0.45	6.39
19005	229.0	28.2	6.87	968	0.10	0.468	4.56
24005	178.45	31.71	6.39	770	0.05	0.451	6.53
28026	368.0	34.1	1.36	697	0.07	0.449	23.78
33015	277.0	39.1	1.03	655	0.05	0.408	17.92
37001	303.0	62.6	1.22	635	0.10	0.41	32.0
37007	136.0	26.9	1.85	620	0.13	0.401	12.67
38007	21.37	5.6	7.47	640	0.29	0.37	3.05
39004	122.0	2.4	4.36	800	0.39	0.165	1.34
39005	43.5	7.4	2.28	640	0.81	0.33	2.63
39007	354.8	32.34	0.98	719	0.33	0.337	11.94
39012	69.1	11.82	3.73	691	0.46	0.346	3.58
39052	50.2	11.01	3.51	697	0.18	0.44	4.79
39053	89.9	14.64	2.25	825	0.09	0.45	8.11
39813	12.69	4.06	7.43	839	0.18	0.45	5.79
39814	4.5	3.46	3.96	825	0.77	0.45	1.35
39830	10.0	5.3	10.11	665	0.64	0.219	2.67
39831	7.0	4.01	16.12	683	0.41	0.195	0.95
41801	3.52	3.48	19.63	762	0.40	0.45	3.12
48005	19.1	7.18	13.1	1121	0.06	0.30	3.67
52005	202.0	37.3	5.6	993	0.06	0.326	9.19
52006	213.1	16.7	5.5	846	0.05	0.338	10.77
53005	147.4	24.6	3.0	998	0.05	0.265	9.11
53009	72.6	16.13	8.15	1025	0.07	0.258	7.18
54004	262.0	28.8	1.92	707	0.25	0.441	11.85
56005	98.1	25.37	14.23	1425	0.16	0.42	4.62
57005	454.8	42.26	9.23	1863	0.05	0.46	5.42
57006	100.5	22.88	7.68	2181	0.13	0.452	1.87
58003	62.9	13.67	7.19	1350	0.05	0.297	6.08
58009	62.5	13.05	7.67	1350	0.05	0.297	4.78
69027	150.0	41.4	5.62	1179	0.22	0.480	6.86
69031	47.9	9.79	5.46	857	0.17	0.440	4.64
70006	28.9	11.33	8.09	965	0.07	0.398	3.24
71004	316.0	37.12	5.02	1227	0.09	0.465	4.62
84008	51.3	18.9	13.45	1175	0.26	0.454	3.34

N.B. This urban dataset is *not* restricted to catchments <25 km^2

Table 5.5 *Catchment characteristics and QBAR: peak flows database, DANI and ADAS catchments*

Station	QBAR (cumecs)	N(1)	AREA (km²)	URBAN	S1085 (m/km)	MSL (km)	SOIL	SAAR (mm)
15002	7.50	24	15.40	0.00	26.04	11.20	0.50	1240
15004	6.37	44	24.70	0.00	13.55	11.65	0.471	1096
15809	7.78	20	16.50	0.00	27.04	9.85	0.49	1142
19010	1.56	6	16.20	0.34	21.66	10.90	0.443	769
21001	18.95	15	23.70	0.00	27.32	7.07	0.467	1741
22003	17.62	13	21.40	0.00	21.68	13.90	0.50	1103
24801	26.00	21	21.00	0.00	35.79	7.18	0.50	1553
25003	16.72	17	11.40	0.00	37.79	5.54	0.50	2027
25011	17.87	14	13.00	0.00	26.64	5.21	0.50	1457
25019	6.70	9	14.80	0.00	10.86	8.59	0.48	858
26007	1.67	12	15.50	0.00	1.29	8.98	0.45	622
27010	10.42	41	18.90	0.00	29.28	8.88	0.48	1038
27032	4.49	16	22.20	0.00	25.73	11.71	0.50	1453
27038	1.45	13	7.80	0.00	4.87	1.55	0.50	725
27051	4.18	5	8.10	0.00	29.35	4.27	0.45	866
27852	19.80	22	21.10	0.00	29.01	9.06	0.50	1270
28033	4.48	12	8.00	0.00	39.25	5.30	0.50	1363
28070	5.34	56	9.10	0.00	31.41	5.00	0.48	985
30014	2.84	12	11.90	0.05	6.08	9.70	0.17	623
31023	2.54	14	4.40	0.00	12.70	2.31	0.45	647
32029	2.32	5	7.00	0.00	14.26	2.41	0.45	644
33813	0.26	20	8.55	0.00	3.15	3.01	0.15	597
38007	7.05	29	21.40	0.289	6.35	6.09	0.37	611
39017	5.90	20	18.60	0.00	5.48	7.30	0.45	650
39036	0.49	15	16.00	0.00	14.69	7.76	0.15	837
39055	6.07	8	17.60	0.70	2.46	9.22	0.45	675
39813	4.73	10	12.69	0.177	8.35	4.63	0.45	843
39824	4.81	17	10.30	0.368	11.09	6.39	0.37	657
39830	2.50	7	10.00	0.64	9.44	5.28	0.22	678
39831	2.30	7	7.00	0.414	10.40	1.68	0.20	684
40809	8.39	15	14.50	0.088	8.10	11.78	0.40	944
41016	9.33	15	18.70	0.00	10.48	6.40	0.40	836
41021	3.19	5	7.10	0.00	3.53	5.70	0.44	804
41028	7.81	17	24.00	0.013	4.92	9.92	0.45	847
41801	2.10	6	3.52	0.397	19.81	3.60	0.45	777
41806	0.76	15	2.30	0.00	15.80	1.12	0.45	946
44006	0.86	17	12.40	0.00	8.35	2.34	0.165	1098
44008	0.43	12	19.90	0.00	5.37	2.51	0.15	1048
45006	9.90	9	20.40	0.00	17.10	10.00	0.315	1540
45801	4.68	5	2.50	0.00	38.35	1.62	0.40	907
46005	41.99	24	21.50	0.00	22.94	12.09	0.50	1987
46801	24.21	9	14.90	0.00	23.90	6.47	0.50	2042
46806	26.39	17	14.00	0.00	25.50	7.68	0.50	2042
48005	5.81	16	19.10	0.06	12.12	7.15	0.30	1107
48009	9.82	12	22.70	0.00	16.87	13.20	0.46	1622
49003	15.38	16	21.70	0.00	12.77	6.68	0.50	1714
50005	27.82	6	13.30	0.01	23.48	6.73	0.50	1203
51002	5.92	9	20.80	0.00	34.09	10.60	0.32	1443
52016	3.43	17	15.70	0.00	18.43	3.22	0.38	969
52020	21.46	8	16.40	0.011	13.71	6.66	0.42	1020
54022	13.95	22	8.70	0.00	67.00	4.58	0.50	2440
54090	2.31	15	0.89	0.00	109.50	2.99	0.50	2512

Table 5.5 continued

Station	QBAR (cumecs)	N[1]	AREA (km^2)	URBAN	S1085 (m/km)	MSL (km)	SOIL	SAAR (mm)
54091	7.21	12	3.67	0.00	59.40	5.60	0.50	2446
54092	6.15	14	3.08	0.00	70.50	4.69	0.50	2496
55008	19.20	33	10.55	0.00	36.30	7.32	0.50	2431
55033	8.15	11	3.98	0.00	20.30	5.73	0.50	2425
55034	5.43	11	3.13	0.00	27.60	4.21	0.50	2385
55035	1.81	11	1.02	0.00	30.70	3.92	0.50	2425
56007	26.66	15	19.90	0.00	15.40	8.49	0.50	1930
60012	17.91	13	20.70	0.00	20.32	10.10	0.42	1677
65005	12.00	13	18.10	0.00	11.34	13.46	0.50	1528
66801	14.87	6	10.44	0.00	16.27	5.77	0.50	2602
67003	16.72	9	20.20	0.00	13.30	6.70	0.50	1300
67010	16.76	9	13.10	0.00	10.90	5.87	0.47	2051
68010	7.85	8	18.40	0.137	7.80	6.10	0.45	784
68014	1.51	5	5.40	0.00	6.00	3.30	0.45	752
69019	7.03	16	24.90	0.34	12.50	9.90	0.42	950
69034	4.87	8	3.10	0.00	94.40	2.40	0.50	1475
69802	14.89	29	13.00	0.00	88.79	4.55	0.50	1550
71003	13.79	15	10.40	0.00	41.57	5.10	0.50	1786
71005	16.34	14	10.60	0.00	30.80	5.02	0.50	1461
73803	8.51	12	20.70	0.00	13.43	9.82	0.33	1507
76011	2.29	12	1.50	0.00	24.10	1.66	0.50	1163
80003	8.83	8	5.70	0.00	105.10	3.40	0.50	2147
80801	12.99	7	18.20	0.00	17.52	7.85	0.50	2127
84002	18.81	18	12.40	0.00	30.55	7.20	0.50	2232
87801	8.60	20	3.10	0.00	94.56	1.71	0.50	3449
91802	6.96	33	6.50	0.00	117.78	3.73	0.45	1876
DANI catchments								
203046	10.75	10	21.72	0.00	17.33	10.00	0.345	1046
205015	4.44	8	15.90	0.15	3.98	7.70	0.30	900
205101	11.43	13	18.40	0.45	19.54	5.80	0.345	1041
ADAS catchments								
Cliftonthorpe	0.198	22	1.12	0.00	12.65	1.33	0.375	714
Lower Smisby	0.603	22	2.60	0.031	13.85	2.17	0.380	714
North Weald	0.489	26	1.60	0.00	13.88	1.64	0.425	650
Redesdale RD2	1.413	24	4.49	0.00	50.66	3.00	0.473	940
Redesdale RD3	0.838	22	1.901	0.00	45.49	2.02	0.475	940
Trawsgoed	0.394	17	2.321	0.00	80.00	2.75	0.413	1199

[1] N denotes the number of annual maxima used in the calculation of QBAR or, in the case of the ADAS catchments, the number of peaks-over-threshold (POT) events used in the estimation of QBAR from a short flood record

6 Analysis of flood response times

6.1 Evaluation of Tp(0) and LAG on instrumented catchments

Methods

Following the approach of Boorman (1985), the time-to-peak of the instantaneous unit hydrograph, Tp(0), is evaluated indirectly. Rainfall and runoff are analysed at a finite data interval to derive a T-hour UH, from which Tp(T) can be derived. Equation 1.2 is subsequently used to convert Tp(T) to Tp(0). The data interval for the analysis is usually selected according to the nature of the catchment response. A suitable interval for a small quickly-responding part-urban catchment could be as short as five minutes, while data from a larger rural catchment might be analysed using a 0.5, 1 or even 3-hour interval. Data from the 15 sites instrumented within the study were analysed at several intervals.

Many different approaches to UH derivation are possible: several methods are outlined in the FSR (NERC, 1975, Vol. I, Section 6.2.2) although the list is by no means exhaustive. A detailed treatment of the various methods available is beyond the scope of this report, but there is an extensive published literature (see Boorman & Reed, 1981). Further details of the method actually adopted in the FSR analysis are included in Vol. I, Section 6.4.6 of the FSR.

Within this investigation, the analysis was undertaken using the 'restricted least-squares' unit hydrograph analysis method (Reed, 1976; Boorman & Reed, 1981). The program is based on a matrix transformation approach, related to the 'matrix inversion' method, and incorporates substantial refinements over the basic solution. These include an option which allows constraints to operate in such a way that a unimodal UH results, incorporating a single point of inflexion on each of the rising and falling limbs.

Rainfall and streamflow data were not recorded at the 15 instrumented catchments: the UH analysis was therefore executed using weather radar and water level data. It was established that water level data could be used as a surrogate for streamflow by analysing the same event using both types of data. In each case a uniform percentage rainfall separation technique was applied, with runoff separation following the standard FSR method (Vol. I, p. 389). Unit hydrographs were derived from several rainfall-runoff events for two small catchments unconnected with the study. Although the unit hydrograph resulting from the use of the water level data was vertically distorted, the temporal position of the peak coincided with that resulting from the use of the corresponding streamflow data.

The temporal delay between the centroid of a hyetograph and the resulting peak flow at the catchment outfall is defined in the FSR (NERC, 1975, Vol. I, Section 6.4.2) as the catchment LAG. Initially five, temporally well-separated, single-peaked events, were analysed at each site: LAG and Tp(0) were calculated for each event. The results for the partly-urbanised catchments were found to be more consistent than for the essentially rural sites. On six catchments, where the derived LAG and Tp(0) values were found to vary considerably, further events were abstracted and analysed. The derived Tp(0) data are listed in Table 6.1. Corresponding LAG data are included in Appendix 1, and reflect a very similar picture.

The way in which the weather radar data can be used to compute a five-minute interval catchment average rainfall sequence was outlined in Section 3.3, and an example was illustrated in Figure 3.1. Clearly, a rainfall sequence can be constructed from this starting point, for an interval of any multiple of five minutes. The unit hydrograph analysis program required the rainfall and runoff data interval to be the same.

Thus, the five-minute radar imposed an effective lower limit on the water level data interval. In practice, rainfall-runoff events could be analysed at either a five-minute interval or at multiples of five-minutes. Events from the fastest responding catchment (Bicester) were analysed at intervals of 5, 10 and 15 minutes, while events from the slowest responding (Bedford) were analysed at 0.5, 0.75, 1, 1.5, 2 and (in one case) 3 hours. The optimum interval T at which the unit hydrograph analysis was most stable was adopted for the calculation of Tp(T); T varied between the 15 catchments and often between events recorded on the same catchment.

Experimental results

Table 6.1 lists the 103 derived Tp(0) data and compares them with estimates from Equation 1.3. The catchments are listed in order of observed response time. These data, including

Table 6.1 *Tp(0) data derived from the analysis of 103 recorded rainfall-runoff events.*

Catchment	Tp(0) (hours)
Bicester	0.3, 0.4, 0.4, 0.4, 0.7, **[1.3]**
Aylesbury	0.2, 0.4, 0.4, 0.4, 0.6, 0.6, 0.7, 0.9, **[1.6]**
Letchworth	0.7, 0.7, 0.7, 0.8, 1.1, **[1.2]**
Tring	0.9, 0.9, 0.9, 0.9, 1.1, **[2.0]**
Stevenage	0.8, 1.3, 1.3, 1.3, 1.3, **[1.9]**
Luton	0.5, 1.1, 1.3, 2.1, 2.3, **[2.6]**
Toddington	0.9, **[1.4]**, 1.6, 1.6, 1.6, 1.9
Beenham	1.4, 1.8, 1.8, 1.8, **[4.1]**, 7.8
Barton-Le-Clay	1.5, 2.3, 2.5, 2.5, 3.3, 4.5, **[5.4]**, 5.5, 7.8, 11.5
Holme Green	2.5, 3.4, 3.4, 3.4, **[3.8]**, 4.1, 4.8, 5.5
South Hinksey	2.4, 2.5, **[3.3]**, 3.5, 3.9, 4.1, 4.3, 5.3, 9.8, 14.3
Wingrave	2.6, 3.0, 3.4, 5.0, **[5.5]**, 5.8, 6.4, 7.5, 8.3, 8.6, 15.5
Hook	3.5, **[3.9]**, 7.0, 7.5, 7.5, 15.0
Easton Maudit	5.3, 5.5, 5.5, 5.6, **[6.9]**, 8.3, 9.5, 9.8, 10.1, 11.8
Bedford	6.3, 9.3, 10.1, 11.3, 11.5, 12.8, **[13.2]**, 15.4, 15.5, 15.8, 27.3, 28.5

Bold bracketed values [1.3] result from the FSSR 16 formula for Tp(0), i.e. Equation 1.3.

their geometric and arithmetic means, are also given in Appendix 1.

Performance of the FSSR 16 equation for Tp(0)

The data in Table 6.1 indicate the extent to which the FSSR 16 estimation equation is able to reflect the observed response times on the 15 instrumented catchments. It can be seen that the estimates [bracketed] for the first six catchments in the table over-predict Tp(0). Reference to Table 4.1 reveals that these six include the five most urbanised catchments. No other catchment characteristic appears to differentiate these six from the remainder.

In contrast, the Tp(0) estimates for the remaining nine catchments appear to be accommodated within the observed data, confirming that the use of Equation 1.3 generally results in reasonable estimates of Tp(0) data for small, essentially rural catchments.

Alternative models for Tp(0) estimation on small catchments were developed and are discussed in Sections 6.2-6.4. However, the final approach, outlined in Section 6.6, was to modify the URBAN component of the FSSR 16 equation to represent small part-urban catchments better.

6.2 Estimation of Tp(0) on small catchments

Geometric means, i.e. the *n*th root of the product of the *n* individual data, were calculated for each of the sites in Table 6.1. The geometric mean is relevant because it corresponds to the arithmetic mean of the logarithm of the variable. The geometric mean values of LAG and Tp(0) are listed in Table 6.2.

In addition to the 15 IH catchments, the dataset used in this section incorporates nine catchments instrumented by the ADAS Soil & Water Research Centre. A summary of catchment characteristic and observed geometric mean Tp(0) data recorded on these nine catchments is given in Table 5.1; DTM-derived catchment characteristics are included in Table 5.2.

Table 6.2 *Derived LAG and Tp(0) information for the 15 IH instrumented catchments*

Catchment	Recording site grid reference	LAG geometric mean	Tp(0) geometric mean
Bicester	SP595231	0.27	0.4
Aylesbury	SP842132	0.5	0.5
Letchworth	TL210335	0.8	0.8
Tring	SP922130	0.9	0.9
Stevenage	TL267227	1.0	1.2
Luton	TL050236	1.2	1.3
Toddington	TL022284	1.6	1.5
Beenham	SU583694	3.0	2.3
Barton-Le-Clay	TL091320	4.7	3.8
Holme Green	SU824670	3.7	3.8
South Hinksey	SP507040	5.3	4.7
Wingrave	SP879176	7.5	5.8
Hook	SU728555	7.1	7.3
Easton Maudit	SP883593	8.3	7.6
Bedford	TL102492	14.9	13.6

The regression analysis was completed with the assistance of Version 6 of the SAS/STAT regression package (SAS, 1989). The 'STEPWISE' option was used to select only those catchment characteristics assessed to be statistically significant. The usual logarithmic transforms having been applied, catchment characteristics were added to the model one at a time. At each stage of model development, the algorithm was able to add or remove variables from the model. At the start of the procedure, AREA, MSL, S1085, SAAR, SOIL, URBAN and FOREST (the percentage of the catchment occupied by woodland) were available to the model.

The three variables selected as being significant were, in order of contribution to the model, URBAN, S1085 and SOIL. The following summary shows the percentage of the variation in log Tp(0) that is explained by the developing model:

r^2	Catchment Characteristics
0.532	log(1+URBAN)
0.739	log(1+URBAN), log(S1085)
0.824	log(1+URBAN), log(S1085), log(SOIL)

$$Tp(0) = 27.9\,(1+URBAN)^{-3.53}\,S1085^{-0.50}\,SOIL^{0.70} \qquad [6.1]$$

($n = 24$, $r^2 = 0.824$, fse $= 1.475$)

The abbreviation fse denotes the factorial standard error of estimate: the standard error of estimation of the logarithm of the dependent variable. This can be thought of as a factor by which the estimate of Tp(0) needs to be multiplied and divided in order to determine the ± 1 standard deviation limits on the estimate.

The resulting exponent of SOIL is seen to be positive. As permeable catchments would be expected to respond more slowly than relatively impermeable ones, conceptually SOIL would be expected to have a negative exponent. It is possible that, for small catchments in particular, the generalised nature of the SOIL map (FSSR 7, 1978) could lead to misleading data being assigned to the catchment. In this study, three of the four catchments with SOIL index values of 0.15 were also partly urbanised, resulting in fast response times and hence small Tp(0) values. It is thought that these particular combinations of URBAN and SOIL are responsible for the positive SOIL exponent, and that Equation 6.1 cannot be sustained for general use.

The analysis was repeated, eliminating SOIL from the available database. As before, the first two variables to be selected were URBAN and S1085 and, in the absence of SOIL, MSL was found to be significant.

$$Tp(0) = 6.86\ (1+URBAN)^{-3.08}\ MSL^{0.41}\ S1085^{-0.35} \quad [6.2]$$

($n = 24$, $r^2 = 0.818$, fse = 1.483)

The r^2 value is only slightly lower than for Equation 6.1. The exponents of URBAN, S1085 and MSL are intuitively reasonable and Equation 6.2 is therefore a candidate model for Tp(0) estimation on small catchments.

