Flood Studies Update

Work Package 2.3
Flood Estimation in Ungauged Catchments

Final Report

Conor Murphy
Irish Climate Analysis and Research Units (ICARUS)
Department of Geography
NUI Maynooth
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Summary

This report provides procedures for estimating Qmed in ungauged catchments. Qmed estimation is especially important because Irish flood growth rates are very slow, making Qmed weigh heavily in the calculation of design flood values. The recommended procedure for Qmed estimation at sites for which there is no data is to use or transfer data from a nearby site, preferably upstream or downstream from the site of interest. In cases where no suitable data transfer is available the following equation can be used to estimate Qmed.

Rural Catchments

Following exhaustive searches for an optimum model structure the following model is advocated for use in estimating Qmed at ungauged sites:

$$Qmed = 1.237X10^{-5}\,AREA^{0.937}\,BFIsoils^{-0.922}\,SAAR^{1.306}\,FARL^{2.217}\,DRAIND^{0.341}$$
$$S1085^{0.185}(1+ARTDRAIN2)^{0.408}$$

The model has an r^2 of 0.909, Standard Error of 0.313 and a Factorial Standard Error (fse) of 1.37. Qmed is estimated from seven catchment descriptors: drainage area (km^2) (AREA), catchment soil and geology index (BFIsoils), average annual rainfall (mm) (SAAR), an index of flood attenuation by reservoirs and lakes (FARL), an index of drainage density (DRAIND), the mainstream slope (m/km) (S1085) and a measure of arterial drainage (ARTDRAIN2), taken as the length of upstream network included in OPW scheme channels (km). The descriptors BFIsoils and ARTDRAIN2 are crucial in determining the response of drained catchments while the descriptors DRAIND and S1085 are more important in predicting Qmed in undrained catchments.

A simple interpretation of the model can be given as follows.

- Qmed increases with Area
- Qmed decreases as BFIsoils increases, therefore Qmed is greater on less permeable catchments.
- Qmed increases with greater values of SAAR
- Qmed increases with FARL, meaning that it decreases for increased attenuation
- Qmed increases with drainage density
- Qmed increases with mainstream slope
- Qmed increases with the extent of arterial drainage works on the river network.

Approximate 68% and 95% confidence intervals for Qmed can thus be given as;

68% confidence interval = (Qmed/fse, Qmedxfse)
95% confidence interval = (Qmed/fse^2, Qmedxfse^2)

Adjusting for Urbanisation

The rainfall runoff response of a catchment can be radically altered by urbanisation where impervious surfaces inhibit infiltration and reduce surface retention, while increases in surface runoff are combined with an increase in the speed of response. The estimation of an adjustment factor was preferred over deriving a separate model for Qmed in urban catchments due to the small number of representative stations (35 in total). The adjustment derived is for catchments that have undergone urbanisation and is not suitable for anticipating the effects of planned urban developments:

$$UAF = (1 + URBEXT)^{1.482}$$

The model returned an r^2 (in ℓn space) of 0.300, a standard error of 0.735 and a Factorial Standard Error of 2.085. The coefficient 1.482 has a standard error of 0.139. The model also has the advantage of decreasing to 1 when URBEXT decreases to zero and returns a value of 2.793 when URBEXT reaches a maximum of 1 (fully urbanised catchment).

Improving Model Predictions

While the model marks an improvement on the FSR approach for Ireland, with a fse of 1.37, uncertainty is still large. Therefore it is advised that every effort is made to increase confidence in predictions by using information from nearby sites to improve model predictions. W.P. 2.2 recommends the use of donor sites through exploiting downstream or upstream gauge(s) where available, with the former being preferable. In the situation where analogue transfers are required W.P. 2.2 recommends a regression adjustment transfer method. The geostatistical mapping of residuals as a means of adjustment is put forward as a viable option here. However, as always the local experience of a discerning hydrologist is always more valuable and it is recommended that the choice of adjustment procedure is made using this best available information where possible. Ultimately, it is recommended that a gauge should be erected prior to any major scheme proceeding to design stage.

1. Datasets Used

The estimation of the index flood for ungauged catchments is based on the construction of an empirically based model from two basic datasets; i) the index flood, Qmed, (or the median annual flood) from gauged catchments and ii) catchment descriptors for gauged catchments. The details of how these datasets were derived are given elsewhere and so are not repeated here, rather an overview of the characteristics of the data used in the model building process are presented.

1.1 Median Annual Flood

The annual maximum series and values for Qmed were provided for a total of 206 gauging stations. Not all of the stations provided were used, with some being discarded following an exploratory data analysis and other questionable stations being brought to light during model building. In total16 stations were omitted from study leaving 190 stations for model building. Section 1.2 below identifies the omitted stations and justifies the decisions taken. Where arterial drainage had taken place within the record, the series in question was split into two and a value for Qmed obtained for the pre-drainage period and post-drainage period. In total 15 stations were divided into pre and post drainage records, giving a total of 205 stations (190 with 15 divided into pre and post drainage records) for model building. Of this dataset 74 stations represent catchments with arterial drainage and 131 stations with no drainage.

In relation to the quality of the data, Figure 1 shows the number of stations in each quality category with 58 A1 stations, 78 A2 Stations and 69 B stations being included for analysis. These stations have an average length of 31.07 years, with a maximum of 65 and a minimum of 7 years. Figure 2 shows a histogram of length of years of station records. There is evidence of bi-modality within the distribution which is likely representative of the different lengths of the OPW and EPA data sets. In total the full data series represents 6,350 annual maximum events. Figure 3 plots a histogram of the Qmed values obtained from this record with a mean of 64.11 cumecs, a minimum of 1.46 and a maximum Qmed of 414.17 cumecs. Figure 4 maps the distribution of gauges employed for model building.

1.2 Stations Omitted

A total of 16 stations were omitted from the study for a range of reasons highlighted below leaving 190 stations for model building.

St 26010 Riverstown, Cloone,

Suspicious outliers revealed that a partially developed OPW rating was erroneously applied to the annual maximum series. Neither the series calculated

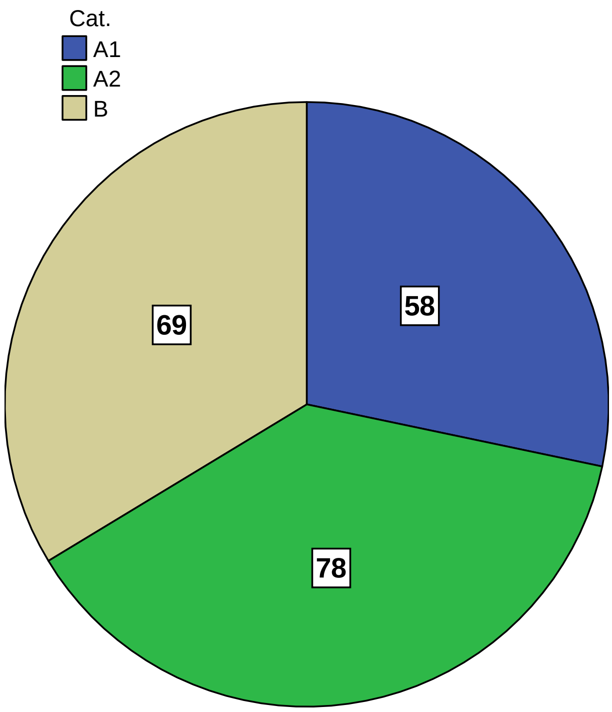

Figure 1: Number of stations in each grade category for the full dataset of 205 stations

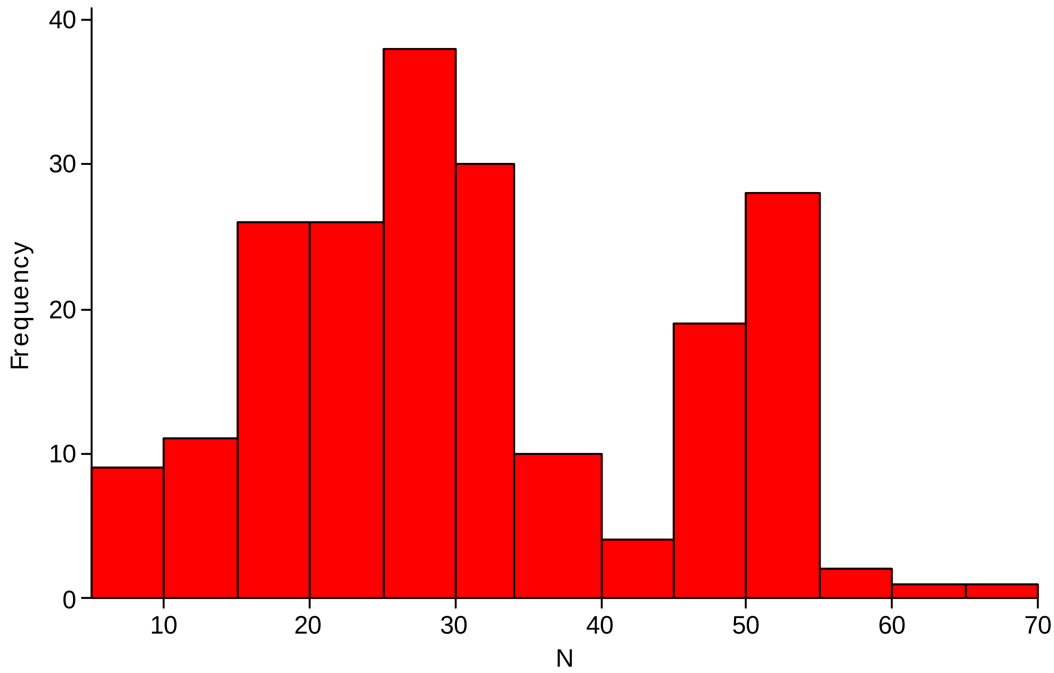

Figure 2: The length of station records in years for the full dataset of 205 stations

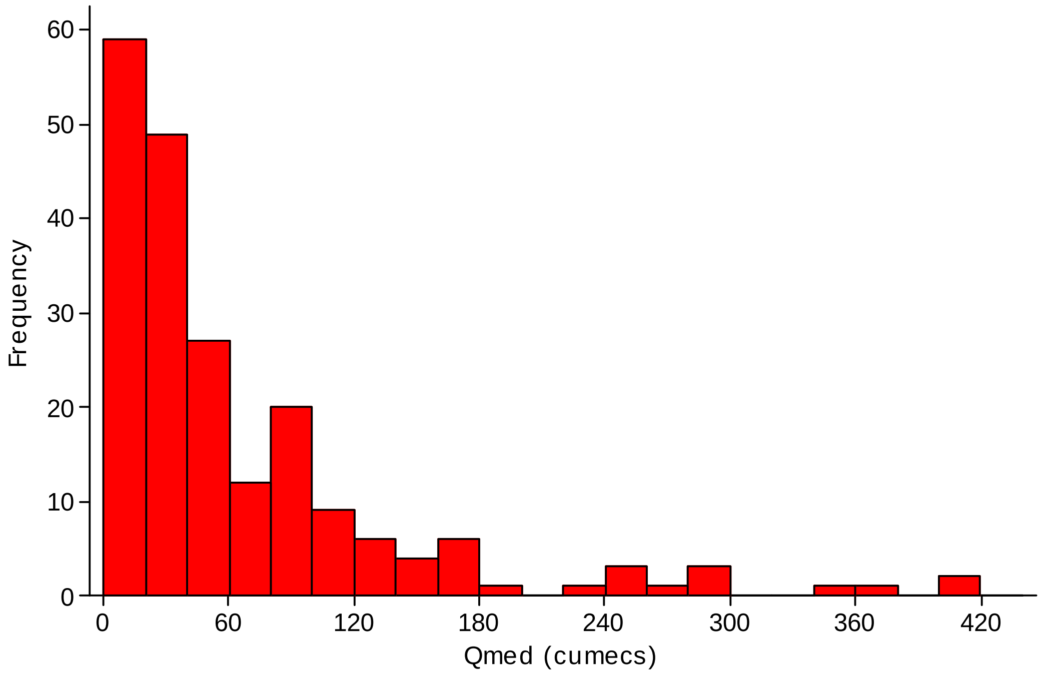

Figure 3: Histogram of observed Qmed values for the full dataset of 205 stations

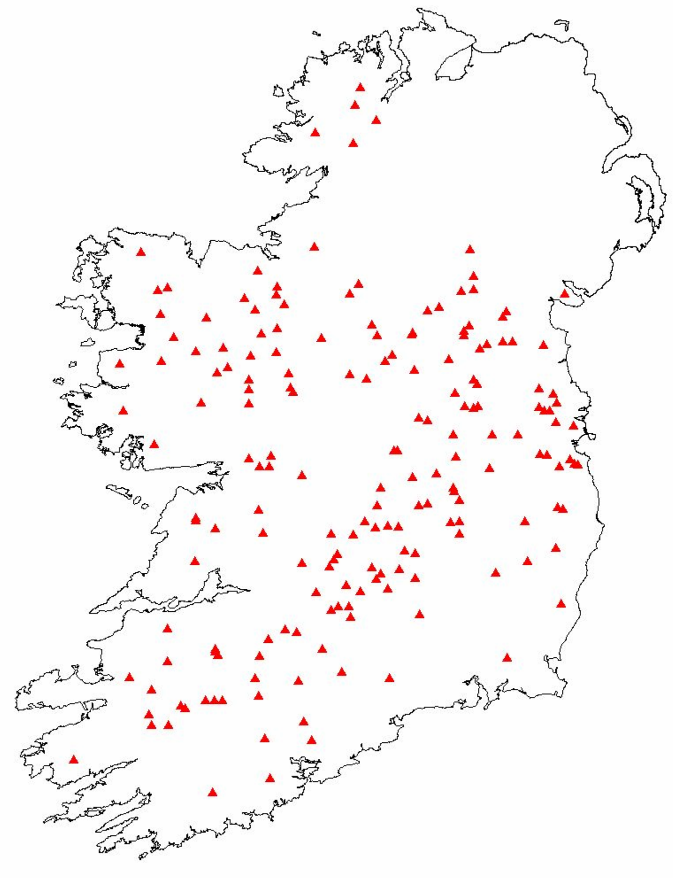

Figure 4: The distribution of stations (plotted at catchment centroids)

using OPW nor the Hydrologic rating should be used as they do not satisfactorily reflect changes in the stage discharge relationship.

St 36027, Bellaheady, Ballyconnel Canal East, Lower Lough Erne
Extremely low outliers, the station name, and the fact that the station is recording a typical annual maximum flood of only 25 cumecs from a nominal drainage area of 1,501 km^2, it can be questioned whether this represents a meaningful flood series for a natural river.

Stations, 25001, 25002, 25003 and 25005, Mulkear Catchment
Stations in the Mulkear catchment were omitted from analysis in line with recommendations made by Joyce (2006, pers. comm.) where he highlights that "this river was subjected to a District Drainage Scheme in the late 1920s and early 1930s that protects large areas of land by extensive lengths of embankments that are overtopped about once in five years. This means that the catchment responds almost without storage attenuation for the smaller annual maxima, including Qmed, and with massive storage attenuation for the larger events.

Stations 19014, 19015, 19016 and 19031 in the Lee Catchment were omitted because of the lack of an annual maximum series and corresponding Qmed value.

Stations 31075, 34005 and 36020 had discrepancies in the metadata decriptions with values for Qmed provided but no indication of series length from which Qmed was calculated, in all cases a series length of zero was provided.

Stations 15003 (the Dinin at Dinin Bridge), 20006 (the Argideen at Clonakilty WTW) and 30037 (the Robe at Clooncormick) were omitted at a later stage during model building due to the exaggerated influence they were having on model coefficients. Further inspection revealed criteria for omission. St30037 has a very small Qmed (1.79 cumecs) for a catchment area of 210 km^2 , well below any other catchment of a similar size. St20006 again has an unusually small Qmed and analysis of the annual maximum series reveals a large number of years with missing months, raising suspicion that the maximum flow in a number of years may have been missed. Finally, closer inspection of St15003 revealed quite a number of low outliers. Additionally, St15003 is noted to be an extremely flashy catchment in a karst area (Castlecomber Plateau).

1.3 Correcting for Period of Record Effects

Due to natural year to year variability in climate there is a tendency for the flood series to contain flood rich periods and flood poor periods. Consequently Robson and Reed (1999) highlight that Qmed estimates obtained from short records can be unrepresentative of the long term. In order to correct for this characteristic, short flood records were adjusted for period of record effects. Short records were taken as those with a flood series of less than 20 years, of which there are 28 in total. The procedure used for adjustment is the same at that outlined in Chapter 20 of the Flood Estimation Handbook which enables the transfer of information from long record sites to short record sites. Category A1 and A2 sites that are free from arterial drainage and have a record length of over 30 years were used as donor sites. For each subject site, potential donor sites were selected as those within a 50 km radius. The selection of sites was made through plotting all stations in a Geographical Information System and querying sites within the specified distance. Only sites with at least 75% of overlap of annual maximum data were considered. The correlation between the subject site and donor sites were derived using Spearman's rank correlation, stations revealing a low or negative correlation coefficient were excluded from the adjustment process. The number of donor sites identified ranged from 1 where stations completely overlapped and where high correlation coefficients were derived (>0.8 Spearman's Rank Correlation) to 5 where no outstanding donor was identified. For all recipient sites, donors that completely overlap the period of record were found.

