INSTITUTE of HYDROLOGY

HYDROLOGICAL INPUTS TO THAMES MODEL

Interim Report

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1. Introduction

The aim of this study is to investigate the flood hydrology of the Thames, with particular reference to the reach between Bourne End and Penton Hook, for the purpose of specifying the tributary inputs required to run the Thames hydraulic model prepared by Sir William Halcrow and Partners (SWHP).

As a more specific objective, the study seeks to establish whether it is possible to define hydrological inputs such that the output from the hydraulic model is the level profile corresponding to a chosen return period. In other words, if the 5 year water level profile is required, the question posed is whether, by imposing the 5 year flow (and hence level) at the upstream site, a consistent set of tributary inputs can be defined such that the flow (and hence the level) at the downstream site and intermediate sites also correspond to the 5 year return period. In general, one cannot expect such convenient relationships to be easily attained. However, it is a reasonable supposition in cases where the main river dominates any tributary inflows, as in the case of the Thames.

In order to explore this problem, and to answer other more immediate problems to be faced in stage 1 of the project, such as the return period of bankfull conditions, it has been necessary to extend the study reach to between Days Weir and Teddington in order to include the long-term gauging stations at these sites.

The hydrological part of the study has been divided into two stages. This report discusses the results of the first stage of the project, relating to the collection and treatment of basic data (Sections 2 and 3) and the evaluation of the frequency of bankfull stage in the Bourne End to Penton Hook reach (Sections 4 and 5). Section 6 concerns the accumulation of flows at given return periods while Section 7 contains recommendations as to the approach to be used in stage two.

2. The Data

2.1 FLOW RECORDS

2.1.1 Thames flows

The two main long-term Thames gauging stations which are relevant to this study are situated at Days Weir and Teddington. There are, in addition, two gauging stations located in the middle of the study reach. Of these, that at Royal Windsor is a relatively new ultrasonic gauging station which has been in operation since 1979; while the preceding longer-term gauging station at Bray is of doubtful accuracy. This section also draws upon material prepared in connection with the Maidenhead Study - in particular, the construction of a long-term peak flow series for Bray (Beran and Field, 1988).

2.1.2 Tributary flows

Flow records have been assembled for all the major tributaries of the Thames between Days Weir and Teddington. In stage 1 of the study, interest spans a range of return periods from several times a year to about 10 years, so both peaks over threshold data (POT) and annual maximum data have been extracted from the archives held at the Institute of Hydrology (IH). The gauging stations involved are shown schematically in Figure 1, with details of the availability of data given in Table 1. Stations with a relatively short period of record - the Misbourne, the Pinn and the River Wey at Weybridge - have not been used in this stage of the analysis. Peaks over threshold data have not been extracted for the sites where groundwater contributions dominate the flow hydrograph. In these cases, the catchment responds to the general wetness of the winter season rather than to individual storm rainfalls, so it is not possible to set a consistent threshold or apply realistically the decision rules concerning independence between events.

Some discrepancies were found between the annual maxima obtained from the POT extraction carried out at IH and the values held in the Surface Water Archive (SWA) obtained directly from the Water Authority's data processing. Discrepancies which were larger than 5% were referred back to the original level recorder charts and, in most cases, the values obtained from IH's POT data set were confirmed. In these cases, the reasons for the discrepancy related either to spikes superimposed on the hydrograph and not recognised as artificially induced in the automated data extraction, or to the omission of pressure tapping corrections on flows recorded over drowned Crump weirs. As a result of this investigation, the IH POT archive data have been accepted for use in the analysis, with two exceptions. First, a new rating curve was supplied by Thames Water for the River Thame at Shabbington and this was applied to the IH POT stage extraction. Second, corrected annual maximum figures were supplied by Thames Water for the River Wey at Tilford and corrections have been made to the POT data based on a regression relationship between the old and new annual maximum values. The complete set of data used in the analysis will be provided in an appendix to the main report.

2.2. STAGE RECORDS

As specified in the study proposal, the analysis of stage frequency has been undertaken for Cookham, Bray and Bell weirs based upon the stages extracted by Thames Water from the weir tackle sheets. It was decided to use post-1937 data only as previous work by Thames Water plotting weir stage against Teddington flow suggested a change in regime around this date. The stage data have been appraised in two ways.

First, the peaks have been cross-referenced between the three sites and the tackle sheets searched for potentially missing peaks, additional peaks, or errors. Second, the list has been checked for independence of events. The criterion used in the original tackle sheet extraction was that the flow must drop below the set threshold between nearby peaks. This means that a number of relatively low, dependent peaks have been included. The more stringent criterion laid out in the Flood Studies Report Volume IV (NERC, 1975) has been applied to the data. This states that the minimum discharge in the "trough" between two peaks should be less than 67% of the earlier peak value, and that the two peaks should be separated by at least three times the average time to peak. The time criterion which has been used is 8 days (three times the mean time to peak at Days Weir is 7 days; at Teddington 9 days). The flow criterion has been converted into a stage criterion based on the rating curve for a fully drawn weir (see Section 3.4).

Annual maximum data have also been derived, with the levels for years not represented in the POT data being taken directly from the tackle sheets. The resulting set of peak over threshold and annual maximum levels which have been used in the analysis will also be provided in an appendix to the main report.

3. Rating Curve Construction

3.1 GENERAL PRINCIPLES

Rating curve construction has also been undertaken for the three weirs of Cookham, Bray and Bell. The results from the rating curves will be used as a check on the flow inputs within the study reach and as a direct comparison with the ONDA hydraulic model.

For the purpose of rating curve construction, the data assembled for stage 2 of the study have been used and a series of values extracted from six months (January 1982, December 1982, February 1985, June 1985, December 1985, and January 1986) of flow and level data, including four of the recent major events and the two hydrographs used by SWHP in the calibration of the ONDA model. The data comprise tackle sheet records for the three weirs and their downstream counterparts, hourly flow data recorded for the Thames at Royal Windsor, and three-hourly flow data for The Cut and the River Colne. Although extracting the data in this way means that the data points used to construct the rating curves are not independent, and may, therefore, lead to inflated correlation coefficients, the method used is the most efficient means of building up a reasonably reliable set of level and flow data that includes information about weir settings.

In constructing the rating curves, it was desirable that, if possible, the form of the rating curve equation should be similar for each weir and that it should conform to a function which is physically justifiable. The stage basis used for the rating curves is the tail water level at each weir measured in metres AOD. The head water level, which might equally be thought of as a basis for a rating curve, by analogy with gauging stations, shows a much lower correlation with flow (see Table 2). This is not unexpected as it is largely under gate control whereas the tail water level is to a considerable extent under regime control. The assumed form of the rating curve is

$$Q = a\ (H\text{-}c)^b$$

where Q is flow (m^3s^{-1})
H is stage (m AOD)
a, b and c are constants.

The regression analysis carried out below has, therefore, been based on the logarithms of the flow and stage variables. The constant c has been taken, in this instance, as the height AOD of the zero point on the tailwater board. This is a rather arbitrary choice of datum and a second analysis was performed using the height of the headwater mark on the downstream weir. This corresponds to the case of zero flow (Bowen, 1965). However, using this constant led to a reduction in the goodness of fit of the rating equations.

For each weir, secondary independent variables are required in addition to the tailwater level. These represent the afflux through the structure and the regime in the downstream reach, as reflected in the headwater levels, gate settings and head losses. These variables have also been transformed to logarithms so that a multiplicative relationship between the variables, consistent with typical flow resistance equations, is preserved.

3.2 CHOICE OF FLOW DATA

In order to align in time the flow with its corresponding level at each weir as accurately as possible, account was taken of the time taken to travel between each weir, or tributary inflow, and the relevant gauging station used to provide the flow. Water velocities were derived from the ONDA hydraulic model for an in-bank flow of 225 m^3s^{-1}. An average was taken of the water velocities for ONDA reaches between each point of interest and the travel time estimated using the wave celerity, assumed to be 1.5 times the water velocity (Table 3). At higher flows, the ONDA model shows water velocities in each reach to be somewhat higher than those used in these calculations. However, they are not so different as to invalidate the relative timings indicated in Table 3. As a consequence, the same timings were used for all stages and flow conditions. Although an approximation, this is thought to be adequate for the present application.

For in-bank flows, Table 3 suggests that it takes 3.1 hours for the flood wave to travel from Cookham weir to Royal Windsor (RW); 1.9 hours from Bray weir to Royal Windsor; 1.8 hours from The Cut to Royal Windsor; and 0.7 hours from Royal Windsor to Bell weir. Consequently, for weir levels at time t, the flows selected for use in deriving the rating curves were as follows.

for Cookham: the flow at RW at time t+3 minus the flow from The Cut at time t

for Bray: the flow at RW at time t+2 minus the flow from The Cut at time t for Bell: the flow at RW at time t-1.

The choice of flow was partly constrained by the availability of data and ignores the fact that The Cut is gauged some distance upstream from its confluence with the Thames.

3.3 SECONDARY INDEPENDENT VARIABLES

For the lower flows of interest when gates are not fully drawn, a potentially significant affect on the rating curve is the gate setting at both the "current" and downstream weirs. These influence the afflux through the structure and the downstream backwater curve respectively. In order to facilitate the extraction of these data and to check their accuracy, use has been made of the SuperCalc4 spreadsheet model designed by SWHP. The tackle sheets provide information on the total number of gates drawn at the beginning and end of the month, with additional intermediate dates when the weir was recorded as being fully drawn. The total number of weir gates is also known.

Using the spreadsheet model, analysis of some of the tackle sheets showed significant discrepancies within the given constraints. In such cases, the figures have been adjusted so that they are consistent with the known weir settings and within the range of physical possibilities. However, absence of complete information on the exact gate movements and their timing must introduce an element of uncertainty into the assignment of gate settings at any given time.

Another problem associated with weir settings relates to the diversity of different component structures at any one location. Weir settings are recorded in two different ways. Some weirs, such as Bell weir, are recorded as a total amount of weir footage which is drawn (raised) or closed. Other weirs are simply recorded in terms of the number of different types of gates drawn or closed. For example, the state of the weir at Cookham might be recorded as "4 deep radials, 6 hand radials, 5 buck gates and 14 parts of the rhymer weir drawn". Given the fact that each of the components of the weir has different dimensions, to make this information more suitable for analysis, it is necessary to express the total weir setting in terms of the total area per unit width.

An additional complication is that the weir at Boveney, downstream of Bray, was rebuilt between 1982 and 1984 which is within the period for which hydrograph data were extracted. In principle, expressing the gate settings in terms of the total weir drawn allows both the data from the old weir and that relating to the new weir to be used in the same analysis. This is valid only if there is sufficient similarity in the hydraulic behaviour of the two weirs not to affect the rating curve relationship. This might be a reasonable assumption as the policy for the reconstruction of weirs is to maintain a similar weir and channel capacity. The rating curves for the new and old weirs are compared in Section 3.4.

It is desirable that the form of the rating equation should be such that the effect of the weir setting is minimal in cases where the weir is fully drawn i.e.

all gates are raised. All weir settings extracted from the tackle sheets were, therefore, converted into the proportion of the total weir drawn. Thus, for a fully drawn weir, the weir setting parameter will have a value of unity.

In addition to the weir and downstream weir settings, the other variables which may act as a control on the form of the rating curve are the head difference over the weir (headwater level minus tailwater level) and head loss in the downstream reach (tailwater minus downstream headwater). This latter represents the gradient of the water surface and, other factors being equal, should correlate positively with flow.

3.4 MODELS FOR INDIVIDUAL WEIRS

The starting point for the analysis is the rating curve based solely on the tailwater levels. These have been produced for cases where the downstream weir was fully drawn to eliminate any variation in the tailwater level due to the gate settings at the downstream weir influencing the backwater curve. The data are plotted in Figure 2 for each of the three weirs. The open circles represent the data points for which the downstream weir is fully drawn; the solid circles represent the other data points extracted. Table 4 gives the rating curve for the fully drawn downstream weir, labelled equation (3.1), and this is plotted as the dashed line in Figure 2. The graph clearly shows the points relating to the non-fully drawn case drifting away from the rating relationship, usually above the curve (less flow for a given level), and showing a marked increase in scatter.

To develop a rating curve which applies to lower levels, it is, therefore, necessary to introduce variables into the equation to account for the increased variability introduced by partial closure of the weirs. The complete set of 36 data points derived for each weir was, therefore, entered into a stepwise regression procedure, with the forced inclusion of the weir tailwater level, in order to select the best multivariate prediction of flow. The results from the stepwise procedure are shown in Table 4. In the case of Bell weir, the tailwater level did not automatically feature in the equation, due to the higher degree of inter-correlation between the logged tailwater level at Bell weir and many of the secondary independent variables at that site (Table 2).

All three equations include the proportion of the current weir that is raised, while the equations for Cookham and Bell weirs also include the downstream head loss and that for Bray prefers the downstream head level. The coefficient of determination is high in all cases, ranging from 96.11% to 98.68%, with a factorial standard error ranging from 1.03 to 1.06. This is considered to be good even by comparison with current metered ratings although it is emphasized that the coefficient of determination may be inflated by serial autocorrelation which follows from the method of data extraction as indicated in Section 3.1.

Alternative relationships were derived in line with the considerations laid out in Sections 3.1 and 3.3. First, the relationship which includes the current and downstream weir settings and the downstream head loss was derived. This led to a slight increase in the coefficient of determination in the cases of Cookham and Bell weirs and a slight decrease in the case of Bray.

However, the exponent of the downstream head loss term was negative in the case of Cookham and Bray and positive in the case of Bell weir. From hydraulic considerations, the increased gradient implied by a larger head loss would be expected to lead to increased flows and hence a positive exponent. Furthermore, the contribution of the downstream head loss to the total explanation is relatively small - 0.9%, 0.1% and 1.7% in the case of Cookham, Bray and Bell respectively. Consequently, this variable was not further considered in exploring alternative rating curve relationships.

Table 4, therefore, shows the rating curve based on the tailwater level and the "current" and downstream weir settings only (equations 3.2). The form of these equations is consistent with hydraulic considerations for all three weirs, and shows only a slight drop in the coefficient of determination and a slight increase in the factorial standard error. The relationship is shown in Figure 2 as the solid line under the assumption that the weirs are fully drawn, i.e. W and W_{ds} are equal to unity. The line lies very close to the fully drawn downstream case (shown as the dashed line) for both Cookham and Bray. However, the two lines deviate markedly in the case of Bell weir. In fact, the behaviour of Bell weir shows many anomalies as described below.

First, a comparison of the different rating curves for Bell weir presented in Table 4 shows a rapid increase in the exponent for the tailwater level as variables are dropped from the equation. This is against a slight decrease in the case of the other two weirs. A second peculiar feature of Bell weir is shown in the correlation matrices given in Table 2. Here, the headwater level at Bell weir is shown to be only weakly correlated with any of the other variables; the sense of any correlation present being in the opposite direction to those found for the other weirs. Third, Bell weir is rarely fully drawn (only three times in the data set used) so that the afflux through the structure is always heavily dependent on the gate settings of the weir.

One possible explanation for the behaviour of Bell weir is that the River Colne flows into the Thames between Bell and Penton Hook weirs. This may introduce a random influence into the backwater curve downstream of the weir and so destroy any simple regime-related dependence. If such an effect is postulated, then it should apply in some measure to the Bray-Boveney reach within which The Cut has its confluence with the Thames. However, no similar phenomenon is observed here, presumably due to the much lower flow contribution from The Cut than that from the River Colne.

As regards the rebuilding of Boveney weir, mentioned in section 3.3, the rating curves for the combined data set are those that are quoted in Table 4 and drawn in Figure 2. This combined relationship is not significantly different from those derived for the new and old weirs separately in terms of the constant and exponent of the tailwater level. However, the exponents of the variables relating to the weir settings are significantly different for the old weir. This implies that the new weir structure behaves in a similar manner to the old weir but that the operation of the weir is rather different. Consequently, the relationship recommended for use for events following the reconstruction of Boveney weir is

$$Q = 13.80\ (H_{tw} - 17.43)^{1.96}\ W^{0.0648}\ W_{ds}^{0.0932}$$

R^2=98.8% s=0.0156 n=22;

and the relationship recommended for use prior to reconstruction is

$$Q = 10.72\ (H_{tw}-17.43)^{2.12}\ W^{0.230}\ W_{ds}^{0.281}$$

R^2=97.8% s=0.01166 n=14.

3.5 COMPARISON WITH ONDA PREDICTIONS

The rating curves derived from the hydrograph and tackle sheet data have been compared with the results of the hydraulic model for in-bank flows, and to see how successfully they extrapolate to out-of-bank flows. It is not possible to compare the results from all the equations quoted in Table 4 due to the unavailability of headwater data for Boveney from the hydraulic model. Equally, the out-of-bank model levels for Bell weir are preliminary estimates and so rather less weight should be placed on these figures. The data output from the hydraulic model are plotted in Figure 2 as open triangles for the in-bank model and solid triangles for the out-of-bank model.

There is reasonable agreement between the rating curves produced in this study and the ONDA model predictions for in-bank flows. In the case of Cookham weir, the rating curves produced in this study slightly underestimate the ONDA model flows. This is less true of the in-bank flows at Bray and Bell weirs which show a much closer agreement between the model predictions and the rating curves developed here. For Bell weir, it is, however, pointed out that the equation relating to the fully drawn downstream weir (dashed line in Figure 2c) is the one which should be used in order to achieve reasonable predictions for levels over 14.47 m AOD and flows greater than 247.6 m^3s^{-1}. For levels and flows less than these values, provided the weir settings are known, the three variable rating curve (3.2c) is preferred due to its much higher coefficient of determination. In these comparisons, it has not been possible to test the effect of the secondary independent variables in the equation against the hydraulic model. If confidence has to be placed in the rating curves which include the weir variables, then some ONDA runs should be used to test this part of the rating (see Section 7.1).

The rating curves developed here, not surprisingly, do not extrapolate to predict over-bank flows. This is shown in Figure 2 with respect to the ONDA model predictions but it is also true of extreme events such as the 1947 flood. Shown on Figure 2b is the rating curve derived for Bray/Windsor in the Maidenhead Study (Beran and Field, 1988). This rating has two segments. In producing the lower segment, the chart levels at Bray were used in conjunction with non-lagged flow values from the ultrasonic gauge at Royal Windsor. This lower segment plots through the data points used in this study, including those for which the downstream weir was not fully drawn. The upper segment of the Bray/Windsor curve was constructed so that it passed through the discharge and level of the 1947 flood. This segment of the rating plots through the ONDA model out-of-bank predictions. It is suggested that if rating curves are required for out-of-bank flows then they should be constructed through the historical events and checked iteratively with the ONDA model, paying attention to the ratio of the in-channel to flood-plain flows, to achieve compromise ratings which are conformable with the hydrological data (see Section 7.1).

