CWRR

CENTRE FOR
WATER RESOURCES
RESEARCH

An investigation of the Flood Studies Report ungauged catchment method for Mid-Eastern Ireland and Dublin

Michael Bruen

with the assistance of

Fasil Gebre

University College Dublin

DEPARTMENT OF CIVIL ENGINEERING

An investigation of the Flood Studies Report ungauged catchment method for Mid-Eastern Ireland and Dublin

Dr. Michael Bruen

With the assistance of Mr. Fasil Gebre

(July, 2005)

1 INTRODUCTION.

This study was commissioned by Dublin City Council. The brief is to investigate the suitability for the Dublin region of the Flood Studies Report (FSR) method for estimating design flows using catchment characteristics, i.e. based on estimates of the mean of the annual maximum series (QBAR).

2 METHODOLOGY

The Flood Studies Report (NERC, 1974) (FSR) methods for ungauged catchments and subsequent modifications are described in Appendix A. In applying the Flood Studies Report's "QBAR" method to a particular catchment, first an estimate of QBAR is calculated using an empirical formula based on catchment characteristics, (Eq. A-1). Then, the FSR calculates the flood discharge for any return period using a table of coefficients ("growth factors"). This is equivalent to specifying an empirical frequency distribution.

Using recorded Annual Maxima Series for specific gauge sites in the study region, this investigation studied each of the above steps separately, i.e.

(i) **Growth Factors:** The appropriateness of the FSR growth factors for Ireland was studied by fitting the EV1 distribution to the recorded data and comparing estimates of flows of various return periods with those given by the FSR method.

(a) QBAR is estimated directly from the Annual Maximum series.
(b) Plotting the data using Gringorten plotting positions.
(c) Fitting the EV1 distribution to the data using the Maximum Likelihood Method, as used in the FSR (vol. 1, p.145).
(d) Applying the FSR growth factors to the calculated mean of the annual maximum series data.
(e) Comparing the results of all the above to indicate whether the FSR growth factors are supported by the data.

In this analysis, the growth factors are multiplied by a QBAR determined from the data. Thus the influence of any errors in the catchment characteristics regression equation for QBAR is removed from this part of the analysis.

(ii) **Regression Equation:** The regression equation for "QBAR" was studied with specific focus on the Mid-Eastern/Dublin side of Ireland. This is done by estimating the appropriate catchment characteristics for each of the study catchments and using the values to estimate the mean of the AM series. This estimate is then compared with the mean value calculated from the data, viz. section 6.

3 DATA

Annual maximum series data were sought from stations which have a long record and, ideally for which a reliable high flow rating curve exists. At least 20 years of record for each station would be ideal, but to reject all stations with shorter records would have restricted the number of stations used in the analysis. The shortest record used was 13 years and the longest 62 years. From the register of gauges in Ireland, maintained by the EPA, a list of potentially suitable stations was compiled and the data was acquired free of charge from the OPW and EPA. Table 1 lists the Stations considered and the number of years of record available at each. The National Grid coordinates of these stations are given in Appendix B.

Table 1 : Stations considered

Station Id no.	Station Name	River name	Area km^2	years record	Comments
06012	Clarebane	Fane	167	45	
06013	Charleville Weir	Dee	307	27	V-weir since 7/75
06014	Tallanstown Weir	Glyde	270	26	V-weir since 10/75
06021	Mansfield town	Glyde	321	47	
06025	Burley	Dee	176	27	
07002	Killyon	Deel	285	22	Post CDS 4/79
07005	Trim	Boyne	1282	25	Post CDS 8/75
07006	Fyanstown	Moynalty	179	15	Post CDS 10/83
07009	Navan Weir	Boyne	1610	26	Post CDS & V-wier10/76
07010	Liscartan	Blackwater(Kells)	717	15	Post CDS ’82 – ‘86
07012	Slane Castle	Boyne	2408	62	CDS effect to ‘79
07023	Athboy	Athboy	98	4	Not used
08004	Owen’s bridge	Ward	40.2	4	Not used
08007	Ashbourne	Broadmeadow	1734	17	
08008	Broadmeadow	Broadmeadow	110	22	
08009	Balheary	Ward	62	10	Not used
08011	Duleek d/s	Nanny	181	22	
08012	Ballyboghil	Stream	22.1	13	
09001	Leixlip	Ryewater	215	45	V-weir 8/80
09002	Lucan	Griffeen	41.2	25	
09009	Willbrook Road	Owendoher	22.4	20	
09010	Waldron’s Bridge	Dodder	95.2	13	
09011	Frankfort	Slang	6.5	15	
09019	Drumcondra	Tolka	141.3	5	Not used
09037	Botanic Gardens	Tolka	137.8	5	Not used
10021	Common’s Road	Shanganagh	30.9	24	
10022	Carrickmines	Cabinteely	10.4	18	
11001	Boleany	Owenavarragh	148	29	v-weir 5/72

Note: CDS denotes Catchment Drainage Scheme.

A total of 600 years of Annual Maxima were used from 22 stations with an average of 26 years per station. From these records, data from before significant arterial drainage works in the catchment were discarded. Within the Dublin area it is virtually impossible to find a catchment in which significant development has not taken place.

4 ANALYSIS

4.1 Growth Factors

Estimates of flows of various return periods (derived from the Annual Maxima series at each station) were compared with estimates derived by the FSR methodology. Visual comparisons are shown in Figures 1 to 18 which show the annual maximum data, plotted according to the Gringorten plotting position, the FSR flow frequency curve (dotted red), and the EV1 (Gumbel) frequency curve fitted to the data by the maximum likelihood method. In Figures 2, 4, 5, 6, 7, 13 and 16 the plotted data points show a break in slope and where this occurs an additional curve is shown which is fitted to the larger annual maxima (dashed blue). In drawing this additional curve for Figure 6 the most extreme flood does not seem to fit the general trend of the data and is treated as an outlier and ignored in drawing this line. However this flood is included in the maximum likelihood fitting of the EV1 distribution, but has only a small influence.

In Figures 14 (Lucan) and 18 (Boleany) the largest floods also plotted above the general trend. There are two possible explanations. First, if a very extreme flood with a high return period occurs in a short record, all the plotting position formulae will underestimate its return period and it will plot above its “correct” position. Secondly, such floods generally exceed the limits of validity of the station rating equations and where this extrapolation leads to an overestimate of the discharge then it too would plot above the line. Typical situations include (a) where, downstream of the gauging station there is a bridge or culvert which takes over as hydraulic control at high flows. This forces higher water levels then would otherwise occur for a given high flow. If this high flow behaviour is not captured in the gauge rating relationship, this could lead to overestimates of the high flows, and (b) if there is a floodplain into which the channel overflows at high flows, and if this is not captured in the rating equation, an underestimate of high flows may occur. Therefore, it would be useful if these rating equations were extended /validated for higher flows.

Table 2 summarises the comparisons. The last column in this Table gives the ratio of the 100 year flood estimated from the fitted EV1 distribution to QBAR estimated from the AM data. A value of 1.96 would be expected if the FSR growth curve applied. Provisionally, they can be categorised into three separate groups:

(1) Where the FSR growth curve overestimates the higher return period flows compared with the data. The two stations in this category are Burley, Liscarton

(2) Where the EV1 and growth curve give comparable results, e.g. the Fane, Dee and Glyde etc.

(3) The remaining stations, where the FSR growth curve underestimates the higher return period flows, compared to the AM data, e.g. Boyne, Broadmeadow, Ryewater and all rivers close to Dublin (Figures 8 through 18)

The FSR underestimation for the Boyne stations may be due to improved channel conveyance and thus increased flood discharge peaks following arterial drainage works from 1970 to 1976. There is a pattern of the FSR growth curve fitting well or, in some cases, overestimating for rural catchments and underestimating for catchments closer to Dublin. This may, at least in part, be due to (i) the higher slopes in catchments near Dublin and/or (ii) urbanisation that has occurred in these catchments since the time of the Flood Studies report.

Table 2 Summary of comparisons

Station Id no.	Station name	River name	Area km^2	Result	Q_{100}/ QBAR
06025	Burley	Dee	176	FSR > EV1	1.62
07010	Liscartan	Blackwater(Kells)	717	FSR > EV1	1.48
06012	Clarebane	Fane	167	Comparable	1.96
06013	Charleville Weir	Dee	307	Comparable	1.93
06014	Tallanstown Weir	Glyde	270	Comparable	2.07
06021	Mansfield town	Glyde	321	Comparable	1.82
07005	Trim	Boyne	1282	Comparable	1.94
07006	Fyanstown	Moynalty	179	Comparable	1.82
11001	Boleany	Owenavarragh	148	Comparable	1.96
07002	Killyon	Deel	285	FSR < EV1	2.09
08011	Duleek d/s	Nanny	181	FSR < EV1	2.08
10021	Common's Road	Shanganagh	30.9	FSR < EV1	2.19
07009	Navan Weir	Boyne	1610	FSR < EV1	2.25
07012	Slane Castle	Boyne	2408	FSR < EV1	2.33
08007	Ashbourne	Broadmeadow	1734	FSR < EV1	2.55
08008	Broadmeadow	Broadmeadow	110	FSR < EV1	2.59
08012	Ballyboghil	Stream	22.1	FSR < EV1	2.94
09001	Leixlip	Ryewater	215	FSR < EV1	2.34
09002	Lucan	Griffeen	41.2	FSR < EV1	2.95
09009	Willbrook Road	Owendoher	22.4	FSR < EV1	2.6
09010	Waldron's Bridge	Dodder	95.2	FSR < EV1	2.65
09011	Frankfort	Slang	6.5	FSR < EV1	2.63
10022	Carrickmines	Cabinteely	10.4	FSR < EV1	2.35

Differences between the FSR growth curve and EV1 flow estimates are to be expected, especially in cases involving relatively short AM series. However, in the majority of cases the FSR is lower than the EV1 and this suggests a pattern of the growth curve underestimating especially for catchments near Dublin. This is a concern.

Note that in Figures 13 and 14, where the fitted EV1 was itself not a good fit to the data, it still lay below the plotted data, i.e. underestimating the data. However, the FSR growth curve was below that again.