In order to transfer information from the donor site to the subject site Qmed was estimated at the donor site using all available data and then recalculated for the period of overlap with the subject site. The ratio of these two measurements was used as an estimate to determine the period of record effect at the subject site. The Qmed estimate adjusted to the donor period was found by:

$$QS_{adj} = QS\left(\frac{QD}{QD_0}\right)^{M(r)} \qquad \text{(Eqn. 1)}$$

where QS_{adj} is the adjusted Qmed at the subject site, QS is Omed at the subject site, calculated from its own available period of record, QD is Qmed at the donor site, QD_o is Qmed at the donor site for the period of overlap and $M(r)$ is a moderating influence on the donor site based on the strength of correlation with the subject site and is given as:

$$M(r) = \frac{(n_o - 3)r^3}{(n_o - 4)r^2 + 1} \qquad \text{(Eqn. 2)}$$

where n_o is the length of overlap between subject and donor sites and r is Spearman's rank correlation between annual maxima at subject and donor sites. When only one donor with a very strong correlation coefficient was identified (>0.8), the adjustment process was finished. However, where a number of donor sites were identified, combined adjustment estimates were made by weighting each donor based on distance from subject site, additional years of data provided by the donor and the strength of correlation with the subject site. The weighting factor is calculated as:

$$w = \left(1 - \frac{d}{100}\right) n_o (n_d - n_o) r \qquad \text{(Eqn. 3)}$$

where n_d is the length of the donor site record and d is distance in km.

Table 1 details the stations which were adjusted for period of record effects while Figure 5 shows the relationship between Qmed and adjusted Qmed values for all sites. In the majority of cases only small adjustments to Qmed were made. The largest adjustment is evident for st09035 (the Cammock at Kileen Road) with an adjustment ratio of QmedAdj/Qmed of 1.306, increasing Qmed from 11.70 cumecs to 15.28.

Station	Cat.	Station name	River name	N Amax	Qmed	Adj Qmed	Diff	%change	Abs%	AdjQmed/Qmed
st01055	B	Mourne Beg Weir	Mourne Beg	9	2.70	2.80	0.10	3.59	3.59	1.036
st07006	A2	Fyanstown	Moynalty	19	27.93	25.20	-2.73	-9.79	9.79	0.902
st07041	A2	Ballinteer Br.	Boyne	7	165.00	165.28	0.28	0.17	0.17	1.002
st08007	B	Ashbourne	Broadmeadow	17	8.24	8.12	-0.12	-1.43	1.43	0.986
st08009	A1	Balheary	Ward	14	5.00	5.09	0.09	1.87	1.87	1.018
st08012	B	Ballyboghil	Stream	19	4.35	4.35	0.00	0.04	0.04	1.000
st09010	A1	Waldron's Br.	Dodder	18	47.05	46.64	-0.41	-0.87	0.87	0.991
st09035	B	Killeen Road	Cammock	9	11.70	15.28	3.58	30.62	30.62	1.306
st10028	B	Knocknamohil	Aughrim	16	46.95	46.29	-0.66	-1.41	1.41	0.986
st13002	B	Foulk's Mills	Corock	19	7.01	6.98	-0.03	-0.48	0.48	0.996
st14034	A2	Bestfield	Barrow	17	117.00	117.07	0.07	0.06	0.06	1.001
st15007	A2	Kilbricken	Nore	13	53.45	53.58	0.13	0.24	0.24	1.002
st15012	B	Ballyragget	Nore	16	77.11	76.18	-0.93	-1.20	1.20	0.988
st16051	B	Clobanna	Suir	13	2.85	2.82	-0.03	-0.88	0.88	0.989
st19046	B	Station Road	Martin	9	29.95	28.33	-1.62	-5.40	5.40	0.946
st22003	B	Riverville	Maine	8	98.01	98.03	0.02	0.02	0.02	1.000
st22035	B	Laune Bridge	Laune	14	116.40	110.42	-5.99	-5.14	5.14	0.949
st23012	A2	Ballymullen	Lee (Kerry)	18	15.66	15.83	0.17	1.09	1.09	1.011
st25038	B	Nenagh	Toyne	17	39.30	37.68	-1.62	-4.13	4.13	0.959
st25124	A2	Ballyganore	Brosna	18	13.65	13.36	-0.29	-2.11	2.11	0.979
st25158	A1	Cappamore	Bilboa	18	43.88	37.06	-6.81	-15.53	15.53	0.845
st26014	B	Banada Br.	Lung	16	42.82	42.18	-0.63	-1.48	1.48	0.985
st26108	A2	Bellavahan Bridge	Owenure	15	57.32	55.92	-1.40	-2.44	2.44	0.976
st30012	B	Claregalway	Clare	9	126.00	116.97	-9.03	-7.17	7.17	0.928
st34010	B	Cloonacannana	Moy	12	95.42	99.21	3.80	3.98	3.98	1.040
st34029	B	Knockadangan	Deel	9	110.00	110.00	0.00	0.00	0.00	1.000
st36016	B	Rathkenny	Annalee	14	50.70	50.70	0.00	0.00	0.00	1.000
st39001	B	New Mills	Swilly	17	47.80	47.05	-0.74	-1.56	1.56	0.984

Table 1: Stations which were adjusted for period of record effects

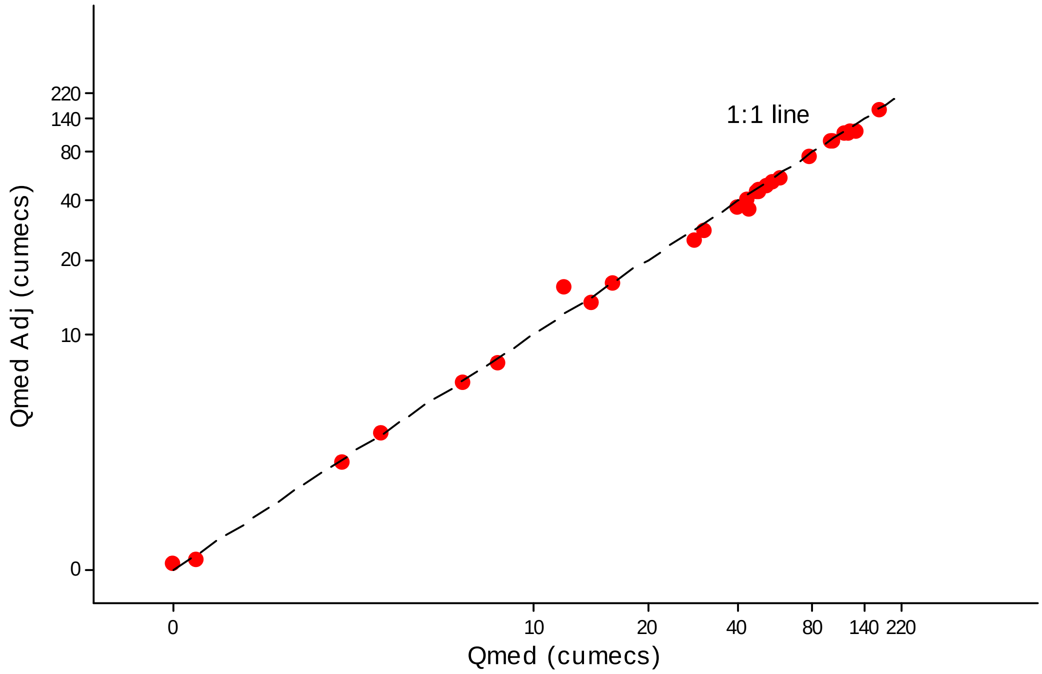

Figure 5: Relationship between Qmed and period of record adjusted Qmed values for all sites

1.4 Uncertainty in Qmed

Chapter four of the Flood Studies Update deals with uncertainty in Qmed at gauged sites. In a random sample from a normal distribution the standard error (se) of Qmed is given as:

$$se(Qmed) \approx 1.253\sigma / \sqrt{N} \qquad \text{(Eqn. 4)}$$

Since Irish flood data are more skewed than the normal distribution then se(Qmed) for flood data will be slightly greater. In Chapter 4 (Section 4.3.1) an approximate value for se(Qmed) is given as:

$$se(Qmed) = 0.36Qmed / \sqrt{N} \qquad \text{(Eqn. 5)}$$

The above is derived by adapting a larger multiplier of 1.30 and taking average values of Cv and the ratio $Qmed / \overline{Q}$ for Irish A1 and A2 stations. Table 2 gives the derived standard error of gauged values of Qmed at different record lengths.

N	se(Qmed)
1	0.360
2	0.255
5	0.161
7	0.136
10	0.114
12	0.104
15	0.093
17	0.087
20	0.080
22	0.077
25	0.072

Table 2: Standard error of gauged values of Qmed at different record lengths

1.5 Catchment Descriptors

A total of 23 catchment descriptors were provided. Table 5 provides a summary of descriptors for the 190 stations used in model building. The catchment descriptors were all ℓn transformed, where the lower range of a particular descriptor can take a value of zero, transformation of ℓn(1+ descriptor) was taken. Where descriptors were provided as percentages (e.g. PASTURE, URBEXT, FOREST, ALLUV, PEAT) they were converted to fractions and treated in the same way. Additionally, catchment descriptors were subject to a factor analysis to examine the dominant factors in estimating ℓn(Qmed). Table 3 displays the results following varimax rotation. The first component is dominated by catchment area, with rainfall, arterial drainage, attenuation and drainage density emerging as the next major components, followed by the extent of alluvium, potential evapotranspiration, catchment soil and geology and slope respectively.

All variables were screened by calculating non-parametric correlations and plotting against QMED (all in ℓn-space) to check for outliers, non-linear relationships and for possible cross-correlation between the descriptors. Strong correlations were found to exist between descriptors relating to catchment area (including ℓn(AREA), ℓn(MSL), ℓn(NETLEN) and ℓn(STRMFRQ)), as such, the traditional descriptor of DTM derived Area was selected and the remainder removed from further analysis to avoid problems of collinearity. Similarly strong correlations exist between ℓn(SAAR), ℓn(FOREST) and the altitude descriptors due to the effect of topography on rainfall and dominant landuse type (with forested areas largely located in upland areas of high rainfall), again the dominant and traditional descriptor of ℓn(SAAR) was selected.

Component	1	2	3	4	5	6	7	8	9
ℓn(AREA)	0.961								
ℓn(MSL)	0.965								
ℓn(NETLEN)	0.986								
ℓn(STMFRQ)	0.957								
ℓn(DRAIND)					0.937				
ℓn(S1085)	-0.620								0.584
ℓn(SAAR)		0.700							0.307
ℓn(1+FOREST)		0.819							
ℓn(1+PEAT)		0.841							
ℓn(1+PASTURE)		-0.877							
ℓn(1+ALLUV)							0.851		
ℓn(SAAPE)						0.902			
ℓn(FARL)				0.870					
ℓn(BFIsoils)								0.836	
ℓn(TAYSLOPE)	-0.603								0.629
ℓn(1+ARTDRAIN)			0.968						
ℓn(1+ARTDRAIN2)			0.961						

Table 3: Principal Component analysis of ℓn transformed catchment descriptors for 190 stations

The slope descriptor ℓn(S1085) showed a stronger relationship with ℓn(Qmed), subsequent exhaustive fitting of catchment descriptors in modelling ℓn(Qmed) consistently selected ℓn(S1085) over ℓn(TAYLSO) with the latter being dropped from further analysis. Furthermore ℓn(S1085) also has a higher correlation with ℓn(Qmed) and is preferred for its simplicity over ℓn(TAYLSO). Table 4 shows the correlation matrix for the ℓn transformed descriptors for 190 stations, while Figure 6 shows the scatter plot matrix and correlations for the more dominant descriptors.

Descriptor	Qmed	Area	MSL	NETLEN	STMFRQ	DRAIND	S1085	SAAR	URBEXT	FOREST	PEAT	PASTURE
Qmed		**0.79**	**0.78**	**0.86**	**0.86**	0.04	**-0.36**	**0.27**	0.04	**0.22**	**0.26**	-0.09
Area	**0.79**		**0.95**	**0.96**	**0.87**	**-0.36**	**-0.71**	-0.05	**0.16**	-0.03	0.07	0.13
MSL	**0.78**	**0.95**		**0.94**	**0.87**	**-0.26**	**-0.68**	0.01	0.13	0.00	0.11	0.10
NETLEN	**0.86**	**0.96**	**0.94**		**0.96**	-0.12	**-0.63**	0.07	0.13	0.05	**0.15**	0.05
STMFRQ	**0.86**	**0.87**	**0.87**	**0.96**		0.03	**-0.51**	**0.21**	0.07	0.14	**0.26**	-0.08
DRAIND	0.04	**-0.36**	**-0.26**	-0.12	0.03		**0.54**	**0.51**	-0.14	**0.29**	**0.25**	**-0.32**
S1085	**-0.36**	**-0.71**	**-0.68**	**-0.63**	**-0.51**	**0.54**		**0.30**	-0.12	**0.29**	0.00	**-0.23**
SAAR	**0.27**	-0.05	0.01	0.07	**0.21**	**0.51**	**0.30**		**-0.45**	**0.60**	**0.62**	**-0.60**
URBEXT	0.04	**0.16**	0.13	0.13	0.07	-0.14	-0.12	**-0.45**		**-0.34**	**-0.34**	**0.25**
FOREST	**0.22**	-0.03	0.00	0.05	0.14	**0.29**	**0.29**	**0.60**	**-0.34**		**0.60**	**-0.70**
PEAT	**0.26**	0.07	0.11	**0.15**	**0.26**	**0.25**	0.00	**0.62**	**-0.34**	**0.60**		**-0.84**
PASTURE	-0.09	0.13	0.10	0.05	-0.08	**-0.32**	**-0.23**	**-0.60**	**0.25**	**-0.70**	**-0.84**	
ALLUV	**0.28**	**0.24**	**0.22**	**0.25**	**0.17**	-0.05	0.00	**-0.30**	**0.23**	-0.06	**-0.37**	**0.47**
SAAPE	-0.03	-0.13	**-0.18**	**-0.14**	**-0.14**	0.04	**0.28**	**-0.31**	**0.20**	**-0.14**	**-0.52**	**0.30**
FARL	-0.09	**-0.22**	**-0.27**	**-0.26**	**-0.33**	-0.10	**0.21**	**-0.36**	**0.20**	-0.08	**-0.36**	**0.32**
BFIsoils	-0.05	**0.34**	**0.30**	**0.21**	0.13	**-0.53**	**-0.45**	**-0.29**	0.08	**-0.20**	**-0.21**	**0.20**
ALTBAR	0.13	**-0.16**	**-0.14**	-0.07	0.00	**0.42**	**0.54**	**0.41**	**-0.23**	**0.58**	0.14	**-0.25**
ALTMIN	**-0.34**	**-0.18**	**-0.21**	**-0.25**	**-0.35**	**-0.21**	-0.05	**-0.20**	-0.10	0.04	-0.03	0.08
ALTMAX	**0.50**	**0.26**	**0.26**	**0.37**	**0.44**	**0.38**	**0.25**	**0.43**	-0.10	**0.55**	**0.29**	**-0.35**
ALTRANGE	**0.53**	**0.27**	**0.28**	**0.40**	**0.48**	**0.40**	**0.26**	**0.43**	-0.08	**0.53**	**0.28**	**-0.34**
TAYSLOPE	**-0.34**	**-0.71**	**-0.69**	**-0.64**	**-0.57**	**0.48**	**0.89**	**0.17**	-0.09	**0.20**	-0.10	-0.10
ARTDRAIN	0.03	0.08	0.09	0.05	-0.01	-0.09	**-0.22**	**-0.20**	**0.26**	**-0.43**	**-0.19**	**0.31**
ARTDRAIN2	0.03	0.06	0.07	0.04	-0.04	-0.10	**-0.19**	**-0.20**	**0.25**	**-0.45**	**-0.21**	**0.33**

Descriptor	ALLUV	SAAPE	FARL	BFIsoils	ALTBAR	ALTMIN	ALTMAX	ALTRANGE	TAYSLOPE	ARTDRAIN	ARTDRAIN2
Qmed	**0.28**	-0.03	-0.09	-0.05	0.13	**-0.34**	**0.50**	**0.53**	**-0.34**	0.03	0.03
Area	**0.24**	-0.13	**-0.22**	**0.34**	**-0.16**	**-0.18**	**0.26**	**0.27**	**-0.71**	0.08	0.06
MSL	**0.22**	**-0.18**	**-0.27**	**0.30**	**-0.14**	**-0.21**	**0.26**	**0.28**	**-0.69**	0.09	0.07
NETLEN	**0.25**	**-0.14**	**-0.26**	**0.21**	-0.07	**-0.25**	**0.37**	**0.40**	**-0.64**	0.05	0.04
STMFRQ	**0.17**	**-0.14**	**-0.33**	0.13	0.00	**-0.35**	**0.44**	**0.48**	**-0.57**	-0.01	-0.04
DRAIND	-0.05	0.04	-0.10	**-0.53**	**0.42**	**-0.21**	**0.38**	**0.40**	**0.48**	-0.09	-0.10
S1085	0.00	**0.28**	**0.21**	**-0.45**	**0.54**	-0.05	**0.25**	**0.26**	**0.89**	**-0.22**	**-0.19**
SAAR	**-0.30**	**-0.31**	**-0.36**	**-0.29**	**0.41**	**-0.20**	**0.43**	**0.43**	**0.17**	**-0.20**	**-0.20**
URBEXT	**0.23**	**0.20**	**0.20**	0.08	**-0.23**	-0.10	-0.10	-0.08	-0.09	**0.26**	**0.25**
FOREST	-0.06	**-0.14**	-0.08	**-0.20**	**0.58**	0.04	**0.55**	**0.53**	**0.20**	**-0.43**	**-0.45**
PEAT	**-0.37**	**-0.52**	**-0.36**	**-0.21**	0.14	-0.03	**0.29**	**0.28**	-0.10	**-0.19**	**-0.21**
PASTURE	**0.47**	**0.30**	**0.32**	**0.20**	**-0.25**	0.08	**-0.35**	**-0.34**	-0.10	**0.31**	**0.33**
ALLUV		**0.46**	**0.45**	-0.09	**0.17**	-0.02	**0.24**	**0.26**	0.08	0.10	0.11
SAAPE	**0.46**		**0.57**	-0.09	**0.18**	**-0.19**	0.11	**0.14**	**0.42**	-0.08	-0.06
FARL	**0.45**	**0.57**		**-0.22**	0.09	0.13	-0.08	-0.08	**0.43**	-0.01	0.02
BFIsoils	-0.09	-0.09	**-0.22**		**-0.25**	0.08	-0.10	-0.11	**-0.46**	0.11	0.10
ALTBAR	**0.17**	**0.18**	0.09	**-0.25**		**0.28**	**0.66**	**0.61**	**0.49**	**-0.42**	**-0.41**
ALTMIN	-0.02	**-0.19**	0.13	0.08	**0.28**		-0.11	**-0.22**	0.01	-0.10	-0.10
ALTMAX	**0.24**	0.11	-0.08	-0.10	**0.66**	-0.11		**0.99**	**0.16**	**-0.34**	**-0.36**
ALTRANGE	**0.26**	**0.14**	-0.08	-0.11	**0.61**	**-0.22**	**0.99**		**0.16**	**-0.32**	**-0.33**
TAYSLOPE	0.08	**0.42**	**0.43**	**-0.46**	**0.49**	0.01	**0.16**	**0.16**		**-0.18**	**-0.15**
ARTDRAIN	0.10	-0.08	-0.01	0.11	**-0.42**	-0.10	**-0.34**	**-0.32**	**-0.18**		**0.98**
ARTDRAIN2	0.11	-0.06	0.02	0.10	**-0.41**	-0.10	**-0.36**	**-0.33**	**-0.15**	**0.98**	

Table 4: Correlation matrix for the ℓn transformed descriptors for 190 stations. Significant correlations are shown in bold.