4. Statistical Analysis of Flow and Stage Frequencies

Analysis of annual maximum data is required to provide flow and level estimates for return periods from 1 year to 10 years as outlined in the study proposal. A generalised extreme value distribution, given by

$$x(F) = u + a\{1-(-\ln F)^k\}/k \qquad \text{for } k \neq 0$$

and (4.1)

$$x(F) = u - a \ln(-\ln F) \qquad \text{for } k=0$$

where F is the non-exceedance probability,

was fitted to the single station annual maximum flow and stage data using the method of unbiased probability weighted moments. The shape parameter k was tested for significance (Hosking *et. al.*, 1984). In cases where k was not found to be significantly different from zero, an EV1 fit was estimated, again using the method of probability weighted moments. For the range of data available, an EV1 fit is adequate in all cases except the rivers Thame and Colne where an EV3 fit is preferred, and the River Wey at Tilford where an EV2 fit best describes the revised data (Section 2.1.2). The level data is also better described by an EV3 model. The results of the calibrations for the single station models are given in Table 5 and the plotted values in Figure 3.

The general IH recommendation with regard to models derived from single station data is that a model with a shape parameter of zero can be used for interpolation purposes, and for extrapolation to twice the return period of the maximum data point provided that the flow record consists of 20 or more years of data. An estimated shape parameter, different from zero, should only be used for interpolation. This is due to distortions caused by a short record of data. The justification for using the single station models here lies in the use to which the results are to be put in this initial phase of the study.

The primary need for estimates of tributary flows for a range of return periods lies in the investigation of the addition of flows down through the Thames basin. In the cumulation of flows, strictly speaking, it should be the actual events which are summed. The use of single station models goes some way towards this idea, although as discussed in Section 7.1, estimates of the total tributary inputs for use in the final method for running the ONDA model may well be revised on a regional basis. This would be derived from pooled data as it is clear from Figure 3 that neither the Flood Studies Report curve for Region 6 nor the Thames Water Authority curve provide a good fit to the plotted points in the majority of cases.

For return periods of less than one year, it is necessary to fit statistical models to POT data. However, it must be borne in mind that a return period of unity on the POT scale is similar to a return period of 1.58 on the annual maximum scale (Langbein, 1949). This is because of the different sampling concept and data used in the model construction. With regard to the POT data, abstraction method 2 from the Flood Studies Report (NERC, 1975; p. 194) was applied to the raw data. This fixes the parameter lambda of the model. The other parameters, Qo and beta, are then estimated using the maximum likelihood method. The parameters are given in Table 6 and the T-year flood is then estimated by

$$Q(T) = Q_0 + \beta (\ln \lambda + \ln T) \qquad (4.2)$$

The model assumes that there is a Poisson distribution of the number of events in a year and that the distribution of flood magnitudes is exponential. These assumptions are consistent with an EV1 fit to the annual maximum series. The POT estimates for the Thame and the River Wey could, therefore, be less reliable, as could the estimates for the level data from the three weirs, although the error within the interpolated range would be acceptably small.

5. Frequency of Bankfull Stage

Table 7 shows the stage for given return periods at each of the three weirs under consideration. The flow has been calculated using the rating curves recommended in Section 3 above and assuming all weirs to be fully drawn. Bankfull flow is given by the hydraulic model to be 240, 240 and 260 m^3s^{-1} at Cookham, Bray and Bell weirs respectively. The return periods of these flows have been assessed on the basis of the rating curves and stage frequency analyses described above.

At bankfull flow, it is assumed that all weir gates are fully raised, although, as discussed above, this may not be the case at Bell weir. The bankfull flows from the ONDA model fall just within the range of the data used to construct the rating curves, so extrapolation is unnecessary. Following the recommendations laid out in Section 3.5, equations (3.2a) and (3.2b) in Table 4 have been used in the case of Cookham and Bray weirs with W and W_{ds} set to unity. Equation (3.1c) in Table 4 has been used in the case of Bell Weir. These equations give bankfull stages of 24.85 m AOD, 21.73 m AOD and 14.58 m AOD for Cookham, Bray and Bell weirs respectively.

To provide return periods for these stages, attention is now drawn to the statistical analyses presented in Section 4. It is important to bear in mind that it is possible to quote a range of return periods dependent on the statistical model and the data used in its construction. These will have different meanings and will be useful under different circumstances. The annual maximum model will provide the probability of a whole year containing at least one event of bankfull stage or over. The POT model, whose parameters are quoted in Table 6, will give the probability of independent peaks, some of which will occur in the same year, which are bankfull or over. A POT model which includes all peaks above a threshold, such as would be given using the original Thames Water stage extractions (Section 2.2), would give the probability of any flow greater than the threshold reaching or exceeding bankfull. These may occur more than once in an individual flood as well as more than once a year.

Table 8 shows the return periods for the annual maximum and POT models. Interpreting this table, at Cookham weir, in a 100 year period, on average, at least one flow which is bankfull or above will occur in 52 of those years; and bankfull flow or above will occur on average in 81 out of 100 independent events; and 85 out of 100 times that the flow rises above the chosen threshold. At Bray, the corresponding figures are 43 years, 52 events and 55 times. At Bell weir, they are 36 years, 45 events and 50 times. These figures are supported by a return period of 2.05 years (49 years in 100) for a flow of 250 m^3s^{-1} for the Bray/Windsor site calculated using the EV1 analysis of the reconstructed annual maximum series (Table 5).

6. Discharge Accumulation through the Study Reach

6.1 STATISTICAL PEAK DISCHARGE ACCUMULATIONS

In the running of the Thames hydraulic model, it is desired that the model is loaded with hydrological inputs specified in such a way that the levels along the Thames all correspond to the same chosen return period. In general, it is found that combining T-year events, for example at a tributary confluence, will result in a total flow somewhat rarer than the T-year event at a point downstream of the confluence. In order to explore how the inputs may be specified, the cumulation of flows through the Thames at different return periods was investigated for the return period ranges represented by both the POT and annual maximum analyses.

Some account is necessary of the ungauged contributions to the Thames. As a first approximation, the gauged proportion of the flow from each tributary was scaled up by the ratio of the area of the whole catchment to the confluence with the Thames, to the gauged catchment area. These areal correction factors are given in Table 9. Account has also been taken of the ungauged area outside the gauged tributaries by applying a further correction factor to the total flow addition. This method was preferred to that of applying the factor to the Thames flow at the upstream station as it can be expected that the response of these areas would more nearly be represented by that of the local gauged contributions rather than the input upstream. The additions are presented in Table 10 for return periods of 0.25, 0.33, 0.5, 1, 2, 5, 10, 25 and 50 years. The results for the upper and lower portions of the Thames study reach will be considered separately.

6.2 RESULTS FOR THE UPPER REACH

In the case of the upper reach of the Thames between Days Weir and Bray/Windsor, the required addition of flow, obtained by subtracting the estimated peak flow at Days Weir from that at Bray/Windsor for a given return period, ranges from 79 m^3s^{-1} at a return period of four times a year on the POT series to 210 m^3s^{-1} at a return period of 50 years on the annual maximum series. Compared with these figures are the sums of the estimated tributary peaks for each return period. In Table 10, three estimates are given. The sum of the gauged peak flows, the sum of the gauged peak flows including the areal correction factor for the ungauged proportion of the tributaries, and the sum of the peak flows including the areal correction factor for all ungauged parts of the basin. A true estimate is thought to lie somewhere within this range and a slightly better estimate of the upper bound may be gained by using a correction factor based on the mean annual flood estimated using the Flood Studies Report method based on catchment characteristics (see Section 7.1). The cumulated tributary peaks amount to between 68 and 103 m^3s^{-1} at a return period of four times a year to between 184 and 278 m^3s^{-1} at a return period of 50 years.

From Table 10, it is clear that the required additional flow, has a very small range for the lower return period events on the POT series but increases rapidly for the higher return period events on the annual maximum series. The reason put forward for this is that the larger flows on the Thames probably result either from larger rainfall events with a stronger spatial coherence or from higher overall antecedent wetness conditions. By contrast, the addition of flow peaks on the tributaries increases more steeply than the required flow for low return periods and less steeply at higher return periods. This could be a function of using the individual station estimation models with the effects of relatively short flow records coming into play (see Section 4).

Another important observation is that the sum of the tributary peaks, when account is taken of the ungauged parts of the basin, greatly exceeds the required additional flow. It has already been pointed out that these "corrected" flows may be an overestimate of additional contributions to the flow but they are probably nearer to the truth than the uncorrected flows. The main reason for the expected overshoot is that, in cases where the same event produces both the tributary and the Thames peaks, the tributary will respond much faster than the Thames and the actual physical combination of flows will occur well down the recession limb of the tributary hydrograph. In other catchments, the tributary peak rarely occurs during the same event as that on the main Thames. This is shown in Figure 4 for annual maximum flows between 1975 and 1986. Peak flows in the catchments which are hardly ever synchronous with the Thames, generally occur in the summer months, but, even if the seasonal effect is taken into consideration, there is little improvement in the synchroneity of annual maximum events.

The overall conclusion, then, is that it is not possible to use the same return period flow on the tributaries as that on the main Thames as inputs to the hydraulic model to give downstream flows of the same return period. However, it is clear from the estimates of the required flow, that the sum of the contingent flows, i.e. those flows which are physically combined in the same event, would increase in relative rarity with increasing return period of the desired water level profile.

6.3 RESULTS FOR THE LOWER REACH

The tendency for the summation of tributary flows to overshoot the target flow addition is even more evident in the lower reach of the Thames between Royal Windsor and Teddington. Here, the additional flow required shows a general increase over the whole range, from 26 m^3s^{-1} at a return period of four times a year to 147 m^3s^{-1} at a return period of 50 years. However, there is a discontinuity at the point at which the POT and annual maximum analyses overlap. In setting a target for later work, this suggests that the additional flow estimates should be smoothed (see Section 7.1). The sum of the tributary peak flows come from different gauging stations in the case of the POT and annual maximum return period ranges. Thus, it is not possible to compare the behaviour of the flow additions over the whole range directly. From the POT analyses, the addition of tributary peak flows ranges from between 43 and 126 m^3s^{-1} at a return period of four times a year to between 76 and 235 m^3s^{-1} at a return period of one year, depending on the treatment of the ungauged contributions. From the annual maximum analyses of the single station data, the range in the summation of tributary flow peaks is from between 106 and 180 m^3s^{-1} at a return period of 2 years and between 221 and 378 m^3s^{-1} for a return period of 50 years.

The large overshoot represented by these figures could be due to a number of factors. It may result partly from the attenuation of the flow peaks as they pass downstream. The extent of this effect should be shown in results from ONDA model runs. However, the dominant reason for the overshoot would appear to be that events in the upper Thames, especially at low return periods, are not always the events that produce the peak flows in the lower reaches of the Thames.

This lack of synchroneity is illustrated for the annual maximum flows between 1975 and 1986 in Figure 4. As can be seen only 75% of the peaks at Teddington result from the same event as the peaks at Days Weir. The others result from high flows on the Wey and the Mole which provide significant contributions to the Thames. This contrasts with the upstream reach where the larger tributary inflows more frequently coincide with the main Thames, and the tributaries which do not coincide are relatively small. Consequently, an annual maximum at Bray/Royal Windsor occurs frequently in the same event as that at Days Weir but much less frequently in the same event at Teddington. From this, one may anticipate that the specification of input flows to the hydraulic model will require rather different treatment in the upstream and downstream portions of the study reach.

6.4 CORRELATION AND SUMMATION OF CONTINGENT FLOWS

In a second approach to this issue of how flows increase along the study reach, attention has been paid to the contingent daily flows i.e. the mean daily flow on the tributaries which occurred on the same day as the peak flow at Days Weir. The correlation coefficients for the mean daily flow at Days Weir and the mean daily flow on the same day on each tributary have been computed and are presented in Table 11. Plots of the data points show that these values are often affected by outliers from the data. This is particularly so in the case of the River Pang, the River Kennet, The Cut and the Mole at Kinnersley Manor, as indicated in Table 11. The overall picture is that there is sensibly no correlation between the daily flow at Days Weir and that on each tributary. The correlation between Days Weir and Teddington, however, is significant.

To arrive at a more physically realistic association of flows, the daily mean flow data were also lagged according to the expected travel time (taken from the ONDA model) between Days Weir and each of the tributary inflows. This was done by taking a weighted mean of the daily flow and the following day's flow, with the weights representing the time delay. The results from this analysis show a slight improvement in the correlation coefficient in most instances, but do not change the general conclusion that the tributary flows which combine with high Thames flows can be of almost any magnitude. The precise magnitude of each tributary flow will depend on the spatial coherence of the storm-producing rainfall, the time pattern of the rainfall in different parts of the catchment, the direction of the storm track, and the antecedent moisture condition and the response time of the tributaries.

Table 12 shows the addition of flows based on the median same-day contingent flow and the time-lagged contingent flow. The two columns of figures are similar and, not surprisingly, the total sum of the flows, incorporating the areal correction factors, agrees fairly well with the difference between the median flows at Days Weir and Teddington. The reason for the mismatch is probably the fact that the median flows are calculated using a different time span in each case depending on the length of the flow record.

The flow additions may be compared with the target additional flows given in Table 10, although one cannot expect any simple equivalence because Table 10 data are concerned with peak flows whereas Table 12 is concerned with mean daily flows. In the upper reach, between Days Weir and Bray/Windsor, the addition of the median contingent daily flows is somewhat less than the required additional peak flow which occurs 4 times a year. In the lower reach, between Bray/Windsor and Teddington, the sum of the median contingent flows corresponds to the required flow which has a return period of around 3 times per year.

This dissimilarity of flow magnitudes means that a single median value, based on the contingent flow, for each tributary is of limited usefulness in defining the input to the hydraulic model. The results, however, might instead be used as an indication of the proportion of flow which each tributary contributes; especially in cases where the proportions differ from those derived from Table 10 which are based on the summation of flows at a given return period. The use of flow proportions derived from the contingent flow analysis has the advantage that some account is taken of the degree to which, on average, individual tributary catchments respond in phase with the main Thames flow.

The percentage contribution from each catchment as calculated from the contingent flows and the 2-year return period peak flows are given in Table 13. There are some significant differences between the two percentage figures quoted, notably for The Cut and the River Colne which have their confluence with the Thames within the main study reach. Applying the percentage contribution based on the contingent flow analysis to the the required flow addition between Days Weir and Teddington taken from Table 10 leads to some paradoxical results. For example, the River Colne contributes 24.9% of the contingent flow summation but this implies that the

10-year peak flow is required from the River Colne to make up the 2-year flow addition on the Thames. This is clearly not correct and the application of the results from the contingent flow analysis is, therefore, not straight forward. Further work is also needed to investigate the stability of the calculated tributary flow percentages through the range of events on the main River Thames (Section 7.1).

7. Suggested Methodology for Stage 2

It is clear from the above discussions that some of the results quoted above need further testing against the hydraulic model and that some of the flow estimates can probably be improved for their use in stage 2. Thus, two sets of recommendations can be made as to the way to proceed - one relating to further refinements to the stage 1 results and one relating to the methodology to be used in stage 2.

7.1 IMPROVEMENTS TO THE ESTIMATES FROM STAGE 1

There are four ways in which the stage 1 results should be further clarified and refined.

First, if rating curves are needed for the out-of-bank flows at Cookham, Bray and Bell weirs, then they must be calibrated against historical data, such as the 1947 flood. The use of one data point to define these curves, however, is unsatisfactory and it will, therefore, be necessary to proceed iteratively with the hydraulic model to come to some compromise rating. One particular point of interest may be in the ratio of in-channel to flood-plain flows during flood events. Another test required to validate the rating curves at low flows, is to conduct at least one ONDA model run in which the weir gates are not fully drawn to compare with the equations presented in Section 3.

Second, in order to have a more secure basis for estimating the additional flow input between upstream and downstream stations on the Thames, two improvements can be considered. The first of these improvements is to use a smoothed curve for the flow additions required for different return periods, thus removing the jump between the POT and annual maximum analyses. The second improvement is to use locally pooled regional growth curves for the Thames and its tributaries, incorporating into this historical data. The main effect of this, in terms of the Thames flows is already apparent from the Maidenhead study and is to increase the Teddington flow at high return periods (Beran and Field, 1988) and so increase the amount of additional flow required from the tributaries in the lower reach.

The third point which needs following up is the estimation of ungauged contributions to the Thames. The area ratios used in Section 5 could be improved by making use of other important catchment characteristics such as stream frequency and channel slope in cases where there is a large difference in area between the ungauged and total catchment (i.e. the Rivers Thame, Cut, Mole and Wey). A ratio based on the Flood Studies Report estimate of the mean annual flood will be used.

The fourth area in which the stage 1 results need clarification is in the analysis of the contingent flows. The median contingent flows for different rarity of events on the Thames needs to be investigated as Table 10 would suggest that these ought to increase whereas the correlation coefficients presented in Table 11 suggest that they may remain substantially constant. The stability of the percentage flow contributions from each tributary also needs assessing and paradoxical results investigated if the work from the contingent flow analysis is to be of use.

7.2 STAGE 2

The suggested methodology for stage 2 entails extending the Flood Studies Report. rainfall-runoff method for use in catchments with an area greater than 1,000 km^2. The method will required some exploratory data work but, once derived for the Days Weir-Teddington reach of the Thames, should then be applicable to other reaches of the Thames. Annual maximum return periods of 2 and 100 years will initially be selected for analysis. For the upstream site, Days Weir, itself having a catchment area greater than 1,000 km^2, design hydrographs, based on an application of the Flood Studies Report rainfall-runoff method using subareas, will be generated with peaks corresponding to the 2 year and 100 year return period flows. These will be checked against existing flow data and modifications made as necessary.

As a starting point, this same design rainfall and catchment wetness condition will be applied to each of the subcatchments between Days Weir and Teddington. These peak flows will then be cumulated and compared with the 2 and 100 year return period peaks experienced at Royal Windsor and Teddington.

In cumulating the flows down the Thames, it is unlikely that a complete match with Royal Windsor and Teddington will be found. This mismatch could be due either to the timing of tributary flows compared to the main stream, or to the incorrect estimation of volumes in the design hydrographs. The latter is probably the more likely. If this is the case, the rainfall-runoff estimates for the tributary hydrograph shape, keeping the peak constant, will be adjusted on the basis of evidence derived from flood volume data over different flow durations. The model will then be re-run for the basin.

Judging from Table 10b, the results from this sort of analysis should provide something akin to the addition of a 50 year flow on the Thames with a 5 year flow on the tributaries in the upper reach and a 1.5 year flow on the tributaries in the lower reach. In order to explore this further, it is suggested that two steady state runs of the ONDA model are performed - one using these inputs and a second using the required flow difference allocated to tributary inputs on the basis of the contingent flow proportions. At the very least, these runs would suggest how sensitive the model is to the input flows.