The urban exponent, -3.08, is appreciably lower than the value of -2.16 which appears in the existing formula for Tp(0) (Equation 1.3). This stronger 1+URBAN exponent has the effect of reducing Tp(0) estimates.

The exponent of S1085, -0.35, is very similar to that in the FSSR 16 (Equation 1.3).

The exponent of MSL, 0.41, is found to be rather larger than in Equation 1.3. It may be that the significant urbanisation of many of the catchments has resulted in the indicated length of 'blue line' on the 1:25 000 Ordnance Survey map being truncated because of streams running in culverts.

SAAR, which appeared in the FSSR 16 equation, was not found to be significant. Given that, of the 24 catchment data set, all 15 IH catchments and one of the ADAS catchments (North Weald) were located within a 76 km circle, there is reduced scope for variation in annual rainfall: the absence of SAAR from the prediction equation is therefore not surprising.

Flood Studies Supplementary Report 6 (FSSR 6) was published in April 1978 and sought to determine whether it was possible to improve on the FSR flood prediction recommendations for small (<20 km²) catchments by using an appropriate subset of the original FSR data. Using 304 rainfall-runoff events from 23 catchments the following equation for estimating Tp was derived:

$$Tp(1) = 9.8\ S1085^{-0.32}\ (1+URBAN)^{-1.97}\ RSMD^{-0.07}\ MSL^{0.19} \quad [6.3]$$

Table 6.3 compares the associated statistics of the equations contained within FSSR 6, FSSR 16 and this report.

If Equation 6.2 were to be recommended for use on catchments of up to 25 km² and the methodology of FSSR 16 were to be retained for catchments above this size, anomalies in the estimation of Tp(0) could result. An incremental increase in the catchment area through the 25 km² transition point, having little or no effect on URBAN, MSL or S1085, could well lead to disparate estimates of Tp(0). Given that Equation 6.2 makes use of three of the four catchment characteristics that feature in the 4-variable Tp(0) equation included in FSSR 16, it was decided to investigate whether a way could be found to modify both equations so as to ensure a smooth transition between the two: this would allow the current analysis to dominate below 25 km² whilst retaining the FSSR 16 result for catchments above that limit. This matter is taken further in Section 6.6.

6.3 Estimation of Tp(0) on small rural catchments

While the URBAN catchment characteristic has been shown to be highly significant in the prediction of Tp(0), estimates are also required for rural catchments with little or no urban land use. The equation derived within Section 6.2 could be used on rural catchments by substituting URBAN = 0.0, but the construction of a specifically rural equation would be preferable.

All nine of the ADAS instrumented catchments listed in Table 5.1 and six of the IH catchments included in Table 4.1 have an urban coverage of less than 5%. These 15 have been used to

Table 6.3 *Performance comparison for time-to-peak prediction equations*

	FSSR 6 Equation 6.3 [Tp(1)]	FSSR 16 Equation 1.3 [Tp(0)]	Current study Equation 6.2 [Tp(0)]
No. of catchments (n)	23	175	24
Squared coefficient of multiple correlation (r^2)	0.578	0.736	0.818
Factorial standard error (fse)	1.45	1.48	1.48

construct a regression equation for use only on small rural catchments.

The broad approach was identical to the one outlined in Section 6.2. As before, MSL and S1085 were found to be significant.

$$Tp(0) = 6.97\ MSL^{0.35}\ S1085^{-0.36} \quad [6.4]$$

($n = 15$, $r^2 = 0.770$, fse = 1.335)

It should be noted that the fse associated with Equation 6.4 is smaller than that for Equation 6.3, even though the r^2 value is inferior. This reflects the smaller variation in Tp(0) values found in the subset of rural catchments.

6.4 The DTM within Tp(0) estimation

The eight DTM catchment characteristics that feature in this section, DTMAREA, DTMMSL, DTMS1085, DTMMAG, DTMLEN, DTMRIVS, DTMLANS and DTMMALT, were introduced in Chapter 4. For the reasons discussed there, it was impractical to calculate DTM characteristics for four of the 15 IH instrumented catchments. DTM-derived characteristics for the remaining 11 catchments are given in Table 4.2. No difficulties were experienced in calculating DTM characteristics for the nine ADAS catchments: the relevant data appear in Table 5.2.

These 20 catchments (11 IH and 9 ADAS) were used in a regression analysis which followed the pattern described in Section 6.2. Although not originating from the DTM, the OS-map-derived URBAN characteristic, having been recognised as being of principal importance, was also allowed into the data set. Stepwise regression yielded this three-variable equation:

$$Tp(0) = 6.54\ (1+URBAN)^{-3.30}\ DTMS1085^{-0.29}\ DTMAREA^{0.26} \quad [6.5]$$

($n = 20$, $r^2 = 0.816$, fse = 1.445)

Although, through necessity, Equations 6.2 and 6.5 were derived from slightly different catchment datasets, a comparison of the two is quite encouraging. The exponents of 1+URBAN and S1085 are broadly similar, while MSL is replaced by AREA with an appropriate exponent.

6.5 Tp(0) estimated from LAG

LAG and Tp(0) information from the 24 sites (15 IH and 9 ADAS) were used in the analysis. The data were examined in the form of site geometric means, taken from Tables 6.2 and 5.1 respectively. Figure 6.1 illustrates the relationship between the LAG and Tp(0) geometric means.

The lowest point on Figure 6.1, representing the Bicester catchment, is seen to lie slightly above the straight line indicated by the other points. Bicester is an exceptionally fast-responding catchment, thought to be because the stream is enclosed in a concrete culvert and passes through a large area of industrial urban development immediately upstream of the catchment outlet (see Appendix 1). Accordingly, the rainfall data interval of five minutes, expressed as a percentage of the typical catchment response time, is significantly greater than for the remaining 23 catchments. Hence, although the time of peak flow was accurately established on all catchments, the temporal error involved in the construction of the event rainfall hyetographs, was potentially more significant at Bicester. Nevertheless, all 24 catchments were used in the derivation of a link equation between Tp(0) and LAG.

When a model of the form $Tp(0) = a\ LAG^b$ was fitted, this equation was the result:

$$Tp(0) = 1.07\ LAG^{0.903} \quad [6.6]$$

($n = 24$, $r^2 = 0.982$, fse = 1.123)

It was found that the multiplier term *a* was not significantly different from one.

The analysis was repeated whilst constraining the intercept of the logarithmic regression to be zero, resulting in:

$$Tp(0) = LAG^{0.94} \quad [6.7]$$

The derived equation can be compared with the one which appears in FSSR 16 (see also Boorman, 1985):

$$Tp(0) = 0.604\ LAG^{1.144} \quad [6.8]$$

($n = 175$, $r^2 = 0.926$, fse = 1.230)

The two equations intersect at a LAG of about 11.8 hours. Using Table 6.4 the two equations may be compared.

It is notable that Equation 6.6 affords an excellent fit to the data, with a much smaller factorial standard error than that associated with Boorman's Equation [6.8]. There are several possible reasons for this improvement. The increased accuracy of recorded clock time and

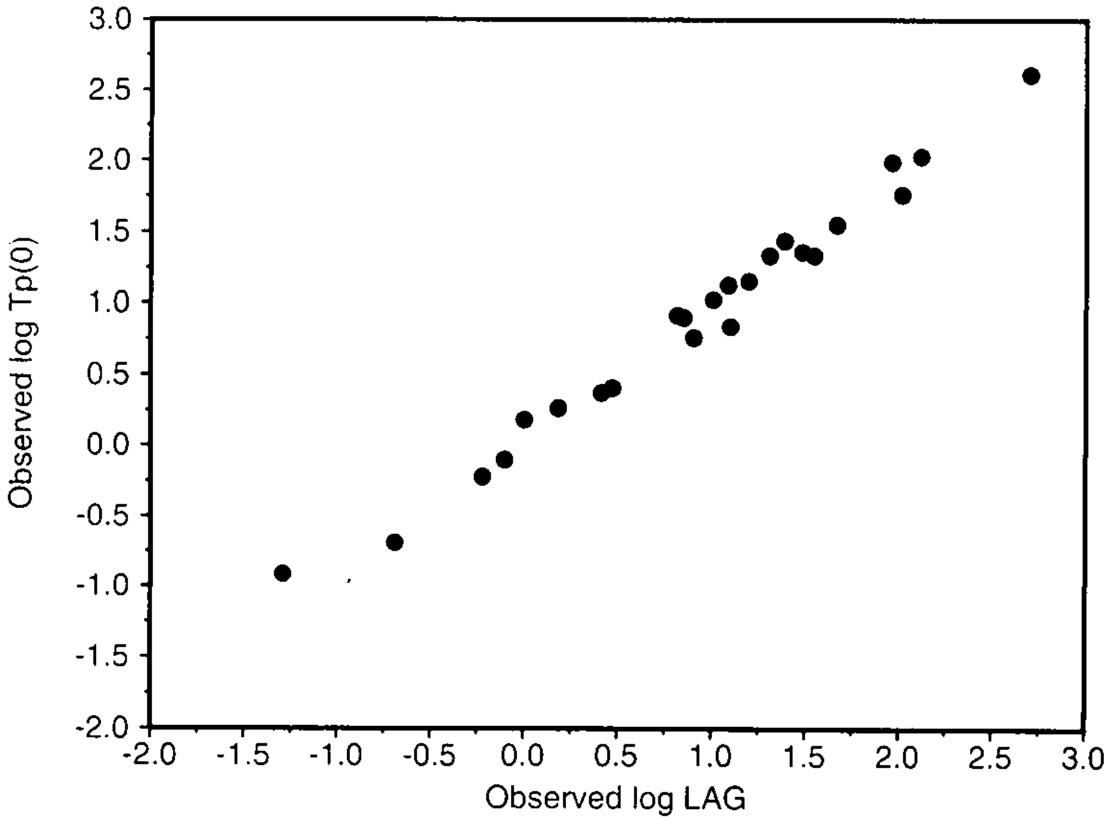

Figure 6.1 *Relationship between catchment LAG and Tp(0) geometric means*

reduced temporal data interval during flood events has generated good quality data. Within the FSR analysis, and in some subsequent work, timing adjustments of an hour were sometimes applied in unit hydrograph derivation and may in some cases have degraded the evaluation of response times. The values of Tp(0) and LAG were always calculated from the same events during the current study. In contrast, Boorman (1985) evaluated average values of LAG and Tp(0) from differing numbers of events, because some events which were deemed satisfactory for LAG analysis were not accepted for unit hydrograph analysis. The current study is restricted to the single-peaked flood events, which are simpler to analyse. Such a constraint, although reducing the number of events available, is likely to lead to more consistent LAG and Tp(0) data. The use of geometric means (i.e. the arithmetic mean of log-transformed values) may have also provided a more realistic definition of catchment average response times.

6.6 Modification of the FSSR 16 equation for Tp(0)

For reasons explained within Section 6.2, the decision was made to amalgamate the main Tp(0) estimation equation derived within this report with the equation in FSSR 16. The process was carried out in three steps, detailed below.

Table 6.4 *Comparison of Tp(0) estimates predicted from LAG data*

LAG (h)	FSSR 16 Tp(0) from Equ. 6.8 (h)	Current study Tp(0) from Equ. 6.7 (h)
2.0	1.3	1.9
4.0	2.9	3.7
6.0	4.7	5.4
8.0	6.5	7.1
10.0	8.4	8.7
12.0	10.4	10.3
14.0	12.4	11.9
16.0	14.4	13.5
18.0	16.5	15.1

Reformulation

First, the 24-catchment dataset was reexamined to confirm that it is sufficient to amend only the urban term. The FSSR 16 estimation equation for Tp(0), Equation 1.3, was reformulated as:

$$Tp(0) = Tp(0)_{rural}\,(1 + URBAN)^{B} \qquad [6.9]$$

where

$$Tp(0)_{rural} = 283.0\ S1085^{-0.33} SAAR^{-0.54} MSL^{0.23} \qquad [6.10]$$

Equation 6.9 was fitted to the 24-catchment dataset by regression of $\log(Tp(0)/Tp(0)_{rural})$ on $\log(1+URBAN)$, resulting in:

$$Tp(0)/Tp(0)_{rural} = 0.966(1 + URBAN)^{-3.57} \qquad [6.11]$$

$(n = 24,\ r^2 = 0.792,\ fse = 1.467)$

The multiplier was found not to be significantly different from one, and forcing the logarithmic regression through the origin yielded the formula:

$$Tp(0)/Tp(0)_{rural} = (1 + URBAN)^{-3.65} \qquad [6.12]$$

The factorial standard error associated with Equation 6.11 is only marginally greater than for Equation 6.2, and it is therefore concluded that the FSSR 16 equation adequately represents the experimental data from the current study if the exponent of (1+URBAN) is modified.

Choice of datasets for recalibration of the urban term

The second step was to determine a rationale for allowing the exponent of (1+URBAN) to vary, so that the estimation equation for Tp(0) provides a reasonable fit to both datasets, i.e. the one underlying FSSR 16 (Boorman, 1985) and the one compiled during the current investigation.

The approach taken was to discard rural catchments from both datasets, so that only the significantly urbanised catchments influenced the recalibration. Boorman's dataset of 123 catchments (Boorman, 1985, p. 7) — those for which at least five events have been analysed — includes 36 catchments with an urban fraction of 0.05 or greater: these are listed in Table 5.4. Similarly, the 24-catchment dataset of the present study includes nine significantly urbanised catchments.

Table 6.5 compares B and $Tp(0)_{rural}$ for the two data sets. The Tp(0) data were derived as geometric means; the B values have been calculated as arithmetic means. The B value for each catchment was derived by inverse application of Equations 6.9 and 6.10.

Table 6.5 *Significantly urbanised catchments ($URBAN \geq 0.05$)*

	Boorman (1985)	Small catchment study
No. of catchments	36	9
B	-1.94	-3.01
$Tp(0)_{rural}$	7.9	4.4

The manner in which the B values have been computed effectively assumes that the FSSR 16 Tp(0) estimation equation is exact, except for its representation of the effect of urbanisation. This is an oversimplification and consequently there is excessive variation in the derived B values. Thus, although the difference between the mean values of B in Table 6.5 are not statistically significant, their difference is nevertheless appreciable and warrants consideration.

A model for the urban exponent

Various approaches to constructing a model for the exponent B were explored. Values of B were regressed against a full range of catchment characteristics, as well as values of $Tp(0)_{rural}$ calculated by Equation 6.10. The data exhibit very considerable scatter, making it difficult to derive a model that reflects the general differences between the two datasets in an acceptable manner. A particular consideration was the desire to formulate a model that did not lead to unduly extreme values of B when applied to catchments outside the range of those studied here.

The problem was resolved by imposing a synthetic model which, while essentially conforming to the average values of B and $Tp(0)_{rural}$ included in Table 6.5, could not yield values of B greater than -1.0 or less than -4.0.

The model of Equation 6.13 is illustrated in Figure 6.2: the crosses indicate the Table 6.5 values. The formulation was contrived to restrict the variation of B when Equation 6.13 is applied outside the range of $Tp(0)_{rural}$ values represented by the study datasets.

$$B = -1.0 - 3.0\exp(-[Tp(0)_{rural}/7.0]^2) \qquad [6.13]$$

The limiting values for B of -1.0 and -4.0 were chosen subjectively but with reference to experimental formulae listed by Packman (1980).

The decision to formulate the model in terms of $Tp(0)_{rural}$ rather than AREA reflects the view that the effect of urbanisation on flood response times is proportionally greater for those catchments that would respond quickly, even when they are rural. The implication of Figure 6.2 is that the shorter the value of $Tp(0)_{rural}$, the lower will be the value of B and the more significant will be the effect of catchment urbanisation. The hypothesis has not been formally tested in this investigation. However, it seems intuitively more reasonable than ascribing the strong urban effect seen in this study to a catchment area effect alone.

The resultant model for Tp(0), summarised in Section 6.7, should be viewed as a realistic compromise. It has regard to the faster response times found on small urbanised catchments in this study, while it also broadly conforms to FSSR 16. In particular, the formulation avoids any discontinuity in Tp(0) estimates that would arise were different equations to be recommended above and below the fixed area threshold of 25 km^2.

6.7 Assessment of recommended method

Chapter 6 has discussed three models for Tp(0) estimation: that of FSSR 16 (Equation 1.3), the small catchment study model (Equation 6.2), and a compromise:

$$Tp(0) = Tp(0)_{rural} (1 + URBAN)^{B} \qquad [6.9]$$

where

$$Tp(0)_{rural} = 283.0\ S1085^{-0.33} SAAR^{-0.54} MSL^{0.23} \qquad [6.10]$$

and

$$B = -1.0 - 3.0 \exp(-[Tp(0)_{rural}/7.0]^2) \qquad [6.13]$$

Independent testing was impractical, but Figures 6.3 and 6.4 compare Tp(0) estimates by the three methods with values observed on two sets of catchments.

Figure 6.3 illustrates the comparison for the IH and ADAS instrumented catchment dataset (see Tables 4.1 and 5.1) developed within the current study. The FSSR 16 method is seen to give rather mixed results, with marked overestimates on the urbanised catchments

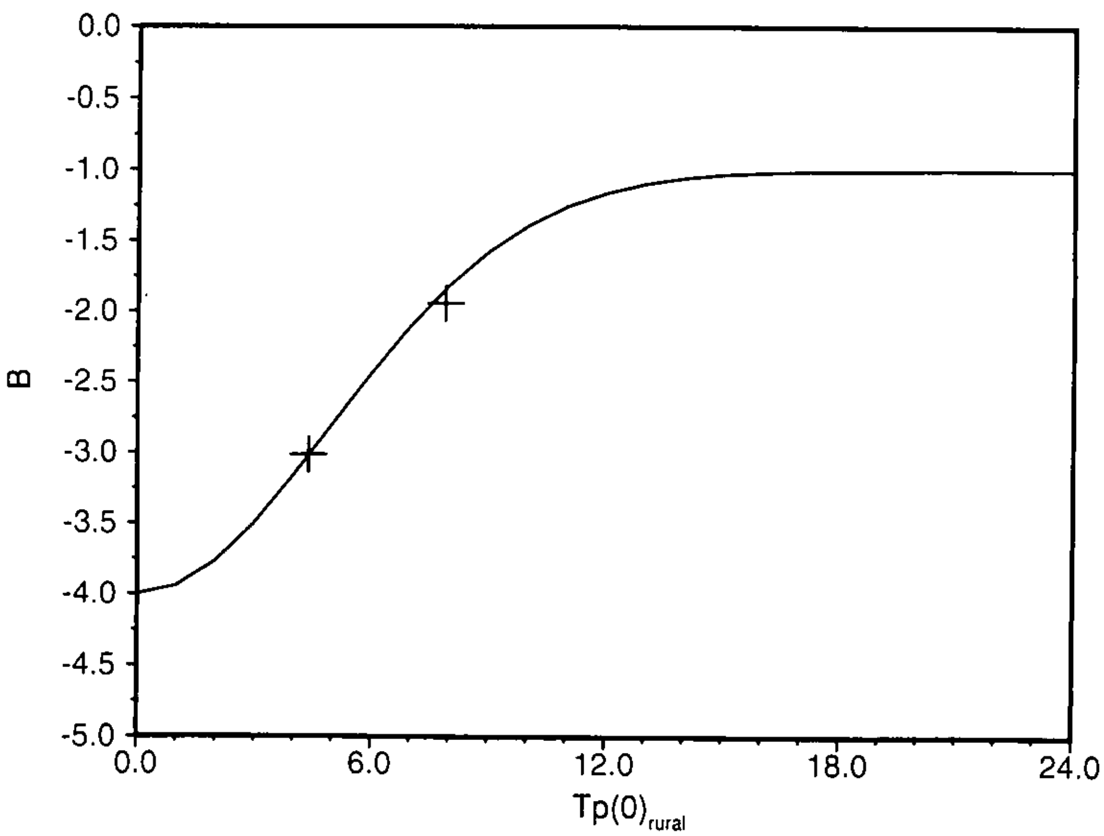

Figure 6.2 *Illustration of synthetic model linking B and $Tp(0)_{rural}$*

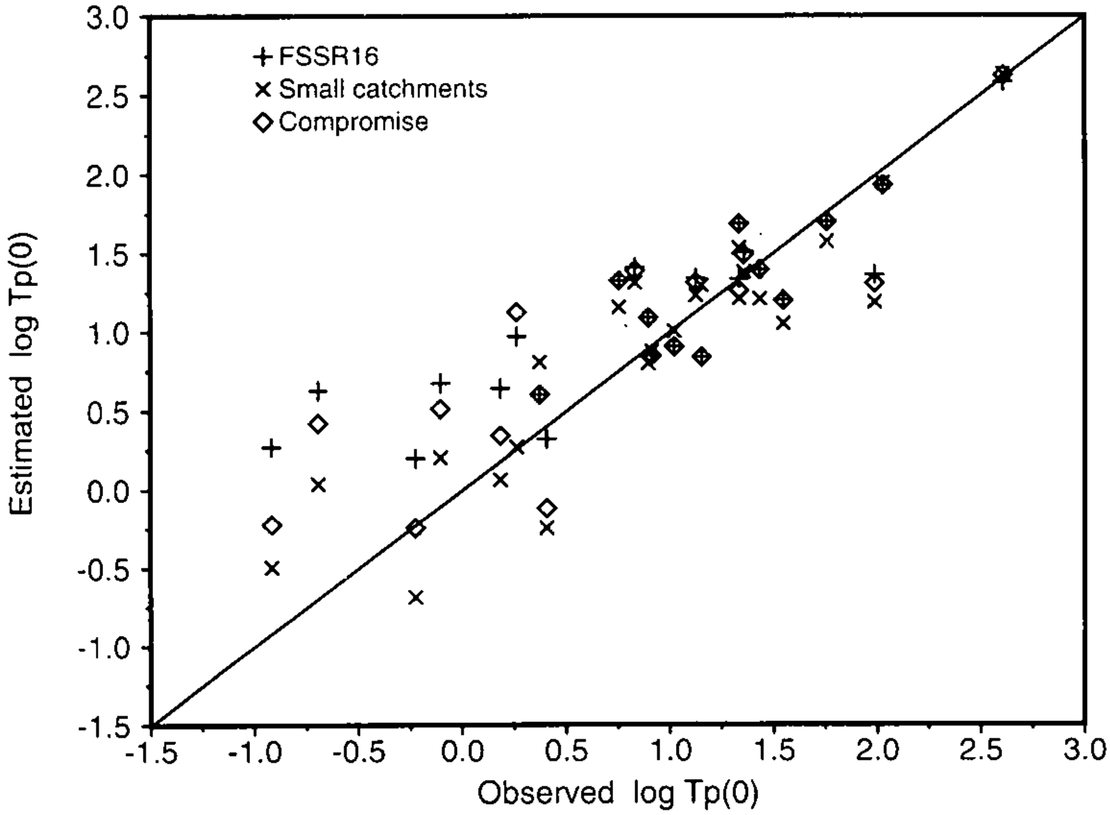

Figure 6.3 *Comparison between observed and estimated Tp(0) data for a 24 catchment dataset*