Descriptor	Units	Note	Mean	Max	Min	ℓn Transform (Variable Used)
AREA	km^2	Catchment area from DTM	539	7980	5.46	ℓn (AREA)
DRAIND		Drainage Density	1.07	2.64	0.27	ℓn (DRAIND)
SAAR	mm	Standard Average Annual Rainfall (1961-90)	1128	2465	711	ℓn (SAAR)
URBEXT	%	% urban extent (CORINE)	1.96	68.3	0.00	ℓn (1+URBEXT)
PEAT	%	% peat extent (CORINE)	13.5	80.2	0.00	ℓn (1+PEAT)
ALLUV	%	% Alluvium extent (EPA/TEAGASC subsoils)	3.45	10.8	0.00	ℓn (1+ALLUV)
PASTURE	%	% pasture extent (CORINE)	71.9	100	0.00	ℓn (1+PASTURE)
SAAPE	mm	Standard Average Annual Potential Evaporation (1961-90)	501	563	448	ℓn (SAAPE)
FARL		Index of Flood Attenuation from Lakes and Reservoirs	0.95	1.00	0.63	ℓn (FARL)
BFIsoils		Catchment soils and geology index	0.59	0.81	0.29	ℓn (BFIsoils)
ARTDRAIN	m^2	Index of arterial drainage extent (area of benefiting land)	4.56	36.7	0.00	ℓn (1+ARTDRAIN)
ARTDRAIN2	km	Length of upstream network included in OPW scheme channels	16.3	84.6	0.00	ℓn (1+ARTDRAIN2)
S1085	m/km	Mainstream slope (excluding top 10% and bottom 15%)	4.16	30.8	0.24	ℓn (S1085)

Table 5 :Summary of descriptors for the 190 stations used in model building.

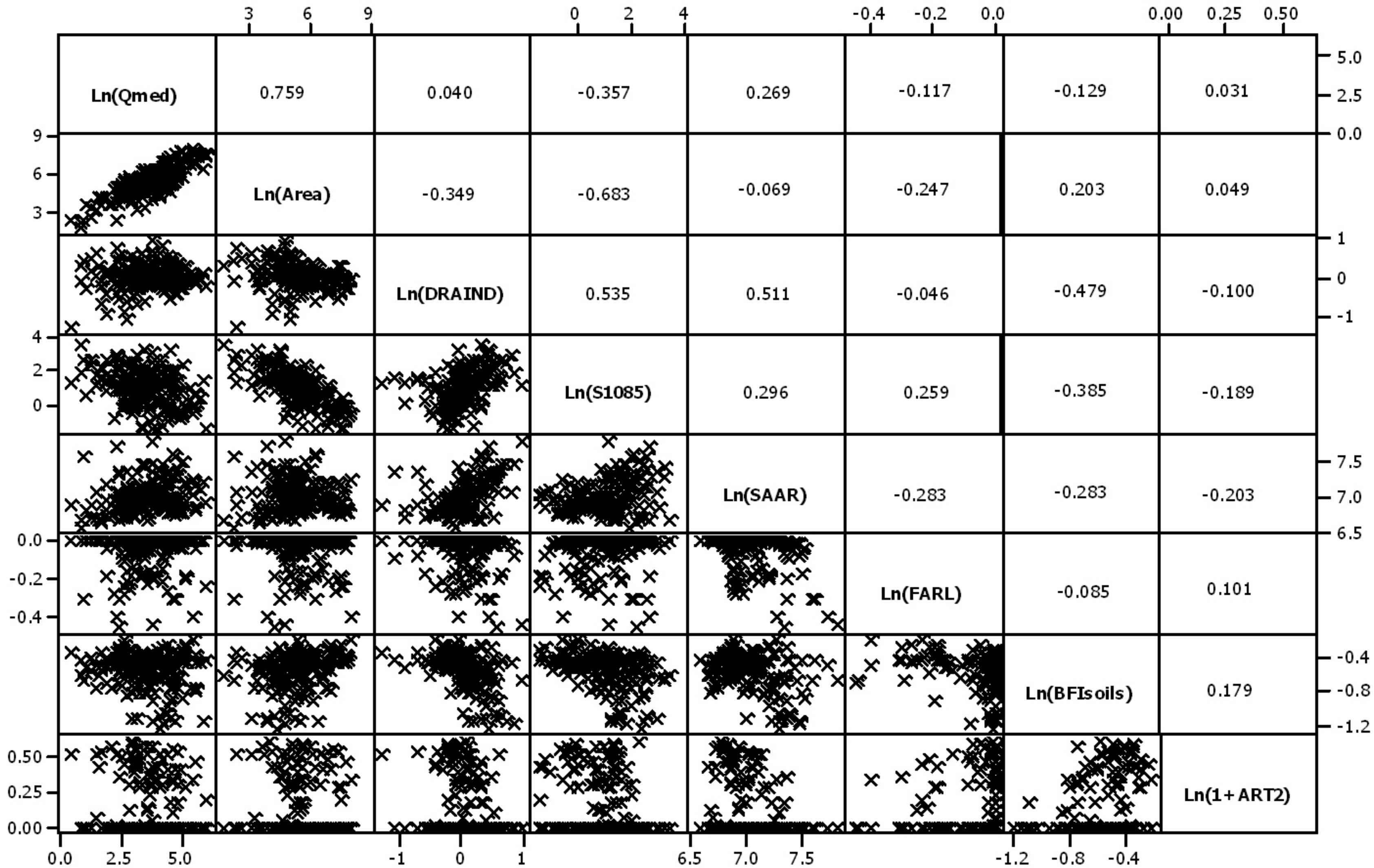

Figure 6: Scatter plot matrix of ℓn(Qmed) and selected catchment descriptors for 190 catchments used.

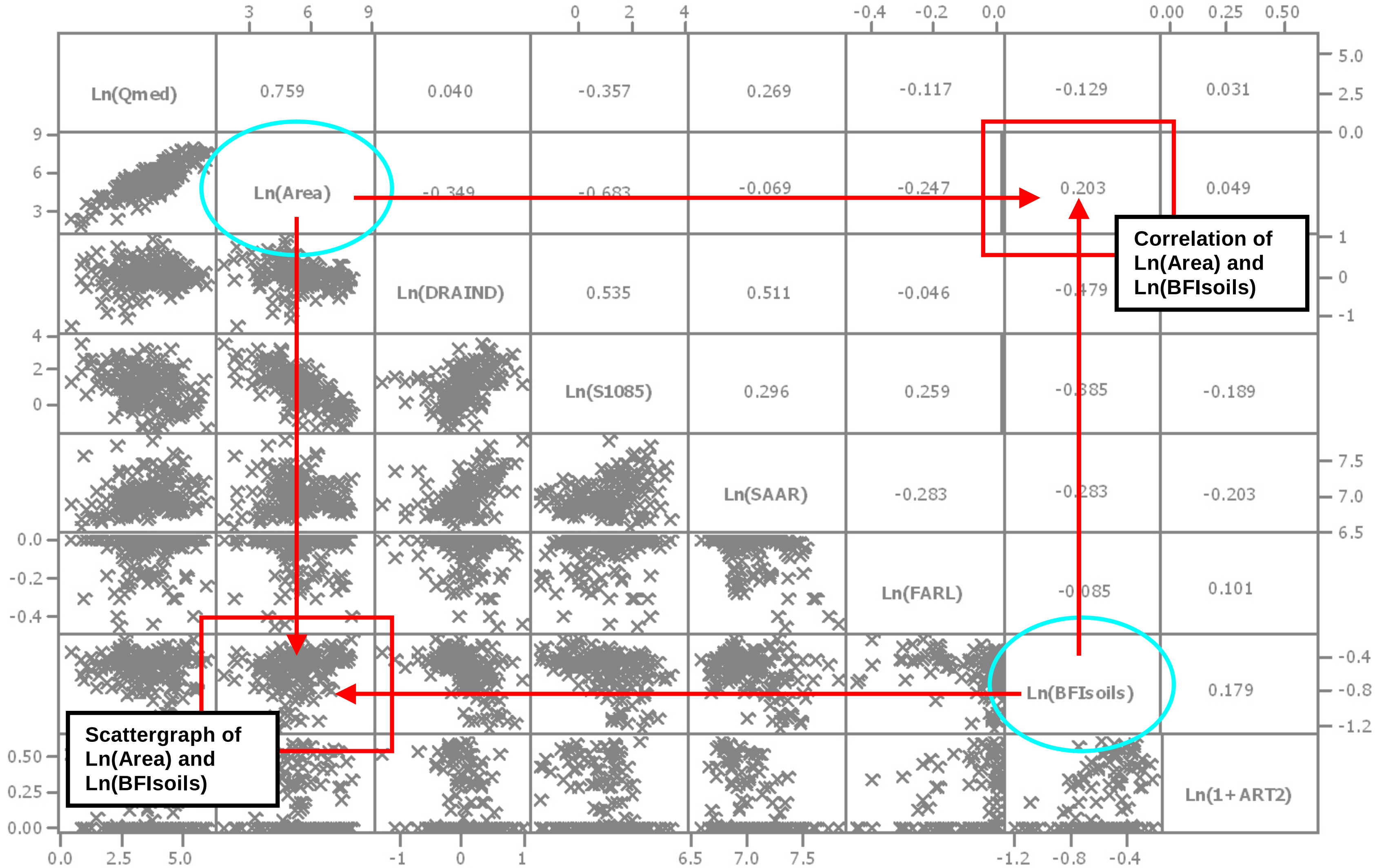

Figure 7: A guide to interpretation of Figure 6.

1.6 Rural Qmed: Calibration and Validation Split

For the purposes of developing a model for Qmed only essentially rural catchments were used. All stations that have experienced urbanisation; those with an URBEXT value of greater than 1.5% were extracted (35 in total) leaving a rural dataset for estimating Qmed for rural catchments of 170 stations (15 pre and post drainage records included). In order to fit and test the derived models a split sample procedure was adopted. Given the practical applications of this work, it was necessary to train models on as wide a range of observations as possible. As such, an approximate 85%:15% split, with stations being randomly selected, was used for calibration and validation respectively, with 25 stations being retained for validation and excluded from model training. Therefore a dataset consisting of 145 stations was used for model building.

2. Modelling Approach

Regression has long been used in hydrology to relate a desired flood quantile to catchment physiographic, geomorphologic, and climatic characteristics (e.g. Nash and Shaw, 1965; NERC, 1975). In the Flood Estimation Handbook (FEH) parlance this is know as the catchment descriptor equation. The analysis is typically performed using the power-form equation of the form:

$$Q_T = a{x_1}^{\beta_1}{x_2}^{\beta_2}{x_3}^{\beta_3}.....{x_p}^{\beta_p} \qquad \text{(Eqn. 6)}$$

where Q_T is the flood quantile of interest, *a* is a constant, x_i is the *ith* catchment descriptor, β_i is the *ith* model parameter and *p* is the number of catchment descriptors. In this work the quantile of interest is the median annual flood which represents the index flood. This form of model holds that changes in catchment descriptors have a scaling effect on the index flood, with the degree of scaling affected by the parameter exponent terms. Many different techniques are available to estimate the model parameters. Linear regression is the most common technique and involves linearising equation 6 through a logarithmic transformation leading to the form:

$$\ln Qmed = \ln(a) + \beta_1 \ln(x_1) + \beta_2 \ln(x_2) + \beta_3 \ln(x_3).....\beta_p \ln(x_p) \quad \text{(Eqn. 7)}$$

Writing the equation in this form gives a linear structure that allows the application of standard multivariate statistical procedures. McCuen *et al.* (1990) highlight that using techniques such as ordinary least squares to estimate the parameters of equation 7 can lead to an unbiased estimate of the index flood in a logarithmic flow domain, however, the estimate will be biased in the real flow domain. In dealing with this problem a number of authors have applied more complicated procedures to avoid this issue such as non-linear and non-parametric regression (*e.g*. Pandey and Nguyen, 1999). However, the use of such techniques was not attempted here, with the more traditional approach of multiple least squares estimation being employed to fit the linear model. In addition, the use of Artificial Neural Networks (ANNs) was also examined in light of the impressive results achieved by Dawson *et al.* (2006) However, the selected approach described below was found to outperform ANNs and so this approach is not dealt with further here.

The catchment descriptor equation was fitted using the multiple least squares regression techniques. Under multiple least squares regression Equation 7 can be written in vector notation as:

$$y = X\hat{\beta} + e \qquad \text{(Eqn. 8)}$$

where *y* is the vector of dependent variables, *X* is the matrix of independent variables, $\hat{\beta}$ is the vector of regression coefficients and *e* is the vector of random errors. These errors are all assumed to be $e \sim N(0, \gamma^2 I)$, meaning that they are uncorrelated, normally distributed with mean of zero and a variance of γ^2, which is referred to as the model error variance. *I* is the identity matrix. Grover *et al*. (2002) highlight that in hydrology the true value of *y* (the flood quantile of interest) is typically unknown, and there is therefore an error associated with its estimation. Using notation developed by Stedinger and Tasker (1985), if $\hat{y}$ is an unbiased estimate of the flood quantile of interest then:

$$E[\hat{y}] = y \qquad \text{(Eqn. 9)}$$

and

$$Var[\hat{y}] = \Sigma \qquad \text{(Eqn. 10)}$$

where Σ is the sampling covariance matrix associated with the estimate of $\hat{y}$. Therefore equation 8 is written:

$$\hat{y} = X\hat{\beta} + u \qquad \text{(Eqn. 11)}$$

where *u* is a random vector of errors that are a combination of model and sampling errors defined as:

$$Var[u] = \Lambda = \gamma^2 I + \Sigma \qquad \text{(Eqn. 12)}$$

where Λ is defined as the full variance covariance residual matrix , γ^2 is a vector of modelling errors and Σ is a matrix of sampling errors. The least squares estimate for β in equation 11 is determined by:

$$\hat{\beta} = \left(X^T \Lambda^{-1} X\right)^{-1} \left(X^T \Lambda^{-1} \hat{y}\right) \qquad \text{(Eqn. 13)}$$

also known as the generalised least squares estimator.

In this study, three least-squares methods, namely ordinary, weighted, and generalised, were applied to solve Equation 13. Ordinary least squares (OLS) is the simplest method used to estimate the parameters and is suitable when the sampling error in the data is small ($\sum \approx 0$) and the error terms have equal variances (homoscedastic) and are uncorrelated. The weighted-least squares (WLS) procedure for hydrologic regression introduced by Tasker (1980) accounts for the sampling error introduced by unequal record lengths. Unequal record lengths mean that the sampling errors of the observations (Qmed) are not equal (heteroscedastic) and the assumption of constant variance in OLS is no longer valid. In this approach a weighting term, proportional to record length (the square root of record lengths) was used to represent the sampling error following Weisberg (1980). Generalised least squares (GLS), introduced to hydrological application by Stedinger and Tasker (1985), is an extension of WLS which also accounts for cross-correlation of flood data between sites. In applying GLS it was assumed that the between site correlations in annual maximum flood data provide a reasonable approximation to the correlations in the regression errors. As such, intersite correlation was assessed and found to be best represented by exponential decay with distance, with inter-site correlation falling to approximately 0.5 at a distance of 50km (Figure 8). An exponential spatial correlation was incorporated into the GLS approach. While it is obvious from Figure 8 that this is an approximation only, it does allow recognition of the possible intersite correlation. Stations with an intersite correlation of 1 are the 15 stations that were divided into pre and post drainage records.