Figure 1 Comparison of flow return period estimation methods for Fane at Clarebane (06012)

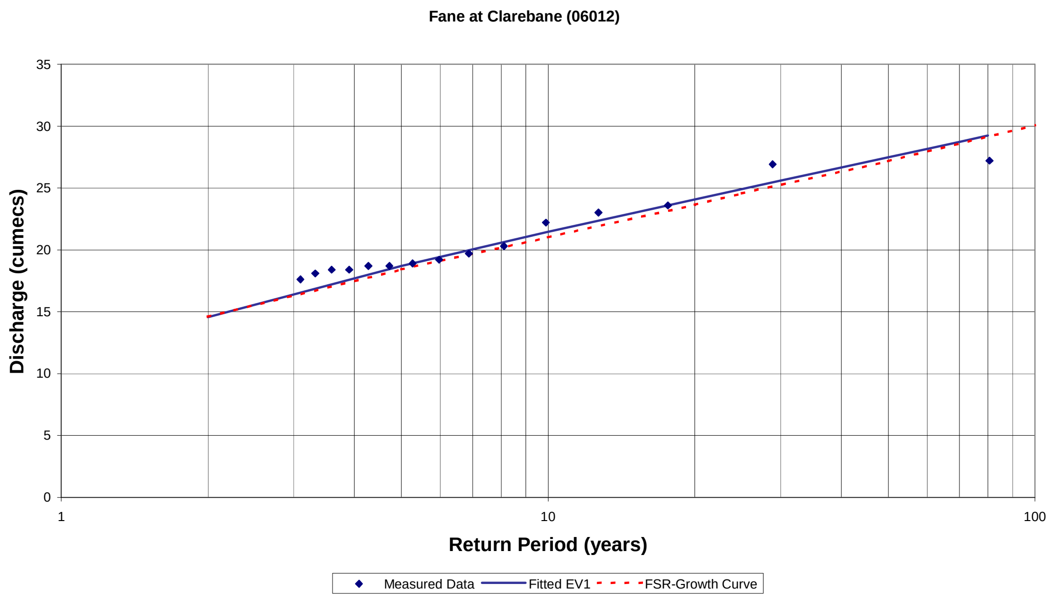


Figure 2 Comparison of flow return period estimation methods for Dee at Charleville Weir

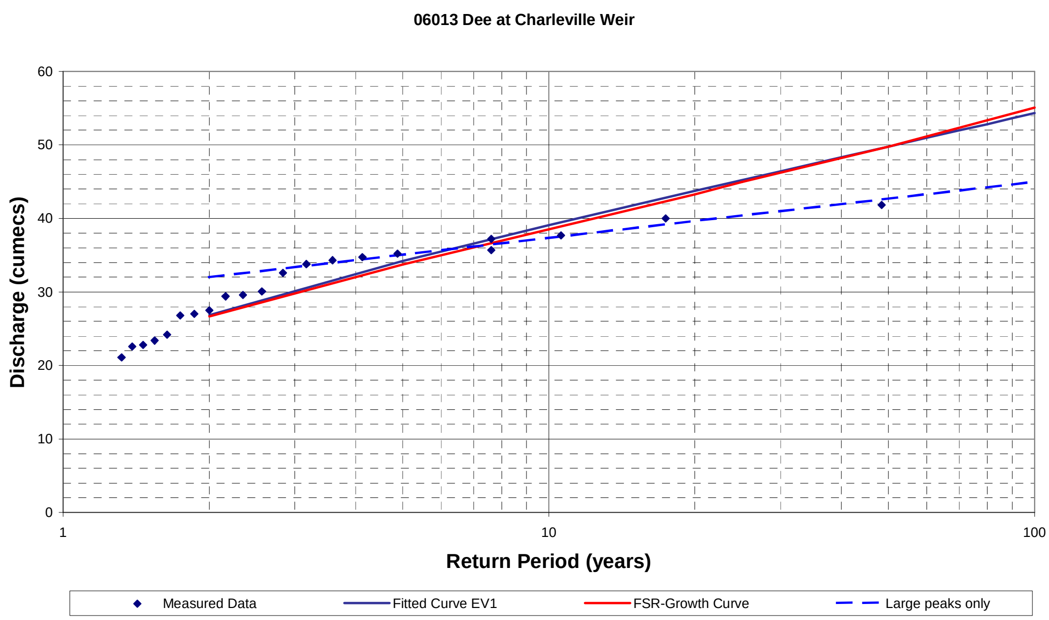


Figure 3 Comparison of flow return period estimation methods for Glyde at Tallanstown Weir

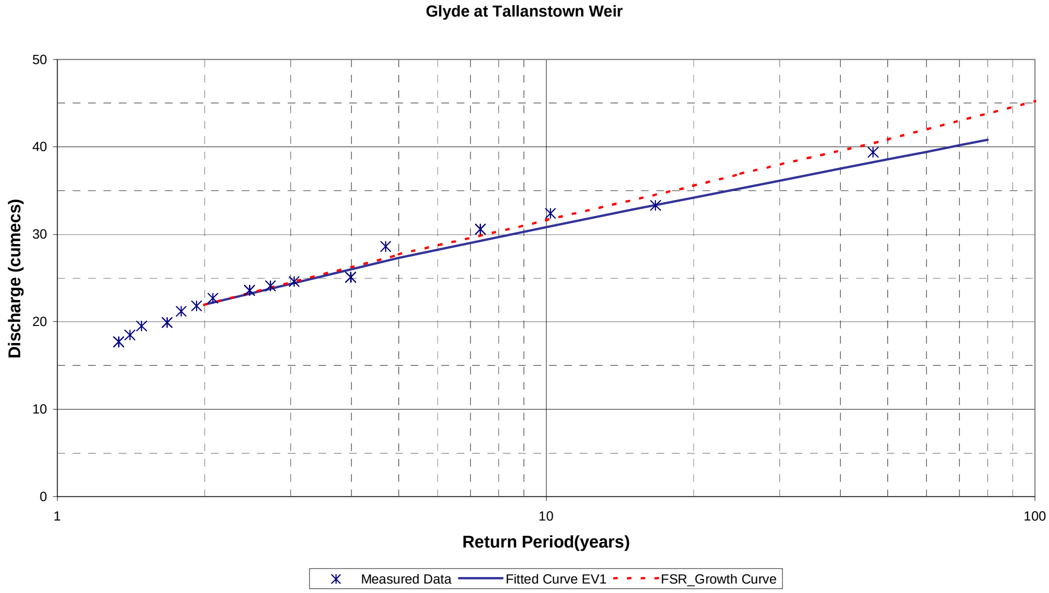


Figure 4 Comparison of flow return period estimation methods for Glyde at Mansfield Town

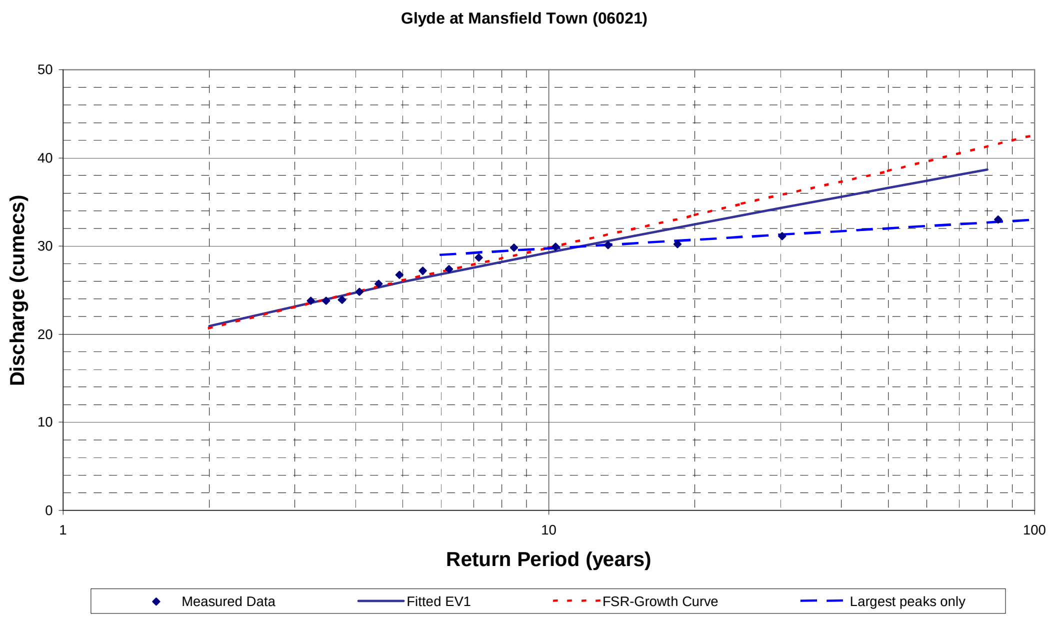


Figure 5 Comparison of flow return period estimation methods for Dee at Burley

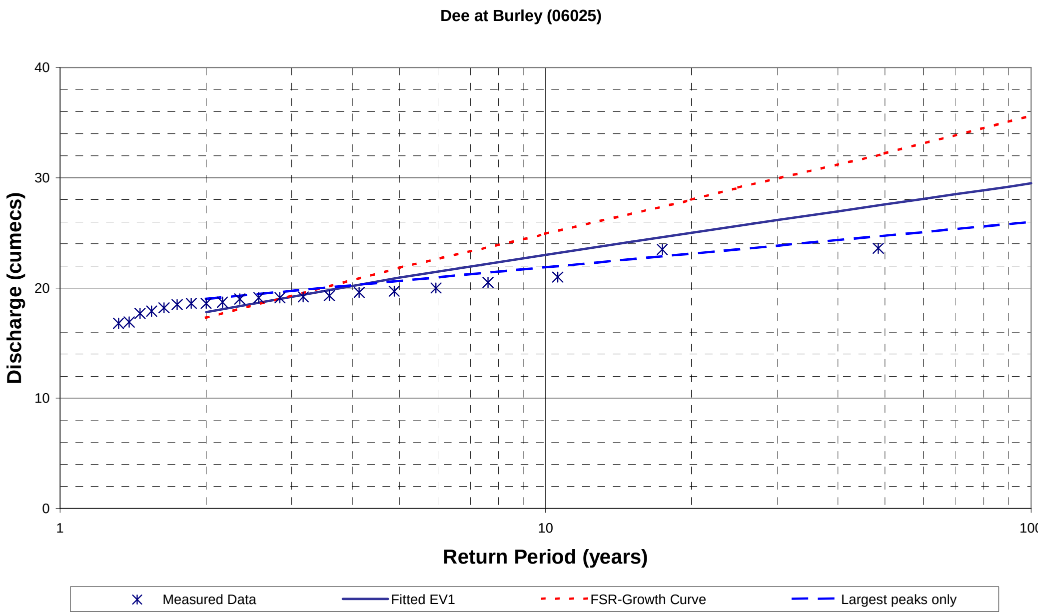


Figure 6 Comparison of flow return period estimation methods for Deel at Killyon

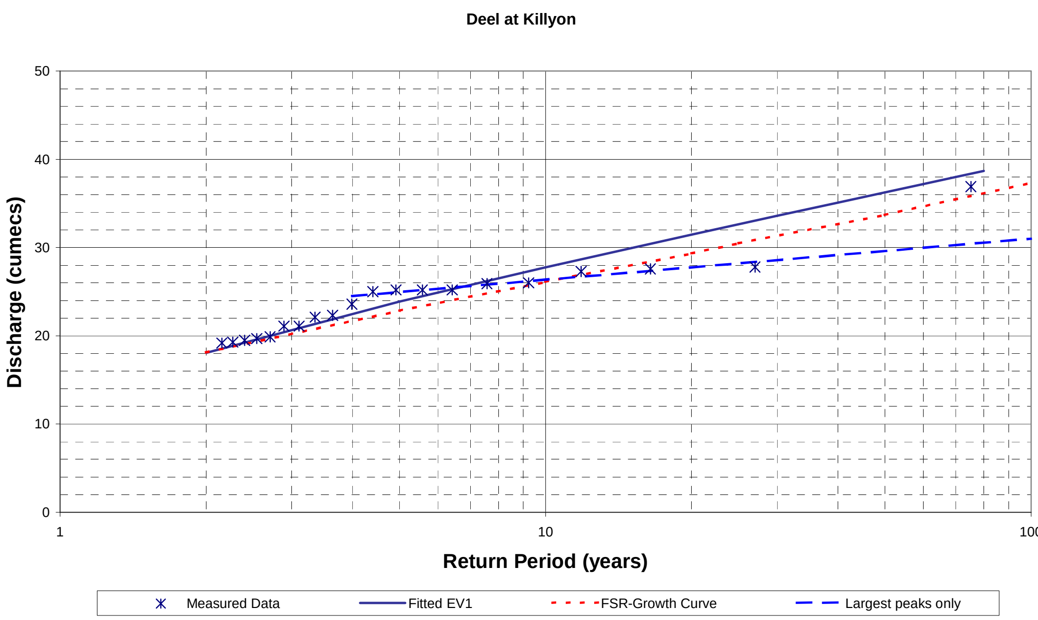


Figure 7 Comparison of flow return period estimation methods for Moynalty at Fyanstown