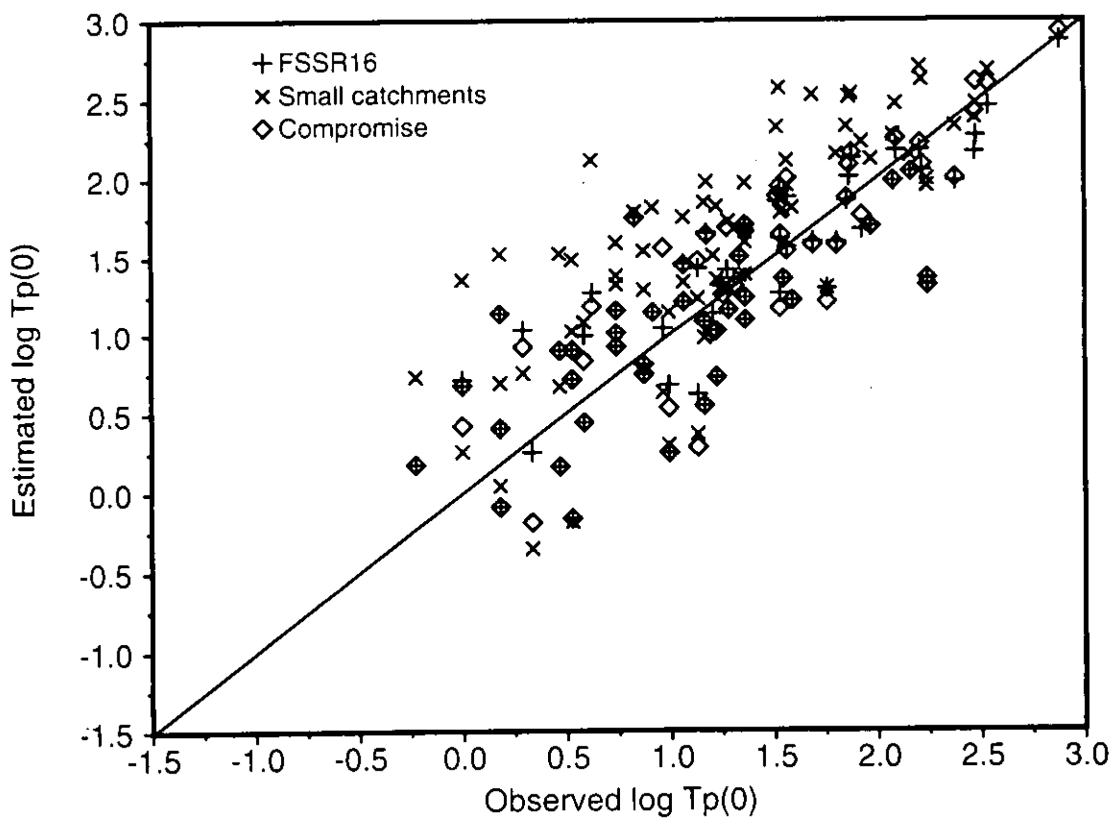

Figure 6.4 *Comparison between observed and estimated Tp(0) data for 75 small and/or urban catchments used in FSSR 16 analysis*

(see Table 6.1). As is to be expected, since it was calibrated on the 24-catchment dataset, the small catchment method performs best. It is seen that in most cases estimates derived using the compromise method lie below those calculated by FSSR 16 and above those given by the small catchment equation. Performance statistics for the three models are given in Table 6.6.

Figure 6.4 makes the same comparison for a set of 75 catchments taken from the FSSR 16 dataset (Boorman, 1985). This set is the union of two subsets of catchments, all of which have Tp values derived for five or more events. Catchments (of any size) having an urban fraction of 0.05 or greater and all those catchments (of any land use) having an area less than 25 km² were included. It is seen that the small catchment method performs rather poorly, tending to overestimate response times, whereas the compromise method performs at least as well as the FSSR 16 method. The generally good performance of the FSSR 16 method on this dataset is to be expected, since almost all of the 75 catchments played a part in its calibration.

It is concluded that the compromise method can be recommended for general use.

Table 6.6 *Performance statistics for the estimation of log Tp(0)*

Model	log Tp(0)	
	Mean error	RMS error
FSSR 16	0.229	0.517
Small Catchments	0.002	0.360
Compromise	0.139	0.446

7 Mean annual flood

7.1 Introduction

Estimation of the mean annual flood QBAR from catchment characteristics was introduced in Section 1.2. Derived QBAR data and map-based characteristics are given in Table 5.5 for a set of 87 small catchments compiled for this study.

Urban land use is a major influence on small catchment flood response: the database was therefore split into two parts, according to the value of URBAN. Of the 87 catchments, 16 were subjected to partial urban land use: the most heavily urbanised had an URBAN value of 0.70. Sixty-eight of the remaining 71 catchments were completely rural (i.e. URBAN = 0.0); the other three had an URBAN value of less than 0.025. Had a dividing line of 0.05 been adopted instead of 0.025 (i.e. in line with Section 6.3), only one catchment, Lower Smisby (ADAS subset), would have been reclassified as non-rural.

The most recently published work on UK small catchment QBAR estimation is FSSR 6 (1978). This section of the report retreads some of the ground covered there, but with the benefit of a more substantial dataset.

7.2 QBAR estimation for small rural catchments

The structure of QBAR estimation equations is well established. Logarithmic transforms are applied to QBAR and catchment characteristics, and multiple regression techniques are employed to provide the link between the two. The subsequent inverse logarithmic transformation results in the now familiar multiplicative equation.

$QBAR_{rural}$ is used here to represent an estimate of QBAR on a rural catchment. Three variables were found to be significant: SOIL, SAAR and AREA. The resulting three-variable equation is:

$$QBAR_{rural} = 0.00108\ AREA^{0.89}\ SAAR^{1.17}\ SOIL^{2.17} \qquad [7.1]$$

$(n = 71, r^2 = 0.847, fse = 1.651)$

Table 7.1 shows the percentage of the variation in log(QBAR) that is explained by the developing model.

The derived equation makes use of the same three catchment characteristics as the three-variable equation from FSSR 6 (refer to Section 1.2). The exponents in Equation 7.1 are fairly similar to those in Equation 1.5. Although the constant multiplier is more than 60% greater, this is largely offset by the slightly smaller exponents of AREA and (particularly) SAAR.

As an example, station number 15809 is fairly typical of the rural catchments listed in Table 5.5. Substitution of its characteristics (AREA = 16.50, SAAR = 1142, and SOIL = 0.49) yields estimates of 10.5 cumecs using Equation 7.1 compared with 11.2 cumecs using Equation 1.5.

Although the r^2 and fse values are less impressive than for the equivalent FSSR 6 result, Equation 7.1 is nevertheless preferred for use on rural catchments of less than 25 km². This is because Equation 7.1 is based on 1225 station-years of data from 71 catchments, compared with only 627 station-years of data from 47 catchments for Equation 1.5. This recommendation should be seen as an alternative to estimating the mean annual flood by the familiar six-variable equation (i.e. Equation 1.4), applicable to catchments of any size.

7.3 QBAR estimation for urban catchments

The CIRIA guide to the design of flood storage reservoirs (Hall *et al.*, 1993) summarises a method of estimating QBAR for a catchment subjected to partial urban development ($QBAR_{urban}$) from a knowledge of $QBAR_{rural}$. This is based on the earlier FSSR 5 method.

A catchment index (CIND) is defined as a function of SOIL and catchment wetness index (CWI):

$$CIND = 102.4\ SOIL + 0.28\ (CWI - 125) \qquad [7.2]$$

A suitable design value of CWI is estimated from the FSR (NERC, 1975, Vol. I, Fig. 6.62) from its relationship with SAAR.

Table 7.1 *Variation in log (QBAR) explained by the model*

r^2	Catchment characteristics			
0.418	log(MSL)			
0.632	log(MSL),	log(SOIL)		
0.715	log(MSL),	log(SOIL),	log(SAAR)	
0.848	log(MSL),	log(SOIL),	log(SAAR),	log(AREA)
0.847		log(SOIL),	log(SAAR),	log(AREA)

A further index, the rainfall continentality factor (NC) is also defined to be a function of SAAR:

$$NC = 0.92 - 0.00024\,SAAR \quad [\text{for } 500 \leq SAAR \leq 1100 \text{ mm}]$$
$$NC = 0.74 - 0.000082\,SAAR \quad [\text{for } 1100 \leq SAAR \leq 3000 \text{ mm}] \qquad [7.3]$$

The ratio of $QBAR_{urban}$ to $QBAR_{rural}$ is then estimated from:

$$QBAR_{urban}/QBAR_{rural} = (1+URBAN)^{2NC}[1+URBAN\{(21/CIND) - 0.3\}] \qquad [7.4]$$

The derivation of the coefficients in Equation 7.4 is somewhat intricate but is based on the assumption that 30% of a mapped urban area is impervious, from which 70% runoff is anticipated (see FSSR 5, 1979).

7.4 Comparison of estimates

Figure 7.1 illustrates the extent to which the procedures described in Sections 7.2 and 7.3 can be used to predict $QBAR_{rural}$ and $QBAR_{urban}$. A 1:1 line has been superimposed to assist in the comparison between observed and estimated QBAR values.

The 'rural catchments' compare Equation 7.1 estimates of $QBAR_{rural}$ [ordinate] with known values of QBAR [abscissa], for the 71 rural catchments.

The 'stage I' data points in Figure 7.1 result from the use of Equation 7.1 to estimate $QBAR_{rural}$ for the 16 part-urban catchments *not* used in its construction. The 'stage II' data points illustrate the result of applying the CIRIA adjustment to generate the corresponding 16 $QBAR_{urban}$ data points. Each of the 16 part-urban catchments is thus represented by a vertically-aligned pair of data points: Equation 7.4 ensures that the magnitude of $QBAR_{urban}$ is greater than that of $QBAR_{rural}$ in each case.

It can be seen from Figure 7.1 that the CIRIA adjustment has improved the estimate of $QBAR_{urban}$ markedly for nine of the 16 catchments, had little or no effect on three catchments and had a detrimental effect on the $QBAR_{urban}$ estimate for the remaining four catchments. It should be appreciated that the adjustment, although appearing to work quite well on small catchments, was not specifically designed for such catchments.

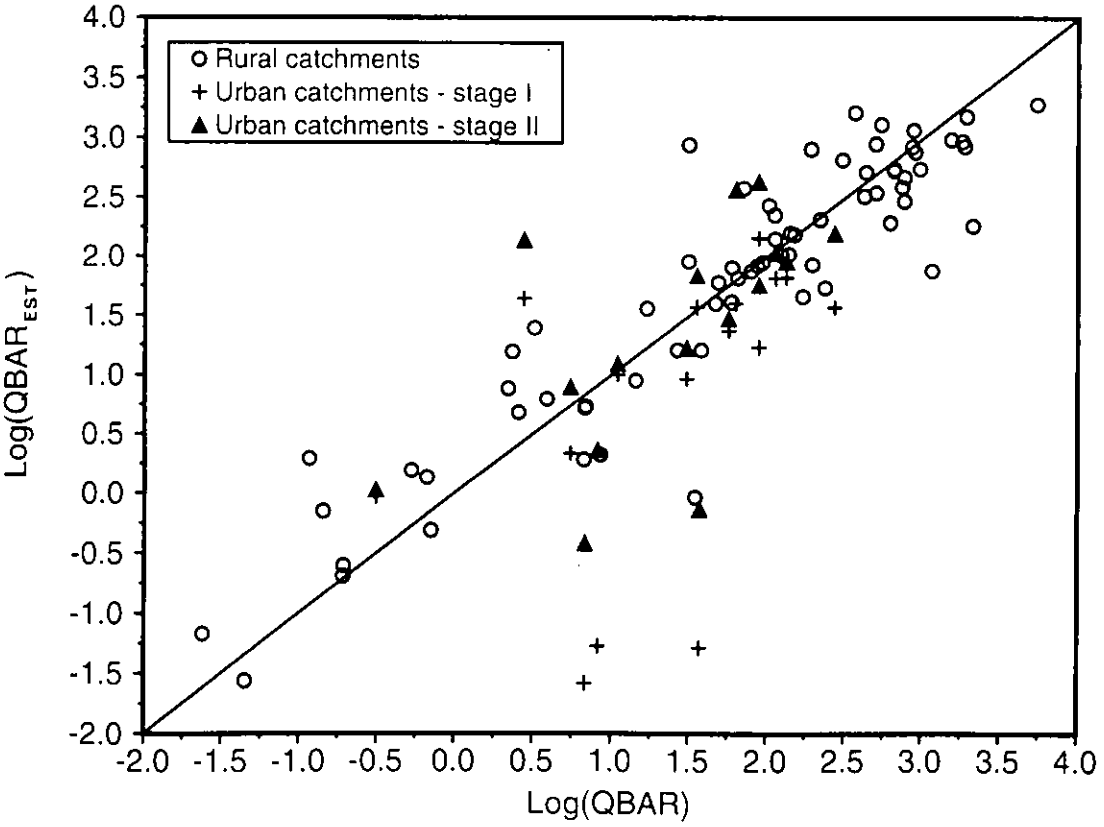

Figure 7.1 *Comparison between estimated ($QBAR_{rural}$ and $QBAR_{urban}$) and observed QBAR data for rural and partially urbanised catchments*

8 Discussion and conclusions

The instrumentation available to this project has allowed the derivation of catchment response times with an accuracy which has hitherto been unachievable. The investigation has demonstrated that the equation recommended in FSSR 16, which is applicable to catchments of any size, tends to overestimate Tp(0) on small urbanised catchments. However, the research has confirmed that the equation works reasonably well on small rural catchments. New equations have been derived (in Chapter 6) which allow the estimation of Tp(0) on part-urban and rural catchments of less than 25 km^2. A synthetic model linking the exponent of URBAN within the FSSR 16 estimation equation to $Tp(0)_{rural}$ has been developed: in effect, this allows the continued use of FSSR 16 for completely rural catchments, whilst modifying the URBAN exponent according to the value of $Tp(0)_{rural}$ for part-urban catchments. The recommended procedure has been summarised in Section 6.7; a revised link between LAG and Tp(0) has been identified (described in Section 6.5).

The testing of DTM-based catchment characteristics within the project has revealed both advantages and difficulties. If, for whatever reason, the DTM is unable to determine the catchment area correctly, this is likely to degrade other catchment characteristics. Small, relatively flat, substantially urbanised catchments can pose particular problems. In some of these cases, neither 1:25 000 OS mapping nor the IH digital terrain model is able to determine the effective drainage area: reference must then be made to drainage plans or site surveys. In further research on the generalisation of flood estimation in the UK, it is desirable that DTM-based catchment characteristics are given full consideration. The advantages of automation are threefold: greater speed, greater objectivity (i.e. reproducibility) and the ability to consider characterisations of a more comprehensive nature. While relatively flat, substantially urbanised catchments may continue to require special treatment, it seems likely that digital terrain models, and digital representations of soils and land cover data, will play an important role in flood estimation on all catchments in due course.

In addition to meeting its principal aim of improving flood response time estimation on small catchments, this study has also explored the estimation of mean annual flood, QBAR, on small rural and urbanised catchments.

In general, the smaller the catchment, the greater the problems in accurately determining its characteristics. If urban development straddles a catchment's boundary, great care is needed when defining its area; almost invariably the true position will differ from the topographical divide. In rural as well as urban cases, the calculation of mainstream slope and gradient (MSL & S1085) are also often difficult on very small catchments. At Bicester (refer Appendix 1) an external import of water was detected. It is accepted that the estimation of Tp(0) is particularly difficult on small part-urban catchments, and that this is an area which could benefit from further research.

Within response time estimation, it may be possible to draw comparisons with an analogue catchment. The 15 catchments described in Appendix 1 may prove useful in this respect, but extreme care is advised.

Practical details of the instrumentation of small catchments for response time estimation have been discussed in Chapter 2. Where flood data can be gathered, it is preferable to estimate Tp(0) by deriving unit hydrographs or by observing LAG and applying Equation 6.7. It is concluded that, with careful attention, a period of record as short as six months can provide useful information on an urbanised catchment, but that between 18 months and two years of data are preferable for rural catchments.

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Philippa Lloyd, Nicolas Mann and Richard Wilson (all sandwich course students from Luton College of Higher Education) undertook the majority of the data collection and assisted with routine maintenance of the 15 water level recorders. Jason Duckers and Robert Skeen from Sheffield City Polytechnic wrote the software for calculation of the DTM-derived catchment characteristics. Sara Rollason from the University of Luton assisted with the production of diagrams. John Griffin edited and typeset the final report.

The project was completed in parallel with a similar ADAS investigation, with which there was a free exchange of data. The staff of ADAS, particularly Adrian Muscutt and Stephen Rose, are thanked for their substantial contribution.