From the modelling conducted it was found that the assumptions of the OLS approach; normally distributed residuals, equal variance and uncorrelated sampling errors in the data were satisfied and therefore the simpler approach was adopted for further use. The extension of the methodology to WLS and GLS returned very minute changes in model performance and parameter values and are not reported here.

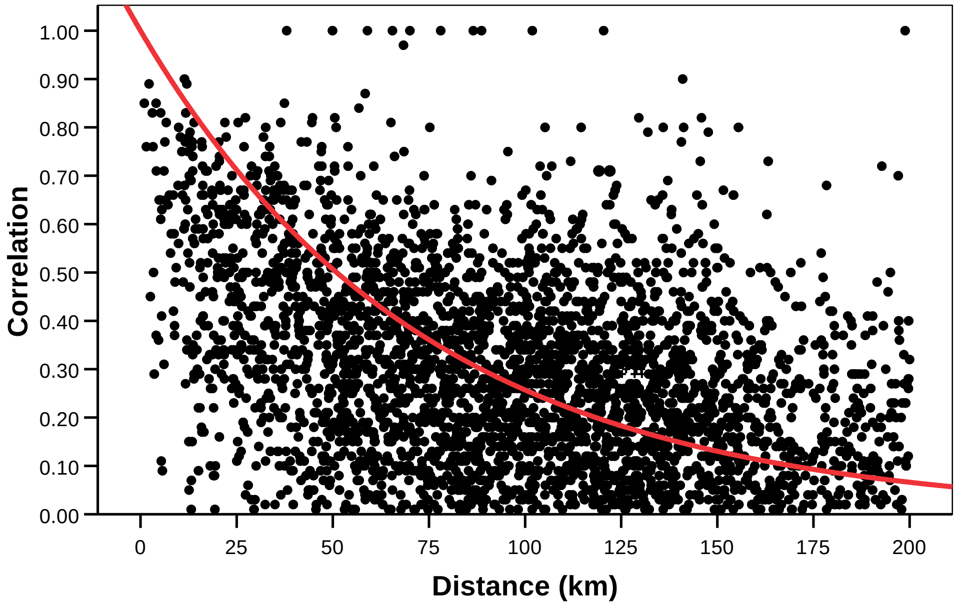

Figure 8. Fitted model for inter-site correlation . Correlation falls to 0.5 at approximately 50km.

2.1 Selecting Catchment Descriptors

Selecting the combination of catchment descriptors to be included in the final QMED model was a lengthy and iterative process and as a consequence not every stage of the procedure is reported here. An exhaustive search was used to select the best 5 sets of variables by fitting every combination of descriptors up to a maximum of nine independent variables using the sites selected for the calibration dataset. The fitted models were assessed based on size, the coefficient of determination (r^2) and the RMSE (Root Mean Square Error) of prediction, their hydrological realism and the behaviour of model residuals. Table 6 shows the three best fitting OLS models using from one to nine catchment descriptors and the resulting r^2 values.

2.2 Choosing a Rural Qmed Model

From the results obtained from the exhaustive search the most appropriate model to represent rural stations in the calibration set was deemed to be a seven variable model. From Table 7 and Figure 9 below, the addition of descriptors eight and nine result in insignificant changes in the coefficient of determination and add little to the model, while also increasing concerns over multi-collinearity.

	ℓn(Area)	ℓn(BFIsoils)	ℓn(S1085)	ℓn(SAAR)	ℓn(Draind)	ℓn(FARL)	ℓn(1+Peat)	ℓn(1+Pasture)	ℓn(1+Alluv)	ℓn(SAAPE)	ℓn(1+Artdrain)	ℓn(1+Artdrain2)	R^2	S.E.E
1	■												0.618	0.629
2	■	■											0.793	0.465
2	■			■									0.753	0.508
2	■		■										0.741	0.520
3	■	■		■									0.843	0.407
3	■	■	■										0.838	0.412
3	■	■			■								0.822	0.432
4	■	■		■		■							0.876	0.362
4	■	■	■	■									0.862	0.382
4	■	■	■		■								0.861	0.384
5	■	■		■	■	■							0.893	0.337
5	■	■	■	■		■							0.887	0.348
5	■	■	■		■	■							0.868	0.375
6	■	■	■	■	■	■							0.903	0.322
6	■	■		■	■	■				■			0.898	0.330
6	■	■	■		■	■		■					0.885	0.352
7	■	■	■	■	■	■						■	0.909	0.313
7	■	■	■	■	■	■					■		0.908	0.316
7	■	■	■	■	■	■				■			0.904	0.322
8	■	■	■	■	■	■				■		■	0.911	0.312
8	■	■	■	■	■	■		■				■	0.910	0.313
8	■	■	■	■	■	■				■	■		0.909	0.315
9	■	■	■	■	■	■		■		■		■	0.911	0.312
9	■	■	■	■	■	■			■	■		■	0.911	0.313
9	■	■	■	■	■	■		■		■	■		0.910	0.315

Table 6: Exhaustive search results for best three models for a model size of up to nine catchment descriptors. Grey cells represent selected descriptors. The coefficient of determination for each model is also shown. ℓn(Area) was forced as the first variable to enter.

N Descriptors	r	r^2	Adj r^2	S.E.E.	r^2 Change	F Change	Sig. F Change
1	0.786	0.618	0.615	0.629	0.618	229.574	0.000
2	0.890	0.793	0.790	0.465	0.175	119.094	0.000
3	0.918	0.843	0.839	0.407	0.050	44.254	0.000
4	0.936	0.876	0.872	0.362	0.033	37.538	0.000
5	0.945	0.893	0.889	0.337	0.017	22.116	0.000
6	0.951	0.903	0.899	0.322	0.010	14.596	0.000
7	0.954	0.909	0.905	0.313	0.006	8.721	0.004
8	0.954	0.911	0.905	0.312	0.001	2.051	0.154
9	0.955	0.911	0.905	0.312	0.001	1.187	0.278

Table 7: Performance diagnostics and significant F change for the addition of each independent variable

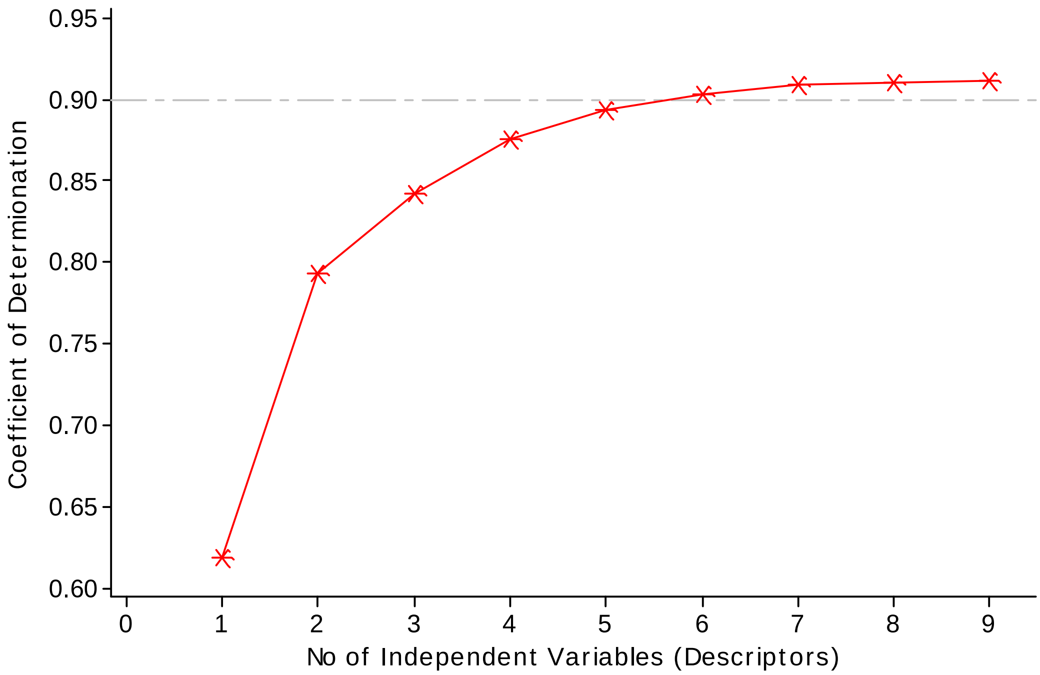

Figure 9: Improvement of R^2 for a model size of one to nine variables

As a result the following seven variable model was selected for use for all rural catchments: (Eqn. 14)

$$\ell n(Qmed)= -11.300+0.937\ell n(AREA)-0.922\ell n(BFIsoils)+1.306\ell n(SAAR) +2.217\ell n(FARL)+0.341\ell n(DRAIND)+0.185\ell n(S1085)+0.408\ell n(1+ARTDRAIN2)$$

The model has an r^2 of 0.909 and Standard Error of 0.313 (Factorial Standard Error of 1.37). Figure 10 plots the fitted and observed Qmed values and shows a good fit with little evidence of heteroscedacisity.

The power function form of the model is given as: (Eqn. 15)

$$Qmed = 1.237X10^{-5}\,AREA^{0.937}\,BFIsoils^{-0.922}\,SAAR^{1.306}\,FARL^{2.217}\,DRAIND^{0.341}$$
$$S1085^{0.185}\left(1+ARTDRAIN2\right)^{0.408}$$

						95% Confidence Interval		Collinearity Statistics	
	β	Std. Error	Beta	t	Sig.	Lower	Upper	Tolerance	VIF
Constant	-11.300	1.151		-9.818	0.000	-13.576	-9.024		
ℓn(Area)	0.937	0.032	1.021	29.456	0.000	0.874	0.999	0.556	1.800
ℓn(BFIsoils)	-0.922	0.169	-0.184	-5.457	0.000	-1.256	-0.588	0.587	1.703
ℓn(SAAR)	1.306	0.173	0.291	7.542	0.000	0.964	1.648	0.449	2.225
ℓn(FARL)	2.217	0.332	0.220	6.669	0.000	1.559	2.874	0.615	1.625
ℓn(DRAIND)	0.341	0.070	0.145	4.853	0.000	0.202	0.479	0.744	1.344
ℓn(S1085)	0.185	0.042	0.178	4.408	0.000	0.102	0.268	0.408	2.453
ℓn(1+ARTDRAIN2)	0.408	0.138	0.080	2.953	0.004	0.135	0.681	0.902	1.108

Table 8: Coefficient diagnostics and collinearity statistics for the rural ℓn(Qmed) seven variable model.

Results from Table 8 show that all coefficients are significant at the 0.05 level. The standardized coefficients (Beta in the table) highlight the relative contribution of each descriptor in describing ℓn(Qmed). ℓn(Area) is by far the most important predictor, followed by ℓn(SAAR), ℓn(FARL) and ℓn(BFIsoils). In order to assess issues of multi-collinearity in the model two statistics were incorporated; namely the Tolerance and the Variance Inflation Factor (VIF). The Tolerance is the percentage of the variance in a given catchment descriptor that cannot be explained by the other descriptors. Small tolerances therefore show that a large amount of the variance in a given descriptor can be explained by others. The Variance Inflation Factor also measures the impact of collinearity among the variables in a regression model. The Variance Inflation Factor is 1/Tolerance, it is always greater than or equal to 1. Values of VIF that exceed 10 are often regarded as indicating multicollinearity, but in weaker models values above 2.5 may be a cause for concern.

From Table 8 good tolerance values are displayed for each of the catchment descriptors. The VIF is less than two for all but ℓn(SAAR) and ℓn(S1085) indicating the correlation between these two descriptors (both high rainfall and high stream slope tend to be associated with high ground, with lower rainfall and shallower slopes at lower elevations). However, the healthy tolerance values supports the retention of both descriptors in the model and suggests that a considerable proportion of the contribution of ℓn(S1085) is not already represented by ℓn(SAAR) in particular.

A simple interpretation of the model can be given as follows.

- Qmed increases with Area
- Qmed decreases as BFIsoils increases, therefore Qmed is greater on less permeable catchments.
- Qmed increases with greater values of SAAR

– Qmed increase with FARL, meaning that it decreases for increased attenuation
– Qmed increases with drainage density
– Qmed increases with slope
– Qmed increases with the extent of arterial drainage works on the river network.

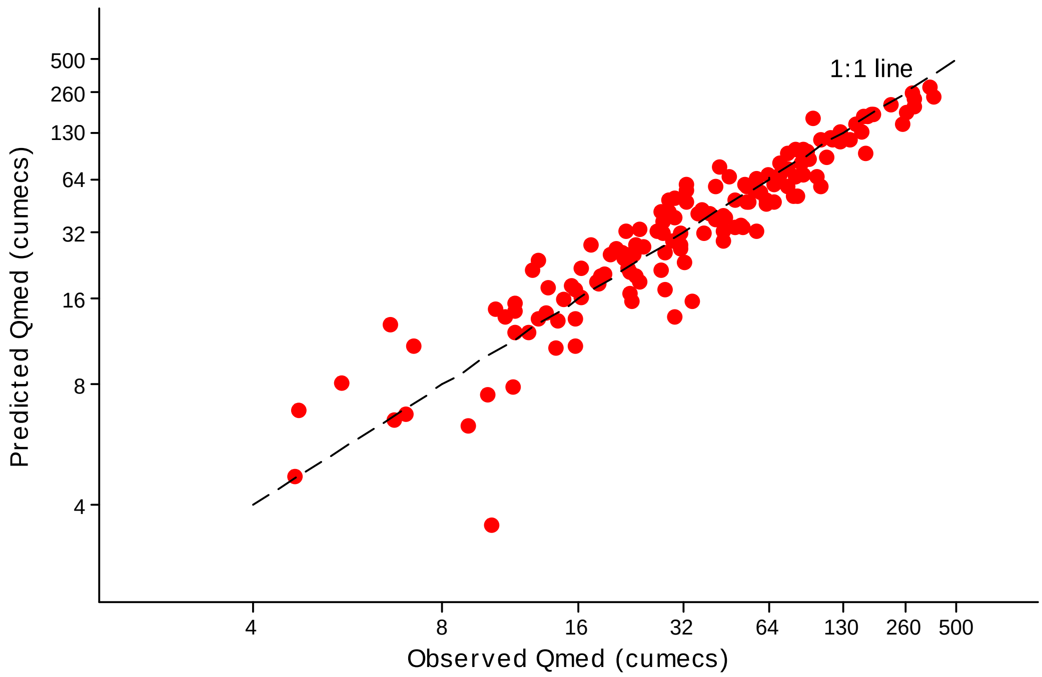

Figure 10: Comparison of Observed and Predicted Qmed for the selected rural model for 145 calibration stations.

2.3 Investigating Model Residuals

As mentioned above the OLS approach to judging and testing the model requires that the residuals are normally distributed with constant variance. From the normal probability plot and ℓn(Residuals) V's fitted ℓn(Qmed) in Figure 11 the residuals appear to be well behaved, with a good visual fit to the assumed normal distribution, even at the tails of the distribution with little evidence of changes in variance with increasing ℓn(Qmed). Figure 12 maps the residuals from the 7 variable rural Qmed model, from the graduated symbols there is some semblance of a tendency to overestimate ℓn(Qmed) in the midlands and west, and underestimate in east and south.

In analysing the residuals further Figure 13 shows scatter plots of the selected rural model against the seven individual catchment descriptors selected. In these plots interest centres on;

- Examining the relationship between residuals and catchment descriptors to assess the success of the model in capturing the range of catchment types represented.

- Identifying the possible presence of a curved pattern in the residuals when plotted against any descriptor. Curvature would indicate non-linear relationships and suggest the need to include additional transformations of the descriptors in model building.

In terms of curvature, the residual plots are well behaved with little evidence of non-linear relationships between catchment descriptors and residuals. In examining model performance for the range of catchment types, particular interest was directed at how well the model performs for permeable catchments, those with a high BFIsoils index, and secondly for the range of catchment areas represented. In relation to catchment area, the dataset used for calibrating or training the model is dominated by larger catchments. From the spread of residuals for the ℓn(Area) plot in Figure 13 it is evident that the selected rural model provides a better fit to larger catchments, in line with the prevalence of such catchments in the training set. Small catchments are less well captured as represented by the spread in residual values. Kjeldsen *et al*. (2008) having found similar issue with an update of the FEH Qmed model highlight that this may be a cause for some concern considering that in practical terms the Qmed model is most often applied to catchments whose areas are in the lower range of those presented in the training set, and indeed somewhat smaller.

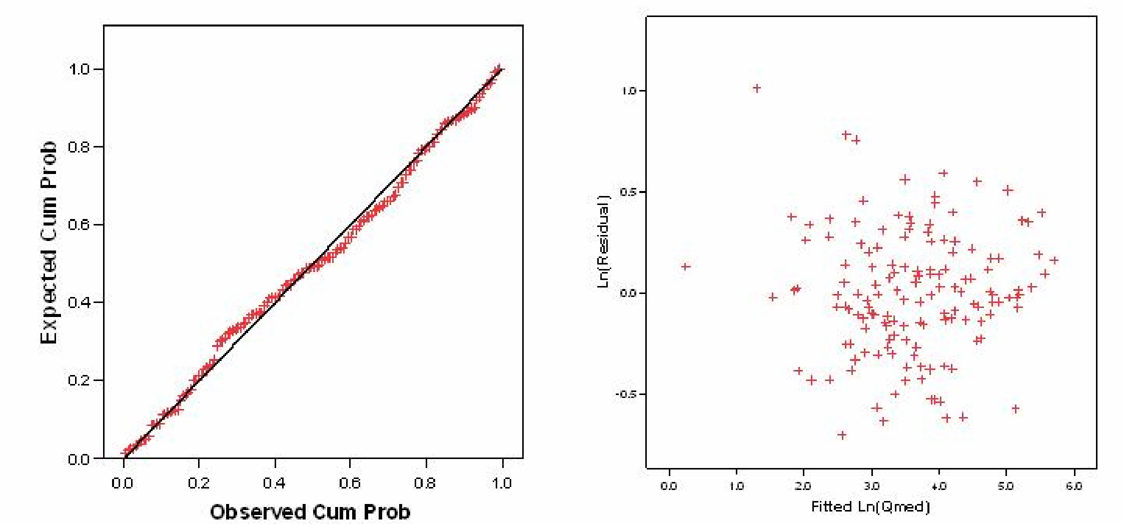

Figure 11: Normal QQ plot and ℓn(residuals) V's Fitted ℓn(Qmed) for the selected rural model.