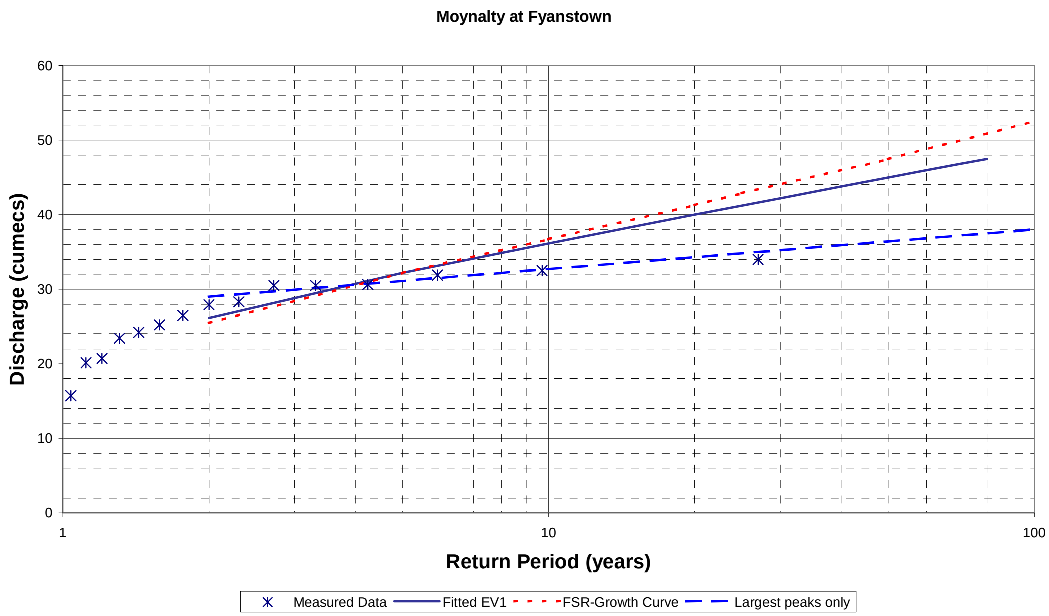


Figure 8 Comparison of flow return period estimation methods for Boyne at Navan Weir

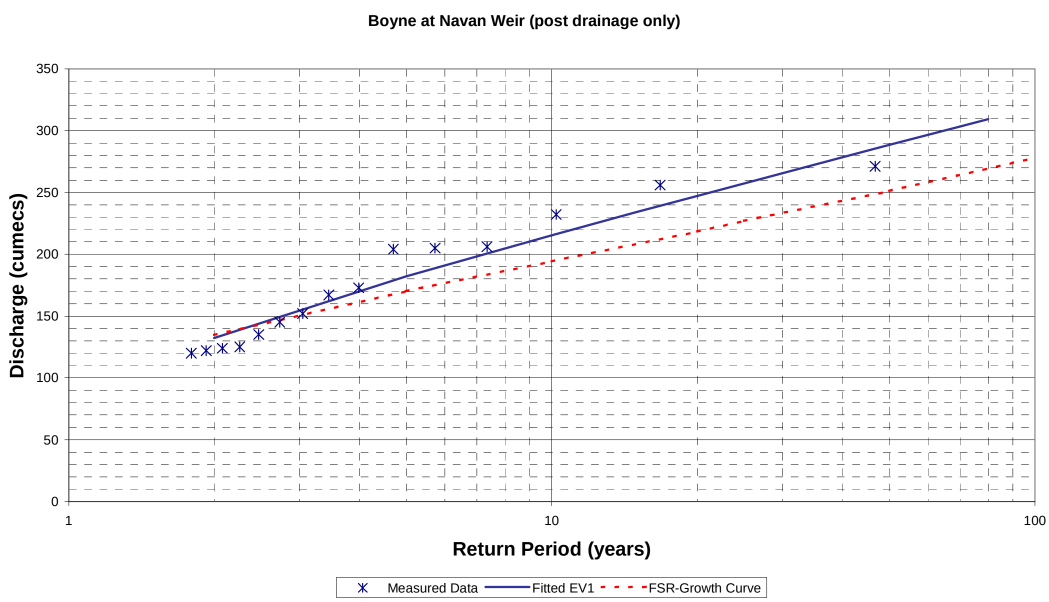


Figure 9 Comparison of flow return period estimation methods for Broadmeadow at Broadmeadow

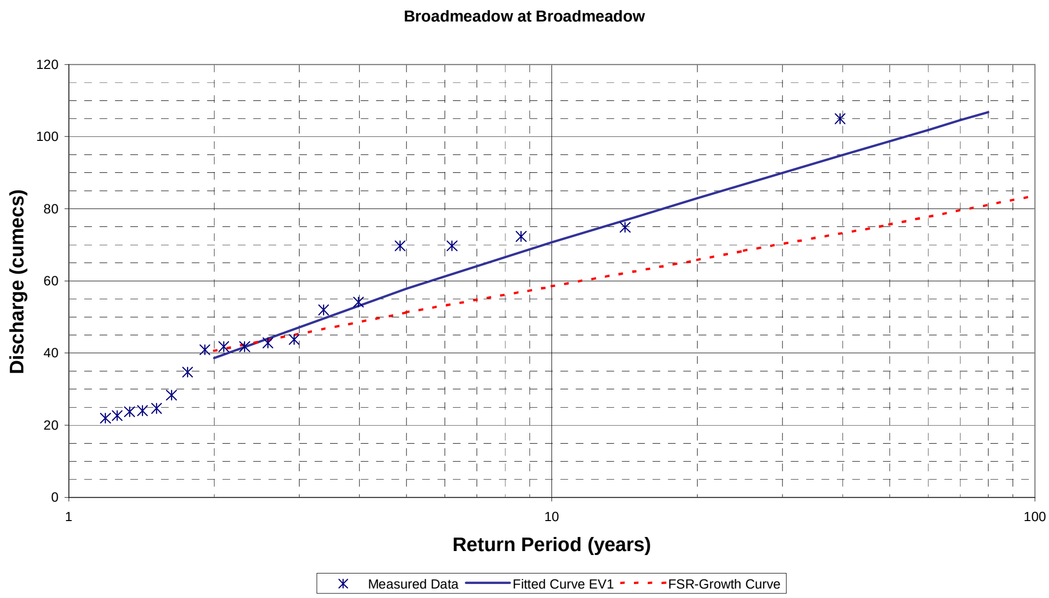


Figure 10 Comparison of flow return period estimation methods for Ryewater at Leixlip