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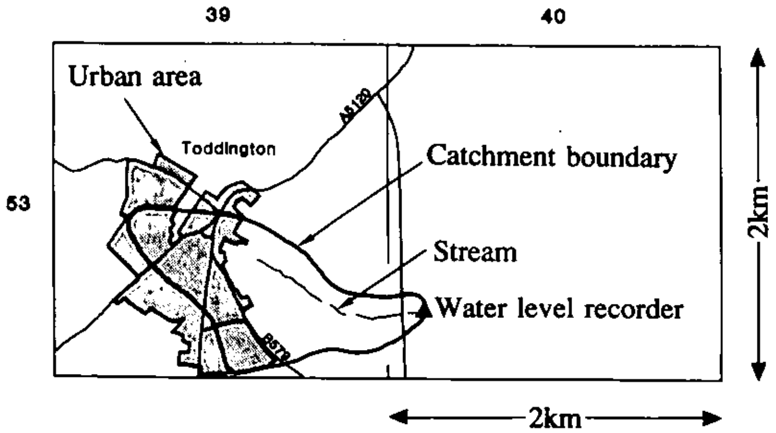
Appendix 1 Catchment descriptions and statistics

For each of the 15 instrumented catchments, Appendix 1 presents a catchment map, description and characteristics. Information regarding record length and highest recorded level is given along with details of analysed events.

Map Legend

Weather radar 2km x 2km cell numbers
(Chenies weather radar is located at 39,38)



Catchment description

Brief details of land use, soils and geology are given together with a description of the gauging point.

Catchment characteristics

Catchment characteristics shown in italics are derived from the Institute of Hydrology Digital Terrain Model and those marked with an asterisk are derived from a stream network based on a contributing area threshold of 0.075 km^2 (7.5 hectares). Mean land slope is not derived directly from this network, but is threshold dependent since it is calculated from grid point elevations *not* designated as part of the network.

Water level records

Details regarding record length and the highest recorded level are presented. Levels given here and on the example event hydrograph are relative to an arbitrary datum.

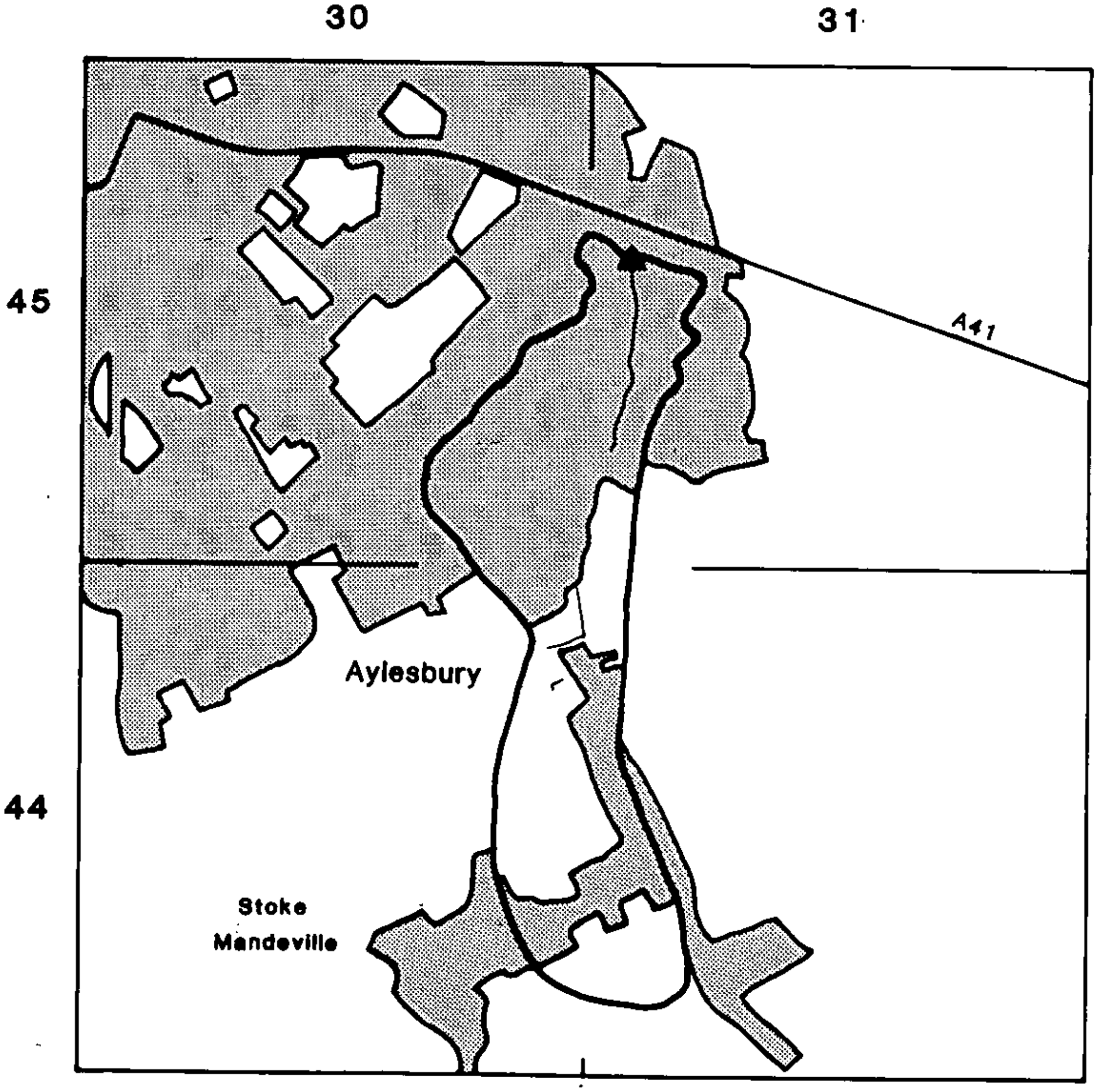
Event statistics

For each event analysed, the date and calculated LAG and Tp(0) times are shown. Arithmetic and geometric means are given for these data.

Aylesbury

Water level recorder at: SP 842 132

Catchment area: 1.74 km^2



Catchment description

The Aylesbury catchment is predominantly urban, with extensive residential development. The source of Bedgrove Brook is near the village of Stoke Mandeville. Here the catchment is primarily rural with cereals grown. The brook is taken under a road in a small culvert, flows in an open ditch for a short distance and then enters a long culvert which takes the stream under playing fields. The brook emerges from the culvert into a small pond, and then runs through a copse before entering a residential area. Instrumentation was secured to a concrete wall adjacent to the downstream end of a culvert taking an estate road (Queens Mead) over the brook. Catchment soils are gleyic brown calcareous earths with an underlying geology of upper greensand and gault.

Catchment characteristics

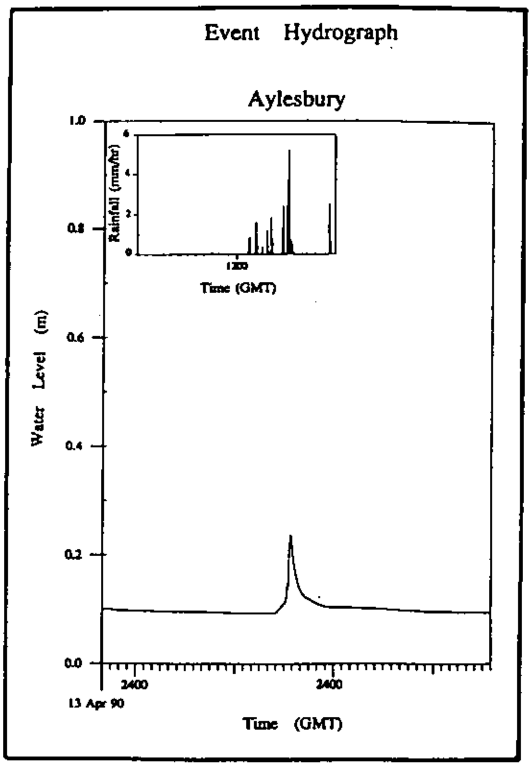
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	1.740	km^2
Main stream length	MSL	1.900	km
10-85% stream slope	S1085	6.340	m/km
Urban fraction	URBAN	0.631	-
Forest fraction	FOREST	0.020	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	1.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.450	-
Average annual rainfall (1941-70)	SAAR	629	mm
Catchment area	*DTMAREA*	*1.365*	*km^2*
Altitude at water level recorder	*DTMALT*	*83.400*	*m AOD*
Mean altitude	*DTMMALT*	*96.281*	*m AOD*
Mean land slope	*DTMLANS*	*14.166*	*m/km*
Mean river slope	*DTMRIVS**	*6.109*	*m/km*
Main stream length	*DTMMSL**	*3.776*	*km*
10-85% stream slope	*DTMS1085**	*5.660*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*3*	-
Total network length	*DTMLEN**	*4.238*	*km*

Summary statistics

Record starts	4 September 1989
Record ends	2 April 1992
Years of record	2.58
Highest level	0.805 m
Date of highest level	12 September 1989

Event statistics

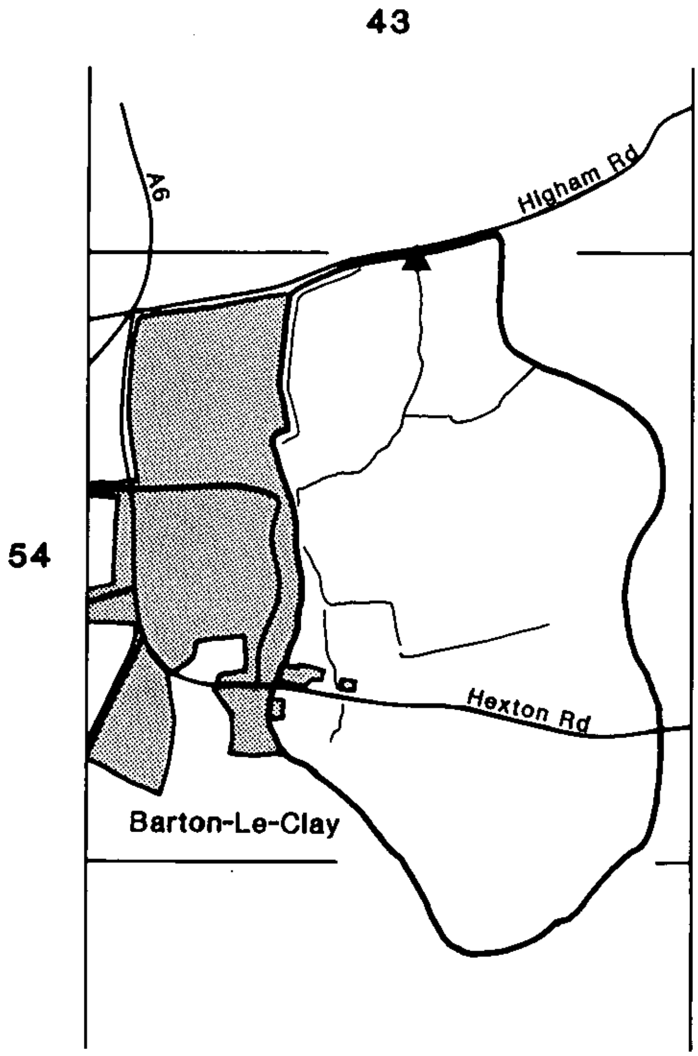
DATE			LAG (hrs)	Tp(0) (hrs)
12	January	1990	1.3	0.2
14	April	1990	0.5	0.4
3	October	1990	0.4	0.6
30	October	1990	0.3	0.4
25	June	1991	0.4	0.7
22	September	1991	0.6	0.9
26	September	1991	0.5	0.6
30	October	1991	0.4	0.4
Arithmetic mean			0.6	0.5
Geometric mean			0.5	0.5



Example event **14 April 1990**
Lag 0.5 hrs **Tp(0) 0.4 hrs**

Barton-Le-Clay

Water level recorder at: TL 091 320 — Catchment area: 2.27 km^2



Catchment description

The Barton-Le-Clay catchment embraces two contrasting areas. The upper part of the catchment is a steep chalk escarpment (Barton Hills) where there is evidence of 'gullying', whereas the lower part is very flat and intensively farmed. Soils on the escarpment are brown calcareous earths and on the lower part grey rendzinas. On the steep slopes oilseed rape is grown while the flatter land below allows intensive cereal production. From its source the brook passes under the Hexton Road (B655) on to the flatter part of the catchment. The brook runs along the edge of the village before flowing towards the Higham Road. There are a number of open ditches and outfalls from agricultural underdrainage are evident along both banks. The stream passes through twin culverts under the road and instrumentation was secured on the upstream side between the culverts, to minimise obstruction to the flow.

Catchment characteristics

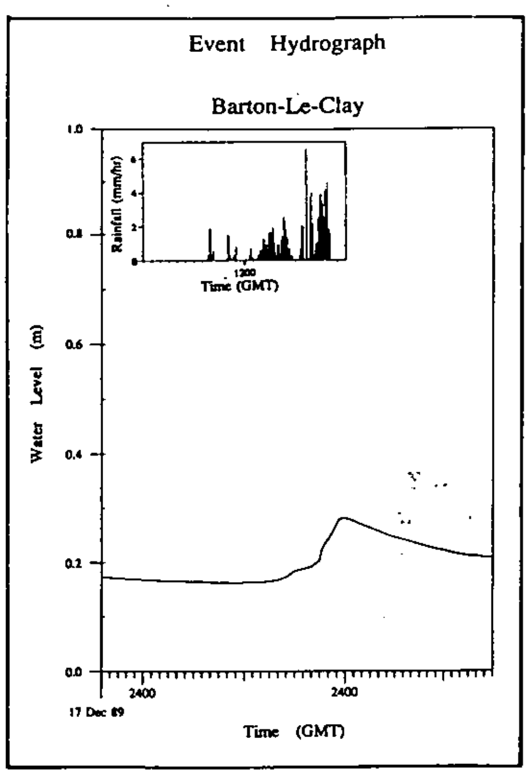
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	2.270	km^2
Main stream length	MSL	2.250	km
10-85% stream slope	S1085	7.700	m/km
Urban fraction	URBAN	0.004	-
Forest fraction	FOREST	0.010	-
WRAP 1 soil fraction	SOIL1	1.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	0.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.150	-
Average annual rainfall (1941-70)	SAAR	612	mm
Catchment area	*DTMAREA*	-----	km^2
Altitude at water level recorder	*DTMALT*	-----	*m AOD*
Mean altitude	*DTMMALT*	-----	*m AOD*
Mean land slope	*DTMLANS*	-----	*m/km*
Mean river slope	*DTMRIVS**	-----	*m/km*
Main stream length	*DTMMSL**	-----	*km*
10-85% stream slope	*DTMS1085**	-----	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	-----	-
Total network length	*DTMLEN**	-----	*km*

Summary statistics

Record starts	14 November 1989
Record ends	26 March 1993
Years of record	3.36
Highest level	0.465 m
Date of highest level	3 February 1990

Event statistics

DATE	LAG (hrs)	Tp(0) (hrs)
18 December 1989	5.4	2.5
2 February 1990	6.0	5.5
7 February 1990	10.9	11.5
11 February 1990	6.4	7.8
25 December 1990	2.5	2.5
3 July 1991	2.5	3.3
23 August 1991	2.3	2.3
19 November 1991	5.9	4.5
9 January 1992	5.8	1.5
Arithmetic mean	5.3	4.6
Geometric mean	4.7	3.8



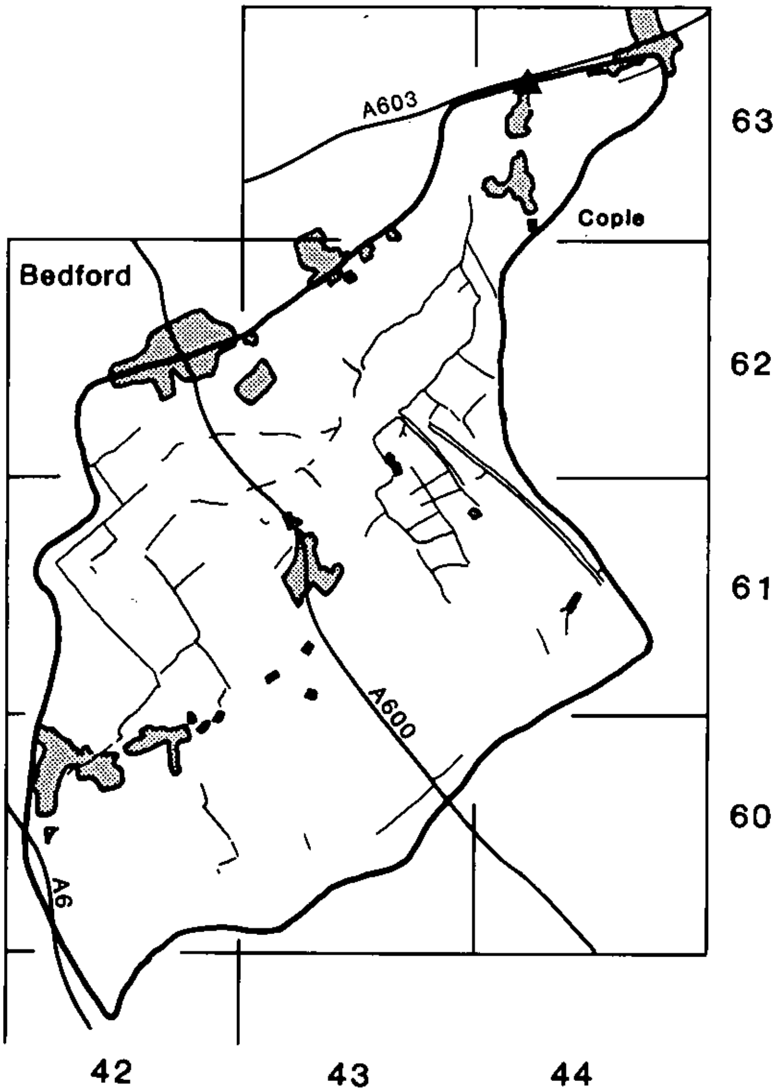
Example event **18 December 1989**

Lag 5.4 hrs **Tp(0) 2.5 hrs**

Bedford

Water level recorder at: TL 102 492

Catchment area: 22.92 km^2



Catchment description

The Bedford catchment, which comes under the jurisdiction of the Bedfordshire and River Ivel Internal Drainage Board, is rural except for a number of small villages. Agricultural activity is predominantly arable farming with cereals and green vegetables the major crops. On the steeper slopes in the south of the catchment there are extensive areas of grassland which are grazed by sheep. Most of the catchment is very flat and the stream network comprises a complex pattern of small streams and drainage ditches. South of the village of Cople these streams merge to form a single watercourse which flows northward towards the A603. The brook passes under the road through the archway of a brick bridge. Instrumentation was fixed on the upstream side of the bridge on the right bank. Catchment soils are typical calcareous pelosols and typical argillic brown earths. Catchment geology is Oxford clay with Kellaways beds.