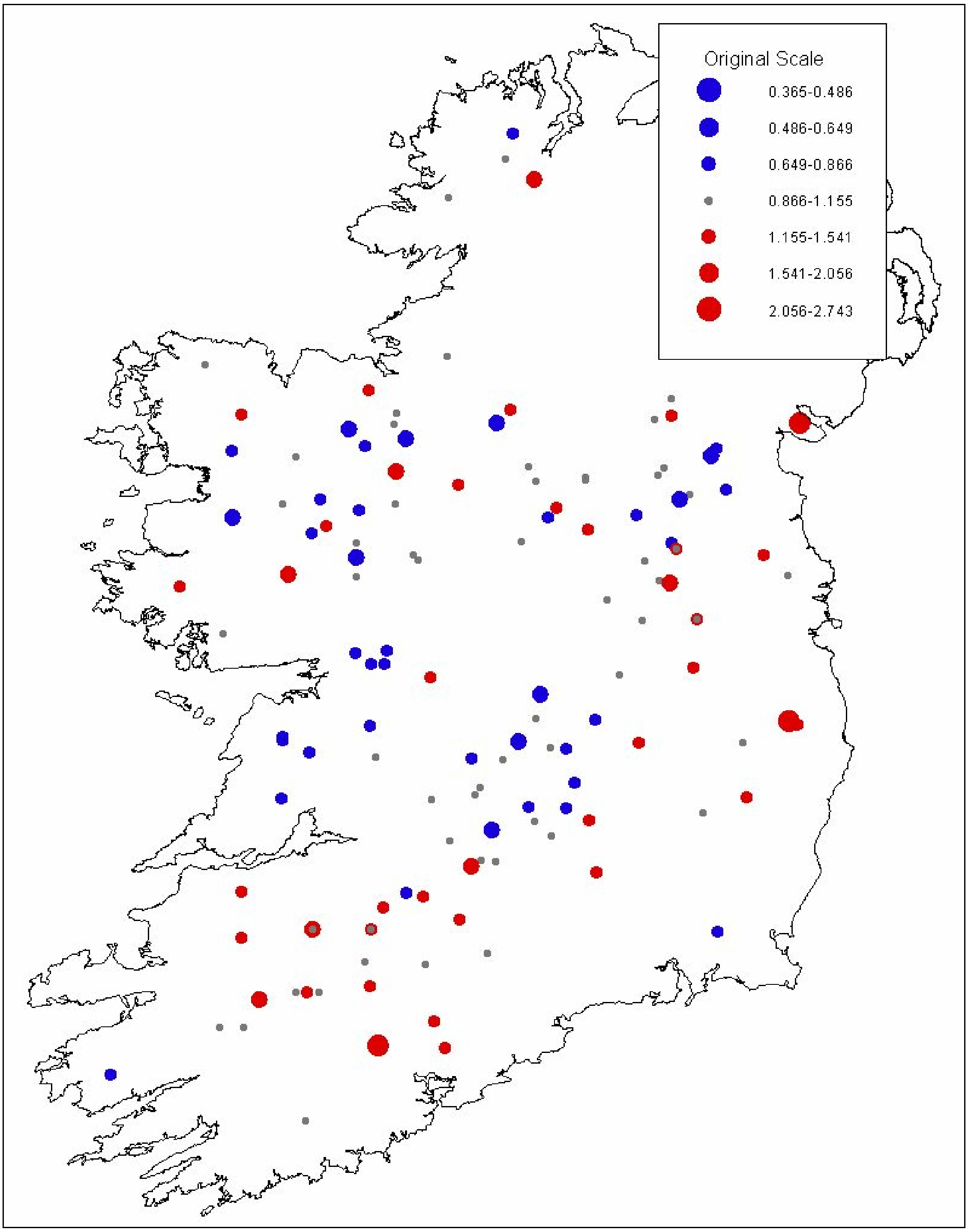

Figure 12: Graduated symbol map of residuals (ℓn scale) at catchment centroids from the selected rural model

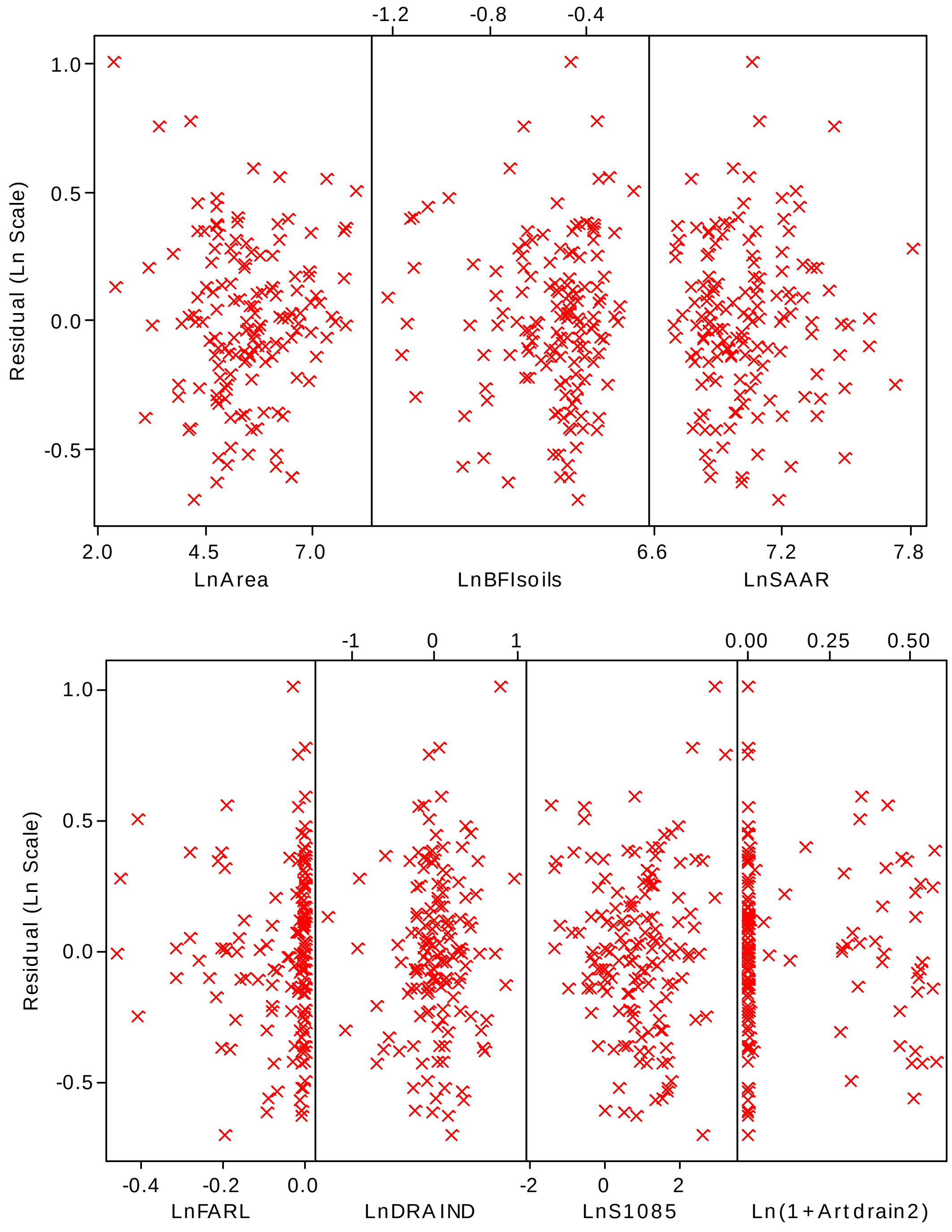

Figure 13: Relationship between regression residuals and individual catchment descriptors for the selected rural model

2.4 Validation Performance

In order to validate the rural ℓn(Qmed) model, the model performance was assessed for stations that were held blind to the training process. The 25 randomly selected stations for validation give a good overall representation of characteristics of stations used in model training and provide a relatively robust method of assessment. Figure 14 shows the resulting scatter plot between observed Qmed and predicted Qmed, with results being more than satisfactory. For these 'blind' stations an r^2 of 0.906 is obtained. Again, the lack of evidence for heteroscedacisity is reassuring that the OLS approach is legitimate for modelling ℓn(Qmed). Concerns over the poorer model performance for small catchments are relaxed following validation. From the histogram in Figure 15 it is evident that the validation stations contain a good degree of spread in relation the range of catchment areas represented with 16 of the stations having a catchment area of less than 300 km^2, 8 stations with an area of less than 200 km^2 and 5 with an area of less than 100 km^2. The model performs well for the smaller catchments in the validation set with an r^2 of 0.920 being returned for the 16 catchments of less than 300 km^2

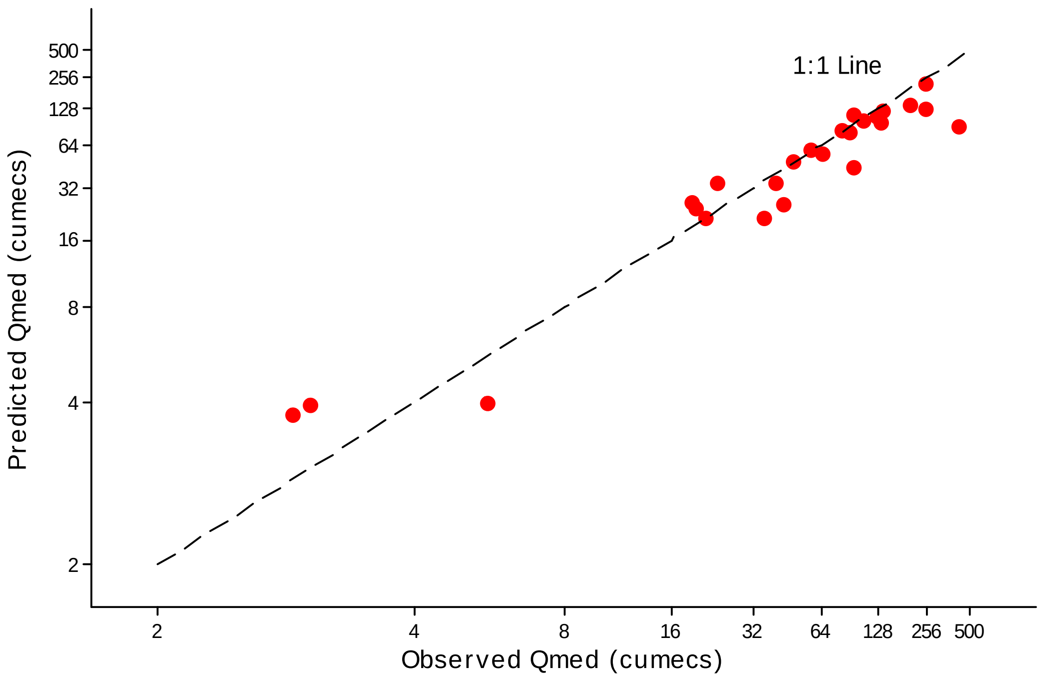

Figure 14: Relationship between Observed and Predicted Qmed for the validation stations

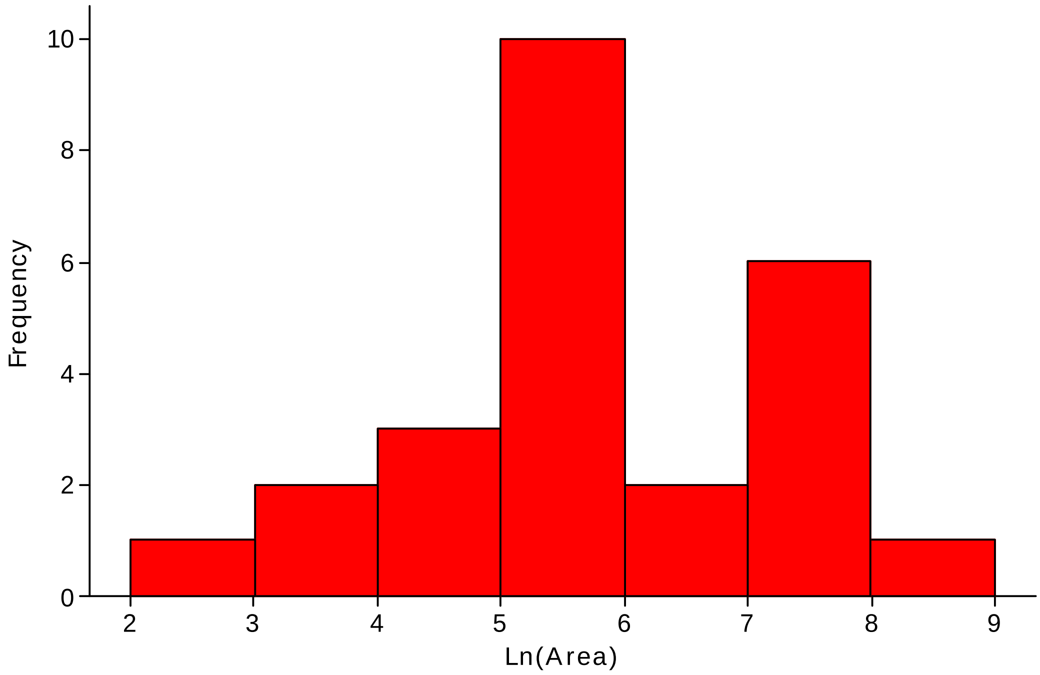

Figure 15: Range of catchment sizes represented in the validation set

2.5 Assessing Model Robustness

2.5.1 Robustness to Influential Stations

Given the importance of assuring model robustness stringent tests were performed to make sure that the omission of certain catchments did not impact significantly on model coefficients. This is always going to be a concern when a seven variable model is fitted to a dataset of 145 observations. In order to test the robustness of parameters to individual catchments the coefficients of the rural ℓn(Qmed) model were bootstrapped and jackknifed.

In conducting the bootstrap resampling, 1000 new samples, each of the same size as the observed data, were drawn with replacement from the observed data. The model coefficients were first calculated using the observed data and then recalculated using each of the new samples, yielding bias corrected and adjusted (BCa) percentile distributions of the model coefficients. In order to assess the influence of individual catchments in deriving the final model coefficients, jackknife resampling was employed to calculate model coefficients for the n possible samples of size n-1, each with one station left out. In testing the sensitivity of model coefficients to the data they were trained on, the model was held to be overly sensitive if the removal of any individual catchment or group of influential catchments from the training dataset resulted in new coefficients becoming insignificant or falling outwith the 95% confidence intervals of the BCa percentiles. Figure 16 shows the normal QQ plots of the bootstrap resampled model coefficients, while Figure 17 shows the absolute relative influence of individual observations in model formulation. Observations with an absolute relative influence of greater than two were selected for further testing. In testing the sensitivity of each parameter the model was rerun with each of the influential observations omitted sequentially without replacement and changes in parameter significance were observed. Table 9 shows the bootstrapped BCa percentiles for each coefficient. From the analysis conducted the model was not found to be overly sensitive to individual observations. Even when all influential points were removed when assessing individual coefficients they remained significant and well within the BCa percentiles.