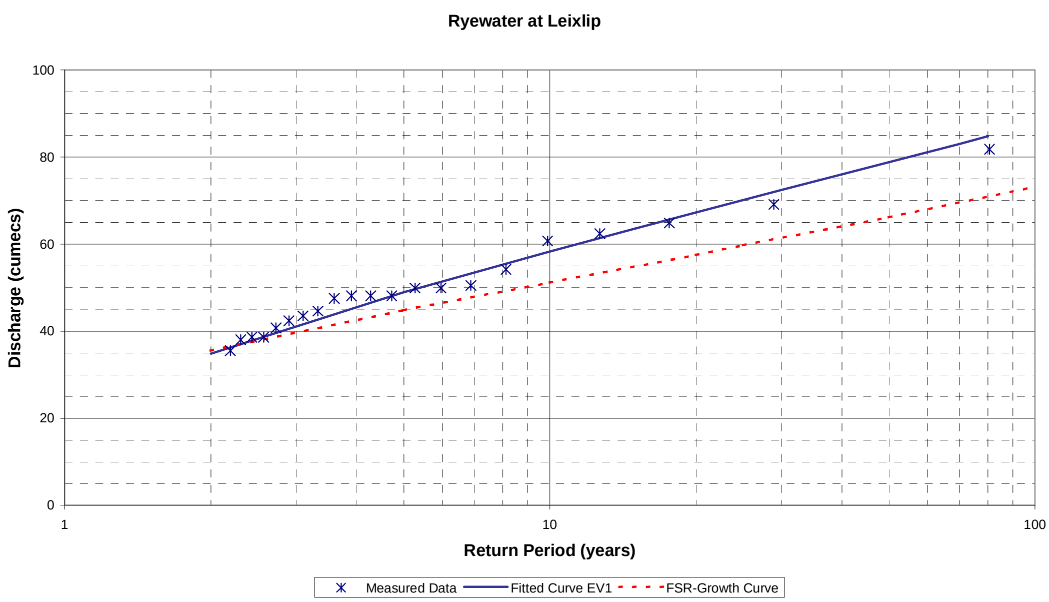


Figure 11 Comparison of flow return period estimation methods for Common's Road

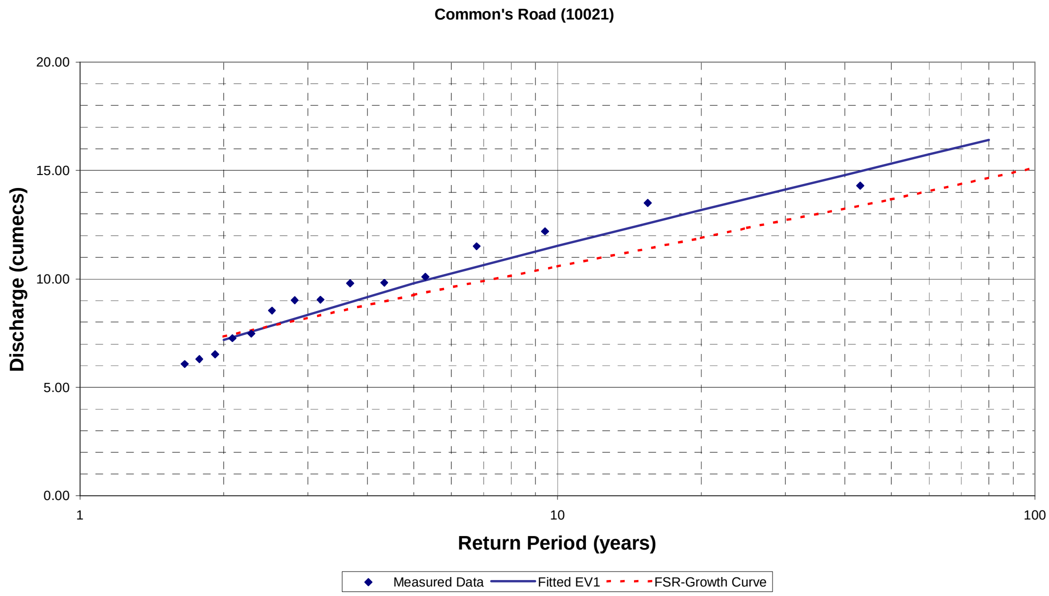


Figure 12 Comparison of flow return period estimation methods for Ashbourne

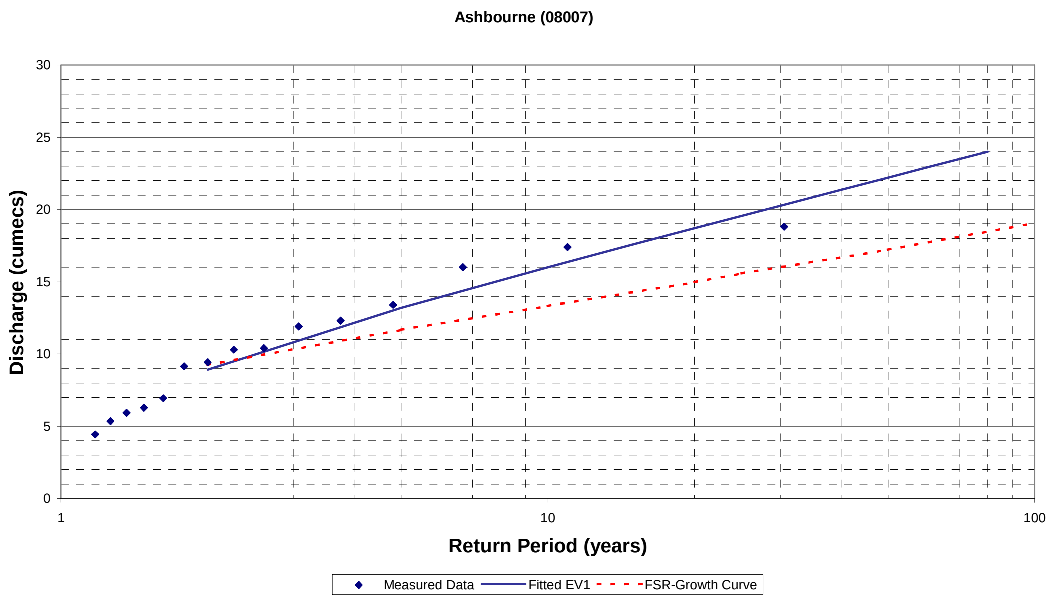


Figure 13 Comparison of flow return period estimation methods for Frankfort

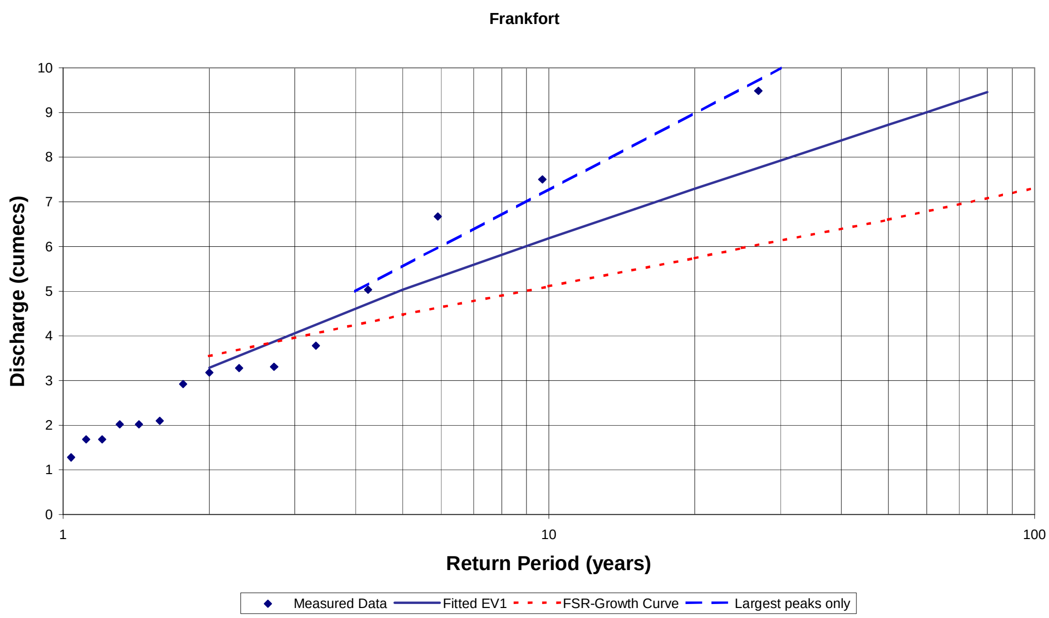


Figure 14 Comparison of flow return period estimation methods for Griffeen at Lucan

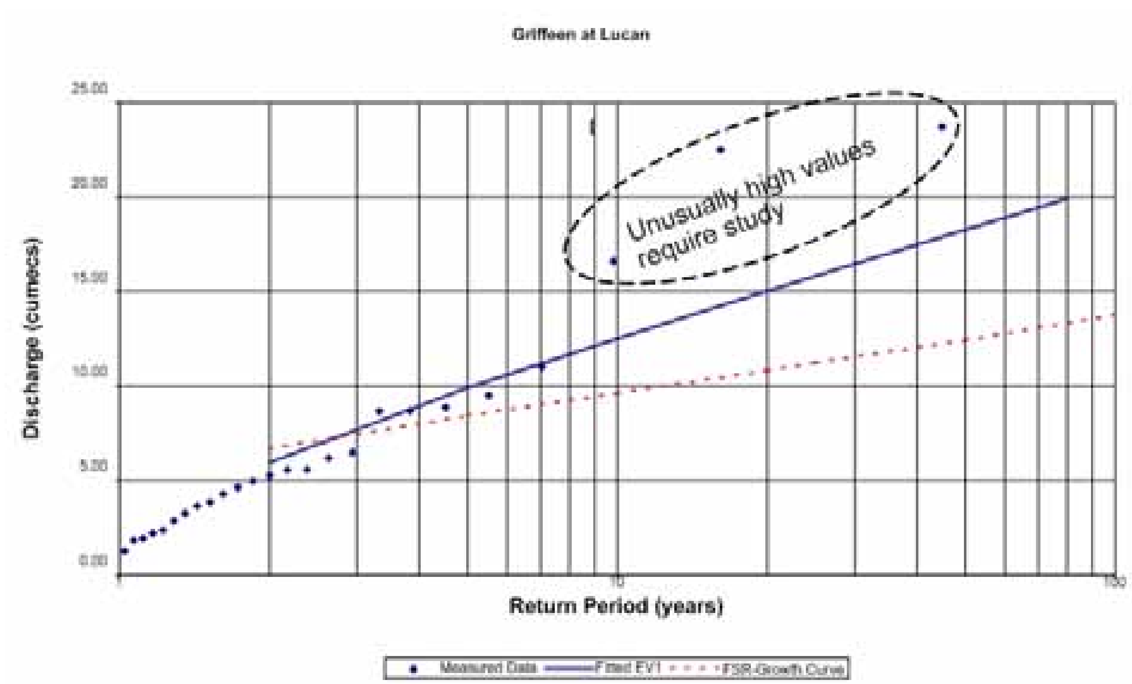


Figure 15 Comparison of flow return period estimation methods for Dodder at Waldron's Bridge