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TABLE 1   Availability of flow data for Thames and tributaries between Days Weir and Teddington

Station	No.	Start date	POT threshold m^3s^{-1}	POT flows/year
Thames at Days Weir	39002	1938	100	2.8
R. Thame at Shabbington	39038	1968	11.19	5.6
R. Pang at Pangbourne	39027	1969	1.8	5.2
R. Kennet at Theale	39016	1961	22.0	6.0
R. Lodden at Sheepbridge	39022	1965	10.0	5.3
R. Blackwater at Swallowfield	39007	1952	12.7	5.4
R. Wye at Hedsor	39023	1964	-	-
Thames at Bray	39009	1965	-	-
The Cut at Binfield	39052	1957	3.8	5.8
Thames at Royal Windsor	39072	1979	-	-
R. Colne at Denham	39010	1952	-	-
Misbourne at Denham	39091	1978	-	-
R. Pinn at Uxbridge	39098	1985	-	-
R. Wey at Tilford	39011	1954	22.6	3.4
R. Wey at Weybridge	39079	1978	-	-
R. Mole at Castle Mill	39068	1971	-	-
R. Mole at Kinnersley Manor	39069	1973	16.0	4.5
Hoggsmill at Kingston	39012	1956	9.4	3.0
Thames at Teddington	39001	1883	200	3.5

TABLE 2 Correlation matrices for weir data

COOKHAM WEIR

	log Q	log h_{tw}	log h_{hw}	log h_{ds}	log W	log W_{ds}	log HL
log h_{tw}	0.963						
log h_{hw}	0.903	0.924					
log h_{ds}	0.888	0.906	0.937				
log W	0.809	0.752	0.585	0.559			
log W_{ds}	0.894	0.849	0.753	0.681	0.929		
log HL	- 0.615	- 0.647	- 0.411	- 0.454	- 0.772	- 0.702	
log HL_{ds}	0.649	0.732	0.553	0.471	0.739	0.704	- 0.737

BRAY WEIR

	log Q	log h_{tw}	log h_{hw}	log h_{ds}	log W	log W_{ds}	log HL
log h_{tw}	0.988						
log h_{hw}	0.749	0.791					
log h_{ds}	0.399	0.423	0.646				
log W	0.873	0.841	0.473	0.005			
log W_{ds}	0.884	0.863	0.597	0.071	0.917		
log HL	- 0.896	- 0.878	- 0.545	- 0.129	- 0.926	- 0.873	
log HL_{ds}	0.923	0.907	0.575	0.066	0.970	0.952	- 0.932

TABLE 2 (cont.)

BELL WEIR

	log Q	log h_{tw}	log h_{hw}	log h_{ds}	log W	log W_{ds}	log HL
log h_{tw}	0.965						
log h_{hw}	- 0.129	- 0.020					
log h_{ds}	0.374	0.523	0.326				
log W	0.966	0.971	- 0.191	0.435			
Log W_{ds}	0.913	0.909	- 0.173	0.351	0.907		
Log HL	- 0.919	- 0.953	0.210	- 0.487	- 0.967	- 0.893	
log HL_{ds}	0.960	0.939	- 0.138	0.239	0.940	0.879	- 0.868

where

log Q is the logarithm to the base 10 of the flow at the weir (m^3s^{-1})

log h_{tw} is the tailwater level expressed as the logarithm of the height on the tailwater board (m)

log h_{hw} is the headwater level of the "current" weir expressed as the logarithm of the height on the headwater board (m)

log h_{ds} is the headwater level of the downstream weir expressed as the logarithm of the height on the headwater board (m)

log W is the "current" weir setting expressed as the logarithm of the proportion of the weir drawn

log W_{ds} is the downstream weir setting expressed as the logarithm of the proportion of the downstream weir drawn

log HL is the logarithm of the head loss over the "current" weir (m)

log HL_{ds} is the logarithm of the head loss in the downstream reach (m)

TABLE 3 Travel times for Thames Study reach

Reach	Wave Celerity (3/2 water velocity ms^{-1})	Distance (km)	Time Taken (hours)
Marlow - Cookham	1.6	7.24	1.26
Cookham - Boulters	1.6	3.64	0.63
Boulters - Bray	1.9	3.78	0.55
Bray - The Cut	1.8	0.56	0.09
The Cut - Boveney	1.7	4.55	0.74
Boveney - Romney	2.1	3.30	0.44
Romney - Old Windsor	2.0	4.38	0.61
Old Windsor - Bell	2.1	5.50	0.73
Bell - River Colne	1.9	1.34	0.20
River Colne - Penton Hook	2.3	3.32	0.40

Note: Velocities used relate to an input of 225 m^3s^{-1} to hydraulic model; inflow of 25 m^3s^{-1} down Colne; no other additions

TABLE 4 Rating curves derived from regression analysis

COOKHAM WEIR

Model for a fully-drawn downstream weir:

$$Q = 14.45\ (H_{tw} - 20.94)^{2.06} \qquad (3.1a)$$

$R^2 = 90.2\%$ $\quad S = 0.0162$ $\quad n = 15$

Stepwise model:

$$Q = 6.64\ (H_{tw} - 20.94)^{2.64} \cdot W^{0.311} \cdot HL_{ds}^{-0.072}$$

$R^2 = 96.63\%$ $\quad S = 0.0222$ $\quad n = 36$

Alternative models:

$$Q = 7.852\ (H_{tw} - 20.94)^{2.51} \cdot W^{0.228} \cdot W_{ds}^{0.125} \cdot HL_{ds}^{-0.0683}$$

$R^2 = 96.7\%$ $\quad S = 0.0222$ $\quad n = 36$

$$Q = 13.8\ (H_{tw} - 20.94)^{2.13} \cdot W^{0.045} \cdot W_{ds}^{0.253} \qquad (3.2a)$$

$R^2 = 94.8\%$ $\quad S = 0.0275$ $\quad n = 36$

BRAY WEIR

Model for a fully-drawn downstream weir:

$$Q = 16.22(H_{tw} - 17.43)^{1.83} \qquad (3.1b)$$

$R^2 = 98.1\%$ $\quad S = 0.00673$ $\quad n = 12$

Stepwise model:

$$Q = 20.18(H_{tw} - 17.43)^{1.698} \cdot W^{0.185} \cdot (H_{ds} - 19.60)^{0.022}$$

$R^2 = 98.68\%$ $\quad S = 0.014$ $\quad n = 34$

Alternative models:

$$Q = 11.48(H_{tw} - 17.43)^{2.14} \cdot W^{0.166} \cdot W_{ds}^{0.0711} \cdot HL_{ds}^{-0.177}$$

$R^2 = 98.3\%$ $\quad S = 0.0158$ $\quad n = 36$

$$Q = 12.59(H_{tw} - 17.43)^{2.02} \cdot W^{0.0866} \cdot W_{ds}^{-0.023} \qquad (3.2b)$$

$R^2 = 98.2\%$ $\quad S = 0.01598$ $\quad n = 36$

TABLE 4 (contd.)

BELL WEIR

Model for a fully-drawn downstream weir:

$$Q = 16.98(H_{tw} - 10.31)^{1.86} \qquad (3.1c)$$

$R^2 = 86.0\%$ $S = 0.0167$ $n = 11$

Stepwise model:

$$Q = 85.7(H_{tw} - 10.31)^{0.67} \cdot W^{0.172} \cdot HL_{ds}^{0.233}$$

$R^2 = 96.11\%$ $S = 0.0233$ $n = 36$

Alternative models:

$$Q = 100.0(H_{tw} - 10.31)^{0.556} \cdot W^{0.151} \cdot W_{ds}^{0.094} \cdot HL_{ds}^{0.224}$$

$R^2 = 96.3\%$ $S = 0.02302$ $n = 36$

$$Q = 67.61(H_{tw} - 10.31)^{0.911} \cdot W^{0.241} \cdot W_{ds}^{0.120} \qquad (3.2c)$$

$R^2 = 94.9\%$ $S = 0.0266$ $n = 36$

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where

Q	is flow (m^3s^{-1})
H_{tw}	is tailwater level (m.AOD)
W	is proportion of "current" weir raised
W_{ds}	is proportion of downstream weir raised
HL_{ds}	is downstream head loss (m)
H_{ds}	is downstream headwater level (m.AOD)

TABLE 5 Frequency Analysis of Annual Maximum Flow and Level Data - Equation Parameters

Station	GEV Parameters u	GEV Parameters a	GEV Parameters k	EV1 Parameters u	EV1 Parameters a
Days Weir	123.10	48.32	0.075	121.50	45.29
Thame	21.15	7.33	1.004*	18.09	5.29
Pang	2.04	0.67	0.059	2.02	0.64
Kennet	32.96	8.51	0.109	32.55	7.77
Loddon	14.40	3.99	0.021	14.36	3.91
Blackwater	18.91	4.11	- 0.014	18.94	4.17
Wye	2.66	0.51	0.033	2.65	0.49
The Cut	6.82	2.89	- 0.060	6.90	3.07
Bray/Windsor [1]	221.12	75.23	0.022	220.36	73.73
Colne	9.20	2.84	0.284*	8.86	2.32
Wey at Tilford	20.15	4.93	- 0.320*	21.01	7.35
Mole at Castle Mill	57.06	19.27	0.177	55.59	16.77
Mole at Kinnersley Manor	36.77	12.85	0.162	35.87	11.29
Hoggs Mill	11.26	4.08	0.094	11.09	3.77
Teddington	265.20	92.69	- 0.068	268.16	99.10
Cookham Weir	24.71	0.51	0.563*	24.59	0.38
Bray Weir	21.46	0.52	0.320*	21.39	0.42
Bell Weir	14.21	0.50	0.237*	14.15	0.42

* Significantly different from zero

[1] based on reconstructed data from Beran and Field (1988)

TABLE 6 Frequency Analysis of Peaks over Threshold Flow and Level Data - Equation Parameters

Station	λ	Q_0	β
Days Weir	2.0	110.84	36.66
Thame	4.0	11.42	7.44
Pang	4.0	1.82	0.51
Kennet	4.0	25.35	7.28
Loddon	4.0	10.55	4.09
Blackwater	4.0	14.76	4.89
Wye	-	-	-
The Cut	4.0	4.53	2.63
Bray/Windsor[1]	2.0	195.05	46.16
Colne	-	-	-
Wey at Tilford	3.0	17.28	7.61
Mole at Castle Mill	-	-	-
Mole at Kinnersley Manor	4.0	18.59	13.80
Hoggs Mill	2.0	10.81	2.64
Teddington	3.0	212.91	76.16
Cookham Weir	2.0	24.54	0.34
Bray Weir	2.0	21.26	0.35
Bell Weir	1.5	14.17	0.34

[1] Based on level data and the rating curves of Beran and Field (1988)

TABLE 7 Flow Calculations Based on a Frequency Analysis of Level Data and the Rating Curve Recommended in Section 3

Return Period	COOKHAM Stage mAOD	COOKHAM Flow m^3s^{-1}	BRAY Stage mAOD	BRAY Flow m^3s^{-1}	BELL Stage mAOD	BELL Flow m^3s^{-1}
POT						
0.25	24.31	175.3	21.02	166.5	13.83	212.8
0.33	24.40	185.4	21.12	176.0	13.92	217.7
0.5	24.54	201.8	21.26	189.7	14.07	225.9
1.0	24.78	231.5	21.50	214.5	14.31	239.0
ANNUAL MAXIMA						
2	24.88	244.5	26.64	229.7	14.38	242.9
5	25.23	293.1	22.07	279.5	14.84[1]	290.7
10	25.36	312.4	22.29	306.9	15.08[1]	320.3
25	25.47	329.2	22.49	333.0	15.33[1]	352.6
50	25.52	336.9	22.61	349.1	15.48[1]	372.6

[1] Use of equation for fully drawn downstream weir (in all other cases, equation incorporating weir settings used - weirs assumed to be fully drawn).

———————— position of bankfull flow as given in hydraulic model.

TABLE 8 Return Periods for Bankfull Flow

Weir	Bankfull flow from ONDA m^3s^{-1}	Stage from rating curves m.AOD	Return period on annual maximum series (GEV fit) Years	Return period on POT Series of independent peaks Years	Return period on full POT series Years
Cookham	240	24.85	1.91	1.24	1.17
Bray	240	21.73	2.33	1.91	1.80
Bell	260	14.58	2.81	2.23	2.00

TABLE 9 Areal Correction Factors

Tributary	Area at gauge (km²)	Total Catchment area (km²)	Areal Correction
Thame	443.0	689.7	1.557
Pang	170.9	183.4	1.073
Kennet	1033.4	1156.4	1.119
Loddon	164.5	647.7	1.299[3]
Blackwater	354.8		1.299[3]
Wye	137.3	140.4	1.023
The Cut	50.2	109.1	2.173
Colne	743.0	992.2	1.335
Wey at Tilford	396.3	895.6	2.260
Mole at Castle Mill	316.0	486.9	1.541
Mole at Kinnersley Manor	142.0		3.430
Hoggs Mill at Kingston	69.1	74.8	1.082
Ungauged catchment area between Days Weir and Royal Windsor		647.6[1]	788.0[2]
Areal correction		1.101	1.126
Ungauged catchment area between Royal Windsor and Teddington		452.5[1]	1444.7[2]
Areal correction		1.048	1.170

[1] for annual maximum data

[2] for POT data (i.e. includes tributaries for which POT data not available)

[3] assumes both sub-catchments are equally representative of downstream catchment

TABLE 10 Addition of flows for Thames tributaries for given return periods

(a) POT analysis

	Return Period			
	0.25	0.33	0.5	1.0
Days Weir	85.43	95.61	110.84	136.25
Bray/Windsor[1]	163.05	175.87	195.05	227.04
required additional flow	77.62	80.26	84.21	90.79
Thame	11.42	13.48	16.57	21.73
Pang	1.82	1.96	2.17	2.52
Kennet	25.35	27.37	30.39	35.44
Loddon	10.55	11.68	13.38	16.21
Blackwater	14.76	16.12	18.15	21.54
Wye*	-	-	-	-
Cut	4.53	5.26	6.35	8.17
addition of gauged flows	68.43	75.87	87.01	105.61
addition including areal correction for each tributary	90.82	101.26	116.89	142.99
including correction for ungauged non-tributary flows	102.26	114.02	131.62	161.00
Bray/Windsor[1]	163.05	175.87	195.05	227.04
Teddington	191.00	212.15	243.79	296.58
required additional flow	27.95	36.28	48.75	69.54
Colne*	-	-	-	-
Wey at Tilford[2]	15.09	17.20	20.36	25.64
Mole at Kinnersley Manor	18.59	22.42	28.15	37.72
Hoggs Mill at Kingston	8.98	9.71	10.81	12.64
addition of gauged flows	42.65	49.33	59.32	76.00
addition including areal correction for each tributary	107.6	126.3	154.3	201.0
including correction for ungauged non-tributary flows	125.9	147.7	180.5	235.2

[1] based on level data at Bray and the Maidenhead rating curves.

[2] includes correction made to annual maxima and extended to the rest of the data via regression analysis.

* POT data unavailable due to dominance of groundwater flow.

Frank 7/10/88

A copy of the report for Thames Water for Tuesday's meeting (Oct. 11th).

(I've not added the figures for a 100 year return period in table 10 as the figures come from individual station records rather than a pooled data set.)

Pam Naden

TABLE 10 (contd.)

(b) Annual maxima analysis

	Return Period				
	2	5	10	25	50
Days Weir	138.1	189.4	223.4	266.4	298.2
Bray/Windsor[1]	248.6	332.1	386.2	456.2	508.1
required additional flow	110.5	142.7	162.8	189.8	209.9
Thame	23.4	26.8	27.7	28.2	28.3
Pang	2.3	3.0	3.5	4.1	4.5
Kennet	35.4	44.2	50.0	57.4	62.9
Loddon	15.8	20.2	23.2	26.9	29.6
Blackwater	20.5	25.2	28.3	32.3	35.2
Wye	2.8	3.4	3.8	4.2	4.6
Cut	8.0	11.5	13.8	16.7	18.9
addition of gauged flows	108.2	134.3	150.3	169.8	184.0
addition including areal correction for each tributary	145.9	181.8	203.6	230.0	249.2
including correction for ungauged non-tributary flows	160.6	200.2	224.2	253.2	274.4
Bray/Windsor[1]	248.6	332.1	386.2	456.2	508.1
Teddington	304.5	416.8	491.2	585.1	654.9
required additional flow	55.9	84.7	105.0	128.9	146.8
Colne	10.2	12.7	13.9	15.2	15.9
Wey at Tilford	22.1	29.7	36.4	47.7	58.5
Mole at Castle Mill	61.7	80.7	93.3	109.2	121.0
Hoggs Mill at Kingston	12.5	16.7	19.6	23.1	25.8
addition of gauged flows	106.5	139.8	163.2	195.2	221.2
addition including areal correction for each tributary	172.2	226.5	265.8	321.4	360.2
including correction for ungauged non-tributary flows	180.4	237.4	278.6	336.8	377.5

[1]based on data from Beran and Field (1988)

TABLE 11 *Correlation Between Mean Daily Flows on Thames at Days Weir and Contingent Daily Flows on Tributaries and at Teddington for Dates Defined by POT at Days Weir*

	Correlation coefficient Same day	Time lagged	No. events	Lag (hours)
Thame	0.249	0.249	42	0.3
Pang	0.393 [1]	0.402 [1]	43	4.5
Kennet	- 0.086 [2]	- 0.069 [2]	57	6.5
Loddon	- 0.244	- 0.214	52	7.8
Blackwater	- 0.062	- 0.022	82	7.8
Wye	0.024	0.001	52	11.8
The Cut	- 0.058 [3]	- 0.054 [3]	72	13.5
Colne	0.128	0.111	82	16.1
Wey at Tilford	0.154	0.201	80	17.4
Mole at Castle Mill	0.027	0.096	28	18.6
Mole at Kinnersley Manor	- 0.052 [3]	0.073 [3]	31	18.6
Hoggs Mill at Kingston	- 0.007	0.017	73	21.6
Teddington	0.628	0.718	121	23.5

[1] affected by outlier - extreme flow on Pang 23/11/74

[2] influenced by low Kennet flow on 14/7/68 when Thames high

[3] several outliers influence results

TABLE 12 Addition of Daily Flows for Dates Defined by the Peak over Threshold Series for Days Weir