Catchment characteristics

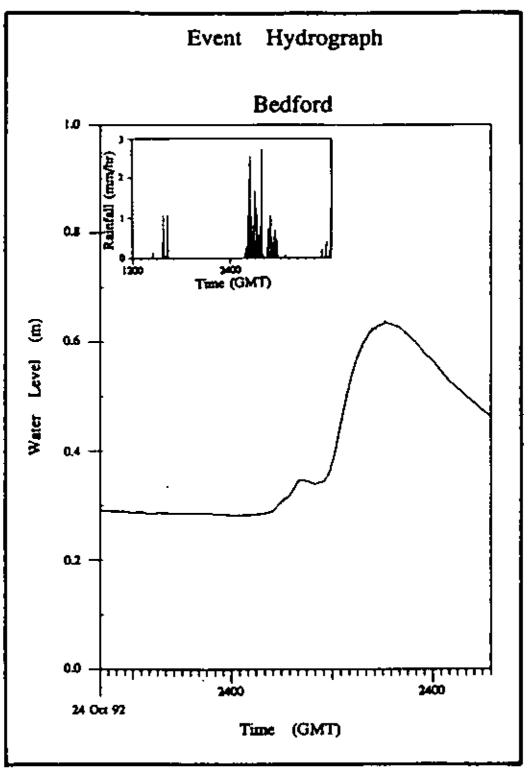
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	22.92	km^2
Main stream length	MSL	9.550	km
10-85% stream slope	S1085	1.330	m/km
Urban fraction	URBAN	0.040	-
Forest fraction	FOREST	0.060	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.080	-
WRAP 3 soil fraction	SOIL3	0.230	-
WRAP 4 soil fraction	SOIL4	0.690	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.426	-
Average annual rainfall (1941-70)	SAAR	550	mm
Catchment area	*DTMAREA*	*26.547*	*km^2*
Altitude at water level recorder	*DTMALT*	*22.300*	*m AOD*
Mean altitude	*DTMMALT*	*39.363*	*m AOD*
Mean land slope	*DTMLANS*	*18.241*	*m/km*
Mean river slope	*DTMRIVS**	*8.377*	*m/km*
Main stream length	*DTMMSL**	*11.625*	*km*
10-85% stream slope	*DTMS1085**	*1.660*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*102*	-
Total network length	*DTMLEN**	*109.213*	*km*

Summary statistics

Record starts	12 February 1990
Record ends	26 March 1993
Years of record	3.11
Highest level	1.424 m
Date of highest level	23 September 1992

Event statistics

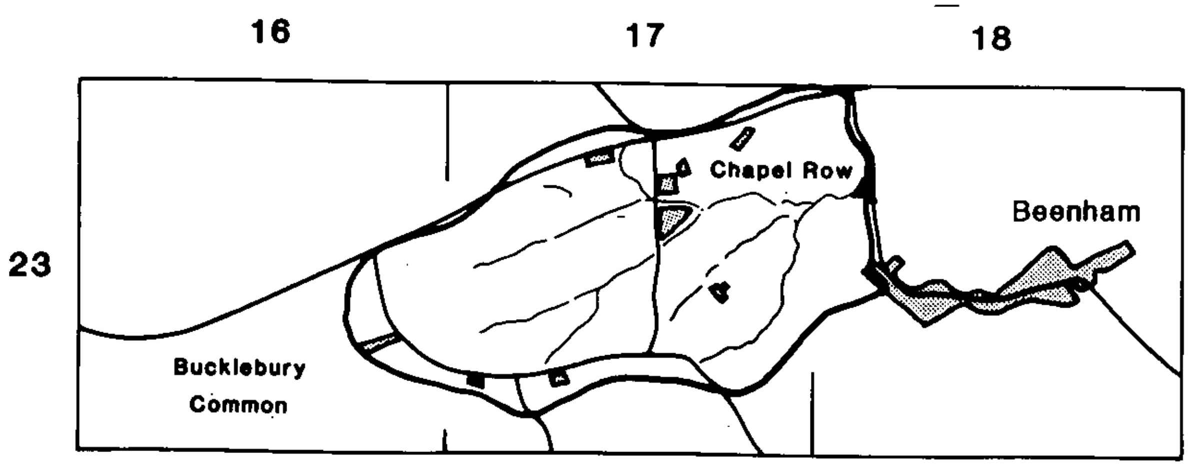
DATE			LAG (hrs)	Tp(0) (hrs)
15	February	1990	14.0	15.5
28	October	1990	7.6	6.3
10	December	1990	27.8	27.3
16	February	1991	28.9	28.5
28	February	1991	11.7	9.3
19	November	1991	14.4	11.5
9	January	1992	15.8	15.8
23	September	1992	12.7	10.1
20	October	1992	14.2	12.8
25	October	1992	14.9	15.4
11	November	1992	12.9	11.3
Arithmetic mean			15.9	14.9
Geometric mean			14.9	13.6



Example event **25 October 1992**
Lag 14.9 hrs **Tp(0) 15.4 hrs**

Beenham

Water level recorder at: SU 583 694 Catchment area: 3.40 km^2



Catchment description

Beenham is a rural catchment with woodland the dominant land cover. The source of the brook ('The Bourne') is found on Bucklebury Common and, after running through woodland, the stream meets a tributary near the hamlet of Chapel Row. From the confluence the brook runs through agricultural land devoted to cereals and grassland before passing under a minor road near the village of Beenham. The instrumentation was secured to the upstream face of the bridge adjacent to the right bank. Catchments soils are typically stagnogleyic or argillic brown earths with an underlying geology of Barton, Bracklesham and Bagshot beds.

Catchment characteristics

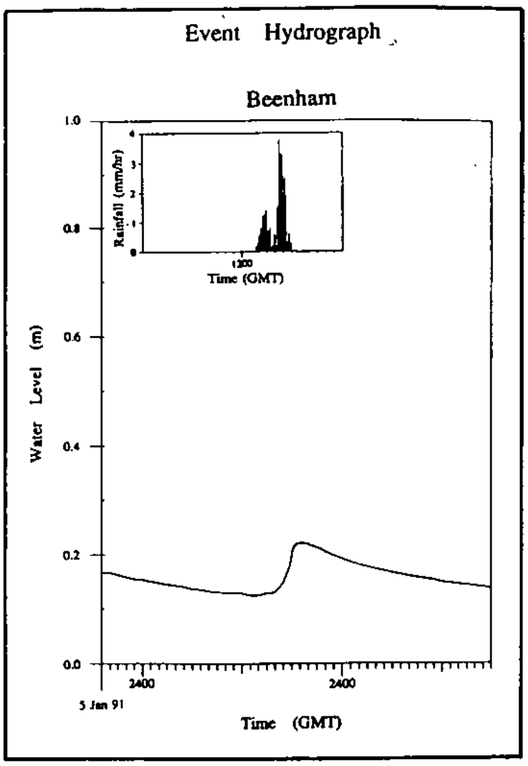
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	3.400	km^2
Main stream length	MSL	2.350	km
10-85% stream slope	S1085	13.300	m/km
Urban fraction	URBAN	0.020	-
Forest fraction	FOREST	0.420	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	1.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.450	-
Average annual rainfall (1941-70)	SAAR	700	mm
Catchment area	*DTMAREA*	*3.160*	*km^2*
Altitude at water level recorder	*DTMALT*	*85.500*	*m AOD*
Mean altitude	*DTMMALT*	*111.086*	*m AOD*
Mean land slope	*DTMLANS*	*43.117*	*m/km*
Mean river slope	*DTMRIVS**	*20.320*	*m/km*
Main stream length	*DTMMSL**	*2.693*	*km*
10-85% stream slope	*DTMS1085**	*12.450*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*9*	-
Total network length	*DTMLEN**	*6.440*	*km*

Summary statistics

Record starts	7 February 1990
Record ends	20 March 1991
Years of record	1.12
Highest level	0.691 m
Date of highest level	7 February 1990

Event statistics

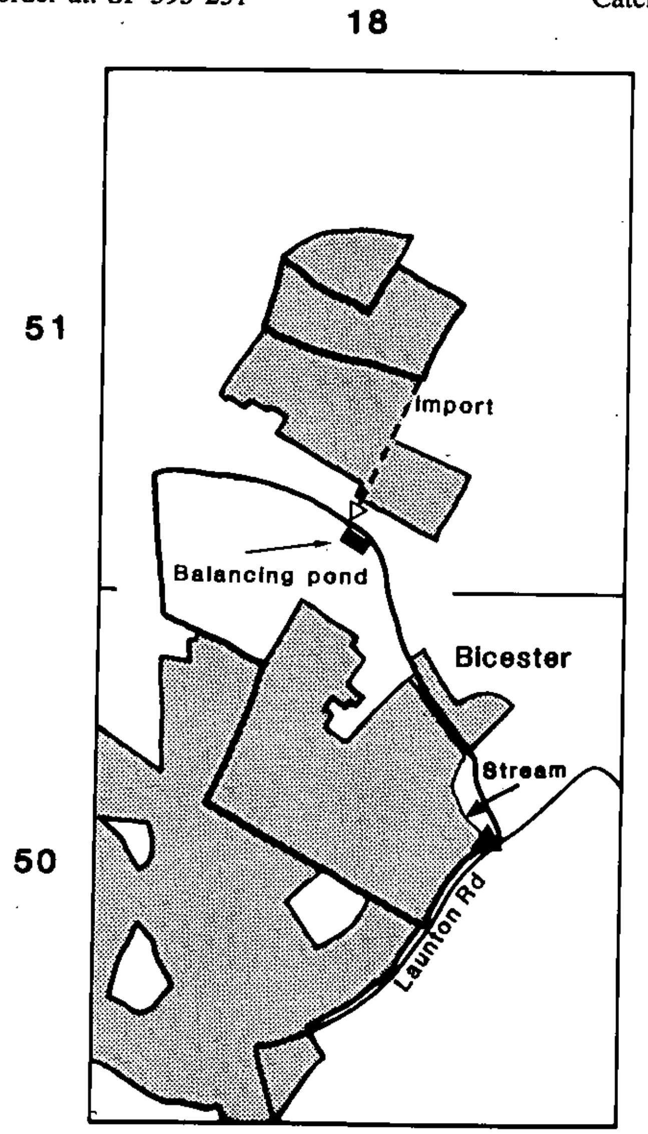
DATE	LAG (hrs)	Tp(0) (hrs)
11 February 1990	2.3	1.8
25 February 1990	1.7	1.4
1 January 1991	4.0	1.8
6 January 1991	2.9	1.8
8 January 1991	5.5	7.8
Arithmetic mean	3.3	2.9
Geometric mean	3.0	2.3



Example event **6 January 1991**
Lag 2.9 hrs **Tp(0) 1.8 hrs**

Bicester

Water level recorder at: SP 595 231 Catchment area: 1.46 km^2



Catchment description

The Bicester catchment is predominantly urban, with both residential and industrial development present. The upper part of the catchment remained undeveloped during the period of instrumentation but was earmarked for the next phase of building. Surface water drainage is brought in to the catchment (dashed line on map) from a recently built housing estate 0.5 km to the north. An off-line storage pond has been built to balance existing and anticipated flood water, but was not observed in operation. The stream is culverted under school playing fields before emerging in an open concrete lined channel, to run through a residential area and an industrial estate before passing through a box culvert under the Launton Road. The water level monitoring equipment was secured on the upstream side of the bridge in a narrow-diameter steel tube designed to minimise obstruction to the flow (Chapter 2, Plate 2.1).

Catchment characteristics

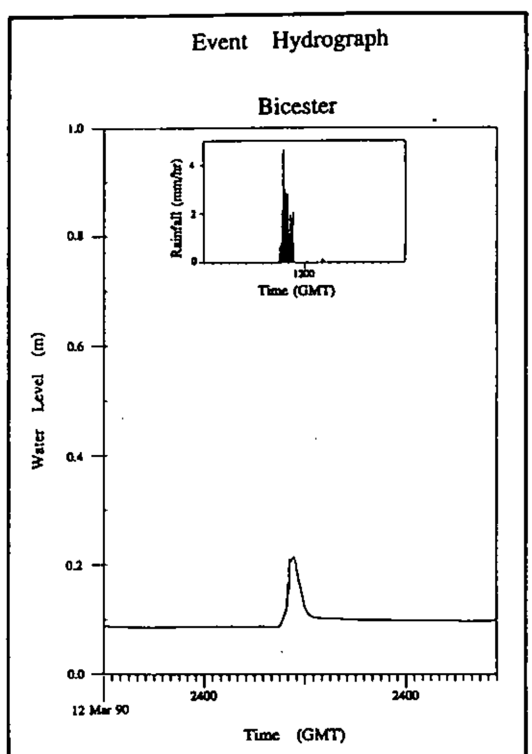
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	1.460	km²
Main stream length	MSL	0.700	km
10-85% stream slope	S1085	8.000	m/km
Urban fraction	URBAN	0.652	-
Forest fraction	FOREST	0.003	-
WRAP 1 soil fraction	SOIL1	1.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	0.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.150	-
Average annual rainfall (1941-70)	SAAR	655	mm
Catchment area	*DTMAREA*	-----	*km²*
Altitude at water level recorder	*DTMALT*	-----	*m AOD*
Mean altitude	*DTMMALT*	-----	*m AOD*
Mean land slope	*DTMLANS*	-----	*m/km*
Mean river slope	*DTMRIVS**	-----	*m/km*
Main stream length	*DTMMSL**	-----	*km*
10-85% stream slope	*DTMS1085**	-----	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	-----	-
Total network length	*DTMLEN**	-----	*km*

Summary statistics

Record starts	21 February 1990
Record ends	3 April 1992
Years of record	2.12
Highest level	0.763 m
Date of highest level	27 September 1991

Event statistics

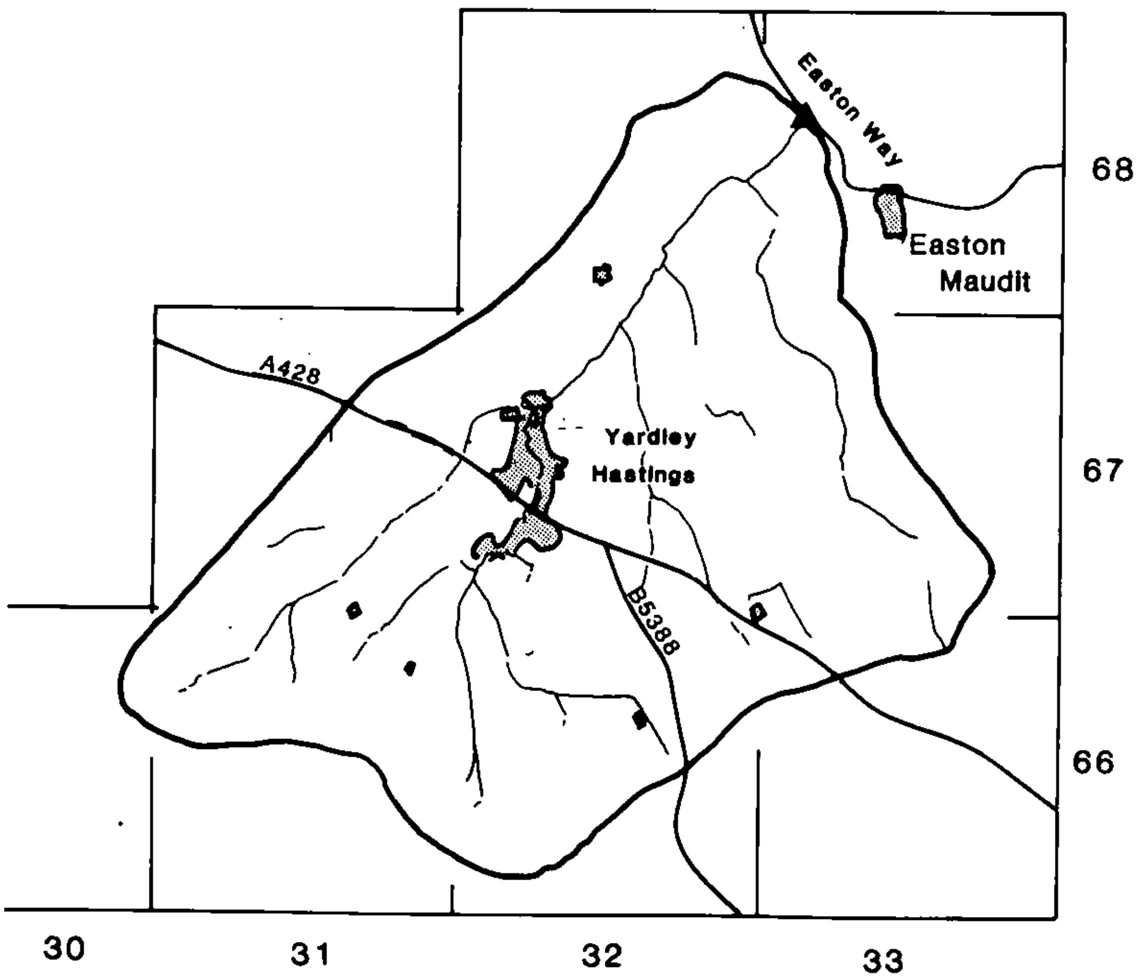
DATE	LAG (hrs)	Tp(0) (hrs)
13 March 1990	0.48	0.7
19 April 1990	0.33	0.4
14 May 1990	0.18	0.4
30 June 1990	0.13	0.3
4 April 1991	0.40	0.4
Arithmetic mean	0.30	0.4
Geometric mean	0.27	0.4



Example event **13 March 1990**
Lag 0.48 hrs **Tp(0) 0.7 hrs**

Easton Maudit

Water level recorder at: SP 883 593 Catchment area: 15.76 km^2



Catchment description

The Easton Maudit catchment is rural except for the village of Yardley Hastings located near its centre. Arable farming dominates agricultural activity in the catchment although there are small areas of grassland. Woodland represents 17% of catchment land cover. A number of small streams which drain the slopes to the south of Yardley Hastings converge to form Grendon Brook which then flows northward towards a minor road (Easton Way). The brook passes under the road, through the rectangular aperture of a bridge. Instrumentation was secured to the upstream side of the bridge on the left bank. Catchment soils are typical calcareous pelosols and typical brown calcareous earths. Catchment geology is Oxford clay with Kellaways beds and Great Oolite series.

Catchment characteristics

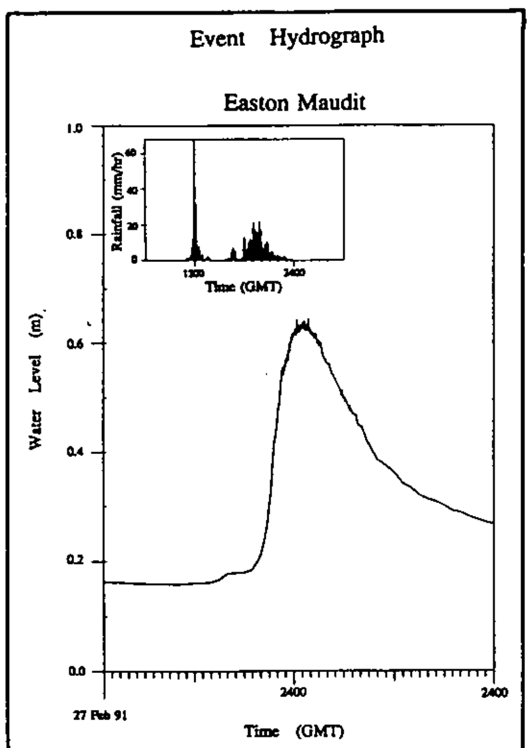
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	15.76	km^2
Main stream length	MSL	5.800	km
10-85% stream slope	S1085	6.440	m/km
Urban fraction	URBAN	0.017	-
Forest fraction	FOREST	0.170	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.800	-
WRAP 4 soil fraction	SOIL4	0.200	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.410	-
Average annual rainfall (1941-70)	SAAR	621	mm
Catchment area	*DTMAREA*	*15.782*	*km^2*
Altitude at water level recorder	*DTMALT*	*66.400*	*m AOD*
Mean altitude	*DTMMALT*	*93.633*	*m AOD*
Mean land slope	*DTMLANS*	*25.816*	*m/km*
Mean river slope	*DTMRIVS**	*13.802*	*m/km*
Main stream length	*DTMMSL**	*7.254*	*km*
10-85% stream slope	*DTMS1085**	*6.016*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*54*	-
Total network length	*DTMLEN**	*35.027*	*km*

Summary statistics

Record starts	12 February 1990
Record ends	26 March 1993
Years of record	3.11
Highest level	1.678 m
Date of highest level	23 September 1992

Event statistics

DATE	LAG (hrs)	Tp(0) (hrs)
13 February 1990	4.9	5.5
15 February 1990	8.7	9.5
10 January 1991	8.7	11.8
28 February 1991	8.8	10.1
19 November 1991	11.0	5.5
9 January 1992	7.6	5.3
30 March 1992	9.2	8.3
15 April 1992	12.5	9.8
23 September 1992	6.1	5.6
Arithmetic mean	8.6	7.9
Geometric mean	8.3	7.6

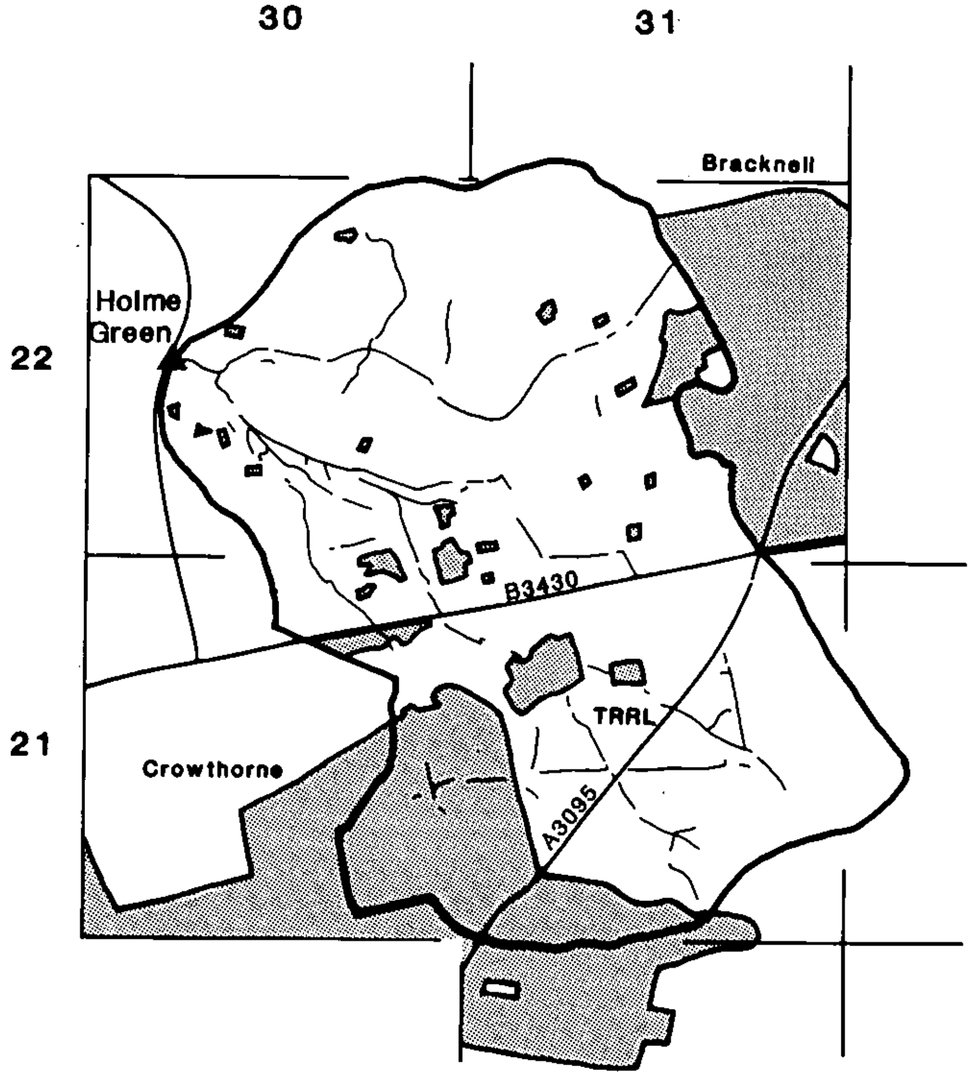


Example event **28 February 1991**
Lag 8.8 hrs **Tp(0) 10.1 hrs**

Holme Green

Water level recorder at: SU 824 670

Catchment area: 9.81 km^2



Catchment description

The Holme Green catchment is predominantly rural with a variety of land uses. The southern half of the catchment encompasses much of the town of Crowthorne and there is extensive commercial woodland. Further north, agriculture is the principal activity, with land used for the grazing of horses, horticulture and cereal production. There is also a large golf course. A number of small streams drain Forestry Commission woodland and then join near the Transport and Road Research Laboratory (TRRL). As the brook flows towards the hamlet of Holme Green it is joined by a major tributary which drains the north of the catchment. About 0.2 km downstream from this confluence a brick bridge takes a minor road over the stream. The water level recorder was secured to the upstream face of the bridge on the left bank. Catchment soils are stagnogley-podzols with an underlying geology of Barton, Bracklesham and Bagshot beds.