Bca Precentiles	2.50%	5%	95%	97.50%
Intercept	-13.697	-13.255	-9.729	-9.411
ℓnArea	0.863	0.871	0.984	0.991
ℓnBFIsoils	-1.210	-1.170	-0.454	-0.361
ℓnSAAR	1.050	1.088	1.634	1.705
ℓnFARL	1.654	1.773	2.765	2.865
ℓnDRAIND	0.259	0.286	0.649	0.698
ℓnS1085	0.081	0.094	0.230	0.242
ℓn(1+ARTDRAIN2)	0.123	0.177	0.633	0.677

Table 9: Bootstrapped BCa percentiles for each coefficient

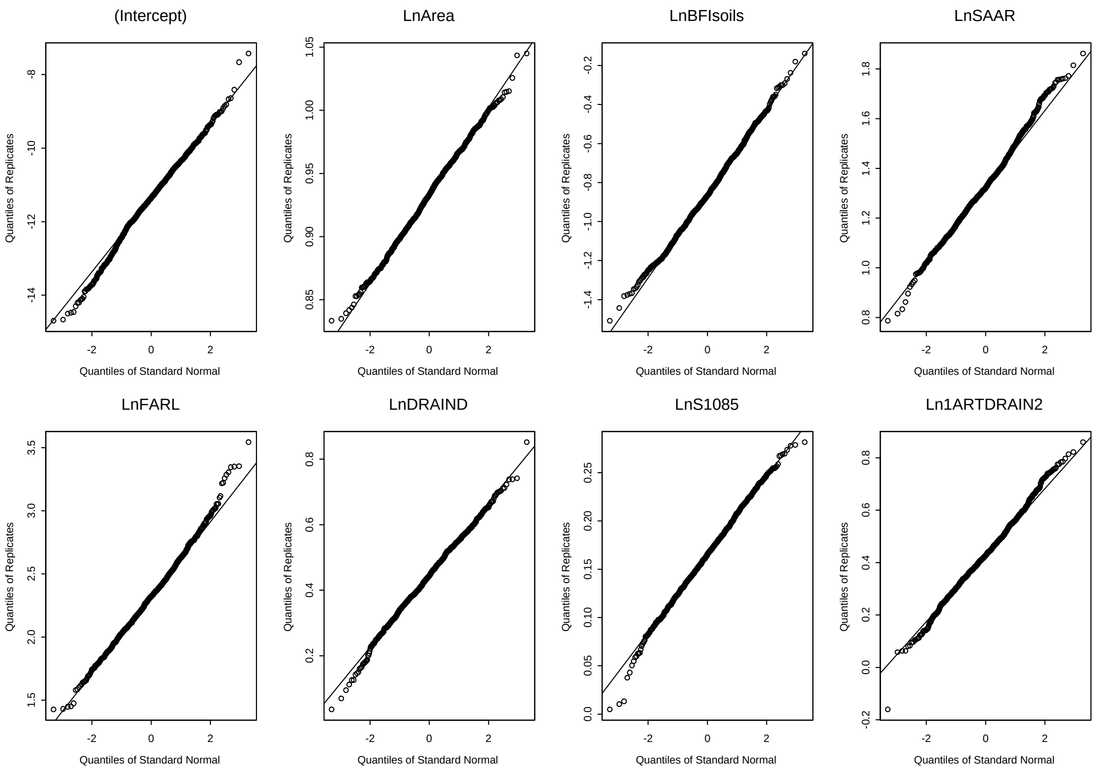

Figure 16: Normal QQ plots of the bootstrap resampled model coefficients

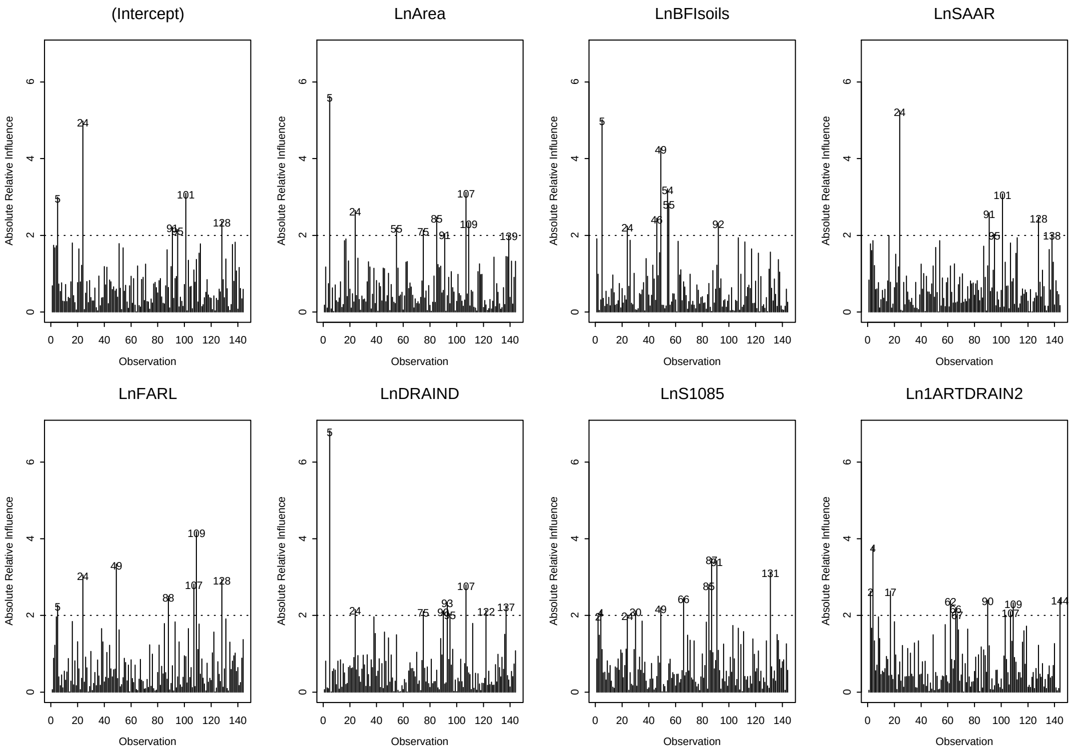

Figure 17: Influence plot for individual stations in determining model coefficients

2.5.2 Robustness to spatial drift in model coefficients

The underlying assumption of the global regression method, as undertaken here using the OLS technique, is that the relationship under study is spatially constant, and thus, the estimated parameters remain constant over space. However, in most cases the relationship varies in space. Geographically Weighted Regression (GWR) is a technique that expands standard regression for use with spatial data (Fotheringham *et al*., 2002). A technique like GWR assesses local influences, allowing for a spatial shift in parameters and a more appropriate fit. Although the technique does not allow extrapolation beyond the region in which the model was established, it does allow the parameters to vary locally within the study area and may provide a more appropriate and accurate basis for descriptive and predictive purposes. In the context of this work the GWR technique was employed to test if model coefficients are spatially constant. GWR works as follows.

A global regression model can be presented as:

$$y = \beta_0(\mu, v) + \beta_1(\mu, v)x_1 + ... + \beta_n(\mu, v)x_n + \varepsilon \qquad \text{(Eqn. 16)}$$

where (μ, v) denotes the coordinates of the samples in space. In Geographically Weighted Regression, the parameter estimates are made using an approach in which the contribution of a sample to the analysis is weighted based on its spatial proximity to the specific location under consideration. Thus the weighting of an observation is no longer constant in the calibration but varies with different locations. Data from observations close to the location under consideration are weighted more than data from observations far away. The parameters are estimated from:

$$\hat{\beta}(\mu,v)=\left(X^{T}W(\mu,v)X\right)^{-1}X^{T}W(\mu,v)y \qquad \text{(Eqn. 17)}$$

where $\hat{\beta}(\mu,v)$ represents an estimate of β, $W(\mu,v)$ is the weighting matrix which acts to ensure that observations near to the location at which the parameter estimates are to be made have more influence on the analysis than those far away. *X* is a matrix of independent variables. Several methods have been proposed to determine the weighting matrix. For fixed kernel size with a Gaussian function, *Wij* (the weight of the specific point *j* in the space at which data are observed to any point *i* in the space from which parameters are estimated) can be represented as a continuous function of *dij*, the distance between *i* and *j*:

$$W_{ij}=\exp\left[-\frac{\left(d_{ij}/b\right)^{2}}{2}\right] \qquad \text{(Eqn. 18)}$$

where *b* is referred to as the bandwidth. An alternative kernel that utilizes the bi-square function can have *Wij* as:

$$W_{ij}=\begin{matrix}[1-(d_{ij}/b)^{2}]^{2} & d_{ij}<b \\ 0 & otherwise\end{matrix} \qquad \text{(Eqn. 19)}$$

Fixed kernels in regions where data are dense may suffer from bias when the kernels are larger than needed. When the kernels are smaller than needed, they may not estimate the parameters reliably where data are scarce, thus spatially varying kernels have also been proposed. Parameter estimation in GWR is highly dependent on the weighting function of the bandwidth of the kernel used. As the bandwidth increases, the parameter estimates will tend to the estimate from a global model. The selection of the weighting function and bandwidth can be determined using a cross validation approach. In this work GWR was deployed using an adaptive bi-square kernel with the selection of weighting functions and bandwidth being based on the cross validation approach.

Table 10 below shows the results of the tests for spatial stability in model parameter coefficients derived for each independent variable in the rural ℓn(Qmed) model. Evident from the results is that the majority of parameter coefficients in the model are indeed spatially constant, with the exception of ℓn(FARL). Figure 18 maps the variation in the ℓn(FARL) coefficient and suggests that the coefficient has higher values in the east and north west of the country and lower values particularly around the upper Shannon basin and the west.

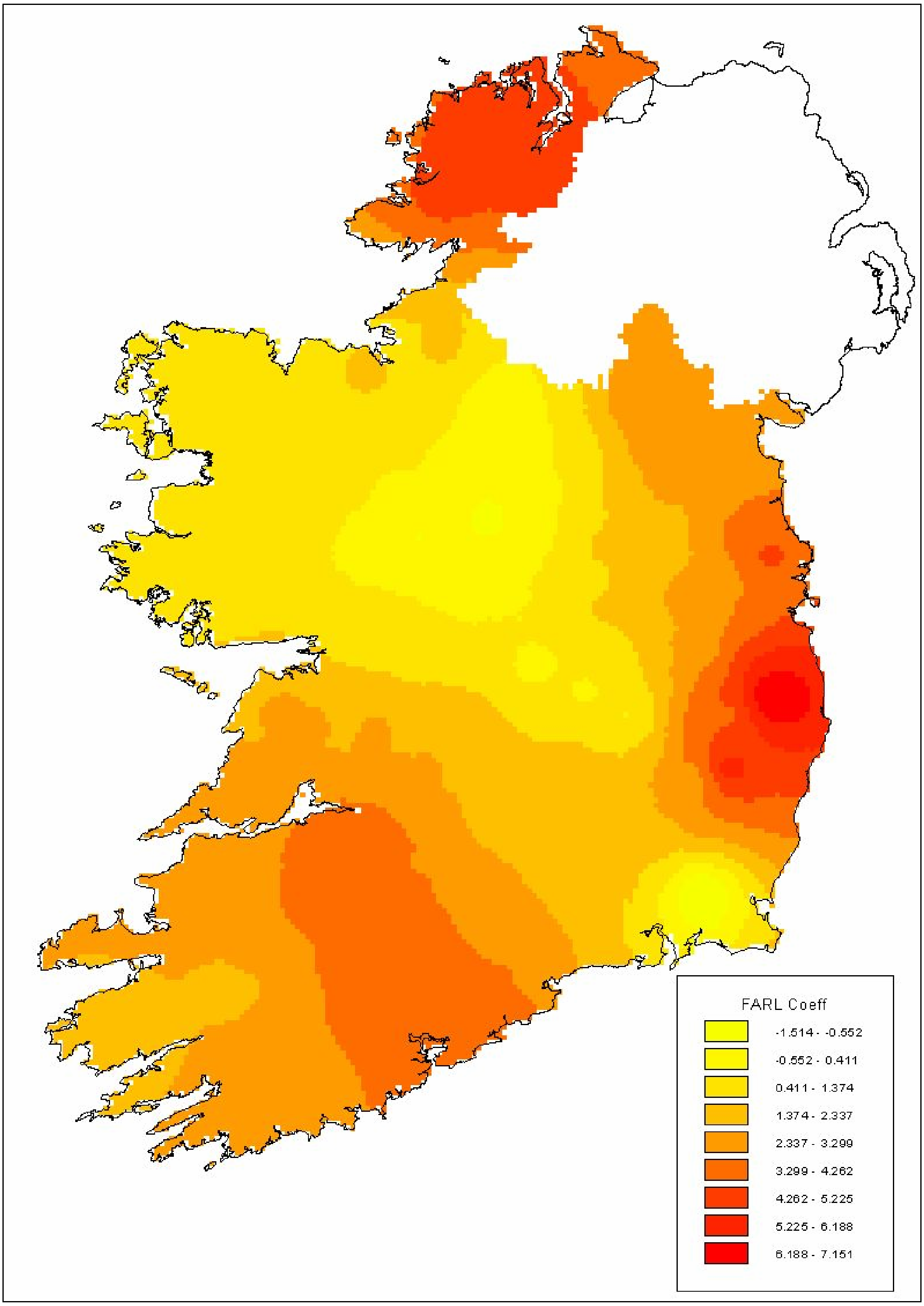

Figure 18: Spatial variation in the FARL coefficient as interpolated from GWR

Parameter	P-value	Significance
Intercept	0.140	n/s
ℓn(Area)	0.840	n/s
ℓn(DRAIND)	0.160	n/s
ℓn(S1085)	0.240	n/s
ℓn(SAAR)	0.130	n/s
ℓn(FARL)	0.050	*
ℓn(BFIsoils)	0.360	n/s
ℓn(1+ARTDRAIN2)	0.860	n/s

Table 10: Results of test for spatial variability in the parameters of the ℓn(Qmed) 7 variable model. * represents significance at the 0.05 level.

2.6 Uncertainty in the Qmed model

In order to express uncertainty in the estimate of Qmed derived from the rural model confidence intervals can be constructed using the factorial standard error (fse) reported. The confidence intervals give an indication of how good an estimate of Qmed is likely to be. Given the lower factorial standard error reported here in comparison to the Flood Studies Report equation, this update is taken to mark an improvement in estimating Qmed from catchment descriptors. Robson and Reed (1999) highlight that it is usual to consider the uncertainty in Qmed in terms of the multiplicative error (i.e. the ratio between the true and estimate value). Multiplicative errors can be estimated from the factorial standard error which is the exponential of the standard error on the ℓn scale.

When it can be assumed that the residuals on the ℓn scale are normally distributed, as is the case here, confidence intervals can be taken as proportional to the estimated value. Approximate 68% and 95% confidence intervals for Qmed can thus be given as:

$$\textit{68\% confidence interval} = (Qmed/fse,\ Qmed x fse) \qquad \text{(Eqn. 20)}$$

$$\textit{95\% confidence interval} = (Qmed/fse^2,\ Qmed x fse^2) \qquad \text{(Eqn. 21)}$$

Consider the example where Qmed is predicted at a location with catchment descriptors: Area=197 km^2, BFI_{soils}=0.67, SAAR=1014.7 mm, FARL=1.00, DRAIND= 0.97, S1085= 1.84 m/km and ARTDRAIN2= 0.78 km.

The resulting estimates of Qmed and upper and lower bounds for both the 68 per cent and 95 per cent confidence intervals are shown in Table 11.

		68%		95%	
Predicted Qmed	**fse**	**Lower**	**Upper**	**Lower**	**Upper**
29.786	1.370	21.742	40.807	15.870	55.905

Table 11: Uncertainty bounds of prediction using the rural ℓn(Qmed) model.

3. Investigating the effects of Arterial Drainage

Given that arterial drainage is such an important facet of Irish hydrology and the fact that a significant number (50) of the rural catchments have been subjected to arterial drainage works, the rural dataset was partitioned and subjected to further tests to assess the potential of:

- Making further improvements to modelling Qmed in rural catchments by deriving a specific model for use with catchments that have undergone arterial drainage (with drainage) and those that have not (undrained).

- To assess in more detail the impact that arterial drainage has on Qmed and to understand the descriptors involved in capturing this response.

The rural dataset was partitioned into 95 no-drainage stations and 50 post-drainage stations.

3.1 Undrained Stations

In line with the methodology described for deriving the rural model above, the undrained stations were subject to an exhaustive search to derive the best combination of catchment descriptors for model building. Following this process a 6 variable model was selected, details of which are given in Table 12. This is similar in make up to the rural model, with only ℓn(1+ARTDRAIN2) being omitted. This result gives confidence to the manner in which ℓn(1+ARTDRAIN2) indexes drainage and in the meaningfulness of the other six variables.

However, there are substantial differences in model coefficients with an increase in the ℓn(BFIsoils) coefficient. Also of note is the fact that the importance of ℓn(BFIsoils) is also reduced when viewed in terms of the standardised coefficient (Beta in Table 12), with ℓn(DRAIND) having a greater contribution. The coefficients of ℓn(SAAR), ℓn(DRAIND), ℓn(S1085) and ℓn(FARL) all increase relative to the all rural model, while only ℓn(AREA) and the Constant reveal a decrease. Overall the model provides good results with an r^2 of 0.892, Standard Error of Estimate of 0.315 and a Factorial Standard Error of 1.37. From the model diagnostics, the OLS approach to fitting the model is again acceptable with ℓn(residuals) being normally distributed and showing little evidence of heteroscedacisity. Figure 19 plots the observed versus predicted Qmed values for the undrained stations. The linear ℓn reduced form of the model is provided below with ℓn($Qmed_{ud}$) representing the undrained model:

$$\ell n(Qmed_{ud}) = -11.145 + 0.910\ell n(Area) - 0.590\ell n(BFIsoils) + 1.328\ell n(SAAR) + 2.762\ell n(FARL) + 0.477\ell n(DRAIND) + 0.214\ell n(S1085) \qquad \text{(Eqn. 22)}$$

	β	Std. Error	Beta	t	Sig.	95% Confidence Interval Lower	Upper	Collinearity Statistics Tolerance	VIF
Constant	-11.145	1.441		-7.737	0.000	-14.008	-8.283		
ℓn(Area)	0.910	0.043	1.054	21.337	0.000	0.825	0.995	0.501	1.996
ℓn(BFIsoils)	-0.590	0.214	-0.132	-2.756	0.007	-1.015	-0.165	0.535	1.869
ℓn(SAAR)	1.328	0.220	0.352	6.026	0.000	0.890	1.766	0.358	2.794
ℓn(FARL)	2.762	0.407	0.310	6.783	0.000	1.953	3.572	0.586	1.707
ℓn(DRAIND)	0.477	0.118	0.183	4.032	0.000	0.242	0.712	0.592	1.690
ℓn(S1085)	0.214	0.053	0.237	4.070	0.000	0.110	0.319	0.362	2.765

Table 12: Coefficient diagnostics and collinearity statistics for the undrained ℓn(Qmed) six variable model.