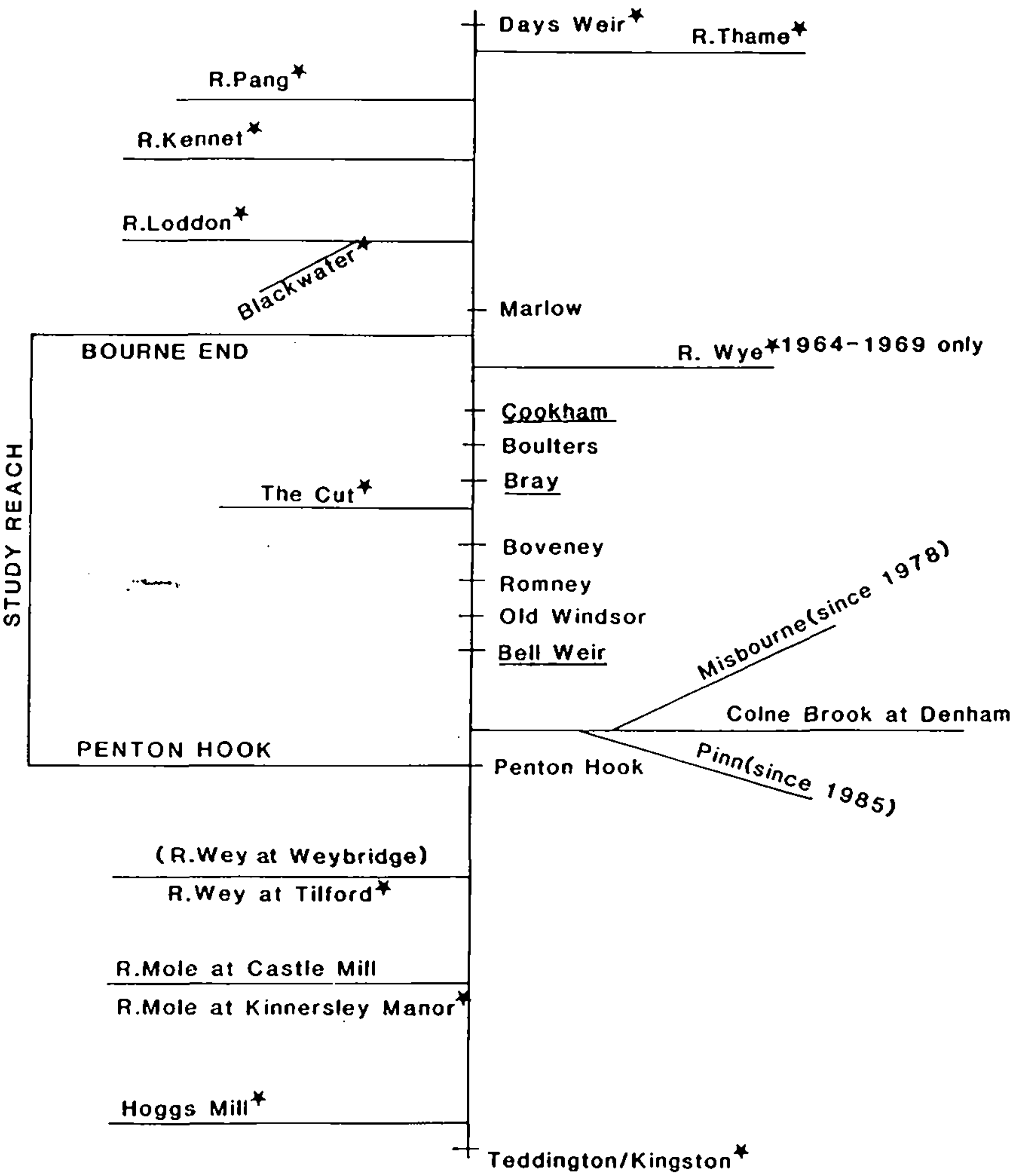
	Same Day Median Contingent flow	Time Lagged Median Contingent flow
Thame	13.55	13.48
Pang	1.41	1.38
Kennet	19.50	19.47
Loddon	4.52	4.26
Blackwater	6.65	6.27
Wye	1.27	1.26
The Cut	0.76	0.69
total gauged flow	47.66	46.81
addition of flows including areal correction for tributaries	61.9	60.7
including correction for ungauged non-tributary flows	68.1	66.9
Colne	6.96	6.49
Wey at Tilford*	5.99	5.45
Mole at Castle Mill	8.61	7.04
Hoggs Mill at Kingston	1.32	1.24
total gauged flow	22.88	20.22
addition of flows including areal correction for tributaries	37.5	33.2
including correction for ungauged non-tributary flows	39.3	34.8
Median for Days Weir	124.0	124.0
Median for Teddington	253.0	238.8
required flow addition	129.0	114.0
actual flow addition	107.4	101.7

* no correction applied to flow data data from Surface Water Archive held at IH.

TABLE 13 Percentage Flow Contribution from Each Tributary Catchment

	Figures based on contingent flow analysis (including tributary areal correction factor)	Figures based on 2-year return period peak flows from annual maximum series (including tributary areal correction factor)
Thame	31.4	22.7
Pang	2.2	1.5
Kennet	32.6	24.7
Loddon	8.3	12.8
Blackwater	12.2	16.6
Wye	1.9	1.8
The Cut	2.2	10.8
ungauged non-tributary contribution	9.2	9.1
Colne	24.9	7.5
Wey	35.4	27.7
Mole	31.2	52.7
Hoggs Mill	3.9	7.5
Ungauged non-tributary contribution	4.6	4.6

Figure 1 *Schematic diagram of the Thames between Days Weir and Teddington including gauged tributaries*



Key

— weirs in or near study reach on Thames (those used in the analysis are underlined)

* gauging stations for which POT data are available

Figure 2a Stage-discharge plot for Cookham weir

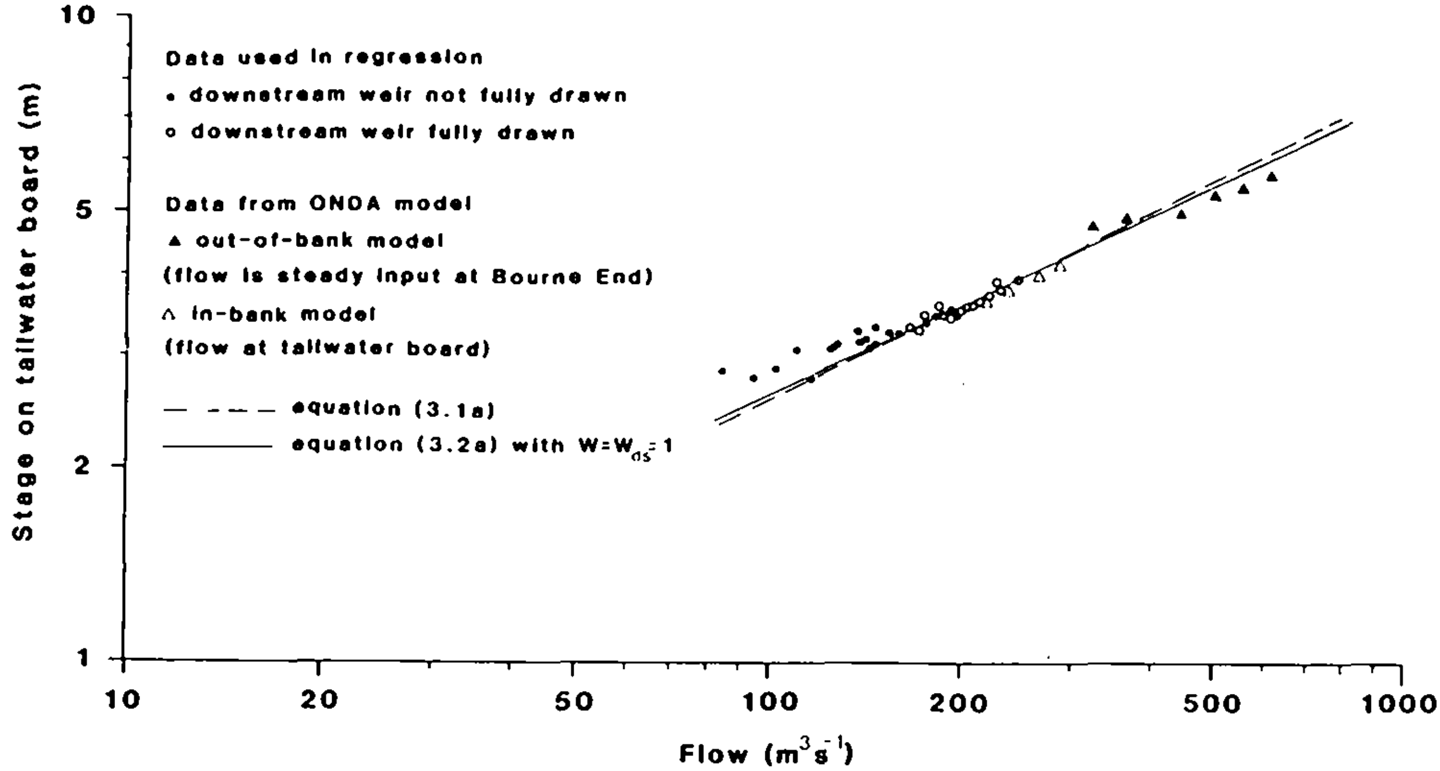


Figure 2b Stage-discharge plot for Bray weir

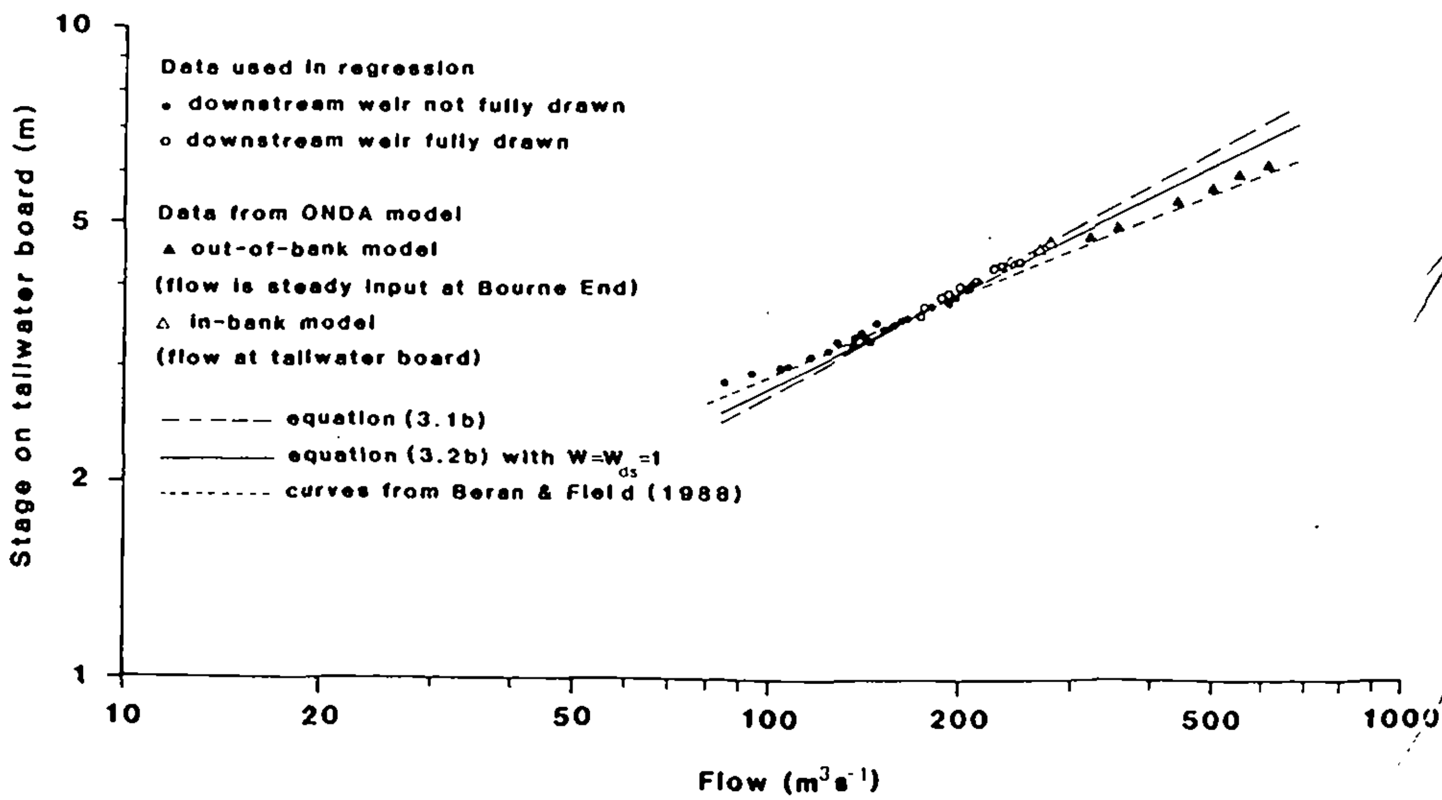


Figure 2c *Stage-discharge plot for Bell weir*

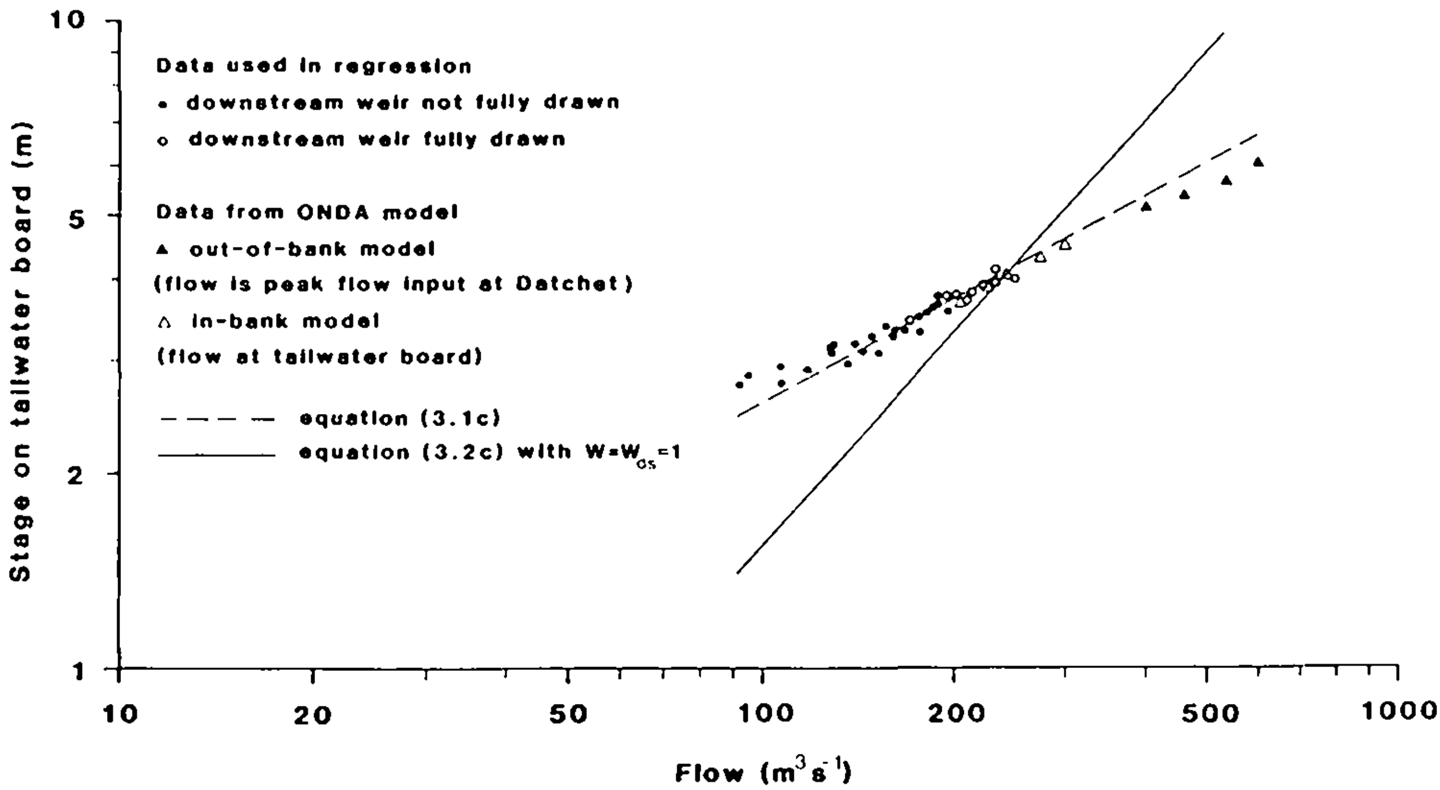


Figure 3a *Flood frequency curves based on annual maxima for River Thames at Days Weir*

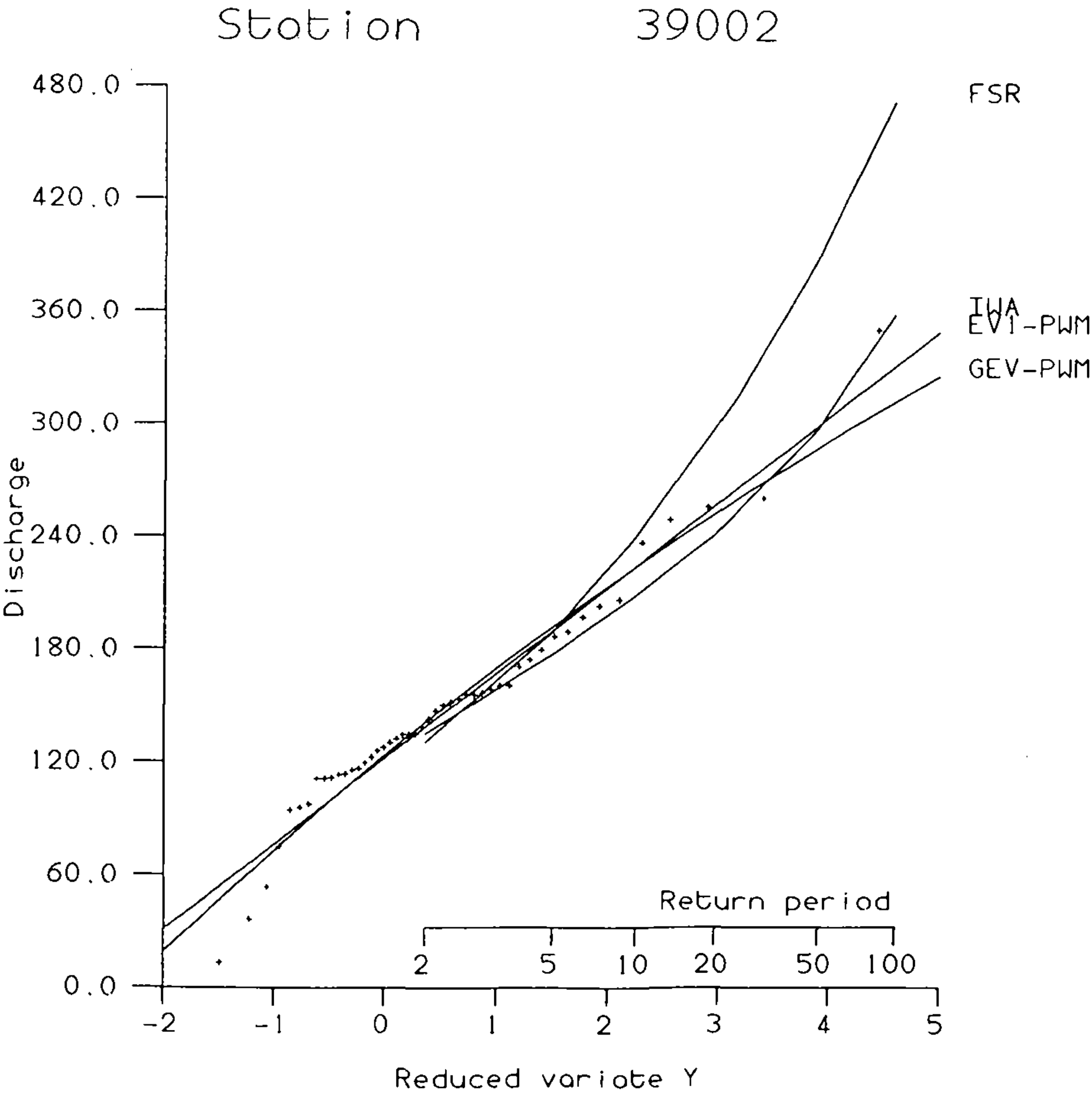


Figure 3b *Flood frequency curves based on annual maxima for River Thame at Shabbington*