Catchment characteristics

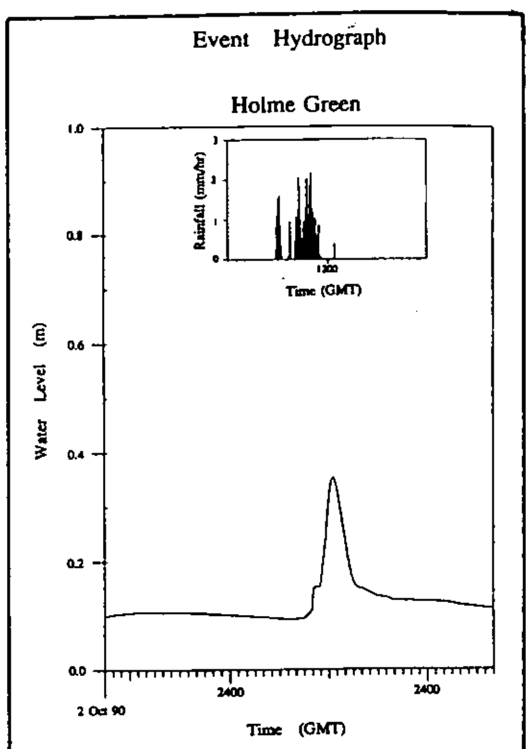
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	9.81	km^2
Main stream length	MSL	4.150	km
10-85% stream slope	S1085	11.570	m/km
Urban fraction	URBAN	0.154	-
Forest fraction	FOREST	0.390	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.730	-
WRAP 4 soil fraction	SOIL4	0.270	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.414	-
Average annual rainfall (1941-70)	SAAR	671	mm
Catchment area	*DTMAREA*	*10.417*	*km^2*
Altitude at water level recorder	*DTMALT*	*53.900*	*m AOD*
Mean altitude	*DTMMALT*	*80.459*	*m AOD*
Mean land slope	*DTMLANS*	*26.949*	*m/km*
Mean river slope	*DTMRIVS**	*13.985*	*m/km*
Main stream length	*DTMMSL**	*5.823*	*km*
10-85% stream slope	*DTMS1085**	*7.597*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*35*	-
Total network length	*DTMLEN**	*27.952*	*km*

Summary statistics

Record starts	7 February 1990
Record ends	3 April 1992
Years of record	2.16
Highest level	0.997 m
Date of highest level	19 November 1991

Event statistics

DATE	LAG (hrs)	Tp(0) (hrs)
4 July 1990	4.5	4.8
3 October 1990	3.7	4.1
26 October 1990	3.2	2.5
24 November 1990	4.0	5.5
26 November 1990	3.8	3.4
27 September 1991	3.9	3.4
29 September 1991	3.2	3.4
Arithmetic mean	3.8	3.9
Geometric mean	3.7	3.8

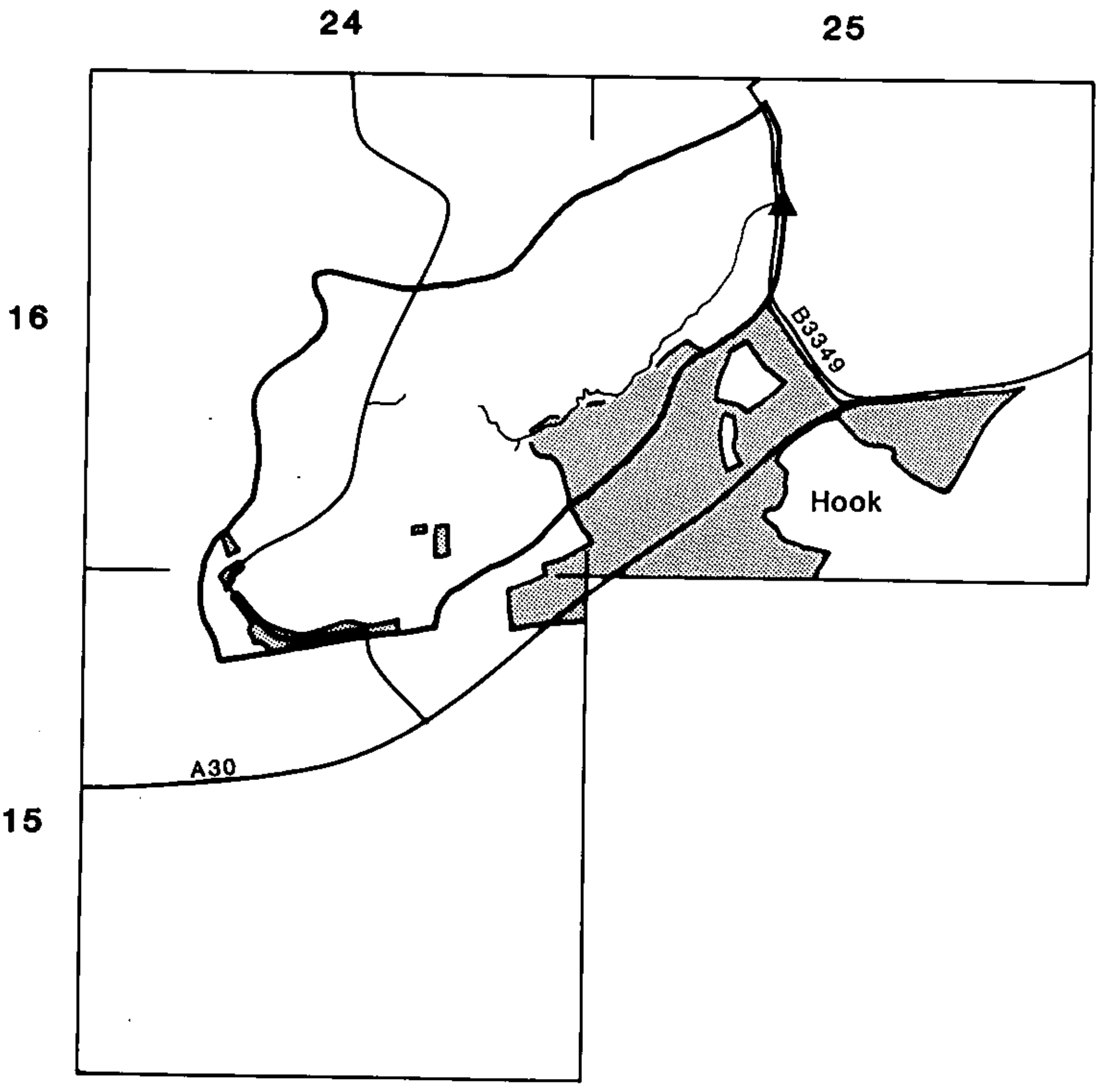


Example event **3 October 1990**
Lag 3.7 hrs **Tp(0) 4.1 hrs**

Hook

Water level recorder at: SU 728 555

Catchment area: 2.49 km^2



Catchment description

The Hook catchment is predominantly rural, although there is a recently developed residential area on the right bank which discharges surface water to the brook. Much of the catchment is woodland or grassland with a small amount of arable and horticultural production. The southern-most watershed is determined by a deep railway cutting. From the source the brook runs through woodland before passing under the B3349 in twin circular culverts. Instrumentation was fixed between the culverts on the downstream side of the bridge. Between 21 May 1990 and 26 October 1990 the stream flowed intermittently, with the bed completely dry during much of this period. Typical stagnogley soils are to be found over most of the catchment with an underlying geology of London clay.

Catchment characteristics

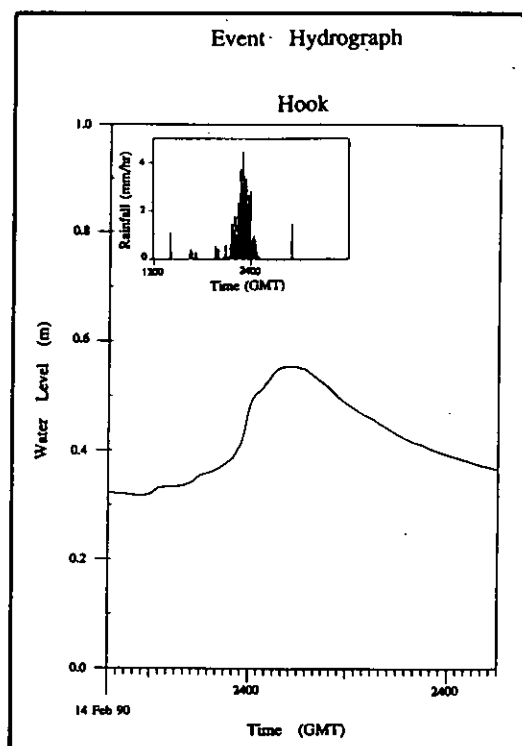
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	2.490	km^2
Main stream length	MSL	1.725	km
10-85% stream slope	S1085	7.730	m/km
Urban fraction	URBAN	0.084	-
Forest fraction	FOREST	0.190	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	1.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.450	-
Average annual rainfall (1941-70)	SAAR	725	mm
Catchment area	*DTMAREA*	*3.507*	*km^2*
Altitude at water level recorder	*DTMALT*	*63.100*	*m AOD*
Mean altitude	*DTMMALT*	*85.502*	*m AOD*
Mean land slope	*DTMLANS*	*27.726*	*m/km*
Mean river slope	*DTMRIVS**	*14.156*	*m/km*
Main stream length	*DTMMSL**	*3.392*	*km*
10-85% stream slope	*DTMS1085**	*9.080*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*12*	-
Total network length	*DTMLEN**	*7.351*	*km*

Summary statistics

Record starts	7 February 1990
Record ends	20 March 1991
Years of record	1.12
Highest level	0.876 m
Date of highest level	7 February 1990

Event statistics

DATE			LAG (hrs)	Tp(0) (hrs)
15	February	1990	6.1	7.5
26	November	1990	4.1	7.0
1	January	1991	4.9	3.5
23	February	1991	10.8	7.5
17	March	1991	13.3	15.0
Arithmetic mean			7.8	8.1
Geometric mean			7.1	7.3

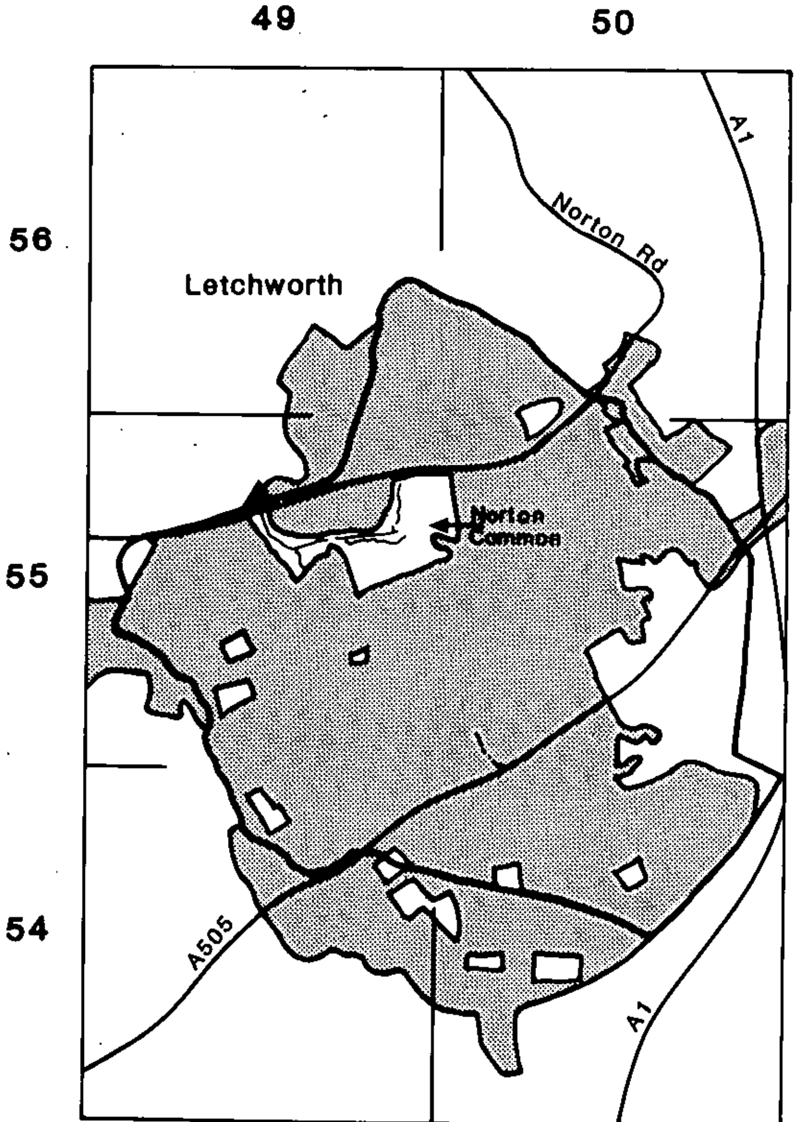


Example event **15 February 1990**
Lag 6.1 hrs **Tp(0) 7.5 hrs**

Letchworth

Water level recorder at: TL 210 335

Catchment area: 8.52 km^2



Catchment description

The Letchworth catchment is almost entirely urban and encompasses much of the town. Most of the development is residential but there is an industrial estate on the eastern side of the catchment. The non-urban areas, apart from Norton Common, are principally allotments and playing fields. Pix Brook emerges from a large culvert in Norton Common and then flows past allotments and through a narrow copse before passing under a minor road in three concrete box culverts. Instrumentation was secured between two of the culverts on the downstream side. Soils in the east of the catchment are grey rendzinas with an underlying geology of chalk, but the remaining catchment soils are unsurveyed since they are in an urban area.

Catchment characteristics

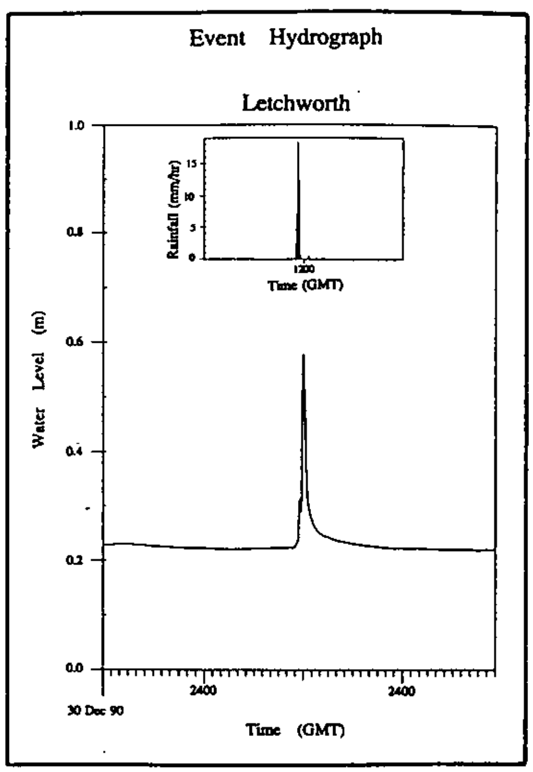
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	8.520	km^2
Main stream length	MSL	0.925	km
10-85% stream slope	S1085	7.210	m/km
Urban fraction	URBAN	0.845	-
Forest fraction	FOREST	0.030	-
WRAP 1 soil fraction	SOIL1	0.225	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.775	-
WRAP 4 soil fraction	SOIL4	0.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.344	-
Average annual rainfall (1941-70)	SAAR	575	mm
Catchment area	*DTMAREA*	*8.795*	*km^2*
Altitude at water level recorder	*DTMALT*	*59.200*	*m AOD*
Mean altitude	*DTMMALT*	*90.931*	*m AOD*
Mean land slope	*DTMLANS*	*28.890*	*m/km*
Mean river slope	*DTMRIVS**	*16.153*	*m/km*
Main stream length	*DTMMSL**	*5.987*	*km*
10-85% stream slope	*DTMS1085**	*9.364*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*31*	-
Total network length	*DTMLEN**	*23.241*	*km*

Summary statistics

Record starts	8 January 1990
Record ends	19 March 1991
Years of record	1.19
Highest level	1.039 m
Date of highest level	3 February 1990

Event statistics

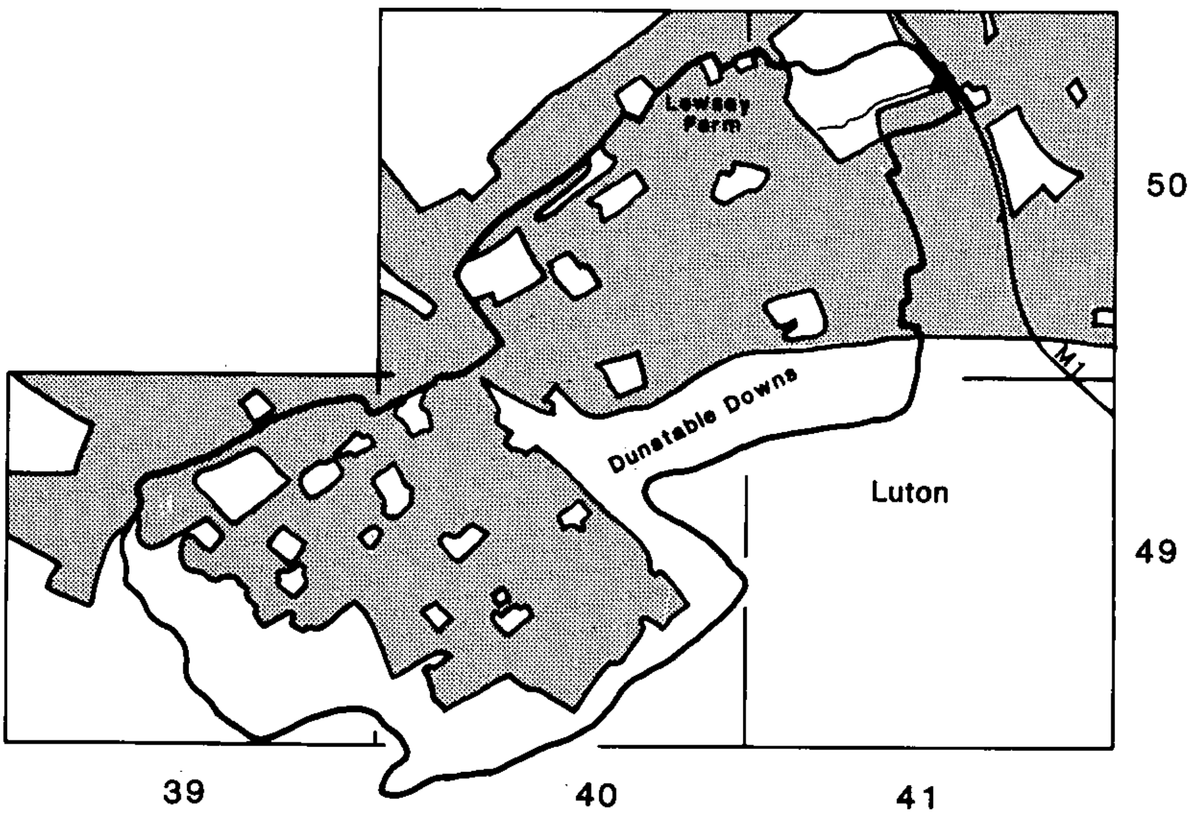
DATE			LAG (hrs)	Tp(0) (hrs)
15	January	1990	0.8	1.1
19	April	1990	0.9	0.7
7	July	1990	0.7	0.7
31	December	1990	0.8	0.7
3	January	1991	0.6	0.8
Arithmetic mean			0.8	0.8
Geometric mean			0.8	0.8



Example event **31 December 1990**
Lag 0.8 hrs **Tp(0) 0.7 hrs**

Luton

Water level recorder at: TL 050 236 Catchment area: 9.05 km^2



Catchment description

The Luton catchment is predominantly urban and includes both residential and industrial development. Non-urban areas are principally the north facing escarpment of the Dunstable Downs, school playing fields and recreation grounds. The stream (Lewsey Brook) first appears above ground when it emerges from a circular culvert into a recreation ground in the Lewsey Farm area of Luton. The brook then flows through the park in open channel until it reaches the M1 motorway, where a concrete archway allows the stream to pass under the road. Instrumentation was secured to the archway entrance. The brook flows intermittently suggesting that the stream is not spring-fed and that any flow is almost entirely urban runoff. Catchment soils on the escarpment are stagnogleyic paleo-argillic brown earths over chalk.