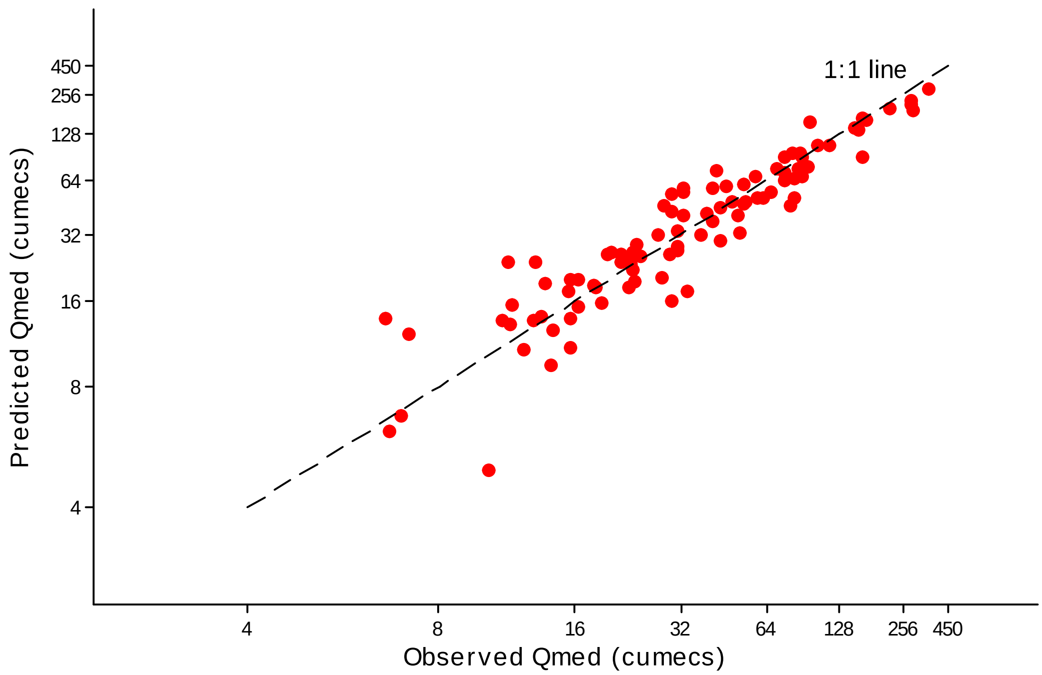

Figure 19: Observed Vs Predicted Qmed for the undrained model.

3.2 Stations with Drainage

The impact of arterial drainage upon the incidence of flooding downstream has long been a source of controversy with the opposing points of view well highlighted by Robinson (1990). In the data provided for the Flood Studies Update there are 15 stations with pre and post drainage records, the Qmed values for each are presented in Figure 20. From this graph it is evident that following arterial drainage there are substantial increases in Qmed at all but four stations. The factorial change in post drainage Qmed relative to pre drainage records is provided in Table 13. From this table arterial drainage has a considerable range of impacts between catchments with the majority showing substantial increases, over 100% in both stations 07010 and 30004. At the other extreme, station 07007 shows a slight reduction in Qmed, while stations 25017 and 30061 show very slight or no changes in Qmed following drainage. In order to try to understand these differences the factorial change was correlated with ℓn(SAAR) and ℓn(BFIsoils). While none of the correlations were significant an interesting relationship is evident with the:

- Change in Qmed following drainage increasing with rainfall.
- Change in Qmed following drainage increasing as BFIsoils decreases, or more simply, the change is greater for less permeable catchments.

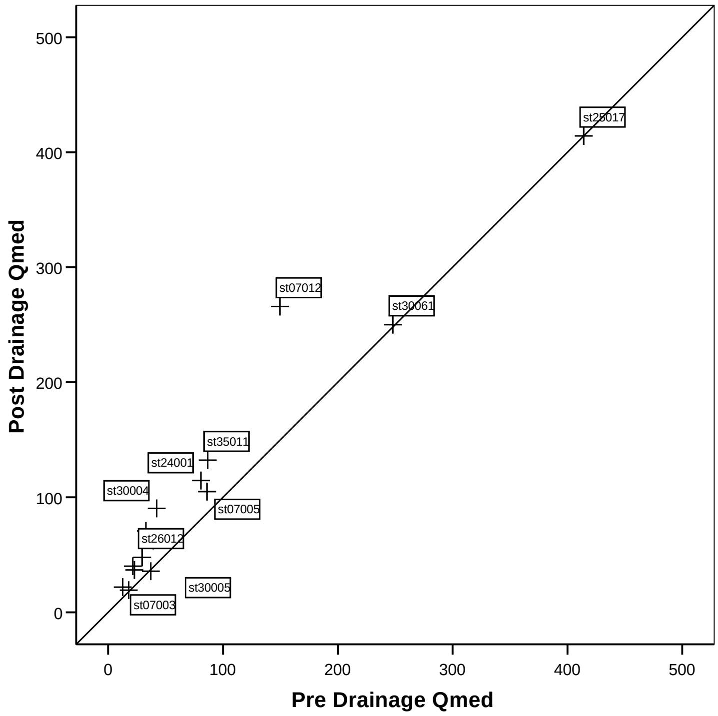

Figure 20: Comparison of Qmed for pre and post drainage records for the same stations

In order to fit a regression (OLS) model to the post drainage data, again the exhaustive regression approach was employed. The final model selected is presented below with model coefficients and diagnostics provided in Table 14 and Figure 21. An excellent model fit is obtained with an r^2 .936, standard error of estimate 0.318, and a Factorial Standard Error of 1.37:

$$\ell n(Qmed_d) = -11.214 + 0.976\ell n(Area) - 1.780\ell n(BFIsoils) + 1.230\ell n(SAAR) + 1.328\ell n(FARL) \quad \text{(Eqn. 23)}$$

Station	Pre (cumecs)	Post (cumecs)	Factorial Change
st03051	21.500	40.100	1.865
st07002	17.910	19.220	1.073
st07003	12.710	21.870	1.721
st07005	86.100	104.980	1.219
st07007	37.150	35.700	0.961
st07010	32.870	70.720	2.152
st07012	149.610	265.860	1.777
st24001	80.840	114.590	1.417
st24004	39.270	62.410	1.589
st25017	414.170	414.170	1.000
st26012	29.610	47.680	1.610
st30004	42.300	90.340	2.136
st30005	22.880	36.780	1.608
st30061	247.970	250.070	1.008
st35011	86.710	132.230	1.525

Table 13: Factorial change in Qmed for post drainage periods relative to the pre-drainage Qmed

It has been suggested that this level of fit may be brought about by the fact that catchments that have undergone drainage are of a similar ilk and thus there is less variance for the model to capture. (Reed, pers. comm.). While the diagnostics confirm the good behaviour of the residuals and the confirmation of the assumption of the modelling approach, Table 14 reveals some interesting results. Firstly, the negative coefficient for ℓn(BFIsoils) is almost three times as large as in the undrained model, highlighting the importance of ℓn(BFIsoils) in modelling catchments with drainage. Furthermore the ℓn(FARL) coefficient is much reduced in line with drained catchments experiencing a faster runoff response. The ℓn(SAAR) exponent is also higher as, logically, it is wet catchments that are normally drained. The coefficients are very much in line with the findings from the observations described above.

						95% Confidence Interval		Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Lower	Upper	Tolerance	VIF
Constant	-11.213	2.088		-5.369	0.000	-15.420	-7.007		
ℓn(Area)	0.976	0.043	0.961	22.688	0.000	0.890	1.063	0.789	1.268
ℓn(BFIsoils)	-1.780	0.283	-0.281	-6.299	0.000	-2.349	-1.211	0.711	1.406
ℓn(SAAR)	1.230	0.309	0.162	3.981	0.000	0.607	1.852	0.856	1.168
ℓn(FARL)	1.328	0.610	0.106	2.179	0.035	0.100	2.556	0.601	1.665

Table 14: Coefficient diagnostics and collinearity statistics for the drained ℓn(Qmed)

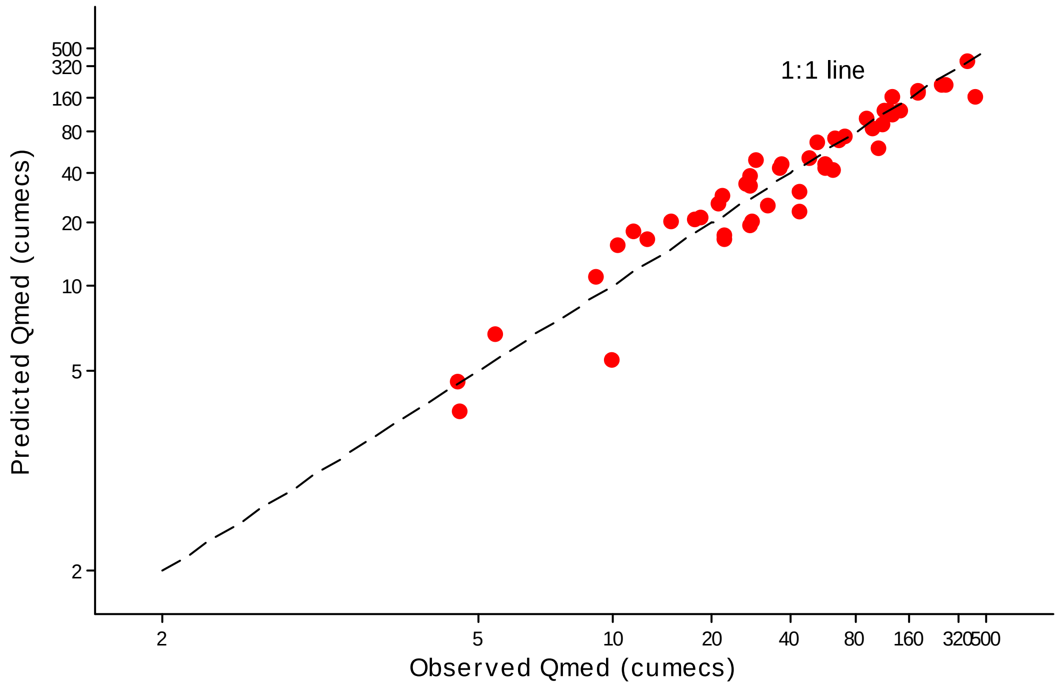

Figure 21: Observed Vs Predicted Qmed for the drained model.

3.3 Choosing a general purpose model

With three different and acceptable models derived for i) all rural catchments, ii) undrained and iii) drained catchments, the problem of which model to use is raised. In order to test the drained and undrained models for ℓn(Qmed), both were assessed on their ability to predict observed ℓn(Qmed) for the validation stations. The validation set contains 17 undrained stations and 8 drained stations. Included within the drained stations are; st07002, st07005 and st35011 which have experienced a 7.29, 21.92 and 52.5 per cent increase respectively in Qmed following drainage. Table 15 shows the success of both partitioned models and the all rural model in validation. For comparison the all rural model is run for both the sets, i.e. both the drained model and the all rural model are used to predict ℓn(Qmed) for the 8 post drainage stations in the validation set. From the results the drained model only marks a slight improvement on the all rural model with an r^2 difference of only 0.043. Additionally, the all rural model performs marginally better than the undrained model for the 17 undrained stations in the validation set. This is likely due to the fact that all of the descriptors selected for the partitioned models are present in the all rural model, with the addition of ℓn(ARTDRAIN2).

Dataset	ℓn(Qmed) Model Rural	 Undrained	 Drained
All Stations	0.906		
Undrained	0.915	0.898	
Drained	0.848		0.891

Table 15: Comparison of each derived model for stations in the validation set

In order to assess the overall improvement in performance by partitioning the dataset the Standard Error of Estimate (S.E.E.) for the all rural model was compared with the combined S.E.E. of the partitioned models. The combined S.E.E. was calculated as:

$$SEE = \sqrt{\frac{ss}{n-2m-2}} \qquad \text{(Eqn. 24)}$$

where *ss* is the residual sum of squares, *n* is the number of stations and *m* is the number of independent variables. The combined partitioned models have a S.E.E. of 0.329, higher that the rural model fitted to the 145 drained and undrained stations together (S.E.E 0.313). In light of this finding, along with the less complicated approach of using a single model, the all rural model for ℓn(Qmed) is advocated for general operational use.

Additionally, from these results it can be suggested that in the all rural model the descriptors ℓn(BFIsoils) and ℓn(ARTDRAIN2) seem to be crucial in determining the response of post drainage catchments while the descriptors ℓn(DRAIND) and ℓn(S1085) are more important in predicting ℓn(Qmed) in catchments that have not undergone drainage.

4. Adjusting the selected model for Urbanisation

The rainfall runoff response of a catchment can be radically altered by urbanisation where impervious surfaces inhibit infiltration and reduce surface retention, while increases in surface runoff are combined with an increase in the speed of response. In assessing the effects of urbanisation it is the change in catchment response that is sought, with the rural model, derived above, assumed to be capable of predicting this response for the type catchments in the dataset. Therefore the aim of this task is to produce an adjustment factor that can be used to augment the performance of the rural model for catchments that have undergone urbanisation. As was highlighted earlier catchments with an urban extent of greater than or equal to 1.5% (URBEXT≥ 0.015) were excluded from the development of the rural ℓn(Qmed) model. The estimation of an adjustment factor was preferred over deriving a separate model for Qmed in urban catchments due to the small number of representative stations (35 in total). The adjustment derived is for catchments that have undergone urbanisation and is not suitable for anticipating the effects of planned urban developments (Robson and Reed, 1999).

Figure 22 shows the results for predictions of the rural Qmed model on the catchments identified as being urban. While it is difficult to extract a definitive influence of urbanisation, with 20 catchments showing an underestimation and 15 showing an overestimation, there is a tendency for more pronounced underestimation, particularly in catchments where URBEXT is large and area is small, i.e. a large proportion of the catchment is urbanised. From Figure 22 the rural model substantially underestimates Qmed for st09011 (The Slang at Frankfort, area 5.46km^2 and urban extent of 68.33%), st10022 (Cabinteely River at Carrickmines, area 12.94km^2, urban extent of 29.72%), and st08005 (Sluice river at Kinsaley Hall, area 9.17km^2 and urban extent 25.01%). This is due to the impact of urbanisation on catchment response where Qmed in urban catchments is likely to be enlarged relative to otherwise similar rural catchments due to the faster response, improved drainage in urban areas and less permeability.

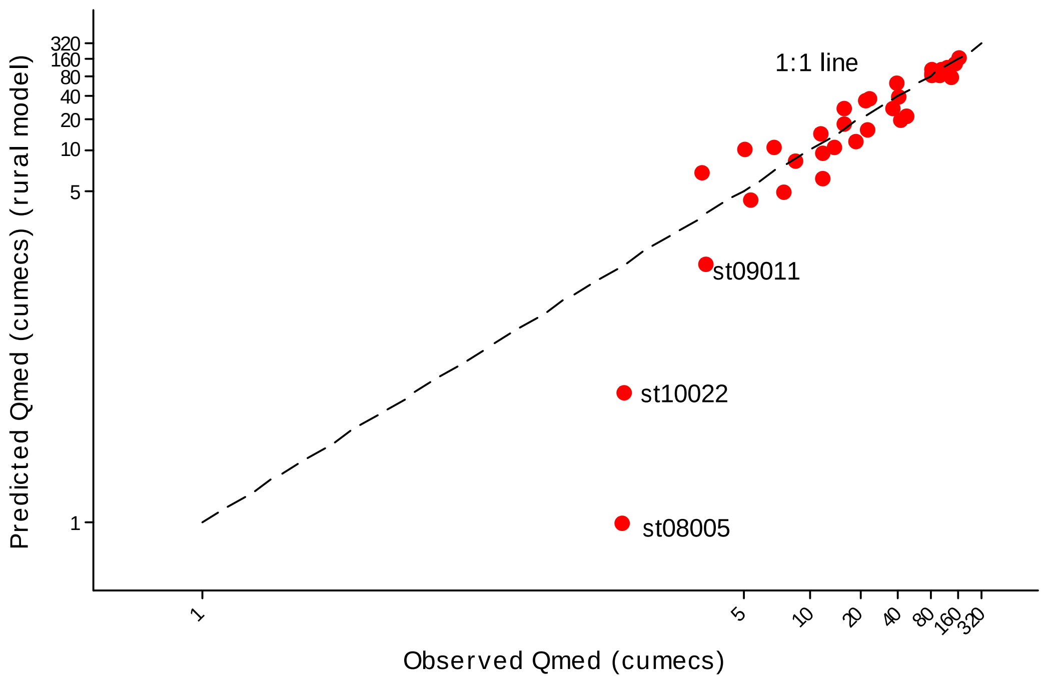

Figure 22: Performance of all rural model in predicting Qmed in urbanised catchments

Given the difficulties in fitting an urban adjustment to the rural model when no clear impact of urbanisation is evident a matched analysis was conducted in which catchments that were similar to the urban dataset in all but extent of urbanisation were identified and the performance of the rural model was assessed for these. In order to selected matched catchments a dissimilarity matrix was produced using ℓn(Area), ℓn(SAAR), ℓn(BFIsoils) and ℓn(FARL) to judge similarity based on a calculated Euclidean distance. From Figure 23 the rural model is judged to perform well on the matched catchments with an r^2 of

0.871, indicating that the model is capable of modeling the type of catchments that are likely to be urbanised. Once again there is no clear indication of over or underestimation. Figure 24 shows the comparison of key descriptors for both the urban and matched rural datasets, with the matched dataset replicating the urban dataset well.