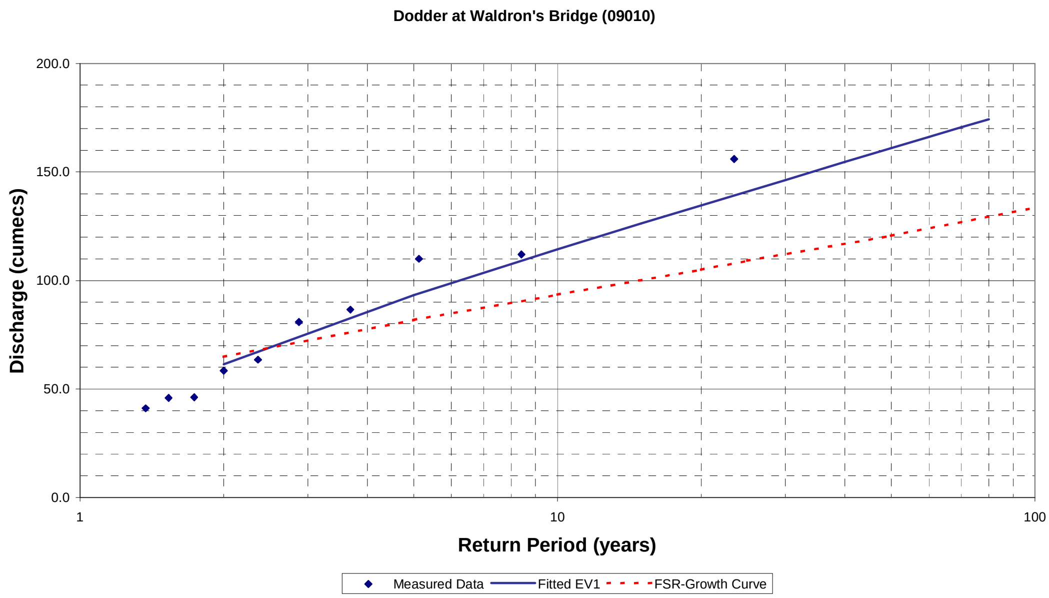


Figure 16 Comparison of flow return period estimation methods for Willbrook Road

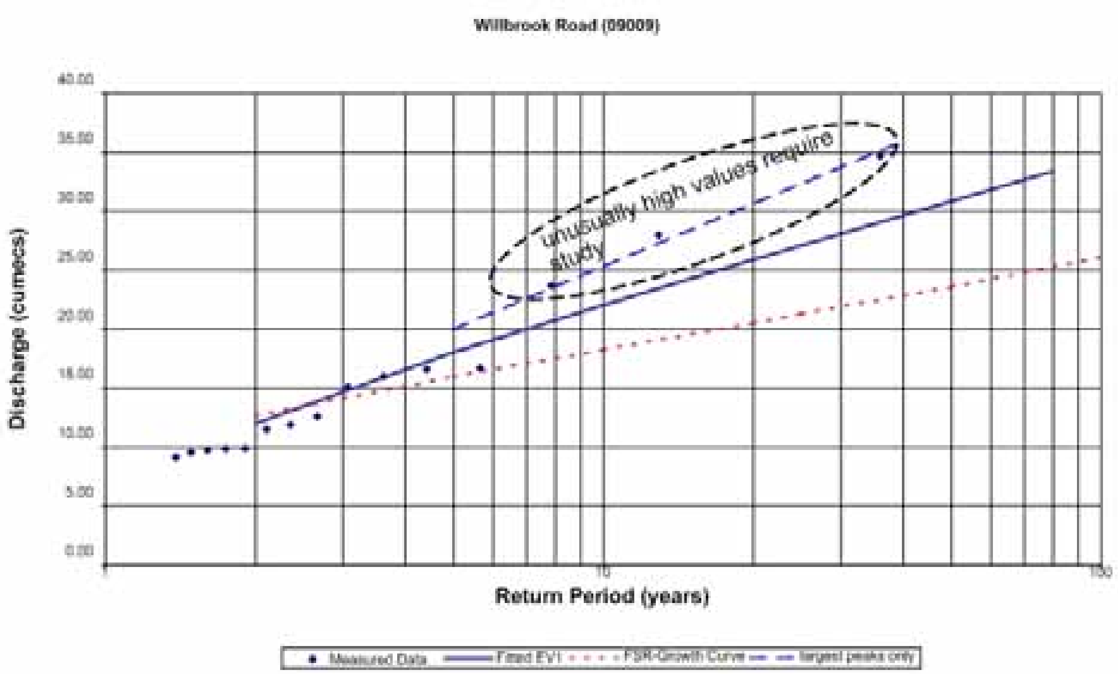


Figure 17 Comparison of flow return period estimation methods for Carrickmines

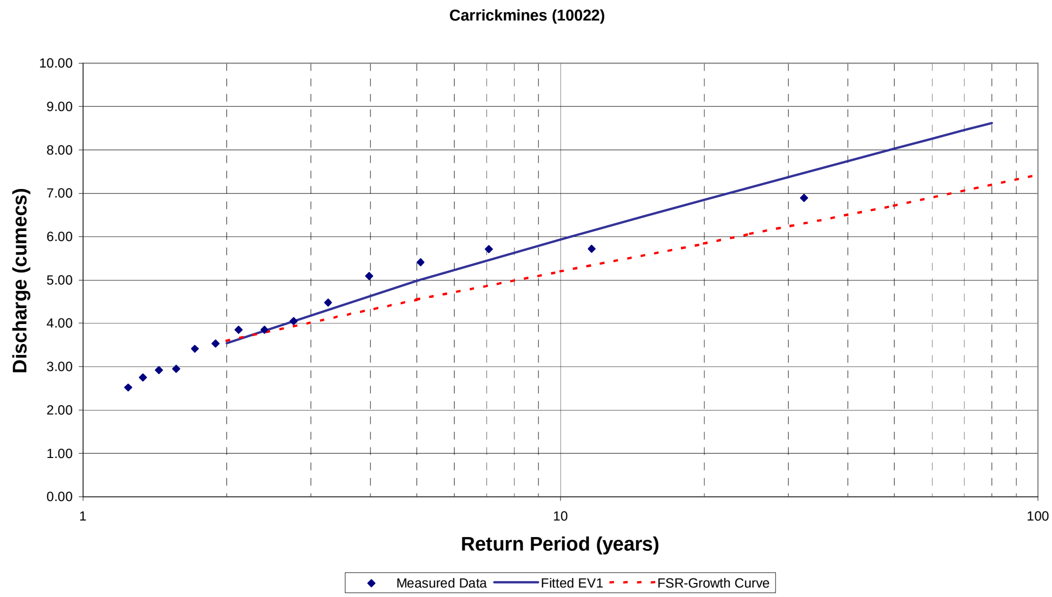
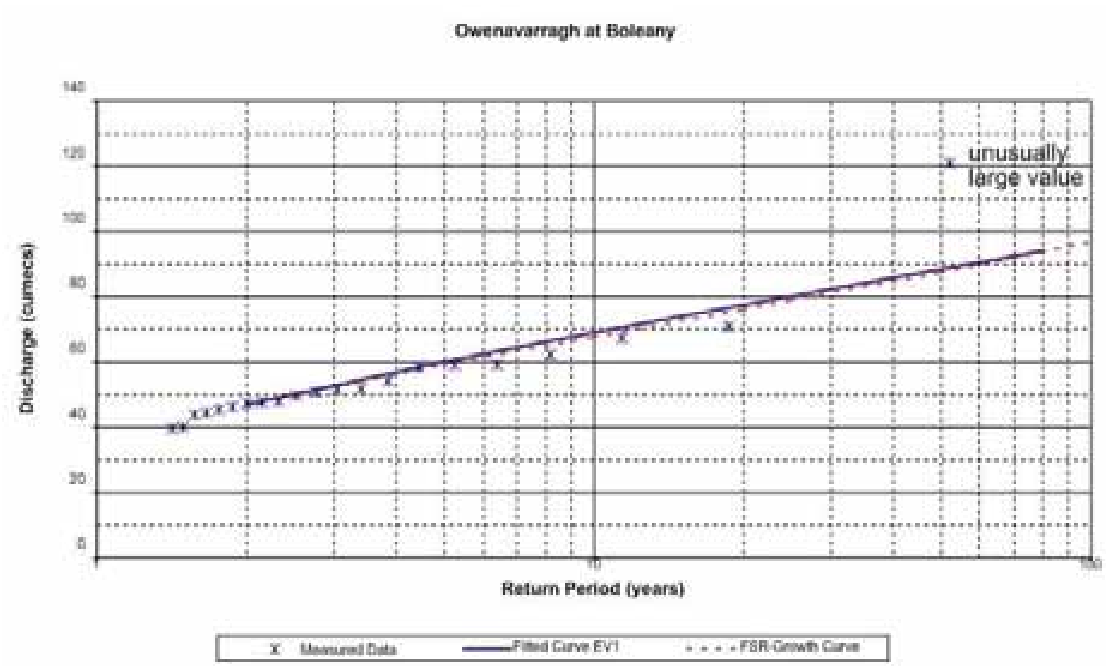


Figure 18 Comparison of flow return period estimation methods for Boleany



5 DUBLIN REGION ONLY

Eight stations within or near the Dublin area were selected for detailed analysis. These were Leixlip, Lucan, Commons, Frankfort, Broadmeadow, Carrickmines, Willbrook and Waldron's

Bridge. The character of the variability in this data can be seen in Figure 19, which shows Q_T/QBAR vs Return Period, T. For return periods less than 10 years the points are reasonably bunched indicating a common relationship. However, for return periods over 10 years the points are quite scattered, indicating a broader range of relationships. Note however that if the highest floods in Lucan were excluded from this analysis, the overall scatter would be considerably reduced.

The 8 curves obtained by fitting the EV1 distribution individually to the stations in the Dublin area, are shown in Figure 20. It is clear that (i) these all lie above the FSR curved (dotted red line) and (ii) although 4 of them do lie very close together, all 8 curves do not conform exactly to a single representative, EV1-based, growth curve. Nevertheless, a first estimate of a new growth curve for Dublin might start in the vicinity of the Frankfort, Broadmeadow, Willbrook and Waldron's Br. group of lines, as the others curves are scattered almost equally above and below this.

The two parameters of the EV1 distribution fitted to the AM data are shown in Table 3 and plotted in Figure 21, which shows a strong linear relationship.

Figure 19 Dimensionless AM data for some gauges around Dublin

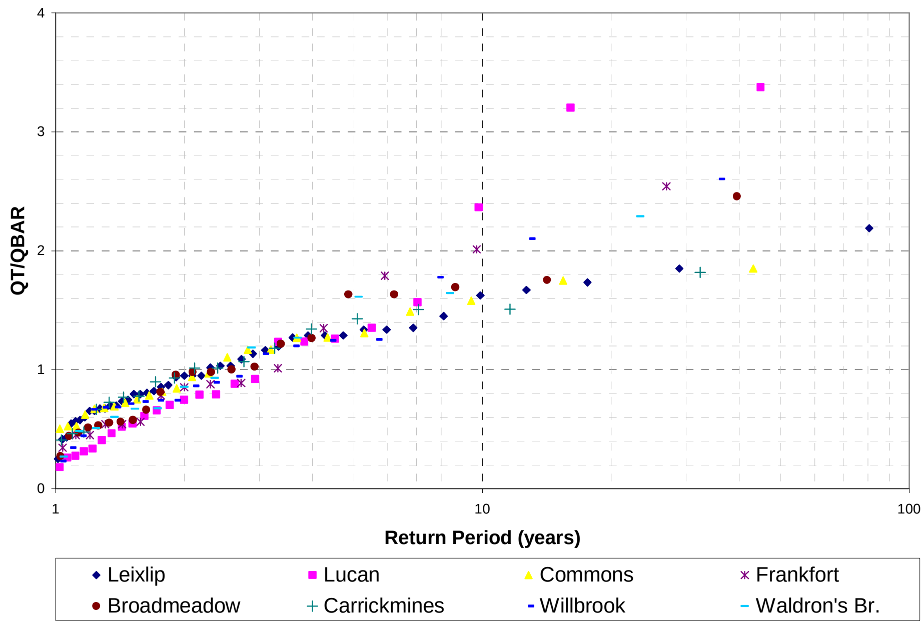


Figure 20 : Growth curves suggested by AM data for some gauges around Dublin

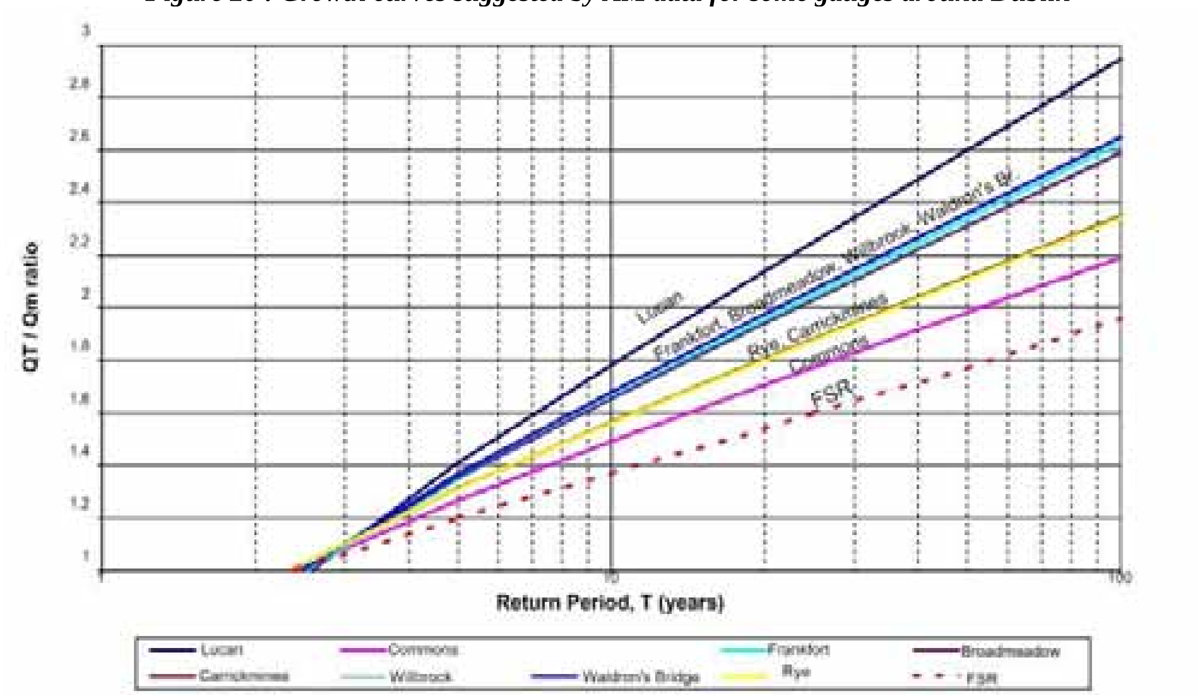
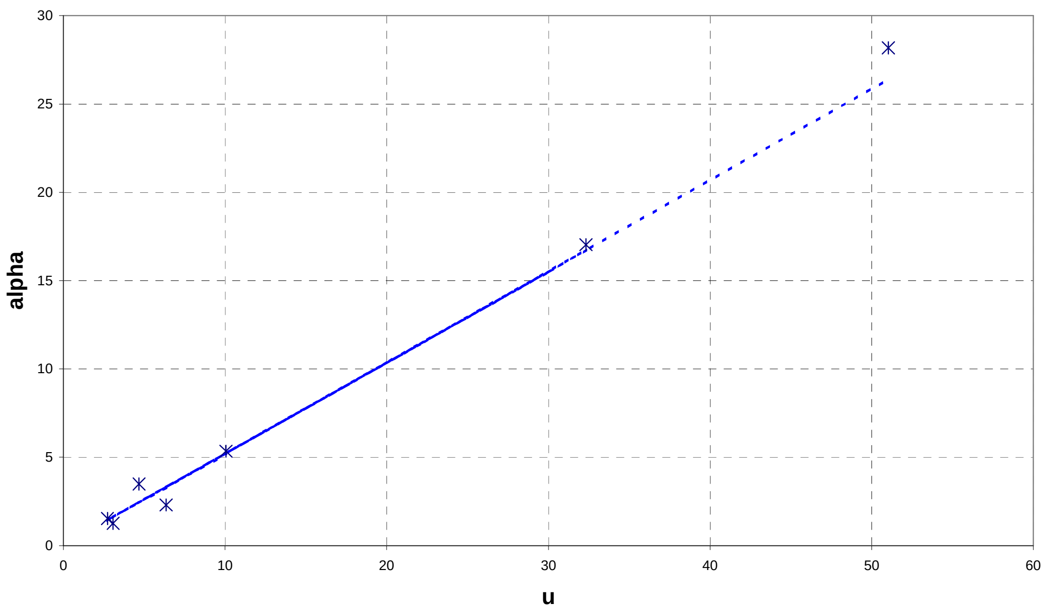