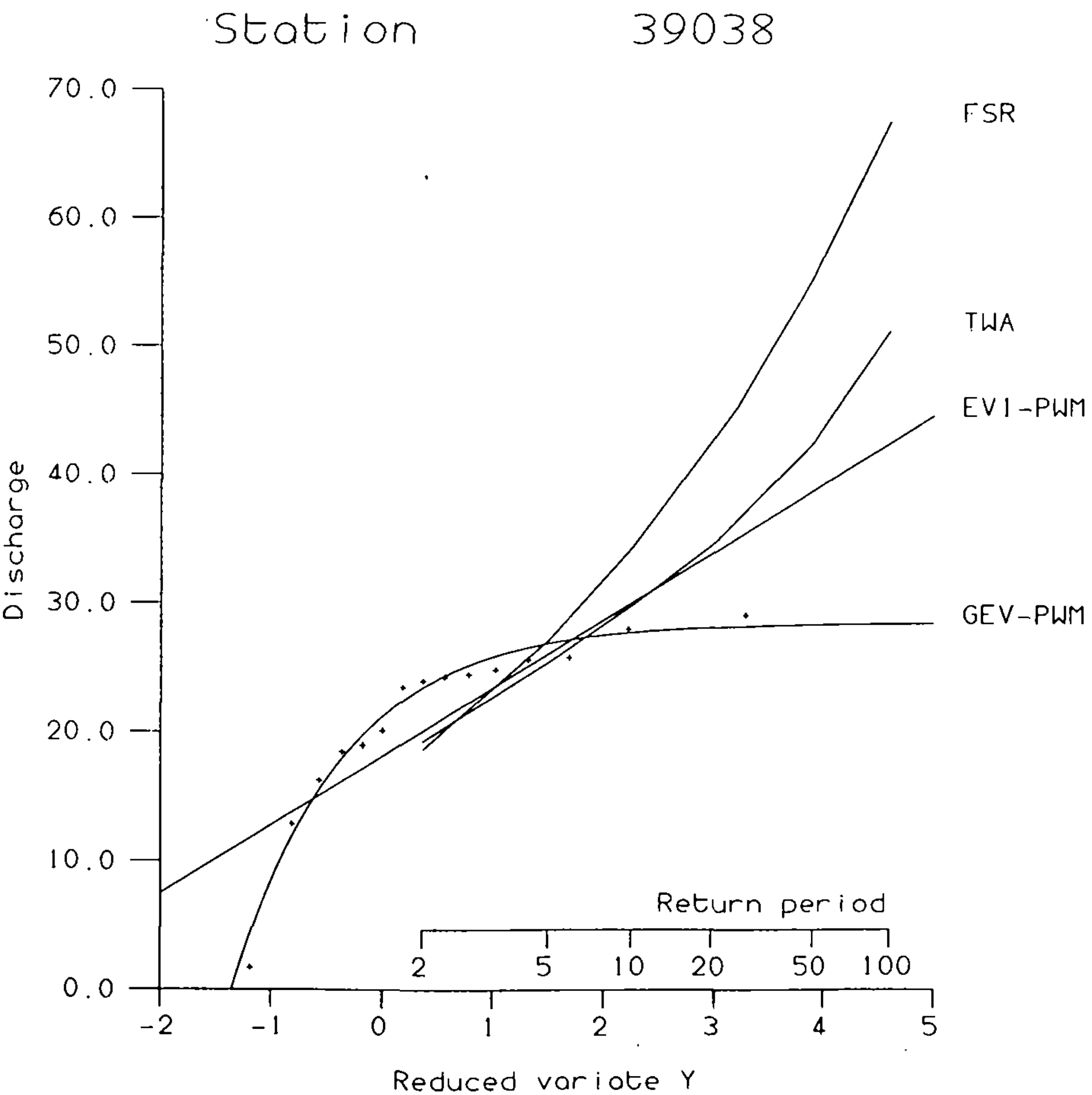


Figure 3c *Flood frequency curves based on annual maxima for River Pang at Pangbourne*

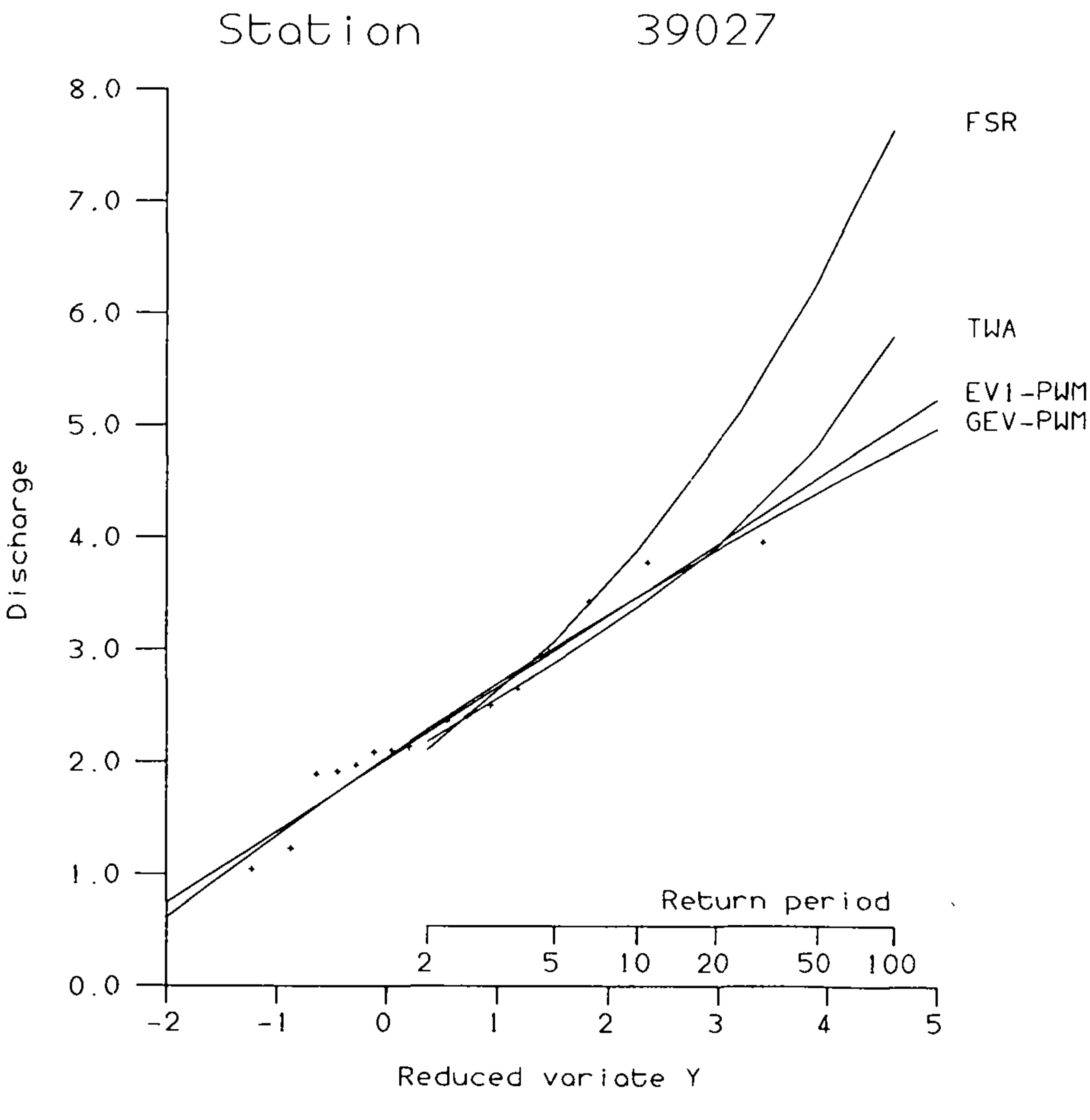


Figure 3d *Flood frequency curves based on annual maxima for River Kennet at Theale*

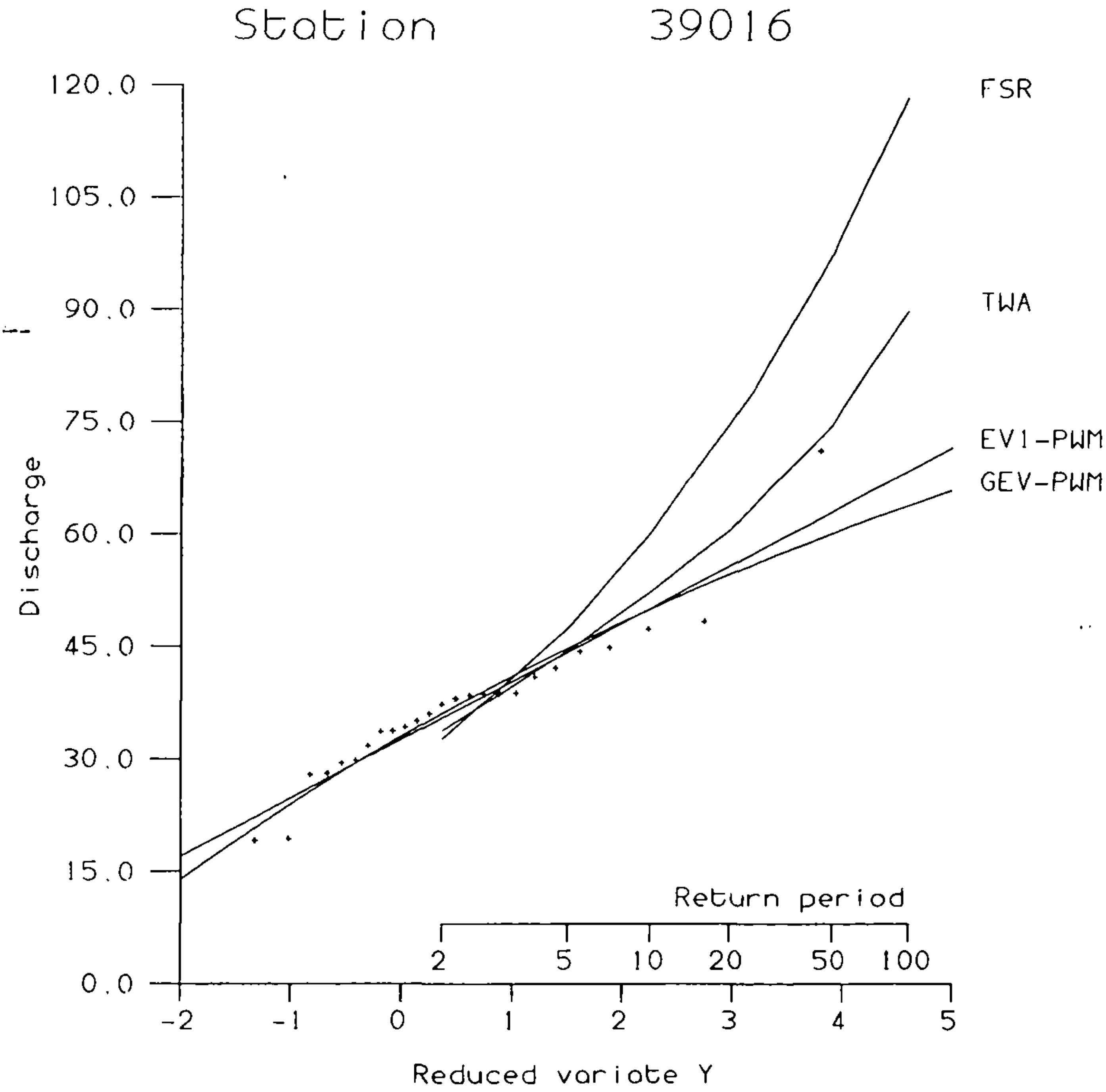


Figure 3e *Flood frequency curves based on annual maxima for River Loddon at Sheepbridge*

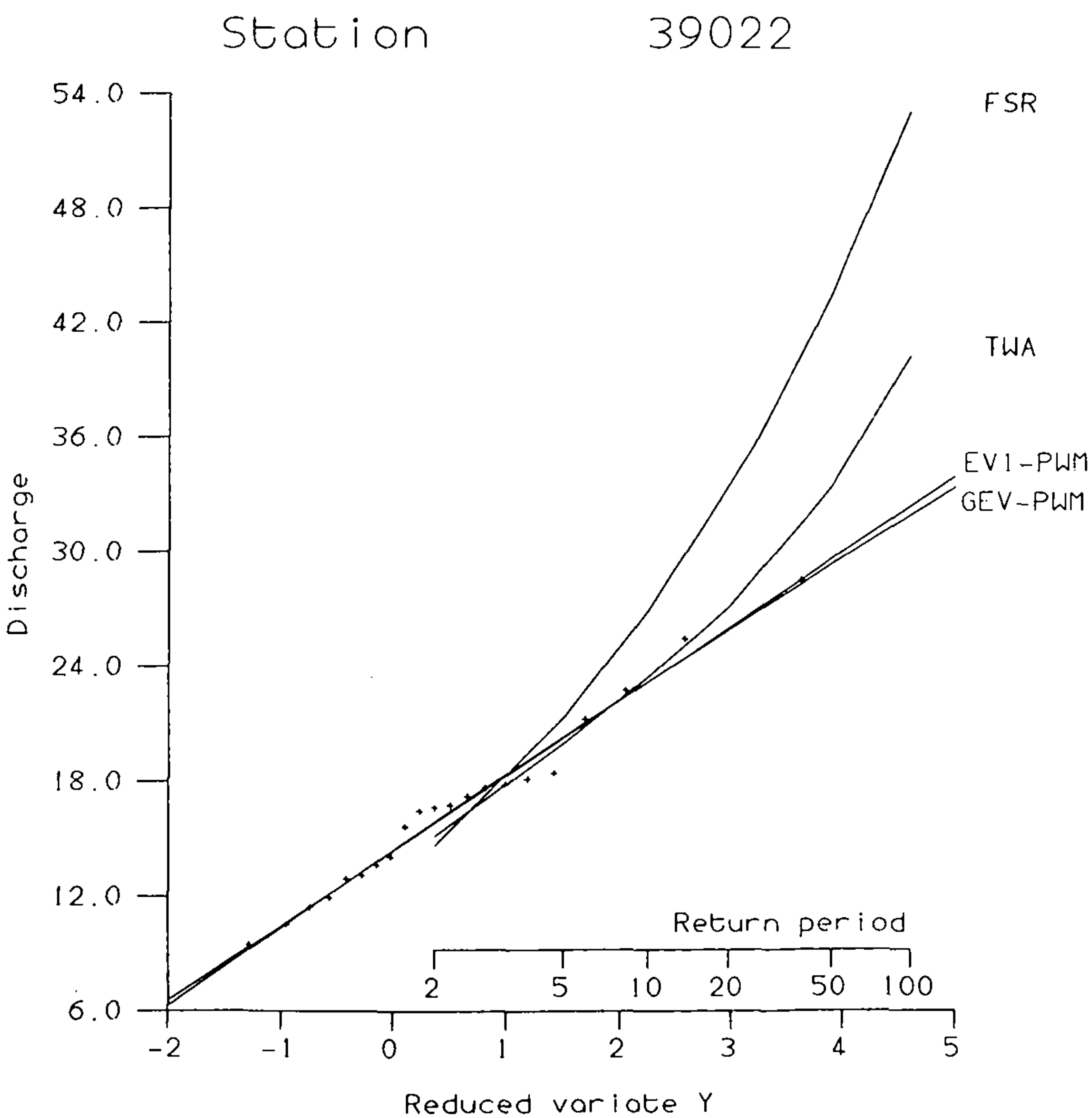


Figure 3f *Flood frequency curves based on annual maxima for River Blackwater at Swallowfield*