Catchment characteristics

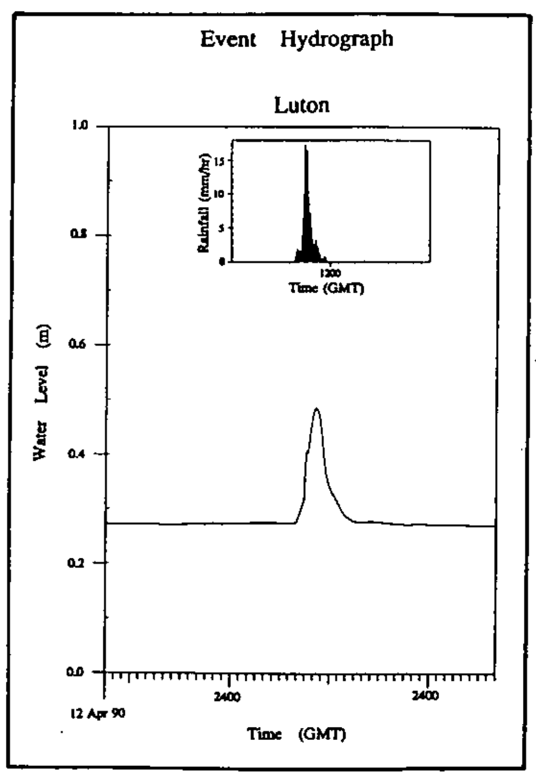
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	9.050	km^2
Main stream length	MSL	0.680	km
10-85% stream slope	S1085	0.980	m/km
Urban fraction	URBAN	0.630	-
Forest fraction	FOREST	0.030	-
WRAP 1 soil fraction	SOIL1	1.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	0.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.150	-
Average annual rainfall (1941-70)	SAAR	675	mm
Catchment area	*DTMAREA*	-----	*km^2*
Altitude at water level recorder	*DTMALT*	-----	*m AOD*
Mean altitude	*DTMMALT*	-----	*m AOD*
Mean land slope	*DTMLANS*	-----	*m/km*
Mean river slope	*DTMRIVS**	-----	*m/km*
Main stream length	*DTMMSL**	-----	*km*
10-85% stream slope	*DTMS1085**	-----	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	-----	-
Total network length	*DTMLEN**	-----	*km*

Summary statistics

Record starts	24 November 1989
Record ends	1 April 1992
Years of record	2.35
Highest level	1.200 m
Date of highest level	27 June 1991

Event statistics

DATE	LAG (hrs)	Tp(0) (hrs)
23 December 1989	0.8	0.5
13 April 1990	1.1	1.3
21 June 1990	1.5	1.1
30 July 1990	1.5	2.3
17 September 1990	1.5	2.1
Arithmetic mean	1.3	1.5
Geometric mean	1.2	1.3

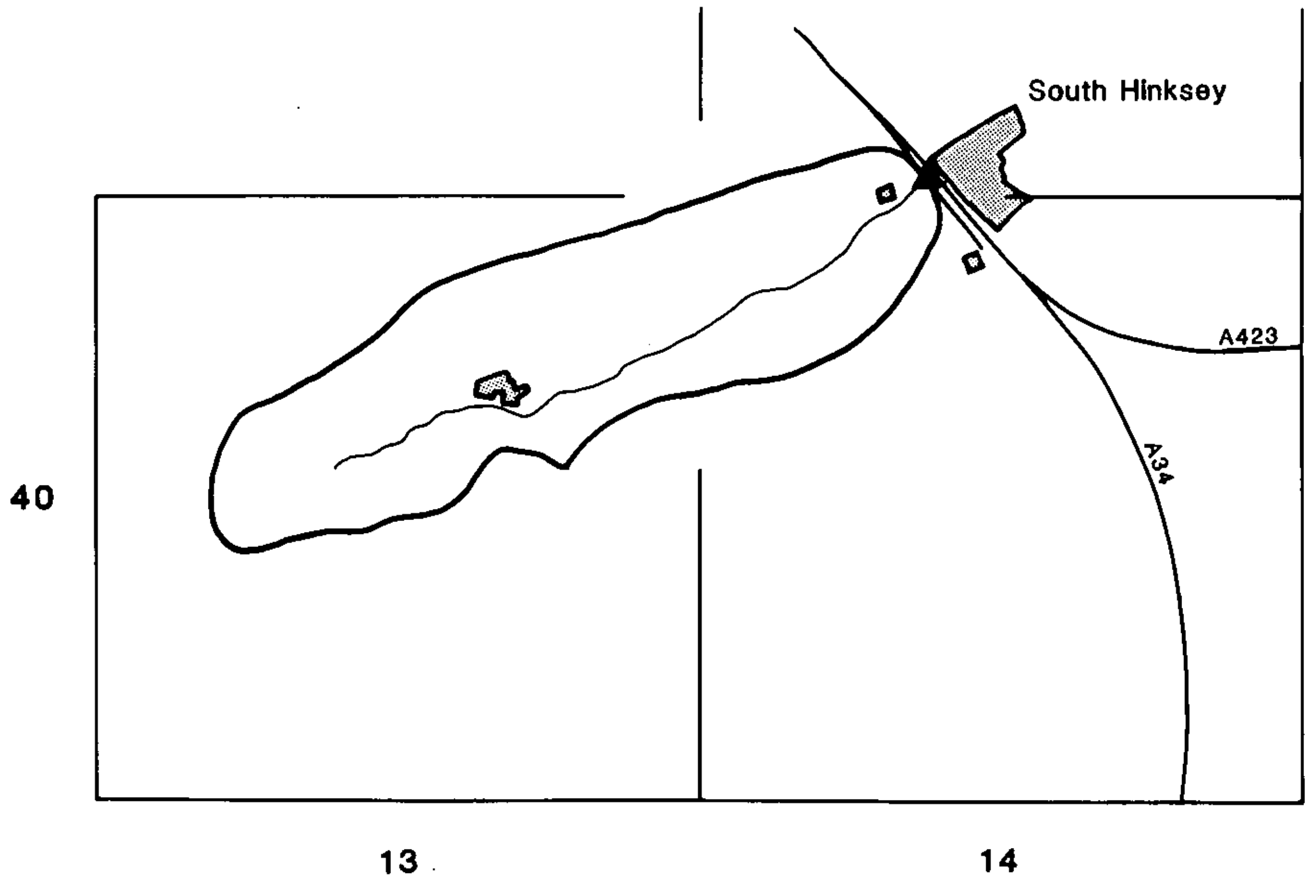


Example event **13 April 1990**
Lag 1.1 hrs **Tp(0) 1.3 hrs**

South Hinksey

Water level recorder at: SP 507 040

Catchment area: 1.49 km^2



Catchment description

The stream at South Hinksey runs along a well defined steep sided valley and is unusual in that it does not appear to be fed by any tributaries, although outfalls from underdrainage are present. Much of the catchment is used to grow cereals but there is some grassland used for grazing livestock. In dry weather the source of the stream appears to be in a conservation area (about 0.09 km^2), managed by Oxford City Council, 0.8 km upstream from the water level recorder. The area is often waterlogged and supports extensive reed beds. The catchment has a mixture of typical and pelo-stagnogleyic soils along with brown rendzinas and argillic brown sands. The underlying geology is principally Oxford and Kimmeridge clays. Before entering the village of South Hinksey the brook runs through a single Armco culvert taking the stream under a service road and the A34. Water level monitoring equipment was placed at the upstream end of the culvert in a PVC stilling well secured to the face of a concrete wall.

Catchment characteristics

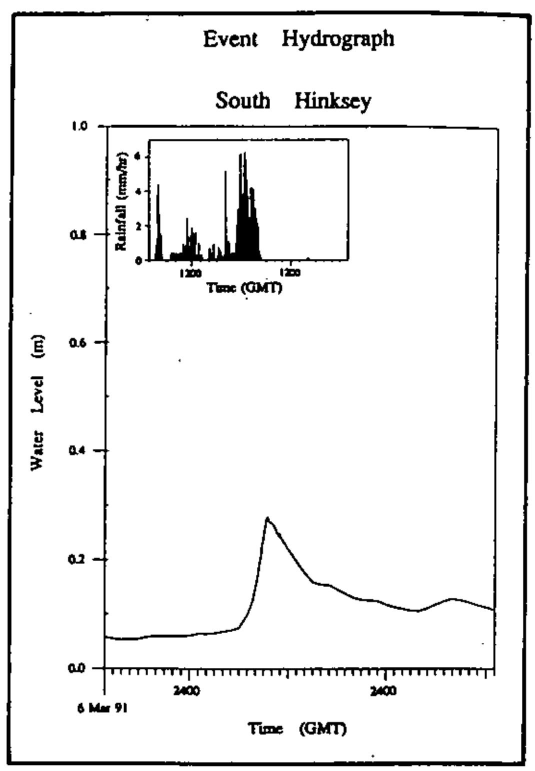
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	1.490	km^2
Main stream length	MSL	2.200	km
10-85% stream slope	S1085	29.390	m/km
Urban fraction	URBAN	0.005	-
Forest fraction	FOREST	0.060	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	1.000	-
WRAP 4 soil fraction	SOIL4	0.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.400	-
Average annual rainfall (1941-70)	SAAR	650	mm
Catchment area	*DTMAREA*	*1.557*	*km^2*
Altitude at water level recorder	*DTMALT*	*61.200*	*m AOD*
Mean altitude	*DTMMALT*	*113.550*	*m AOD*
Mean land slope	*DTMLANS*	*74.622*	*m/km*
Mean river slope	*DTMRIVS**	*28.807*	*m/km*
Main stream length	*DTMMSL**	*2.423*	*km*
10-85% stream slope	*DTMS1085**	*28.487*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*2*	-
Total network length	*DTMLEN**	*3.297*	*km*

Summary statistics

Record starts	21 December 1989
Record ends	29 March 1993
Years of record	3.27
Highest level	0.510 m
Date of highest level	3 February 1990

Event statistics

DATE	LAG (hrs)	Tp(0) (hrs)
6 January 1990	4.6	3.9
31 January 1990	4.5	2.5
2 February 1990	5.0	5.3
10 January 1991	6.6	9.8
7 March 1991	5.3	3.5
19 November 1991	7.4	2.4
15 April 1992	8.4	14.3
29 May 1992	3.3	4.1
1 June 1992	4.4	4.3
Arithmetic mean	5.5	5.6
Geometric mean	5.3	4.7

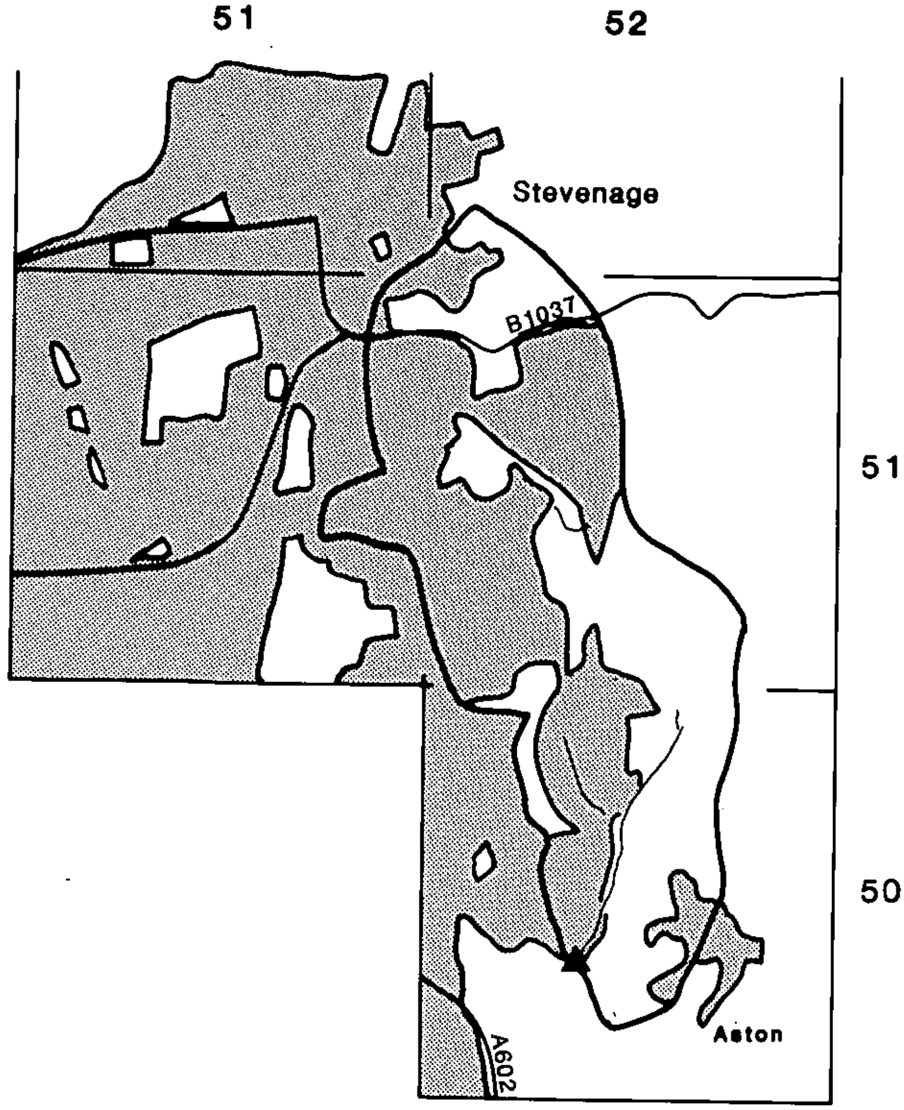


Example event **7 March 1991**
Lag 5.3 hrs **Tp(0) 3.5 hrs**

Stevenage

Water level recorder at: TL 267 227

Catchment area: 4.14 km^2



Catchment description

The principal land use in the Stevenage catchment is suburban housing. Much of the development has been recent and the northern part of the catchment is earmarked for further building. There is some agricultural land on the slopes near the village of Aston where cereals are grown and there is grazing for horses. Aston End Brook emerges from a culvert near the hamlet which gives the stream its name and then runs southwards to be joined by a tributary. The brook then flows in open channel between a housing estate and a minor road before entering a concrete box culvert taking the stream under another minor road. Bridge rails were used to secure the stilling well (Chapter 2, Plate 2.3) to the upstream side of the culvert. Catchment soils are typical calcareous pelosols with an underlying geology of chalk, although they appear to have little impact on catchment response which is typically urban.

Catchment characteristics

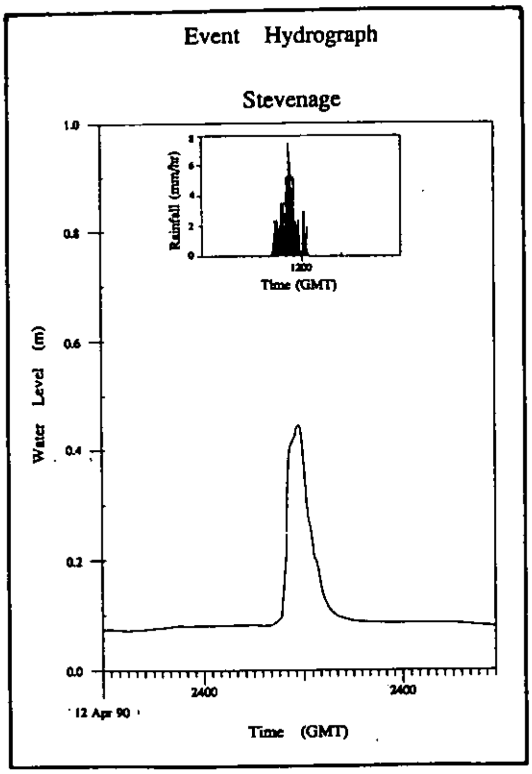
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	4.140	km^2
Main stream length	MSL	1.300	km
10-85% stream slope	S1085	8.210	m/km
Urban fraction	URBAN	0.492	-
Forest fraction	FOREST	0.030	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	1.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	0.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.300	-
Average annual rainfall (1941-70)	SAAR	638	mm
Catchment area	*DTMAREA*	*4.022*	*km^2*
Altitude at water level recorder	*DTMALT*	*77.400*	*m AOD*
Mean altitude	*DTMMALT*	*107.109*	*m AOD*
Mean land slope	*DTMLANS*	*34.663*	*m/km*
Mean river slope	*DTMRIVS**	*16.864*	*m/km*
Main stream length	*DTMMSL**	*4.295*	*km*
10-85% stream slope	*DTMS1085**	*13.661*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*9*	-
Total network length	*DTMLEN**	*10.406*	*km*

Summary statistics

Record starts	14 November 1989
Record ends	1 April 1992
Years of record	2.38
Highest level	1.308 m
Date of highest level	7 August 1991

Event statistics

DATE	LAG (hrs)	Tp(0) (hrs)
12 December 1989	1.1	1.3
23 December 1989	0.7	0.8
8 January 1990	1.2	1.3
13 April 1990	1.0	1.3
4 May 1991	1.3	1.3
Arithmetic mean	1.1	1.2
Geometric mean	1.0	1.2

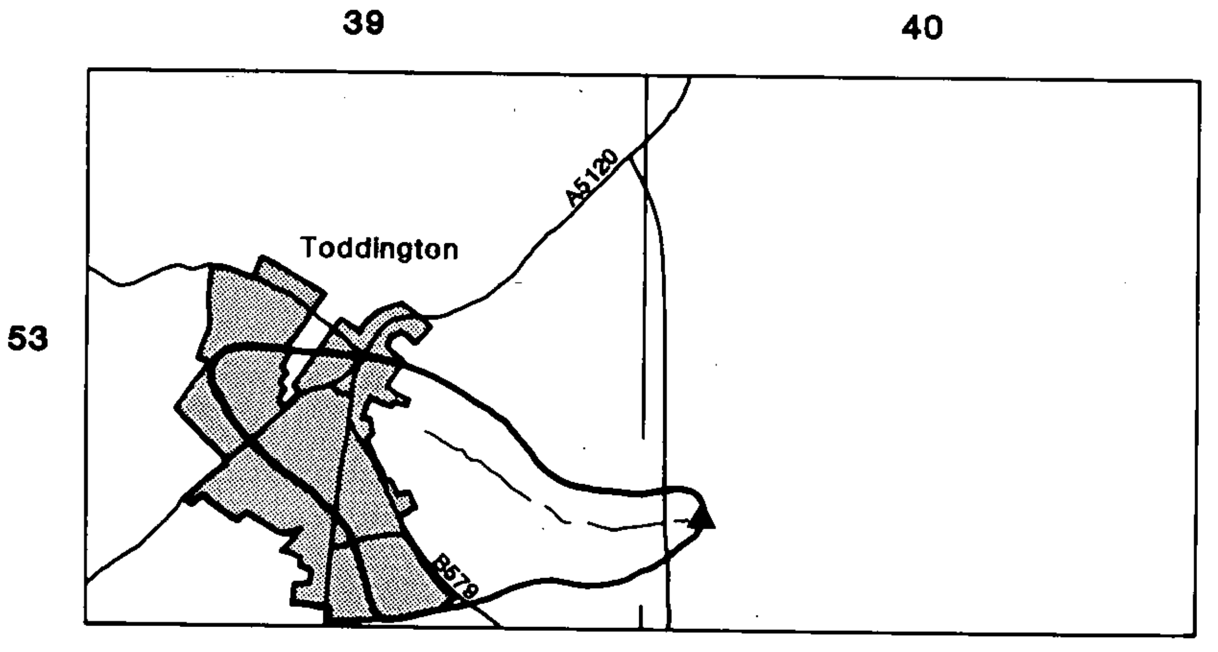


Example event **13 April 1990**
Lag 1.0 hrs **Tp(0) 1.3 hrs**

Toddington

Water level recorder at: TL 022 284

Catchment area: 0.88 km²



Catchment description

Toddington village straddles the upper part of this relatively steep catchment, with the stream first appearing above ground to the east of the village centre. The brook then runs through intensively grazed pasture, with cereals grown on the steeper slopes. Catchment soils are predominately typical and stagnogleyic argillic brown earths with the underlying geology comprising upper greensand and gault clay. After running through a culvert under a minor road the brook enters the fenced compound of a disused sewage works owned by Anglian Water. An old brick pier provided a suitable location for securing the stilling well and water level monitoring equipment.