Table 3 Estimated parameters of the EV1 distribution for gauges around Dublin

Gauge	u	alpha
Lucan	4.68	3.48
Commons	6.34	2.30
Frankfort	2.72	1.54
Broadmeadow	32.32	17.03
Carrickmines	3.08	1.27
Willbrock	10.05	5.34
Waldron's bridge	51.02	28.18
Rye	30.30	12.44

Figure 21 Relationship between EV1 parameters for Dublin stations



The line in Figure 21 is dominated by three large catchment points. However, the same fitted line in Figure 22 is also a good fit to the lower cluster of points, Figure 22.

The EV1, (Gumbel) probability distribution can be written as

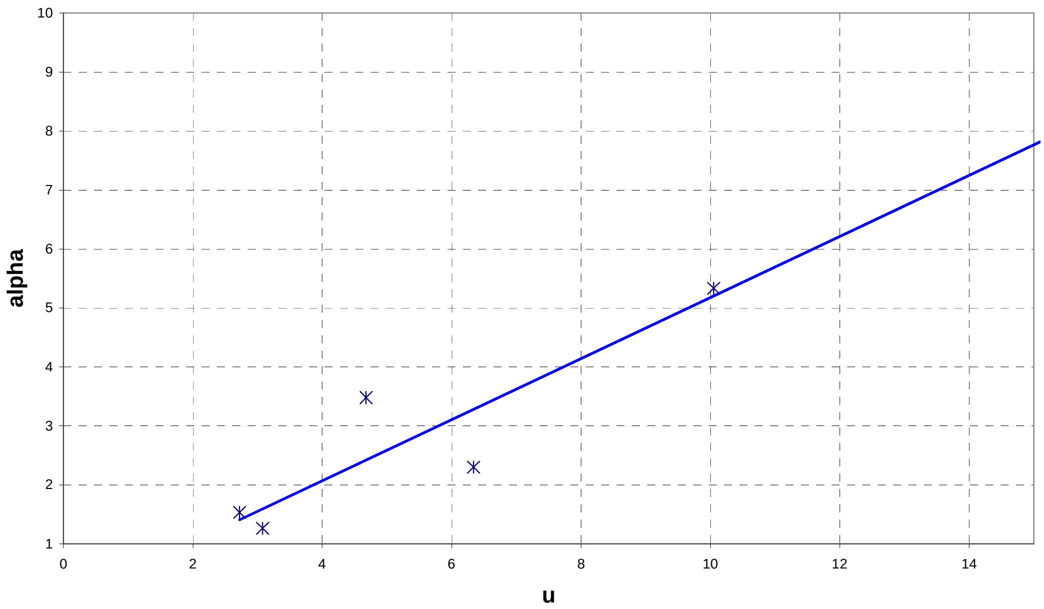
$$p(Q \leq q) = \exp\left(-\exp\left[-\frac{q-u}{\alpha}\right]\right) \qquad \text{(Eqn. 1)}$$

where, u is the location and α the scale parameter of the EV1 distribution.

A linear regression with the estimated u and α for the Dublin area (Table 3) suggests the relationship..

$$\alpha = 0.52\,u \qquad \text{(Eqn. 2)}$$

Figure 22 Relationship between EV1 parameters for Dublin stations, with larger catchments removed.



The moment equations for estimating the EV1 parameters from data moments are..

$$q_m = u + 0.5772\,\alpha \qquad \text{(Eqn. 3)}$$

Substituting equation 2 into equation 3 gives

$$u = 0.77\,q_m \qquad \text{(Eqn. 4)}$$

$$\alpha = 0.4\,q_m \qquad \text{(Eqn. 5)}$$

This suggests the following procedure for estimating the flood of any return period for the Dublin area.

Estimate the mean of the annual maximum series, QBAR, from measured data if possible, otherwise from an equation linking it to catchment characteristics, such as in the FSR (as updated by Institute of Hydrology Report no. 124, Marshall & Bayliss , 1994).

Use equation 4 and 5 to estimate the parameters u and α, for the EV1 distribution

Use the EV1 distribution equation to estimate the required Q_T, i.e.

$$Q_T = u - \alpha \ln\left(-\ln\left[1 - \frac{1}{T}\right]\right) \qquad \text{(Eqn. 6)}$$

or,

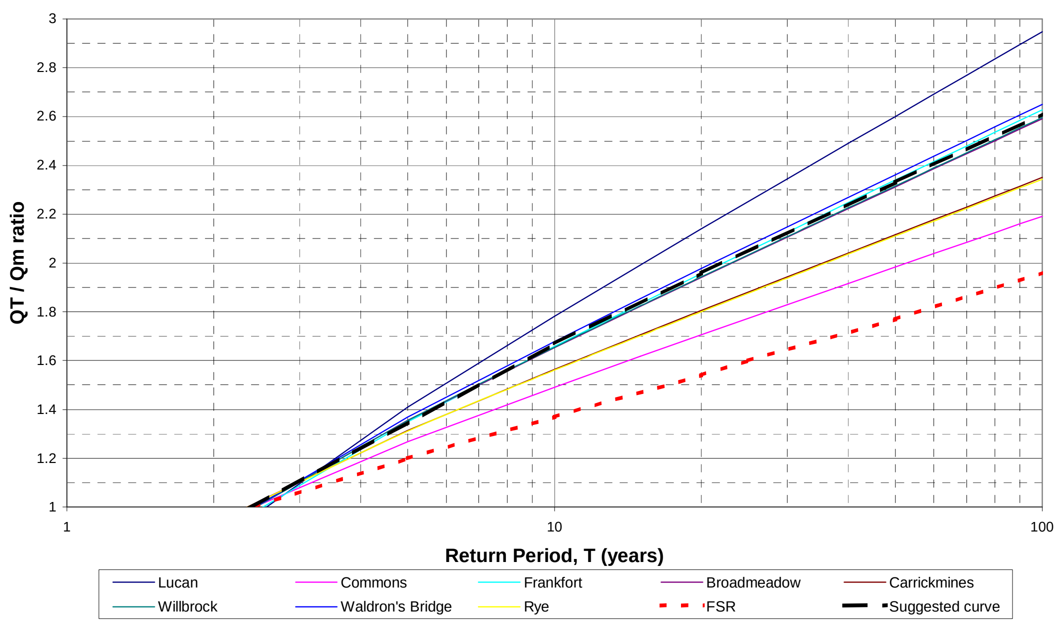
$$Q_T = q_m \left\{ 0.77 - 0.4 \ln\left(-\ln\left[1 - \frac{1}{T} \right] \right) \right\} \quad \text{(Eqn. 7)}$$

Equation 7, in effect, defines a growth curve as, for any QBAR, it defines a relationship between Q_T and T. This suggested new curve is shown superimposed on the individual gauging station curves in Figure 23 and on the combined Annual Maximum data set in Figure 24. The corresponding multipliers are listed in Table 4. For return periods over 10 years, these factors are from 20% to over 30% higher than the corresponding FSR factors, with greater relative differences for the higher return periods. Note that, in Figure 23, the suggested curve lies on the group of four curves identified earlier as a visually good starting point for a new growth curve. In Figure 24, the suggested curve is a reasonably good fit to the higher Annual Maximum values, if the three highest values for the Griffeen at Lucan are excluded.

Table 4 Suggested Growth curve multipliers

T (years)	Multiplier (QT/QBAR)
2	0.92
10	1.67
20	1.96
50	2.33
100	2.61

Figure 23 Suggested interim growth curve for Dublin area



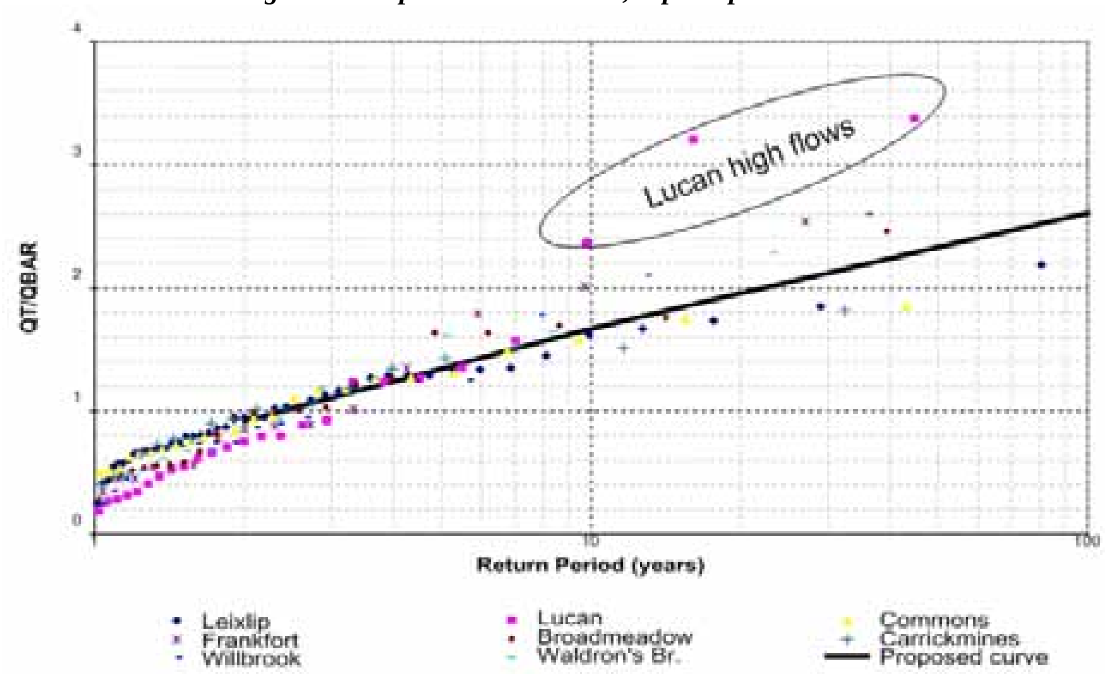
Notes

1. Equation 2 is based on a limited amount of annual maximum series information for a number of gauges in or close to Dublin. It should only be regarded as a temporary

expediency, pending equations/relationships derived from a more comprehensive flood and data study.