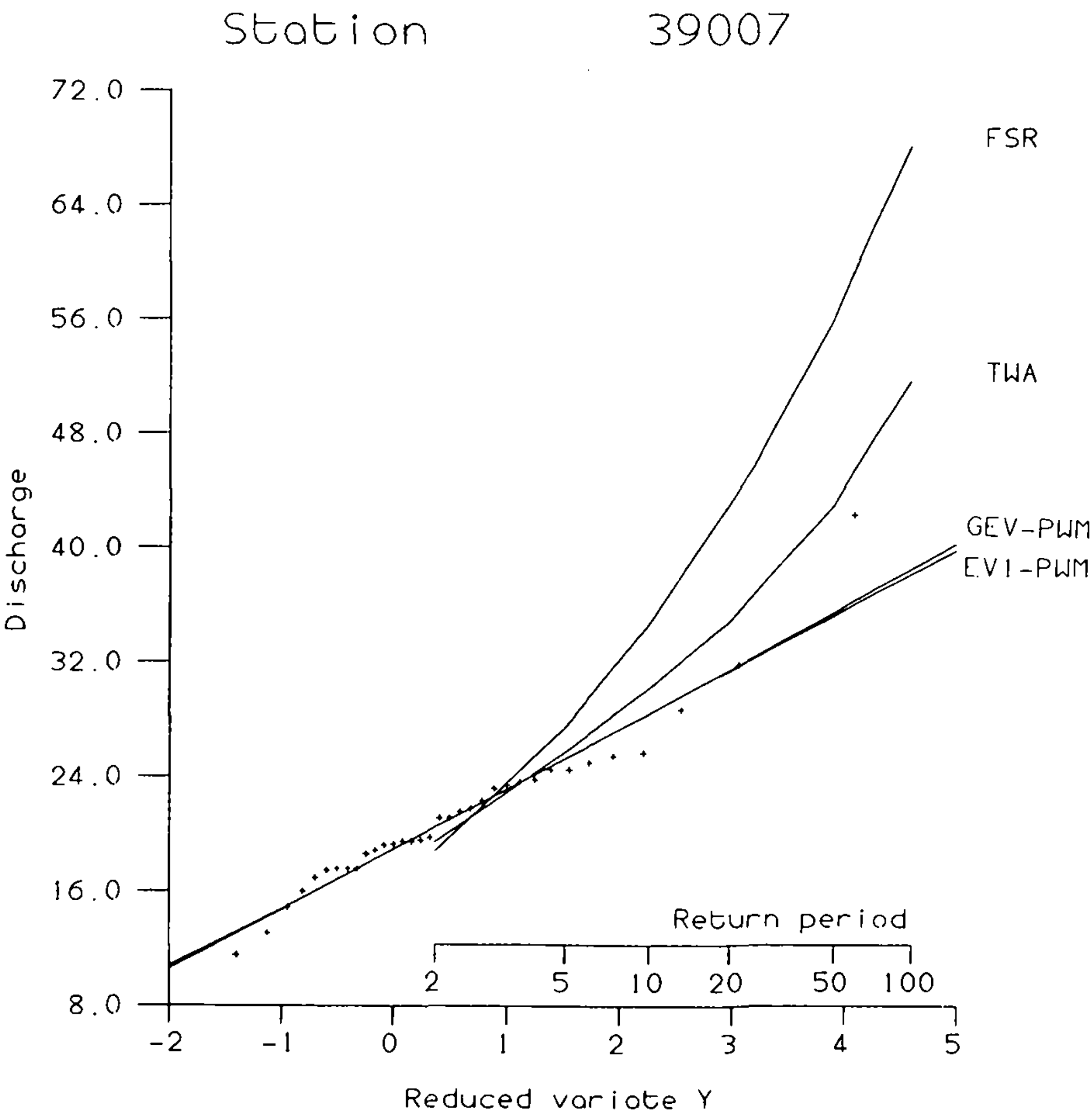


Figure 3g *Flood frequency curves based on annual maxima for River Wye at Hedsor*

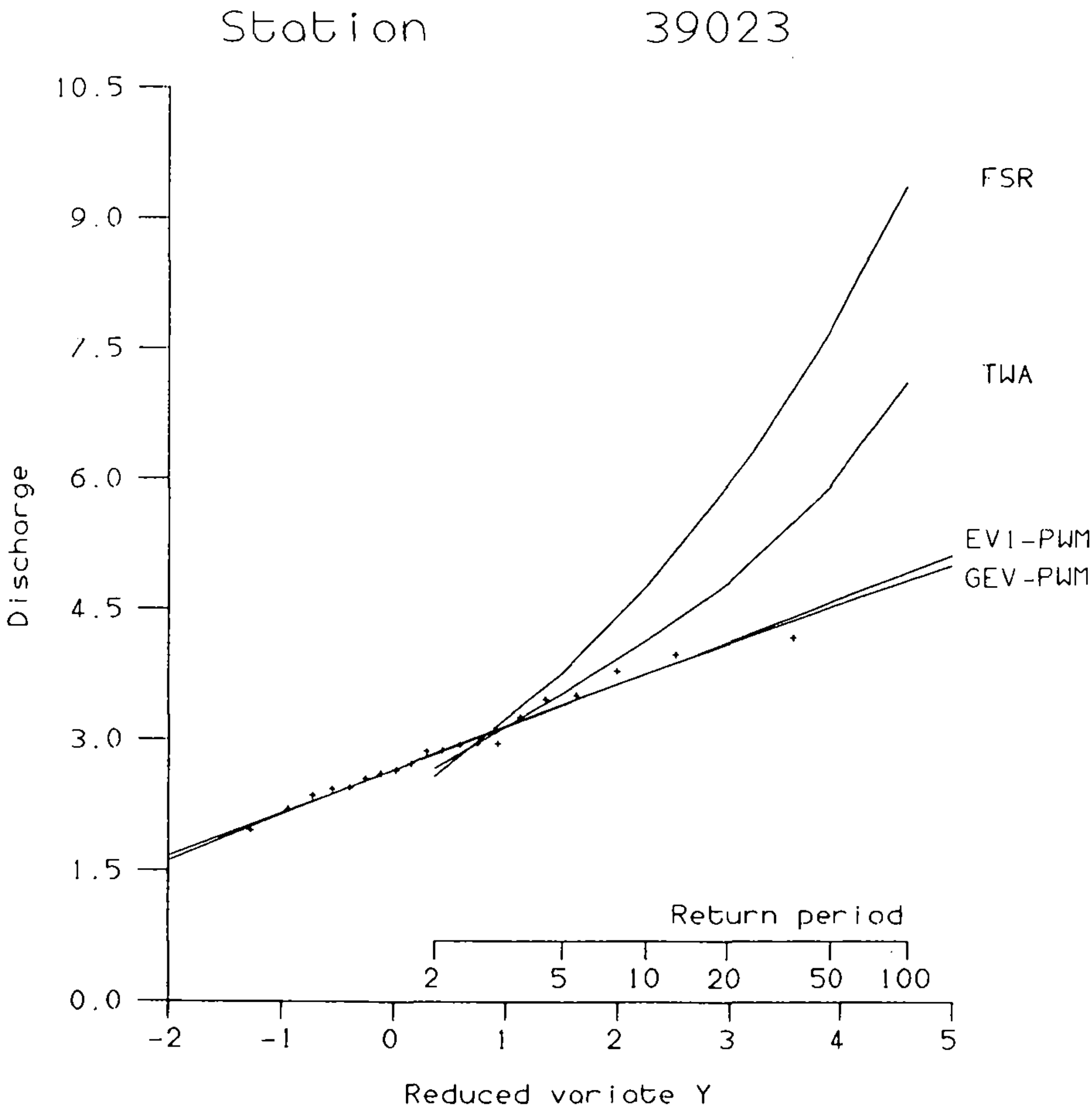


Figure 3h *Flood frequency curves based on annual maxima for The Cut at Binfield*

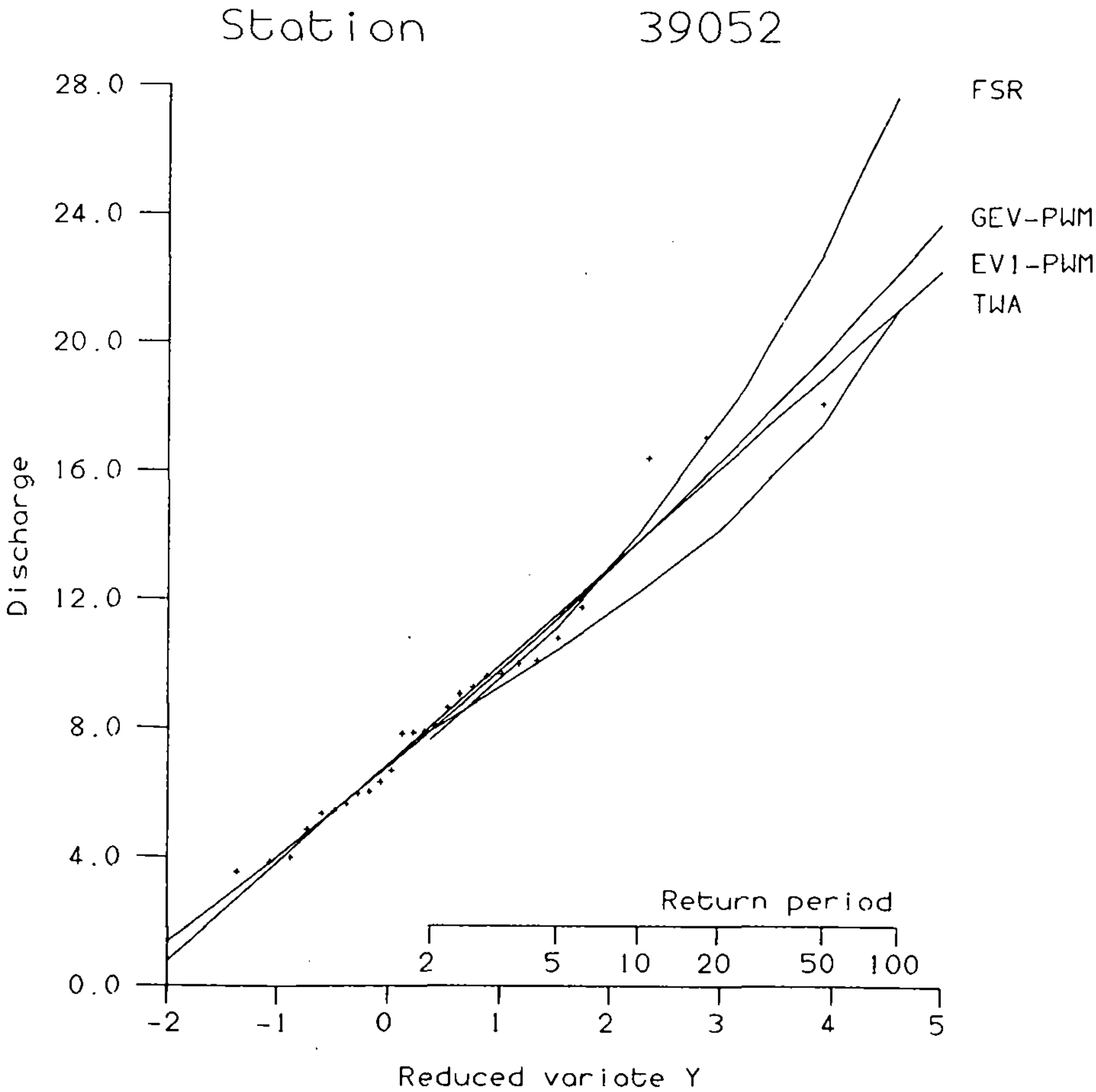


Figure 3i Flood frequency curves based on annual maxima for River Thames at Bray-Windsor - data from Beran and Field (1988)

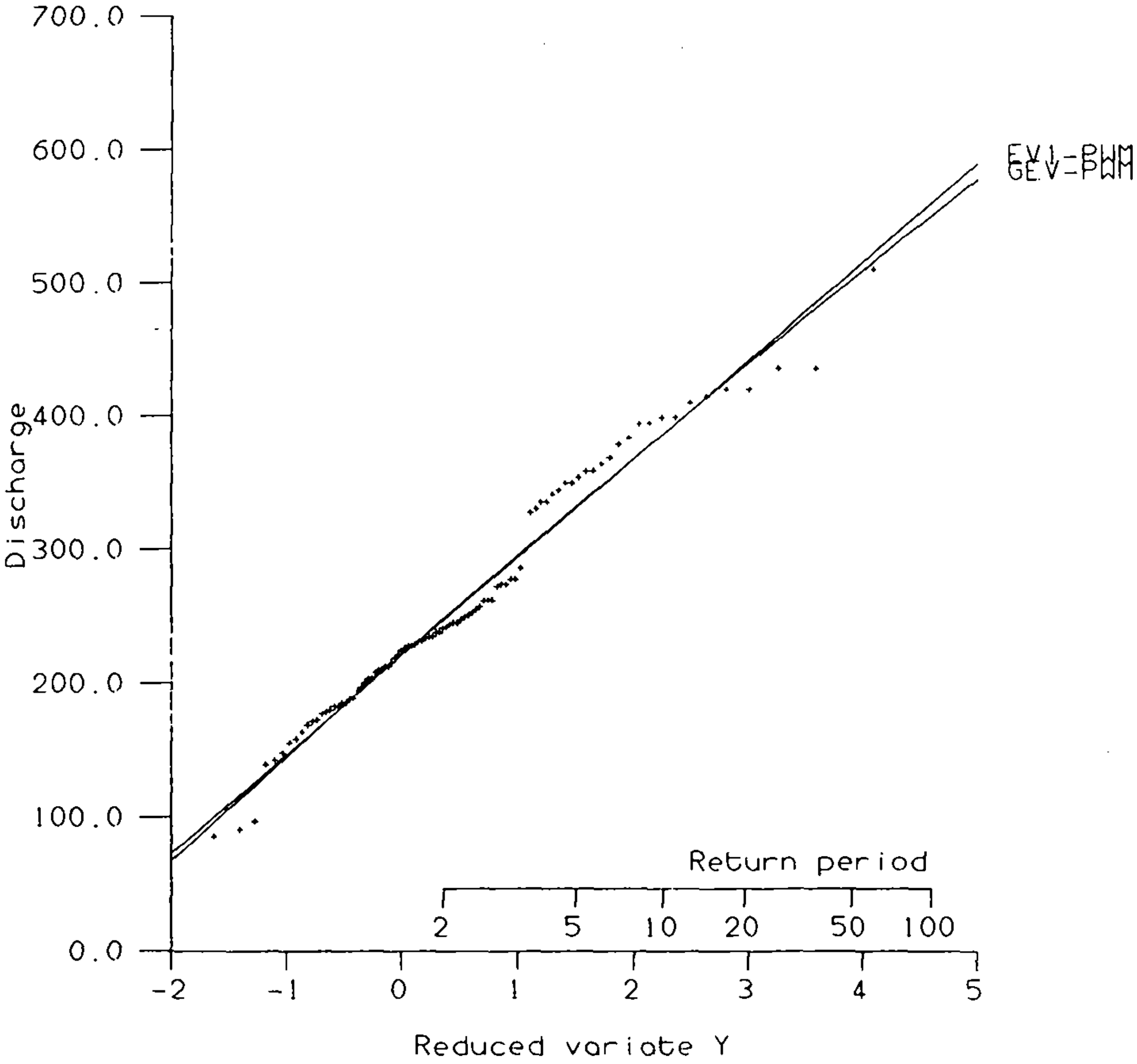


Figure 3j *Flood frequency curves based on annual maxima for River Colne at Denham*

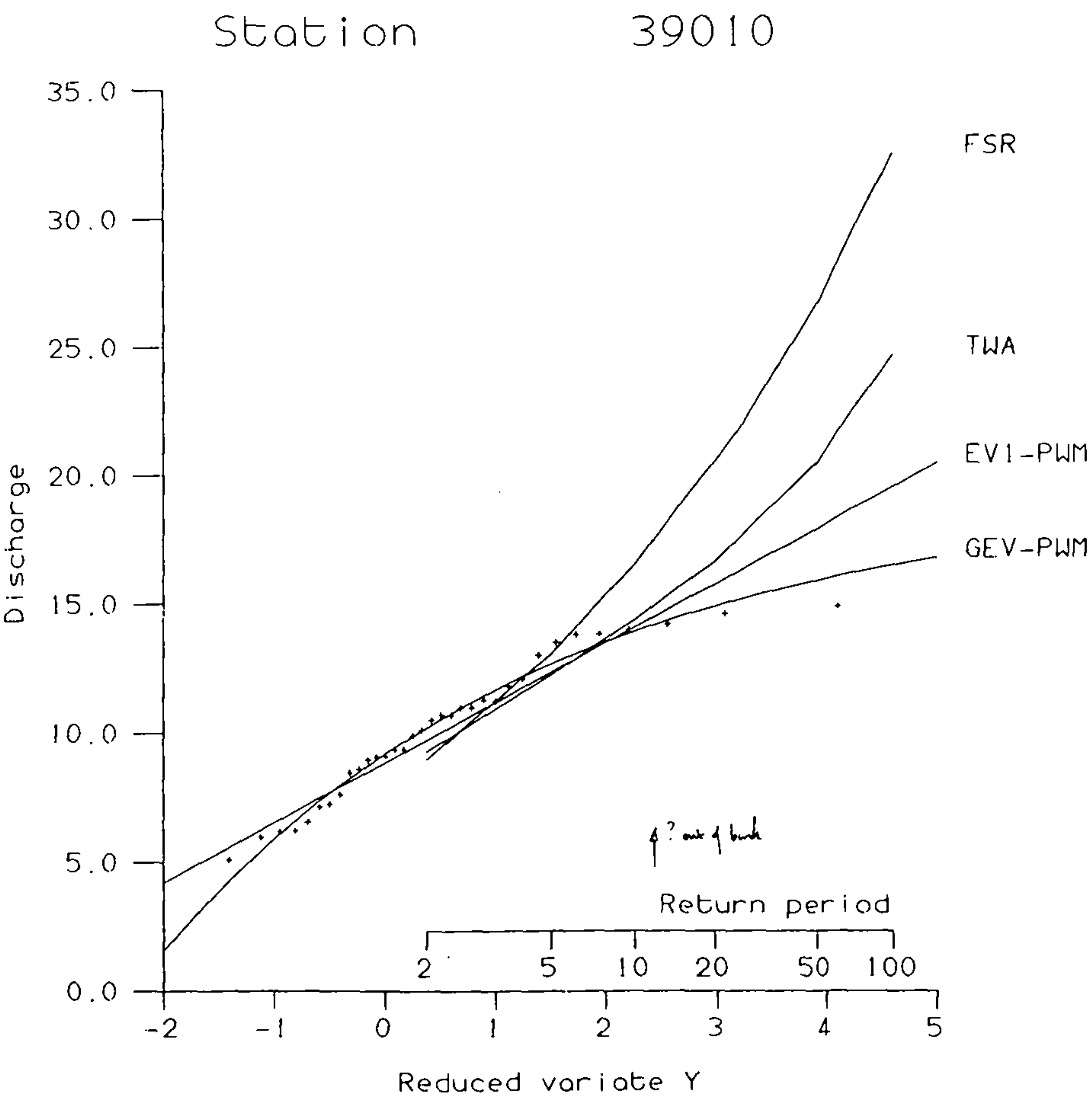


Figure 3k *Flood frequency curves based on annual maxima for River Wey at Tilford - using revised data*