Catchment characteristics

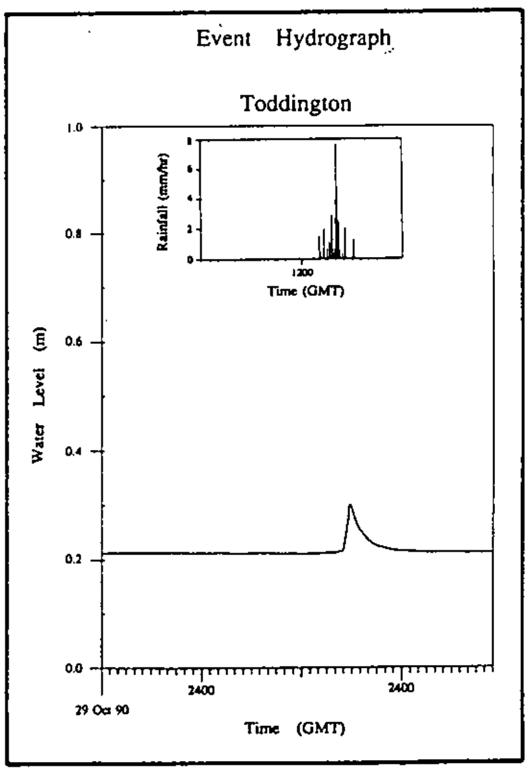
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	0.880	km^2
Main stream length	MSL	1.100	km
10-85% stream slope	S1085	31.510	m/km
Urban fraction	URBAN	0.384	-
Forest fraction	FOREST	0.006	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	1.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.450	-
Average annual rainfall (1941-70)	SAAR	645	mm
Catchment area	*DTMAREA*	*0.927*	*km^2*
Altitude at water level recorder	*DTMALT*	*96.100*	*m AOD*
Mean altitude	*DTMMALT*	*135.371*	*m AOD*
Mean land slope	*DTMLANS*	*48.674*	*m/km*
Mean river slope	*DTMRIVS**	*38.777*	*m/km*
Main stream length	*DTMMSL**	*1.519*	*km*
10-85% stream slope	*DTMS1085**	*34.557*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*3*	-
Total network length	*DTMLEN**	*2.052*	*km*

Summary statistics

Record starts	6 March 1990
Record ends	19 March 1991
Years of record	1.04
Highest level	0.519 m
Date of highest level	27 February 1991

Event statistics

DATE			LAG (hrs)	Tp(0) (hrs)
21	June	1990	2.1	1.6
7	July	1990	1.3	0.9
3	October	1990	1.1	1.9
30	October	1990	1.8	1.6
12	November	1990	2.1	1.6
Arithmetic mean			1.7	1.5
Geometric mean			1.6	1.5

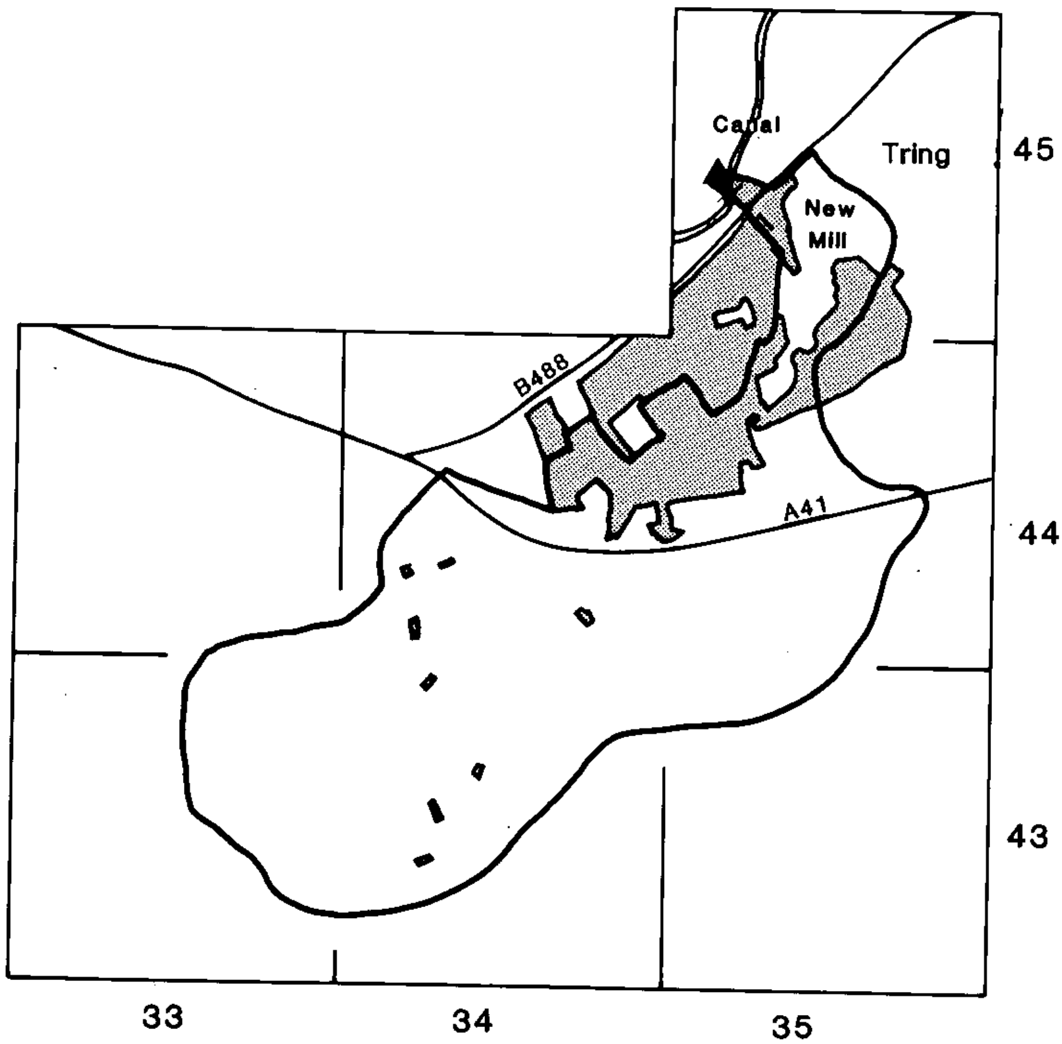


Example event **30 October 1990**
Lag 1.8 hrs **Tp(0) 1.6 hrs**

Tring

Water level recorder at: SP 922 130

Catchment area: 8.92 km^2



Catchment description

The Tring catchment is predominantly rural with the southern-most watershed found on the Chilterns. However, near the gauging point, surface water drainage from a number of residential areas in the town of Tring is directed into the brook and it is the urban areas which dominate the flood response. The south of the catchment, on the chalk escarpment, is a mixture of woodland and parkland with grazing for horses, and some cereals grown. The brook appears in open channel for a short distance near the New Mill area of Tring but then enters a culvert taking the stream under the B488, a housing estate, and the Wendover Arm of the Grand Union Canal. After emerging from the culvert the brook flows a short distance to a British Waterways gauge and is confined within a concrete channel before passing over a thin plate weir. The water level recorder was secured adjacent to the gauge. Catchment soils are stagnogleyic paleo-argillic brown earths and typical argillic brown earths with underlying chalk.

Catchment characteristics

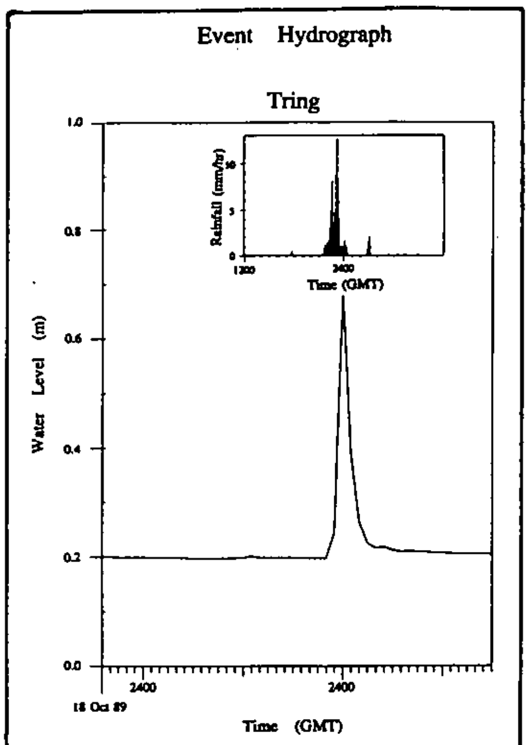
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	8.920	km^2
Main stream length	MSL	0.425	km
10-85% stream slope	S1085	18.820	m/km
Urban fraction	URBAN	0.118	-
Forest fraction	FOREST	0.240	-
WRAP 1 soil fraction	SOIL1	1.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	0.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.150	-
Average annual rainfall (1941-70)	SAAR	729	mm
Catchment area	*DTMAREA*	-----	*km^2*
Altitude at water level recorder	*DTMALT*	-----	*m AOD*
Mean altitude	*DTMMALT*	-----	*m AOD*
Mean land slope	*DTMLANS*	-----	*m/km*
Mean river slope	*DTMRIVS**	-----	*m/km*
Main stream length	*DTMMSL**	-----	*km*
10-85% stream slope	*DTMS1085**	-----	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	-----	-
Total network length	*DTMLEN**	-----	*km*

Summary statistics

Record starts	9 October 1989
Record ends	1 April 1992
Years of record	2.48
Highest level	1.075 m
Date of highest level	20 December 1989

Event statistics

DATE	LAG (hrs)	Tp(0) (hrs)
19 October 1989	1.1	0.9
23 December 1989	0.7	0.9
7 July 1990	1.1	1.1
30 October 1990	1.1	0.9
3 January 1991	0.6	0.9
Arithmetic mean	0.9	0.9
Geometric mean	0.9	0.9

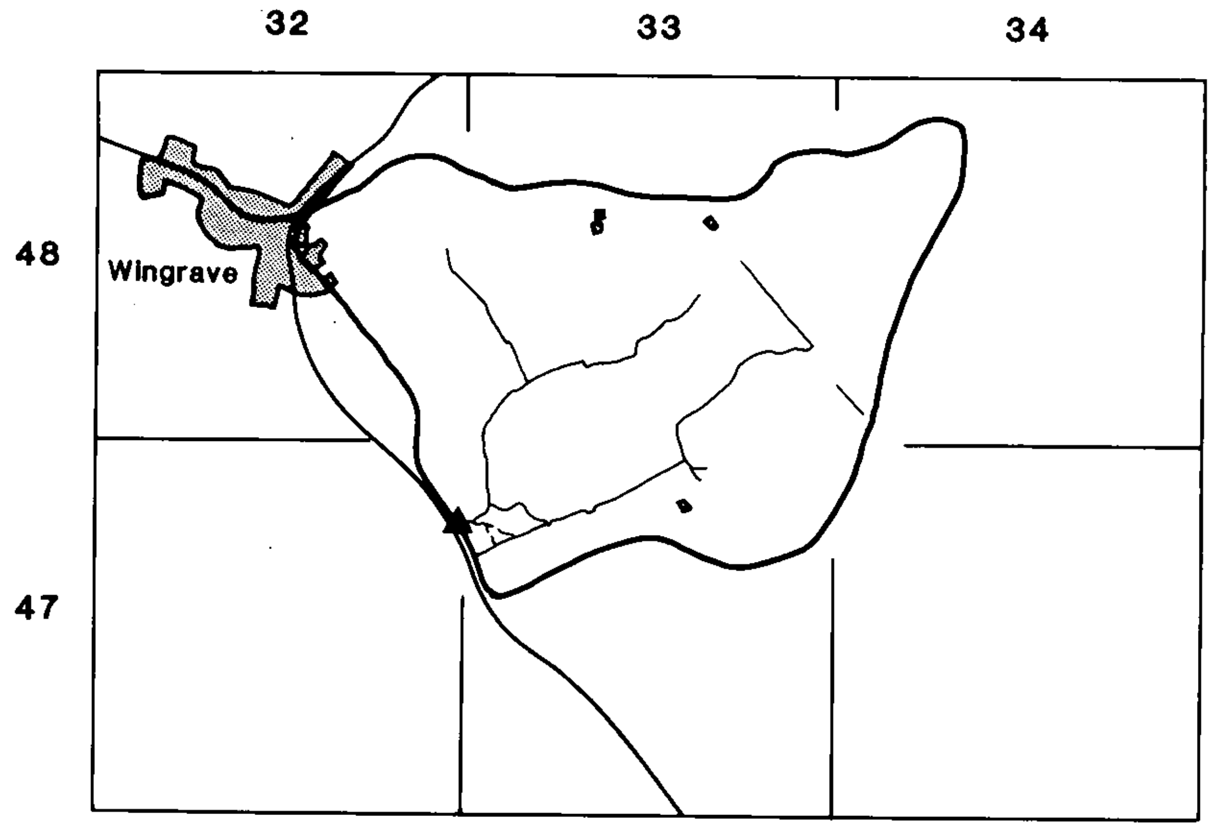


Example event **19 October 1989**
Lag 1.1 hrs **Tp(0) 0.9 hrs**

Wingrave

Water level recorder at: SP 879 176

Catchment area: 5.85 km^2



Catchment description

The Wingrave catchment is rural with the valley slopes mainly supporting the production of cereals and oilseed rape and the fields adjacent to the stream (Thistle Brook) principally devoted to the grazing of livestock. From its source, the brook flows in a south-westerly direction and receives water from a number of open ditches and underdrainage outfalls.. As it nears a minor road it is joined by a ditch draining the flatter part of the catchment to the east. The brook then passes under the road in twin circular brick culverts. The water level recorder was secured between the culverts on the upstream side of the bridge. During the period of instrumentation bankfull was exceeded on the 21 December 1989 and 3 February 1990. The stream flowed intermittently, with the bed completely dry for much of the time, during the periods 4 September 1989 (start of record) to 14 December 1989, 25 April 1990 to 27 December 1990 and 23 May 1991 to 26 September 1991. Catchment soils are typical calcareous pelosols with an underlying geology of upper greensand and gault.

Catchment characteristics

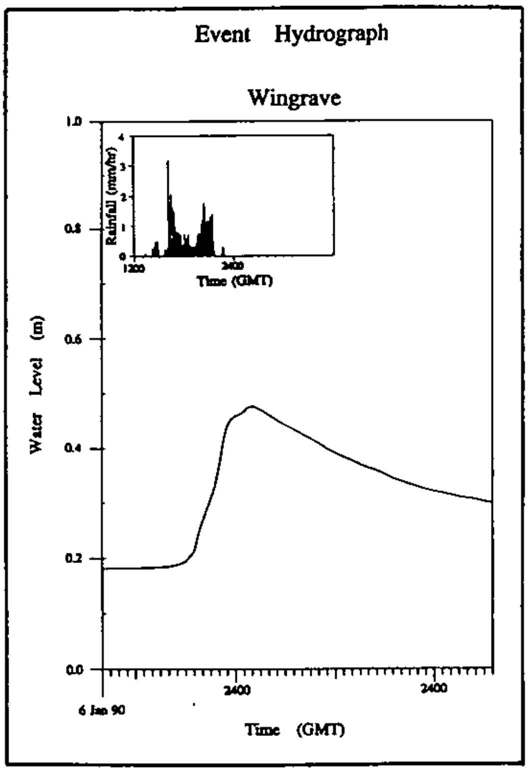
Characteristic	Abbreviation	Value	Units
Catchment area	AREA	5.850	km^2
Main stream length	MSL	2.100	km
10-85% stream slope	S1085	6.350	m/km
Urbàn fraction	URBAN	0.004	-
Forest fraction	FOREST	0.050	-
WRAP 1 soil fraction	SOIL1	0.000	-
WRAP 2 soil fraction	SOIL2	0.000	-
WRAP 3 soil fraction	SOIL3	0.000	-
WRAP 4 soil fraction	SOIL4	1.000	-
WRAP 5 soil fraction	SOIL5	0.000	-
Soil index	SOIL	0.450	-
Average annual rainfall (1941-70)	SAAR	654	mm
Catchment area	*DTMAREA*	*4.080*	*km^2*
Altitude at water level recorder	*DTMALT*	*83.800*	*m AOD*
Mean altitude	*DTMMALT*	*99.227*	*m AOD*
Mean land slope	*DTMLANS*	*33.262*	*m/km*
Mean river slope	*DTMRIVS**	*12.486*	*m/km*
Main stream length	*DTMMSL**	*2.976*	*km*
10-85% stream slope	*DTMS1085**	*4.254*	*m/km*
Network magnitude (no. of sources)	*DTMMAG**	*14*	-
Total network length	*DTMLEN**	*9.827*	*km*

Summary statistics

Record starts	4 September 1989
Record ends	2 April 1992
Years of record	2.58
Highest level	1.499 m
Date of highest level	3 February 1990

Event statistics

DATE			LAG (hrs)	Tp(0) (hrs)
21	December	1989	9.7	7.5
7	January	1990	7.5	6.4
23	January	1990	8.1	5.8
3	February	1990	8.8	8.6
19	March	1990	4.5	2.6
28	February	1991	6.6	3.4
3	July	1991	8.0	8.3
25	July	1991	15.0	15.5
19	November	1991	6.9	5.0
9	January	1992	4.7	3.0
Arithmetic mean			8.0	6.6
Geometric mean			7.5	5.8



Example event **7 January 1990**
Lag 7.5 hrs **Tp(0) 6.4 hrs**