2. The Flood Studies Report equations for estimating QBAR are of very limited use for very small urban catchments as they were derived for larger, predominantly rural catchments. For very small urban areas, say less than 5 km^2, methods of the "Rational" type, based on rainfall statistics and a runoff coefficient may be more appropriate. Alternatively, equations derived especially for smaller, more urban catchments (e.g. Institute of Hydrology Report no.124, Marshall & Bayliss, 1994) should be considered. In any case, there still are relatively large uncertainty bands associated with these estimates.

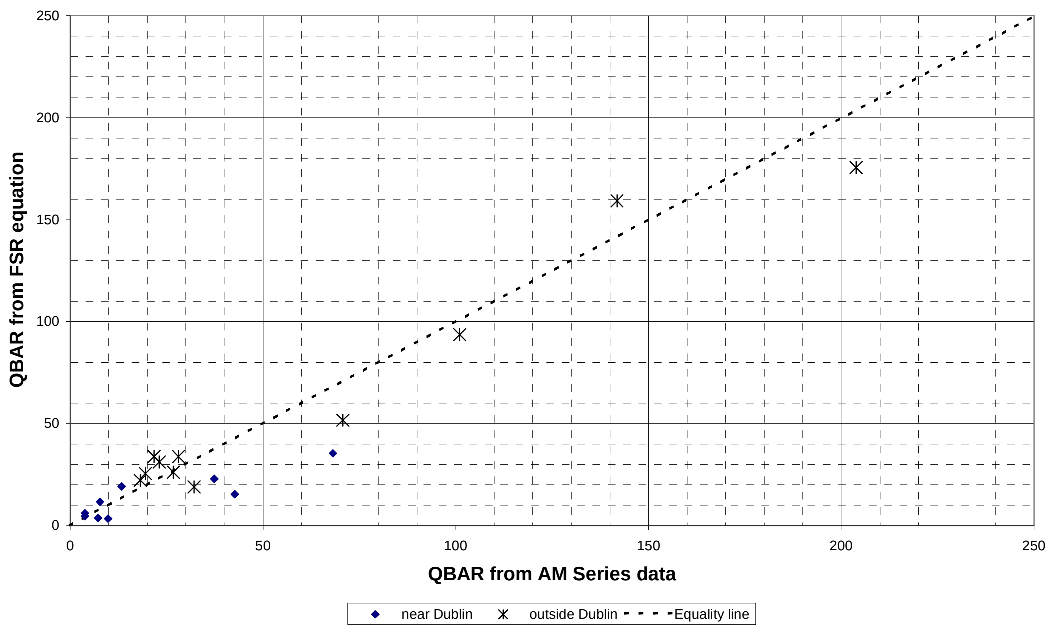
Figure 24 Proposed interim curve, superimposed on AM data set



6 TEST OF THE FSR QBAR EQUATION.

The appropriate catchment characteristics for the study catchments were estimated from readily available maps and were used to estimate the mean of the annual maximum series, using the FSR equation for "QBAR". These were then compared with the mean of the measured annual maximum data, Figure 25 and Table 5. All the AM data was used to estimate this mean and suspected outliers were not removed. For 10 stations the estimate from the Flood Studies Report "QBAR" equation was less than the mean calculated from the measured data. This underestimate ranges from just above -3% to over –65%. In 4 cases in the Dublin area the FSR estimate was higher, by up to 60%, than the QBAR calculated from the data (Willbrook, Frankfort, Common's Road and Carrickmines). However, in 5 other Dublin cases (Waldron's Bridge, Lucan, Ashbourne, Leixlip and Broadmeadow) the FSR estimate under-predicts the data estimate by similar percentages. Overall, no strong pattern can be deduced with confidence.

Figure 25 Comparison of QBAR estimates from FSR and AM data



However, note that the FSR over-prediction is for the smaller catchments closer to the city, while the under-prediction is for the larger catchments at the periphery of the city. However, there is insufficient data to draw reliable conclusions from this pattern. A high degree of variability in the estimate of "QBAR" is to be expected and is acknowledged in the FSR. For instance 95% of the estimates are expected to lie between +117% (more than double) and – 54% of the value predicted by the QBAR equation. (FSR, p342) A later report by the Institute of Hydrology (Marshall & Bayliss (1994)) also shows a high degree of scatter, of approximately an order of magnitude, between measured and estimated "QBAR", e.g. Figure 7.1 of that report. While the QBAR equation should, in any case, be used only when no measured data is available and only for catchments with characteristics within the range of those used to derive the equation, its use in rapidly urbanising catchments near to Dublin, with relatively high degrees of urbanisation, is questionable.

Table 5 Comparison of QBAR values estimated from FSR and from data

River	Site	Area (km^2)	QBAR FSR	QBAR data	% difference
Nanny	Duleek	212	19.0	32.1	-41
Broadmeadow	Broadmeadow	110	15.3	42.7	-64
Ryewater	Leixlip	213	22.9	37.4	-39
Glyde	Tallanstown	267	31.1	23.1	35
Glyde	Mansfieldstown	325	33.8	21.8	55
Dee	Burley	184	22.2	18.2	22
Dee	Charleville	316	33.9	28.1	21
Fyanstown	Moynalty	185	26.1	26.8	-3
Blackwater	Liscartan	709	51.6	70.7	-27
Deal	Killyon	269	25.6	19.5	31
Boyne	Trim	1302	93.6	101.0	-7
Boyne	Navan	2011	159.2	141.8	12
Boyne	Slane	2407	175.5	203.8	-14
Broadmeadow	Asbourne	41	3.5	9.9	-65
Dodder	Waldron's Brig	89	35.4	68.2	-48
Griffeen	Lucan	43	3.7	7.2	-48
Owendoher	Willbrook Rd	28	19.1	13.3	44
Slang	Frankfort	9	4.5	3.8	18
Shanganagh	Common's Rd	39	11.6	7.7	51
Cabinteely	Carrickmines	16	6.0	3.8	58

7 COMBINATION OF GROWTH CURVE AND QBAR EFFECTS.

There are strong indications that the FSR growth curve underestimates peak discharges in the Dublin area. There are also indications of a high variability in the accuracy of estimates of QBAR from the FSR regression equation. Analysis of the combined effect of both influences is outside the scope of this study, but it should be noted that in some cases these influences will tend to combine and reinforce each other’s impact and in other cases, may tend to cancel or reduce each other’s impact.

8 CONCLUSIONS

1. The Flood Studies Method growth curve method, applied to a known QBAR, is likely to lead to an underestimation of the flood flows for high return periods in the Mid-Eastern side of Ireland, and especially in the Dublin area.

2. Comparison of QBAR estimated from the FSR regression equation with measured data shows a large range of differences for most catchments tested in the Mid-Eastern part of Ireland. There are similar numbers of over and underestimates. There are some catchments in the Dublin area for which the FSR equation seems to overestimate. While there is insufficient data to draw firm conclusions from this, the large variability in estimating QBAR from the FSR regression equation indicates the need for further study if this variability is to be reduced.

3. In the light of these findings, I consider it imperative that the question of design flood estimation, particularly in the Dublin area, be urgently addressed. It is of critical importance to enhance the flow data sets being collected by OPW, EPA and Local Authorities, so that long term high quality data sets are available for this type of analysis. In particular, the

rating curves for many sites do not extend to include some of the higher flows and this should be addressed by direct measurement and hydraulic modelling.

9 LIMITATIONS:

The data used in this report are subject to various caveats and warnings which are explained by the primary data providers, the OPW and EPA. In particular it is very difficult to establish rating curves for very high flows and many of the high flows in this analysis exceeded the range of flow gauging used in developing the rating curve. The potential impact of this on this study may be significant. In conversations with the skilled hydrometric personnel who collect and process the data, a sense can be obtained of which rating curves are well founded and reliable and which are not. In certain cases some specific feature of a gauging site may be the most likely explanation for some of the data "outliers" I have flagged. However, because I did not have the time for a detailed study of individual sites, I have hesitated to ascribe specific reasons for individual outliers, leaving this for further investigation. Thus, the data is used here on the basis that it is the best estimate of the flows concerned available at the present time. For any station, where an annual maximum value was missing from the record, that year was ignored in the analysis. This is justified on the basis that each year is assumed independent of other years. However, if the years with missing values were correlated with high or low flow periods this would distort the analysis. What is important here is not the specific result or its magnitude for any individual station, but rather the results that ALL of the near-Dublin stations examined showed the FSR to underestimate to some degree. It is thus the number of stations contributing to the conclusions which gives them their weight.

10 ACKNOWLEDGEMENTS

This report benefited greatly from discussions with Padraig Doyle (DCC), Tim Joyce (OPW), Micheál Mac Cárthaigh (EPA) and Michael Stapleton (EPA). The author is grateful for their contribution of their experience and knowledge.

11 REFERENCES

NERC (1974) **Flood Studies Report**, HMSO, UK.

D C W Marshall & A C Bayliss (1994) **Flood estimation for small catchments,** Hydrology Report 124 , ISBN 0948540621, Institute of Hydrology, Wallingford, UK.

Appendix A

Methods of estimating design flood peaks for ungauged catchments

If catchments are gauged and there is a sufficiently long flow record (typically more than 20 years) then a relationship between peak flood discharges and return periods can be established using an annual maximum (or Peaks Over Threshold, POT) analysis of that data. An appropriate probability distribution, usually the Extreme Value Type 1 (Gumbel) is assumed to represent the data. If less data is available (typically from 10 to 20 years) then this can be used to give an approximation to the location parameter of the EV1 and a corresponding value for its scale parameter can be estimated from regional statistics.

In the absence of actual data, the most appropriate method for estimating design floods in Ireland is based on the Flood Studies Report (NERC, 1974) and subsequent modifications. This resulted from a comprehensive study of the available, quality controlled, rainfall and discharge data available in the UK and Ireland up to 1970. Specific analyses were done on a regional basis, but the Republic of Ireland, despite the large East-West differences in rainfall amounts and frequencies, was treated as a single region. The Flood Studies Report (FSR) contains a collection of maps of the various quantities derived from the rainfall and discharge data. A number of different techniques were developed each for use in different circumstances of data availability and specific design requirements. When a design peak flow only is required then Method 1 (or possibly a later amendment for small catchments, Method 2) was recommended. When the complete hydrograph (including the peak) is required, e.g. for storage or flood routing requirements, a more complex method, which starts by estimating the critical rainfall can be used (Method 3). Method 4 (peak flood only) is a sub-set of Method 3.