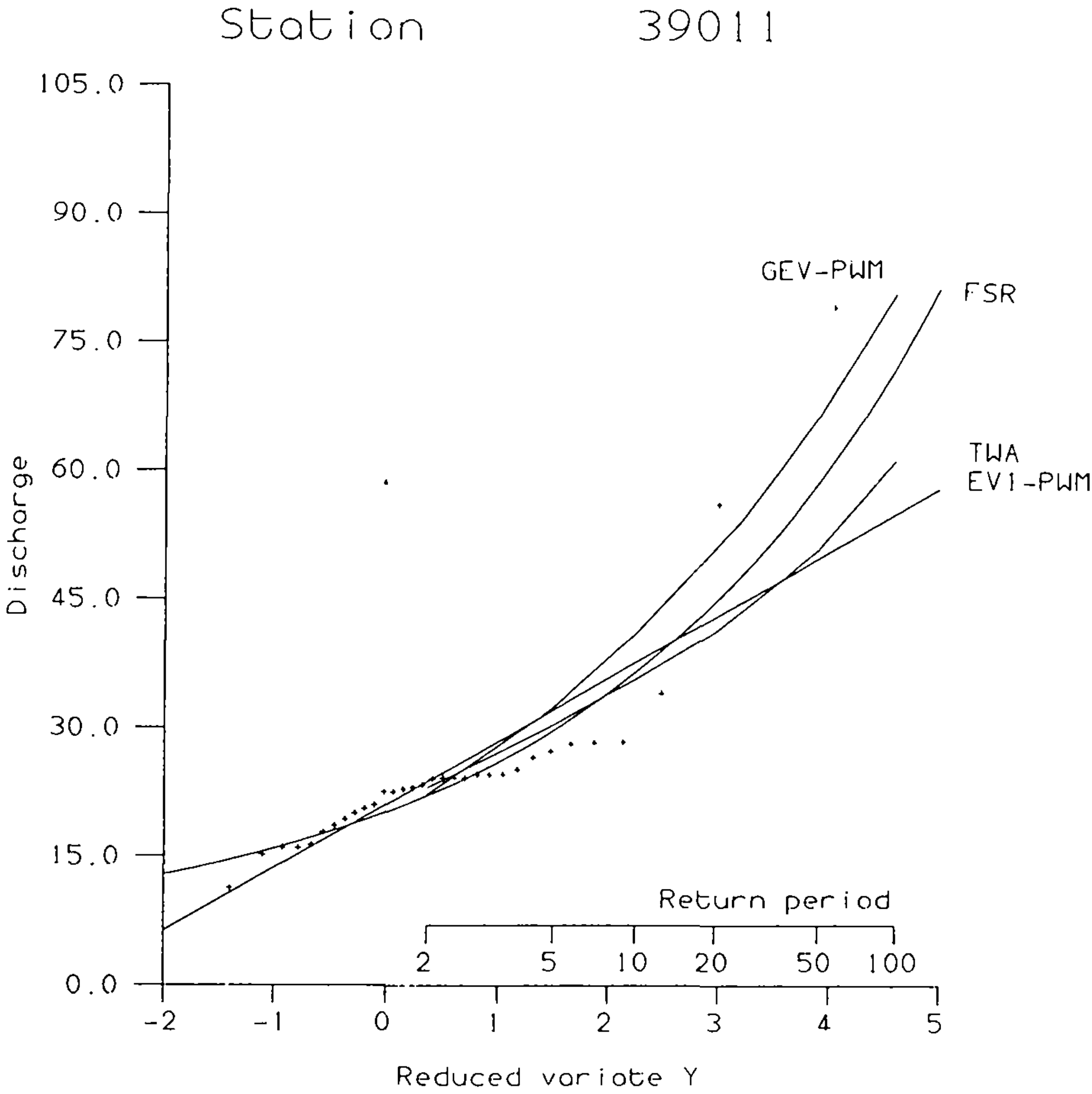


Figure 31 *Flood frequency curves based on annual maxima for River Mole at Kinnersley Manor*

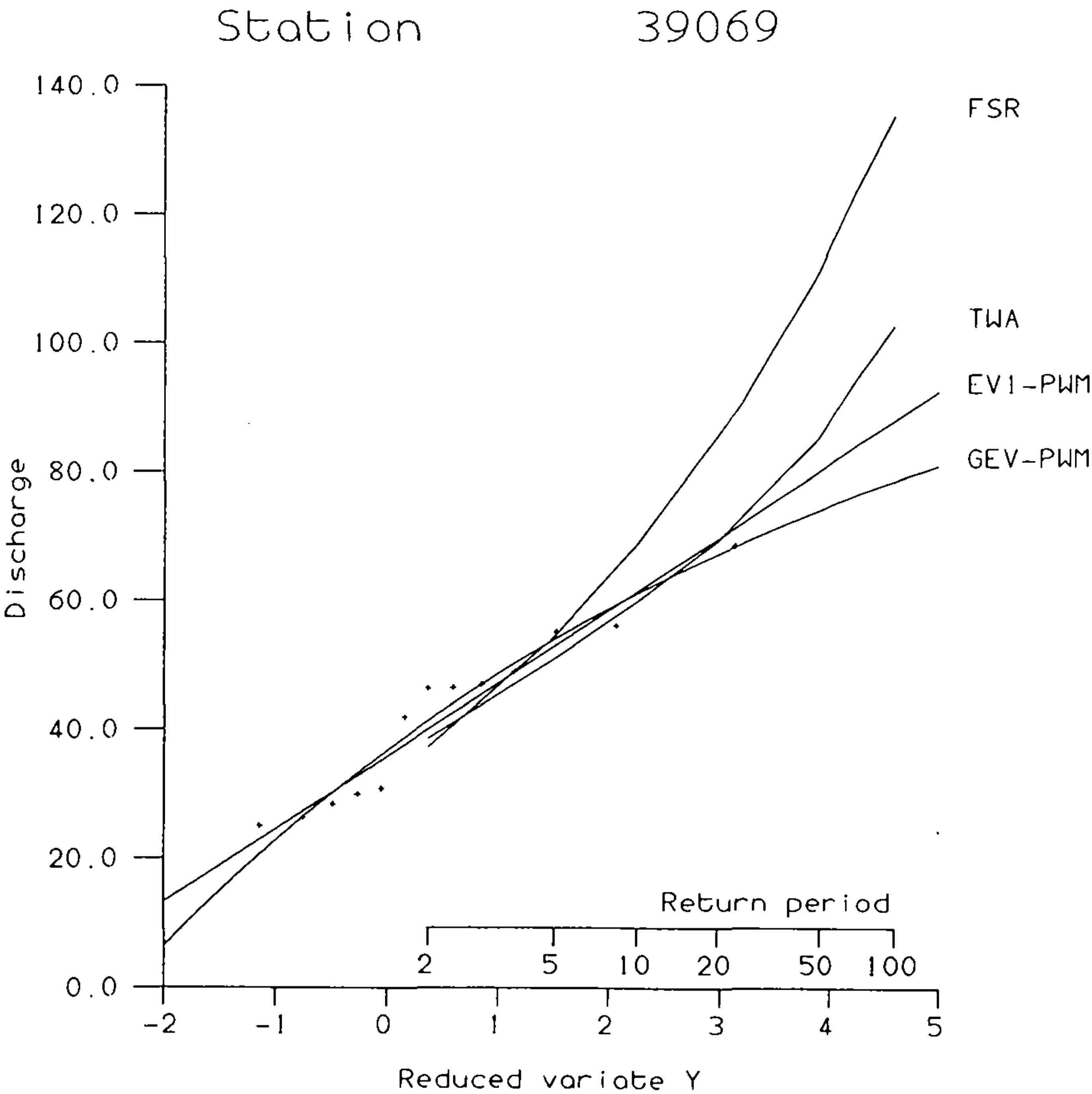


Figure 3m *Flood frequency curves based on annual maxima for River Mole at Castle Mill*

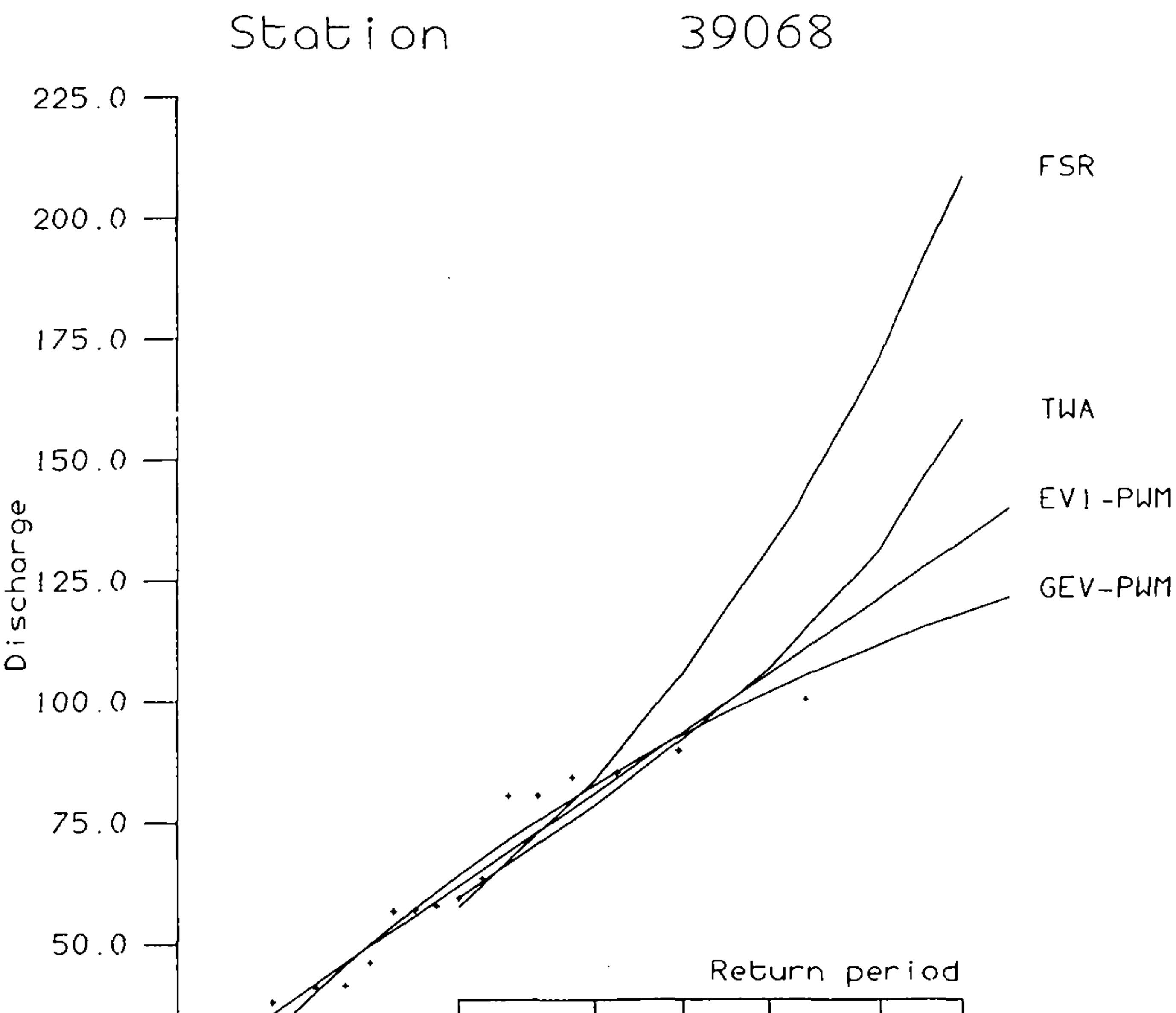


Figure 3n *Flood frequency curves based on annual maxima for Hoggsmill at Kingston*

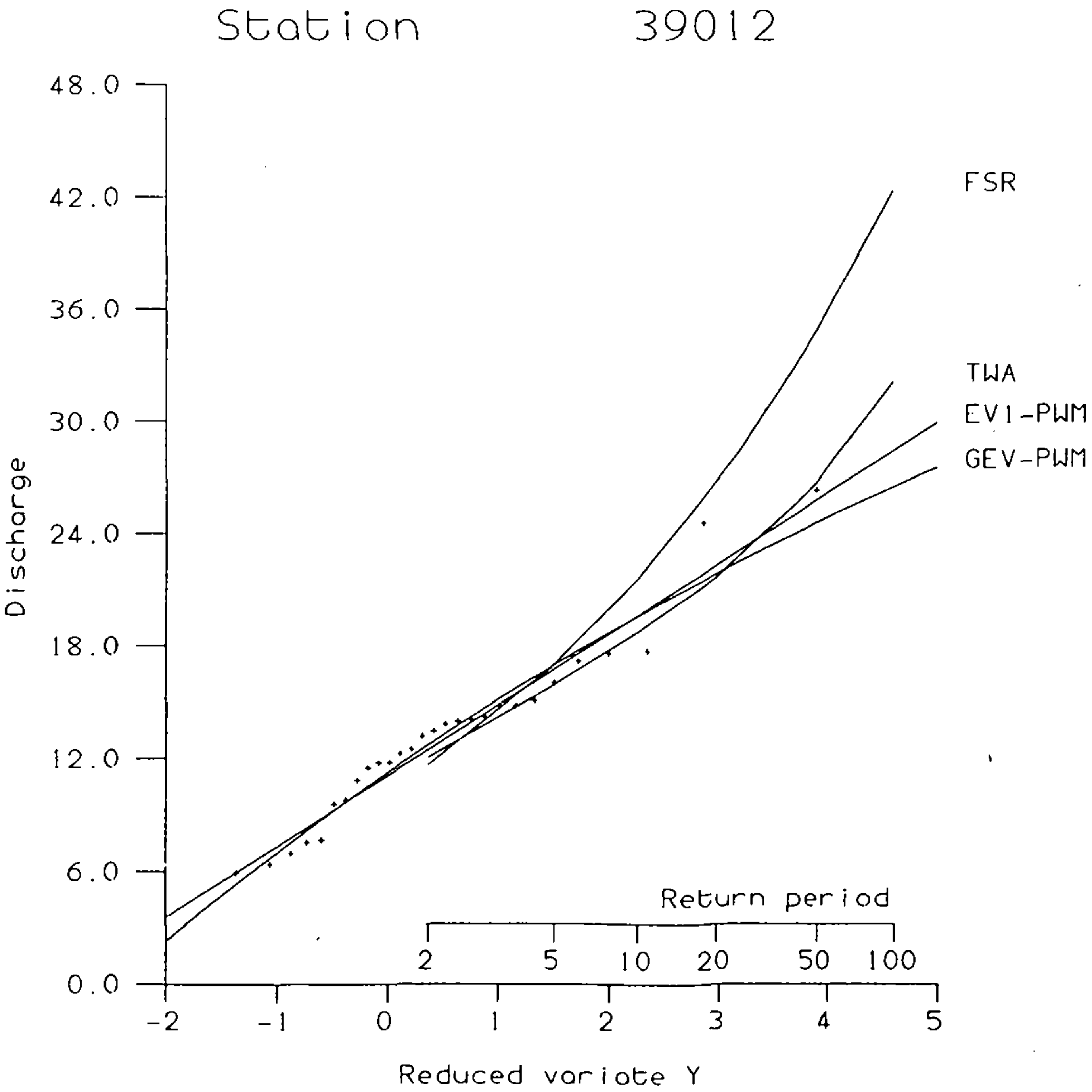


Figure 3o *Flood frequency curves based on annual maxima for River Thames at Teddington*