Method – 1 : Flood Studies Report – ungauged catchments QBAR method

This is the original Flood Studies Report method, with the regression coefficient for Ireland.

$$QBAR = 0.0172\, AREA^{0.94}\, STMFRQ^{0.27}\, S1085^{0.16}\, SOIL^{1.23} RSMD^{1.03} (1 + LAKE)^{-0.85} \qquad \text{(A-1)}$$

AREA is the catchment area (km^2)

STMFRQ (stream frequency) is the number of stream junctions per km^2 on a 2.5 inch map. For Ireland this can be determined from a 1 inch map and converted (using a formula given in the FSR) to an equivalent 2.5 inch number.

S1085 is the slope of the main stream between 10% and 85% of its length measured from the catchment outlet (m/km)

SOIL is an index of how the soil may accept infiltration. It can be determined from maps in the FSR

RSMD is the 1-day rainfall of 5-year return period (adjusted for catchment area)
less the mean soil moisture deficit. Both can be determined from maps in the FSR.

LAKE is an index related to the amount of the catchment area draining through lakes.

The equation is regressed on data for Ireland and includes catchments on the west as well as the east of the country with quite a wide variation in conditions. The equation can be expected to have a large variability in performance, over estimating for some catchments and underestimating for others. Some measure of the variability is given in the FSR (Vol.1, p.342), i.e. for the mean annual flood, 68% of the actual measured mean annual floods are within - 32% to +47% of the equations estimate and 95% are within -54% to +117% of the equation. The FSR states that "the prediction from catchment characteristics gives a slightly more precise estimate of the mean annual flood than would be obtained from one year of record. It is obvious, therefore, that estimates form these equations must be used with extreme caution .. It is recommended that these equations should be used only for preliminary flood estimates during the earliest stages of the design of a project, and that as soon as a site is decided upon for a project a gauging station should be established to collected records from which more precise flood estimates may be made."

The above formula gives the mean flood, QBAR (cumecs). The flood of 5 year return period for Ireland can be obtained by multiplying this by 1.2. Factors for calculating floods of other return periods are listed below.

Table A-1 *Formula for frequency factors used in Flood Studies Report*

Return Period (years)	Frequency factors (Ireland)	Frequency factors (Great Britain)	Frequency factors SE England
2	0.95	0.89	0.88
5	1.20	1.22	1.28
10	1.37	1.48	1.62
20	1.54	1.77	2.00
25	1.60	1.88	2.14
50	1.77	2.22	2.62
100	1.96	2.61	3.19
200	2.14	3.06	3.86
250	2.20	3.22	4.10
500	2.40	3.76	4.94

Method – 2 : Institute of Hydrology: Report no. 124.

This report was developed specifically for small (< 25 km^2) catchments in the UK. It has the advantages of concentrating on smaller catchments and of having more of them than in original FSR. However, it did not have any Irish catchments. Figure 7.1 from the IoH Report shows a scatter plot of the fitted equation vs. observed QBAR. This is a Log-Log scale graph and it is apparent that the variability is approximately an order of magnitude. However, for the smallest of the UK catchments used, the equation tends to overestimate QBAR. Regardless of the lack of Irish catchments in its derivation, in the absence of data or other methods, it would be prudent to at least check this equation for small catchments.

The IoH equation is

$$QBAR_{rural} = 0.00108\, AREA^{0.89} SAAR^{1.17} SOIL^{2.17} \qquad \text{(A-2)}$$

where, $QBAR_{rural}$ is an estimate of the mean of an annual maximum series (cumecs) ,
AREA is catchment area (km^2),
SAAR is the Standard Annual Average Rainfall (mm) and
SOIL is a soil index (dimensionless, but varying from 0 to 0.5)

The IoH Report 124 study also gave a new equation for the time to peak of the instantaneous unit hydrograph of the small catchments. This is

$$T_P = 6.97\ MSL^{0.35}\ S1085^{-0.36} \qquad \text{(A-3)}$$

This may sometimes be used as a check on the validity of the method, if sufficient data is available to estimate independently the time to peak.

Method 3 : Flood Studies Report unit hydrograph method (full hydrograph)

A more complicated procedure from the Flood Studies Report based on both rainfall and catchment response (unit hydrograph). It includes a procedure for taking account of observed catchment lag.

Step-1 : Determine catchment area AREA (km^2) and main stream length, MSL, (km) from topographic catchment maps. Calculate channel slope between points 10% and 85% of the length of the main stream measured from the outlet, S1085 (m/km).

Step 2 : Estimate the average annual rainfall, SAAR (mm) for the catchment from a map of rainfall distribution.

Step 3: Calculate RSMD (mm) the 1-day rainfall of 5 year return period (corrected for the 24hr/ 1 day difference and for Areal reduction factor) less the soil moisture deficit, SMDBAR, (mm) for the catchment. (RSMD = M5 1-day * ARF – SMDBAR)

Step 4: Estimate the percentage urban area of the catchment from maps, URB (%).

Step 5: Calculate URBT = 1 + URB/100 (A-4)

Step-6 : Estimate the time to peak, T_p (hours) of the 1-hour unit hydrograph either from catchment LAG determined from data (T_p = 0.9 LAG) or, failing that, from equation 6.18 in FSR.
The original FSR had

$$T_p = 46.6\, MSL^{0.14}\, S1085^{-0.38} URBT^{-1.99} RSMD^{-0.4} \qquad \text{(A-5)}$$

but this was modified in Flood Studies Supplementary Report No. 16 to

$$T_p = 283\, MSL^{0.23} S1085^{-0.33} URBT^{-2.2} SAAR^{-0.54} \qquad \text{(A-6)}$$

Step 7 : Set the basic data interval, T (hours) as some convenient number or fraction of hours such that T is approx. $T_p/5$.

Step 8 : Adjust time to peak for data interval

$$\text{New } T_p = \text{old } T_p + (T-1)/2 \qquad \text{(A-7)}$$

Step 9 : Estimate the recommended design storm duration D, (hours) from FSR equation 6.46

$$D = \left(1.0 + \frac{SAAR}{1000}\right) T_p \qquad \text{(A-8)}$$

Step 10 : Establish the required flood return period for the design and from that the corresponding rainstorm return period SRP (years)

Step 11: Calculate the areal rainfall amount, P (mm), for the required return period and storm duration and multiplying by the appropriate area reduction factor.

Step 12 : Estimate the design catchment wetness index (CWI) from Figure 6.44 and equation 6.43.

Step 13 : Calculate soil index, SOIL,

$$SOIL = 0.15S_1 + 0.30S_2 + 0.40S_3 + 0.45S_4 + 0.50S_5 \qquad \text{(A-9)}$$

where, S_i, is the percentage area of the catchment which has the I th soil type.

Step 14 : Calculate the standard percentage runoff, SPR (%) and thence the percentage runoff,PR, (%)

The original FSR had

$$SPR = 95.5\ SOIL + 0.12\ URB \text{ and} \qquad \text{(A-10)}$$

$$PR = SPR + 0.22(CWI-125)+0.1(P-10) \qquad \text{(A-11)}$$

However this was subsequently modified in the Flood Studies Supplementary Report number 16 to

$$Pr_{rural} = SPR + DPR_{CWI} + DPR_{RAIN} \qquad \text{(A-12)}$$

Where,

$$SPR = 10\ S_1 + 30\ S_2 + 37\ S_3 + 47\ S_4 + 53\ S_5 \qquad \text{(A-13)}$$

$$DPR_{CWI} = 0.25(CWI-125) \qquad \text{(A-14)}$$

$$DPR_{RAIN} = 0.45\ (P-10)^{0.7} \quad \text{for } P > 40 \text{ mm} \qquad \text{(A-15)}$$

$$DPR_{RAIN} = 0 \quad \text{for } P <= 40 \text{ mm} \qquad \text{(A-16)}$$

$$PR_{TOTAL} = PR_{RURAL}\ (1.0 – 0.3\ URBAN) + 70\ (0.3\ URBAN) \qquad \text{(A-17)}$$

Step 15: If only the peak flow is required then a curve number, CN, can be determined from Figure 6.64 in the FSR and the peak calculated as

$$q = \frac{CN\ x\ AREA\ x\ P\ x\ PR}{T\ x\ 10^5} \qquad \text{(A-18)}$$

Step 16: If the full flood hydrograph is required then the rainfall amount, P, is distributed over the storm duration, D, according to a chosen profile from the FSR, usually the 75% winter profile.

Step 17
A triangular unit hydrograph is constructed. Its peak, Qp (cumecs), may be calculated from

$$Q_p = \frac{2.2 \ x \ AREA}{T_p} \qquad \text{(A-19)}$$

(note in the FSR report, an equation is given for Q_p (cumecs/100 km^2) which must then by multiplied by AREA/100 to give cumecs. The equation given above combined both steps.

The time base of the unit hydrograph is determined from

$$TB = 2.52 \ T_p \qquad \text{(A-20)}$$

Step 18 :
The rainfall pattern is multiplied by the runoff coefficient, PR, to give the net rainfall pattern, which is then convoluted with the unit hydrograph to give the direct storm response.

Step 19:
The base flow, ANSF (cumecs/km^2) is calculated. In the original FSR it was given by

$$ANSF = 0.00033 \ (CWI - 125) + 0.00074 \ RSMD + 0.003 \qquad \text{(A-21)}$$

However, in FSSR no. 16 this was altered to

$$ANSF = [3.3 \ (CWI - 125) + 3 \ SAAR + 5.5 \ ] \ x \ 10^{-5} \qquad \text{(A-22)}$$

This is multiplied by the catchment area, AREA (km^2) and added to the direct storm response to get the complete storm hydrograph as required.

In assessing the performance of this method the FSR (Vol.1 p.428) reported from tests with 64 events that the method predicts the peak to within 25% for 50% of the cases and to within 50% for 70% of the cases.

Method 4: Flood Studies Report unit hydrograph method (peak only method)

That part of method 3 required for flood peak estimation only, it is the same as method 3, except that since only the peak is required it can stop at step 15.

Appendix B : Locations of Stations Considered

Station Id no.	Station Name	River name	Easting	Northing
06012	Clarebane	Fane	287300	316700
06013	Charleville Weir	Dee	304400	290700
06014	Tallanstown Weir	Glyde	295300	297800
06021	Mansfield town	Glyde	302300	295200
06025	Burley	Dee	292500	289600
07002	Killyon	Deel	268300	249100
07005	Trim	Boyne	280100	256900
07006	Fyanstown	Moynalty	279000	275700
07009	Navan Weir	Boyne	287800	266700
07010	Liscartan	Blackwater(Kells)	284600	268900
07012	Slane Castle	Boyne	294900	273900
07023	Athboy	Athboy	271700	264000
08004	Owen's bridge	Ward	313100	244800
08007	Ashbourne	Broadmeadow	308700	252400
08008	Broadmeadow	Broadmeadow	317400	248600
08009	Balheary	Ward	318300	248400
08011	Duleek d/s	Nanny	305300	268500
08012	Ballyboghil	Stream	315200	253600
09001	Leixlip	Ryewater	300500	236400
09002	Lucan	Griffeen	303300	235200
09009	Willbrook Road	Owendoher	314200	228700
09010	Waldron's Bridge	Dodder	315600	229800
09011	Frankfort	Slang	316800	228700
09019	Drumcondra	Tolka	316200	236100
09037	Botanic Gardens	Tolka	313200	237600
10021	Common's Road	Shanganagh	325200	223000
10022	Carrickmines	Cabinteely	323400	224200
11001	Boleany	Owenavarragh	317000	156000