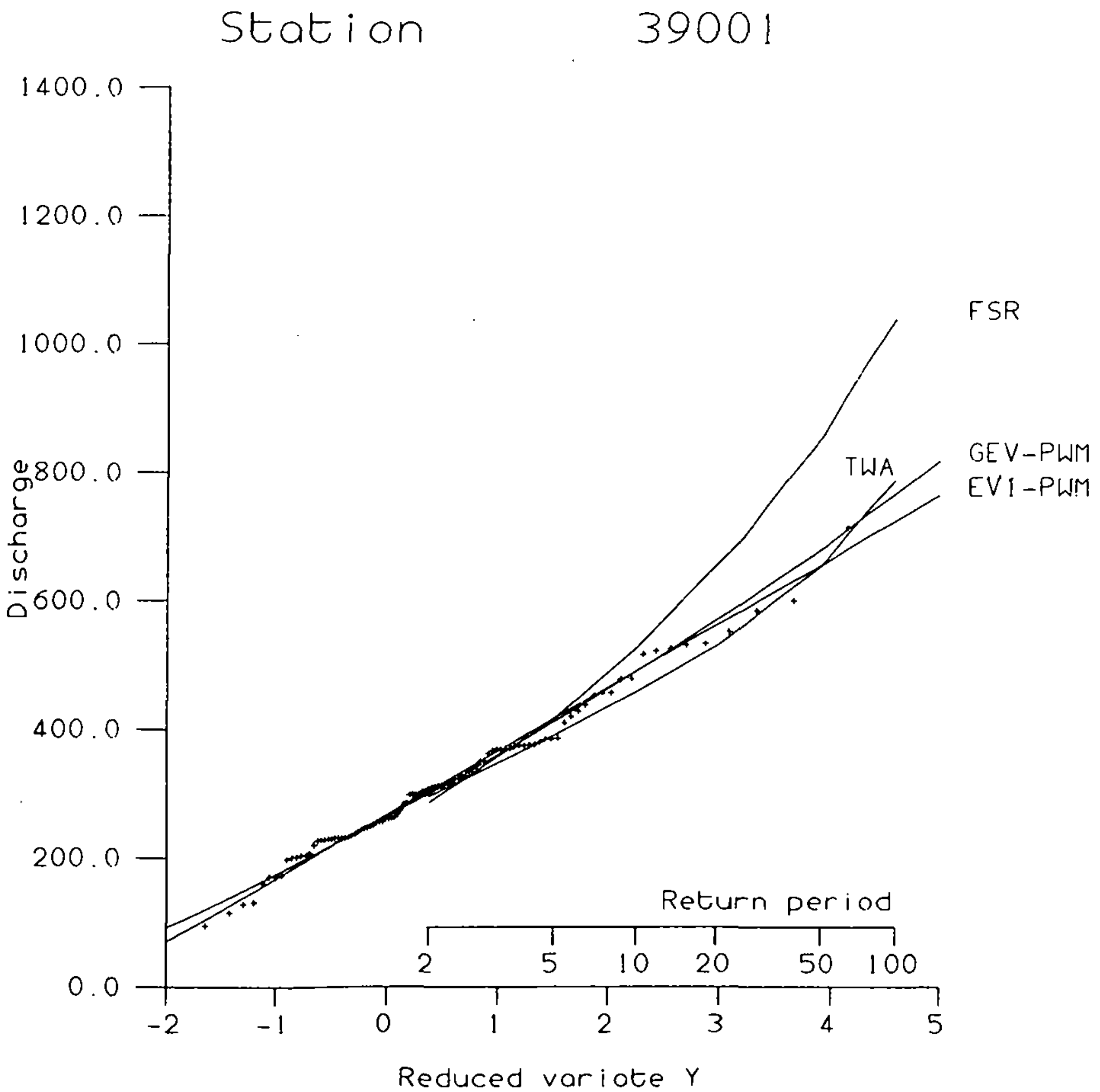


Figure 3p *Level frequency curves based on annual maxima for Cookham weir*

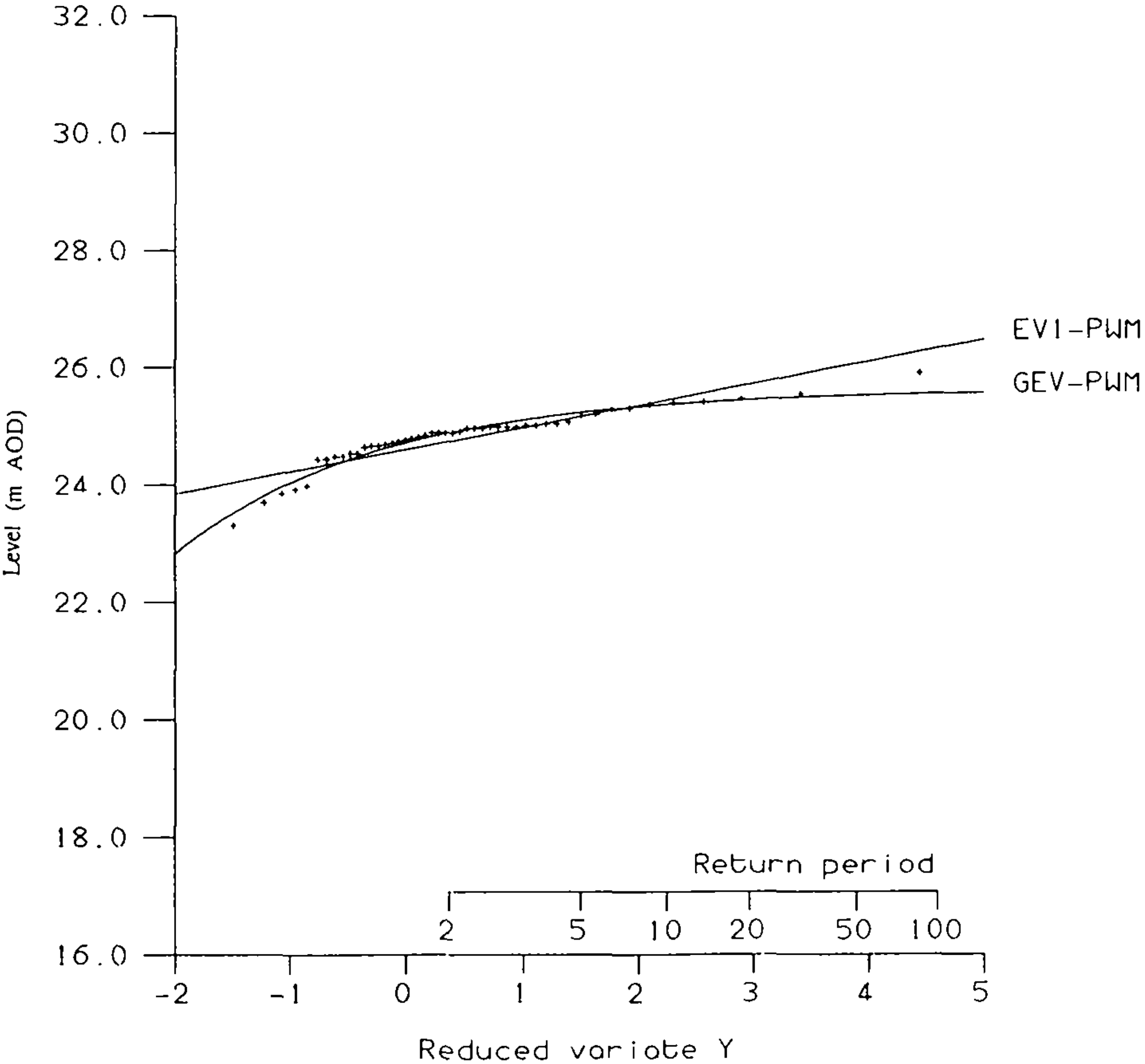


Figure 3q *Level frequency curves based on annual maxima for Bray weir*

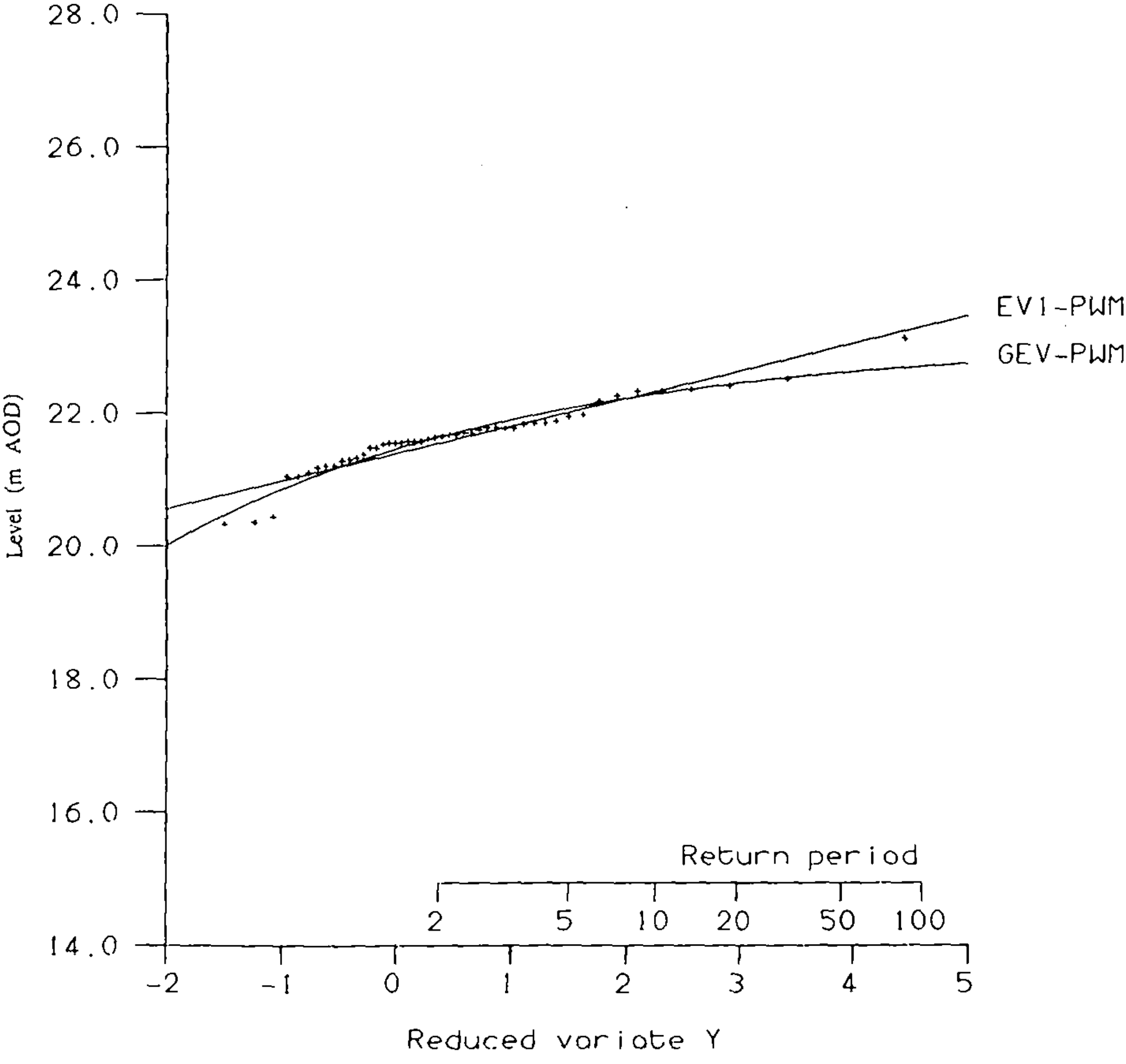


Figure 3r *Level frequency curves based on annual maxima for Bell weir*

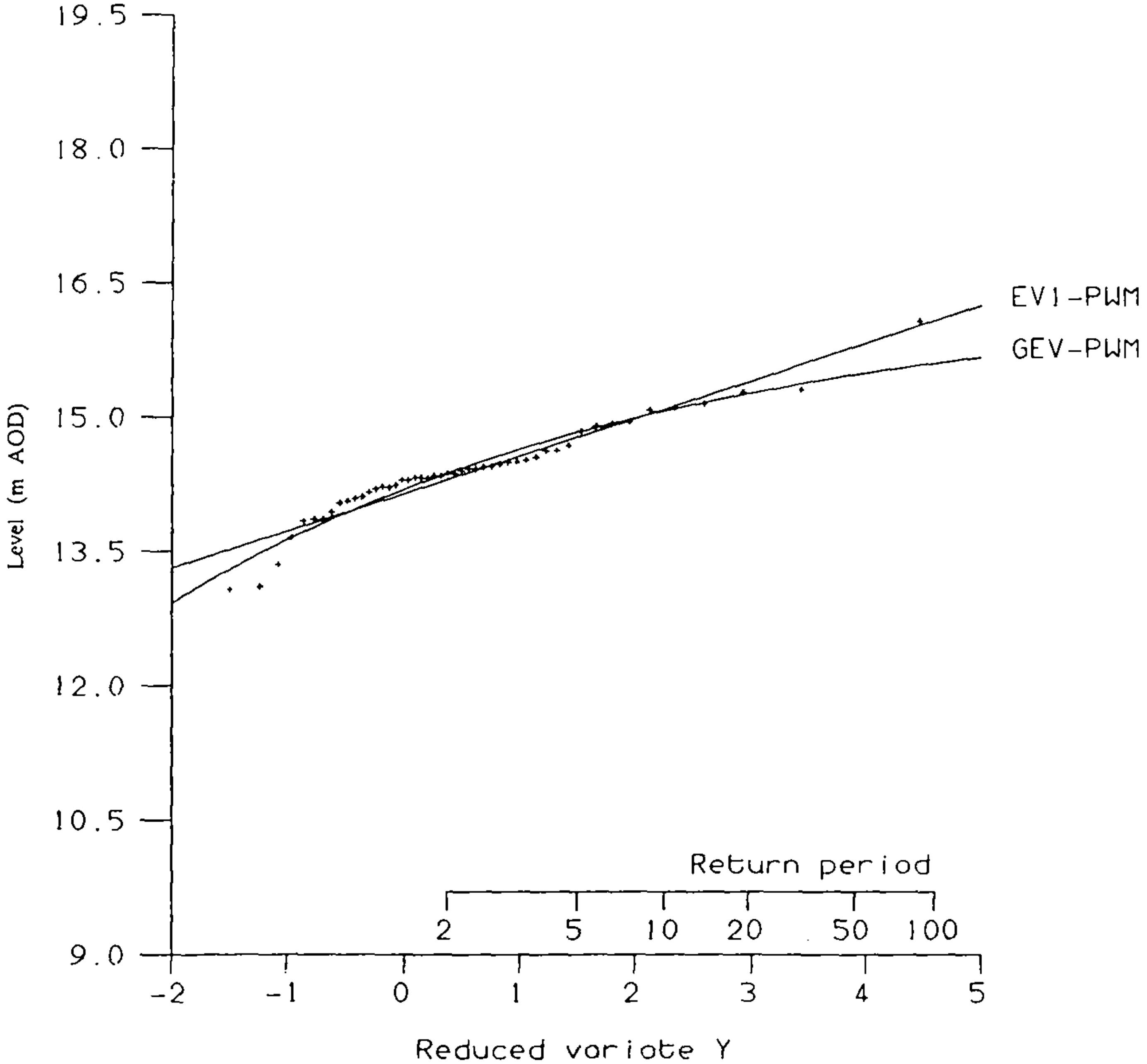


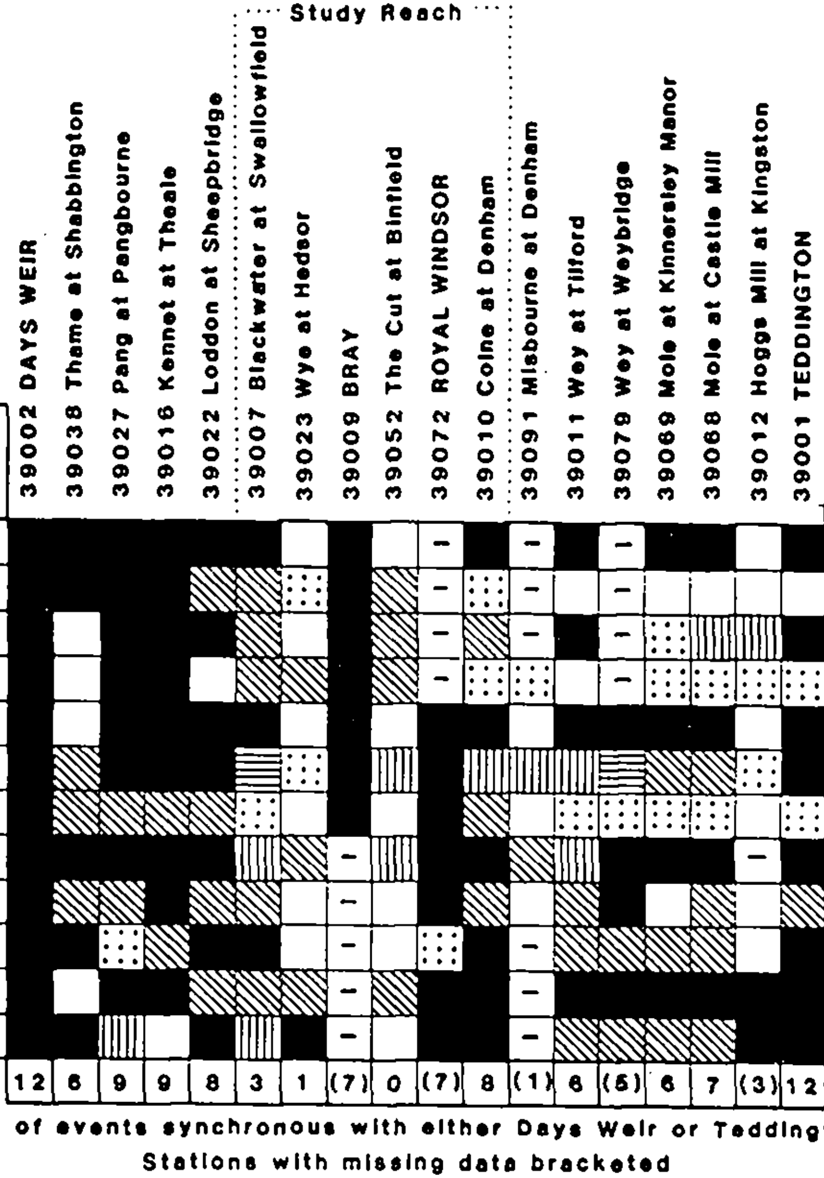
Figure 4 *Synchroneity of annual maxima on the River Thames and its tributaries between Days Weir and Teddington*

KEY

Same shading...... Flows occurred during same event

Unshaded............ Event unique to gauging station

— ....No flow data available



Water Year	Flow at Days Weir m^3s^{-1}	Flow at Teddington m^3s^{-1}	No. of stations synchronous with Days	Teddington
1975	13.1	129.0	11	11
1976	160.0	309.0	4	0
1977	127.0	310.3	6	6
1978	156.0	304.0	3	5
1979	174.0	419.5	12	12
1980	155.0	261.5	6	6
1981	160.0	303.0	2	5
1982	119.0	327.7	10	10
1983	122.0	268.5	3	7
1984	134.0	248.0	5	5
1985	158.0	395.0	10	10
1986	126.0	288.0	7	7

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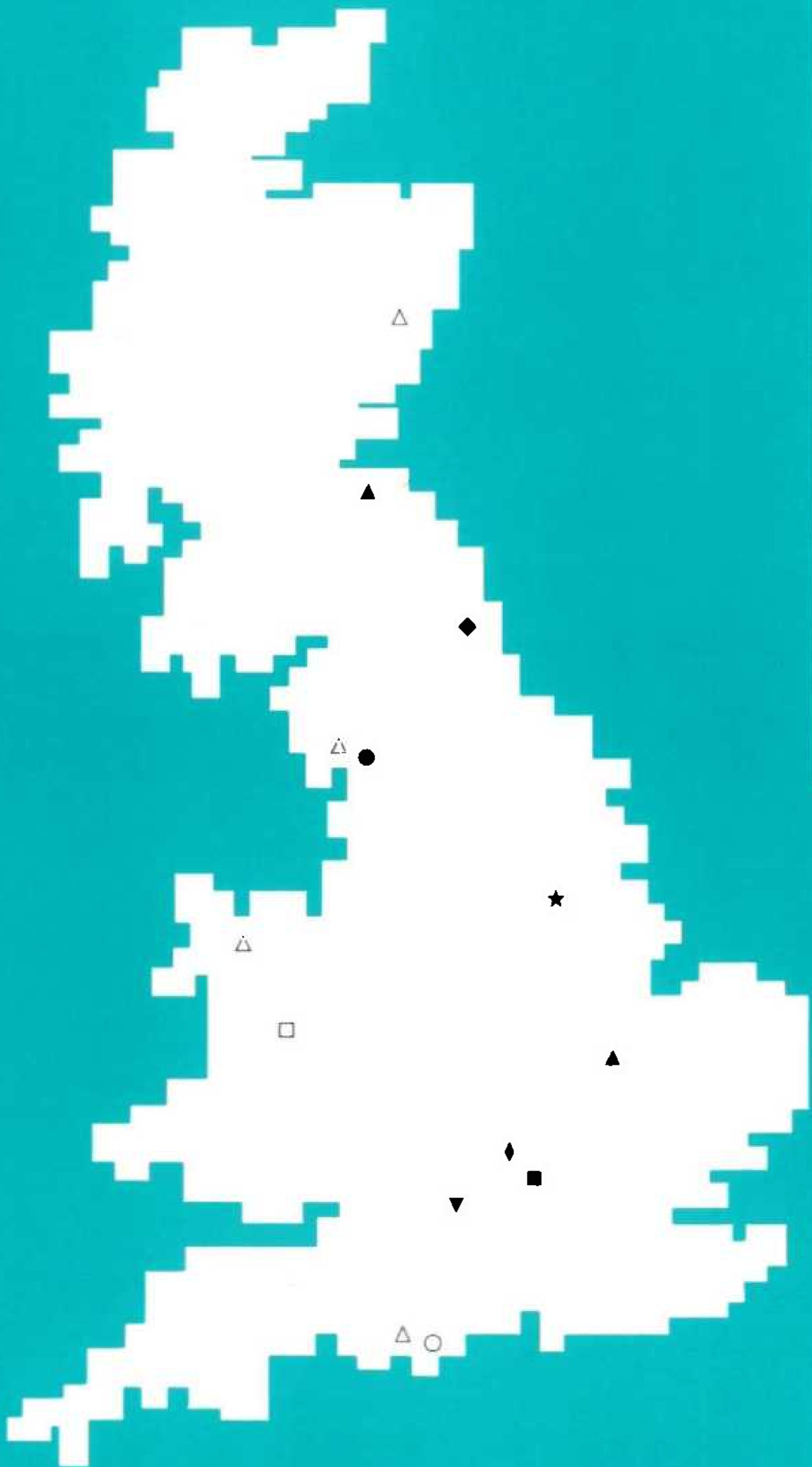

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