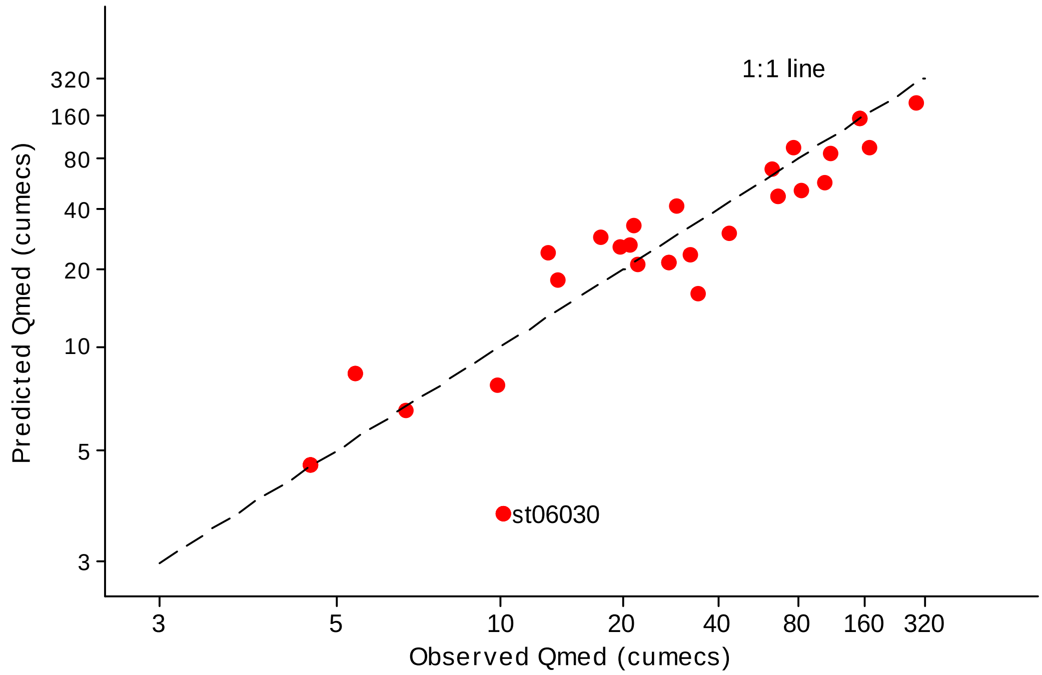

Figure 23: Performance of the all rural model for 'matched' rural catchments (some matched catchments used more than once)

Despite the difficulties in extracting a clear fingerprint of urbanisation, effort was made to derive an adjustment factor for urbanisation that could be used to scale up the rural model results using the form:

$$Qmed = UAF Qmed_{rural} \qquad \text{(Eqn.25)}$$

where *UAF* is an urban adjustment factor that describes the proportional increase in Qmed caused by urbanisation, and $Qmed_{rural}$ is the rural estimate for Qmed explained above. The calculation of the UAF was approached in a similar way to the methods described in Chapter 18 of the FEH (1999), where a separate model is derived for describing UAF. UAF was constrained to have a minimum of 1 due to the fact that urbanisation is unlikely to reduce Qmed. For each of the 35 urban catchments, UAF was estimated by:

$$UAF = \frac{Qmed}{Qmed_{rural}} \qquad \text{(Eqn.26)}$$

where *Qmed* is the observed value, and $Qmed_{rural}$ is that predicted by the 7-variable rural model. UAF was then ℓn transformed and its relationship with

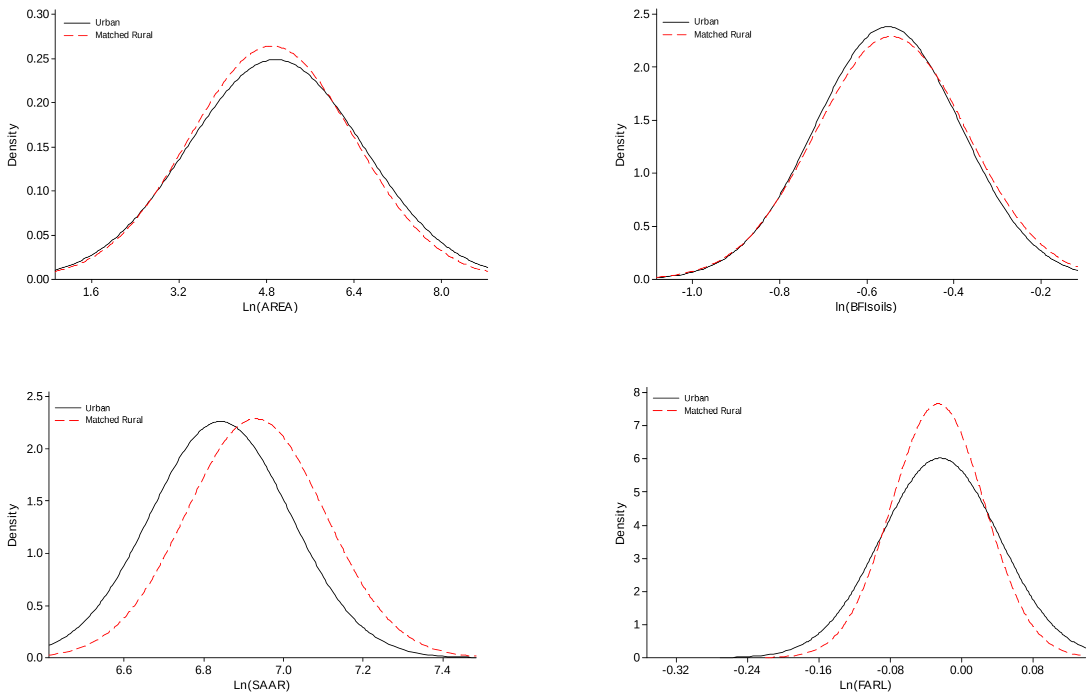

Figure 24: Comparison of key descriptors for both the urban (black) and matched rural (red) datasets for a total of 35 stations.

catchment descriptors examined. Figure 25 shows the scatter plot matrix comparing ℓn(UAF) with a selection of catchment descriptors. From the results ℓn(UAF) is only weakly correlated with the majority of descriptors with the strongest relationships evident for ℓn(1+URBEXT), ℓn(AREA) and ℓn(SAAR). Interestingly there is a significant negative correlation (0.05 level) between ℓn(UAF) and ℓn(AREA) and between ℓn(1+URBEXT) and ℓn(AREA) which is likely related to the fact that the most heavily urbanised catchments are also small catchments, especially those located in the east of the country around the Greater Dublin Area, where catchments draining from the Wicklow mountains, for example, tend to be small and heavily urbanized.

Taking the above relationships on board a number of approaches to modeling UAF were examined beginning with the basic model form of:

$$\ln(UAF) = g\ln(1+URBEXT) \qquad \text{(Eqn.27)}$$

The model was fitted using weighted least squares (WLS) regression with the weights proportional to the urban extent, with more weight given to data from more urbanised catchments. The resulting calibrated model is:

$$\ell n(UAF) = 1.482\,\ell n(1+URBEXT) \quad \text{(Eqn.28)}$$

And in its multiplicative form:

$$UAF = (1 + URBEXT)^{1.482} \quad \text{(Eqn.29)}$$

The model returned an r^2 (in ℓn space) of 0.300, a standard error of 0.735 and a Factorial Standard Error of 2.085. The coefficient 1.482 has a standard error of 0.139. The model has the advantage of decreasing to 1 when URBEXT decreases to zero and returns a value of 2.793 when URBEXT reaches a maximum of 1 (fully urbanised catchment). The value of g in this model is very similar to the coefficient derived for the simpler urban model in the FEH which gave a value of 1.49 (see table 18.1 page 198 in FEH Vol. 3). The high factorial standard error also highlights the large uncertainties involved in modelling UAF. Nonetheless the model represents a theoretically plausible description of the impact of urbanisation on the index flood and can be interpreted as:

- Urban adjustment factor increases with urban extent
- Urban adjustment factor increases to a maximum of 2.793 when a catchment is fully urbanised (URBEXT=1)
- Urban adjustment factor decreases to one as URBEXT tends towards zero.

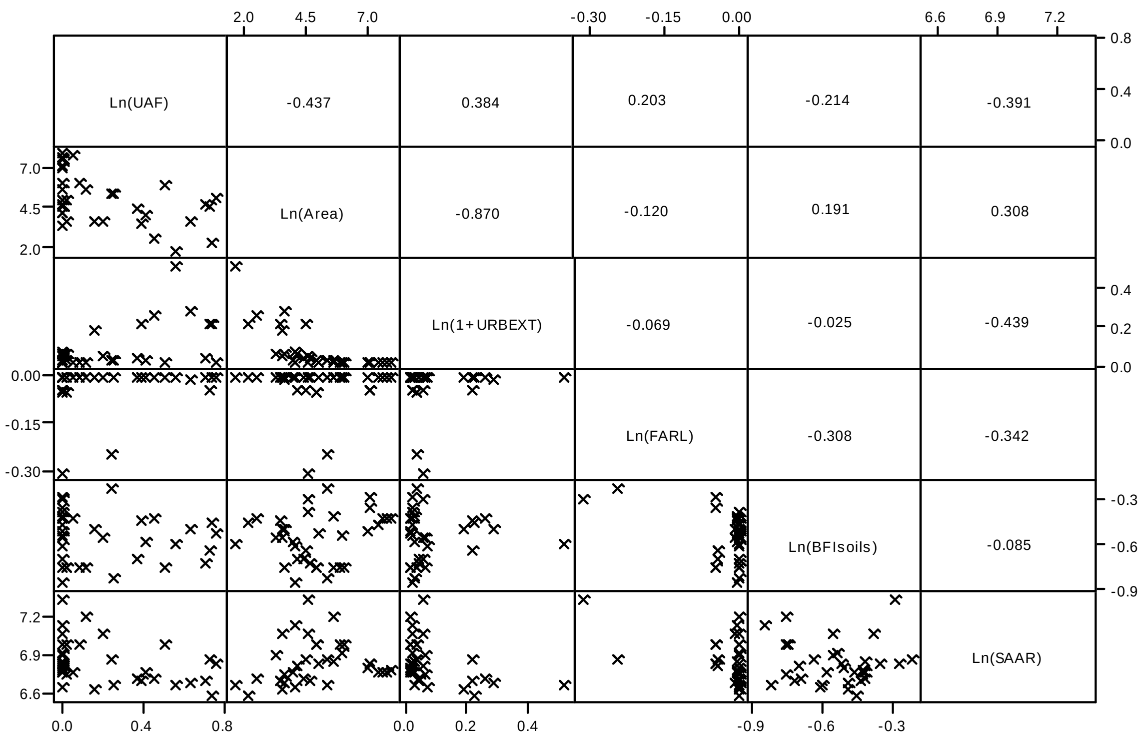

Figure 25: Scatter plot matrix showing the relationship of ℓn(UAF) with selected catchment descriptors

When the UAF is applied to scale up the rural Qmed predictions a slight improvement is made when the full urban dataset is considered increasing the r^2 for the rural model from 0.897 to 0.909 (ℓn scale), however more substantial improvements are evident when only catchments with an URBEXT of greater than 0.04 are considered, with r^2 (ℓn scale) values increasing from 0.728 to 0.787 following adjustment. Furthermore the improvement following adjustment is also substantial for catchments with an URBEXT of over 0.07 showing an r^2 improvement from 0.784 to 0.834 following adjustment. Figure 26 shows the fit between observed Qmed for urban catchments and UAF adjusted predictions. A significant improvement is evident, particularly for the outlying stations identified above, with the exception of st08005 which remains significantly underestimated.

Additional models used in modelling UAF involved the addition of an area term to account for the fact that small catchments draining from the Wicklow mountains tend to be the most heavily urbanised. However, the adjustment factors and coefficient factors derived did not make strong hydrological sense. Additionally it was not possible to consider a permeable catchment adjustment (urbanisation tends to have a greater effect on permeable catchments) due to the very small number of such stations in the available dataset. It is advised that gauges are established in such catchments as a matter of priority.

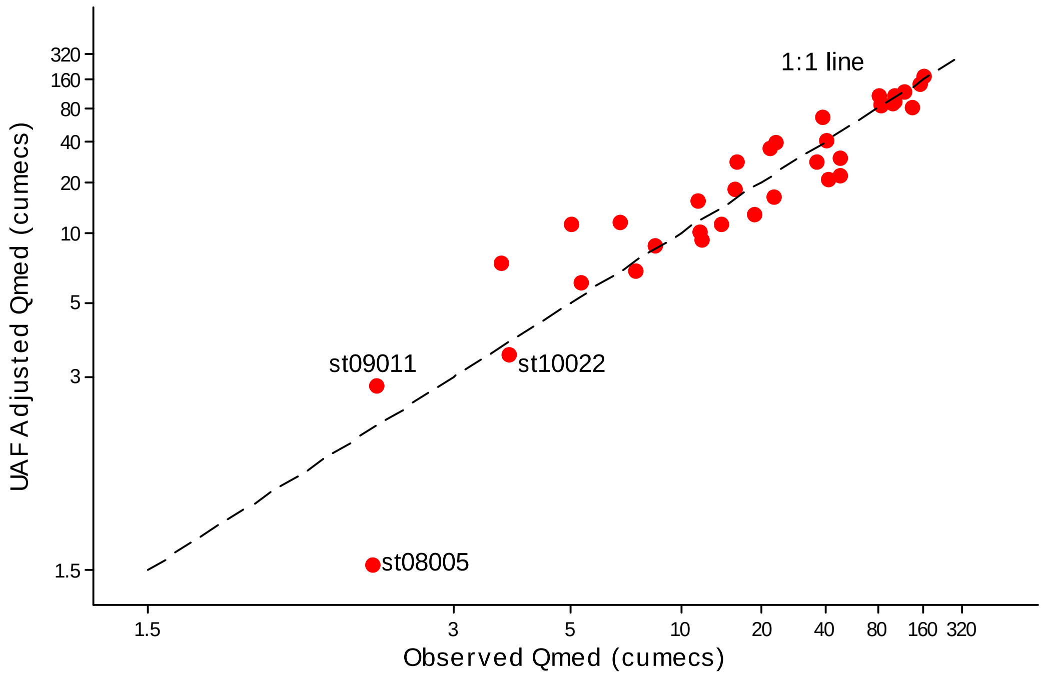

Figure 26: UAF Adjusted Qmed plotted against observed Qmed

5. Improving Model Performance by Data Transfer

Even though the rural model selected for use marks an improvement on previous approaches for Ireland, the uncertainty ranges are still large and every effort should be made to adjust the Qmed values derived using the descriptor model with observed data available from similar catchments.

In terms of adjusting model predictions based on the transfer of information from gauged sites there has been a lot of recent debate within the literature as to whether adjustments should be made using information from catchments that are geographically close to the site of interest (subject site), or from catchments that are hydrologically similar (analogue catchments), in terms of key descriptors, but located anywhere within the study domain. Previous work has tended to highlight the strong clustering of residuals in regression models and to use this to underscore the recommendation to use local data in Qmed adjustments.

In a comprehensive assessment of the FEH statistical method for adjusting Qmed values, Morris (2003) found that inappropriate adjustment of QMED using donor and analogue catchments to be a potential source of error. Morris (2003) suggested that the selection of gauges for the transfer of information should be based on catchment similarity using key catchment descriptors. However, the selection and use of analogue catchments is subjective and the choice of catchment greatly affects the Qmed estimate. Additionally, Morris (2003) concluded that consideration of whether the target and donor catchments are located on the same river network or not (on-line or off-line) could potentially help to reduce prediction errors further. In contrast Kjeldsen *et al*. (2008) suggest that a method where the weight is based on geographical distance should be the preferred option, rather than a method where the choice of donor is based on catchment similarity

Within the Flood Studies Update for Ireland, Chapter 4 compared four approaches to improving estimates of Qmed using a subset of data. Comparative results of adjustment procedures found the use of donor sites to be the most useful for adjusting Qmed regression estimates. A donor site is considered to be a gauging station that is on the same river as a subject site and either upstream or downstream from it. From the work conducted in Chapter 4, the selection of a downstream gauge(s) is most appropriate for data transfer in adjusting Qmed estimates. This work also highlights that the selection of upstream gauge(s) also performs well and performs better than the use of analogue sites.

5.1 Adjustment using Geostatistical Methods

In addition to the traditional approaches discussed above and in Chapter 4, Grover *et al* (2002) highlight that the performance of global regression models can be improved by mapping regression residuals using geostatistical methods and using these mapped residuals to adjust Qmed estimates at point locations. Therefore, as an alternative approach this section aims to:

- Use geostatistical mapping to explore the spatial pattern of mapped residuals and to identify potential regions in the study domain where the selected model tends to overestimate or underestimate the true value of ℓn(Qmed).
- Explore the usefulness of the geostatistical mapping of residuals for adjusting Qmed

By using geostatistical methods to interpolate and map model residuals, Qmed, as estimated from the regression model can then be corrected by:

$$\hat{Q}med_{cor} = \hat{Q}med_{allrural}(\delta) \quad \text{(Eqn.30)}$$

where δ is the interpolated error term. In its ℓn reduced additive form the global regression model can be corrected by adding the error term to the predictions of ℓn(Qmed). In this work an interpolated residual map was constructed for the selected seven variable all rural model. Regression residuals were interpolated using a number of interpolation techniques including Kriging, Spline Interpolation and Inverse Distance Weighting. Based on the assessment of a small validation set the Inverse Distance Weighting (IDW) technique was found to be the most appropriate.

The IDW function determines interpolated values using a linear weighted combination of a set of sample points. The weight assigned to each is a function of the distance of an input point from an output cell location. The greater the distance, the less influence the point has on the output value. In this work a fixed radius of 55 km was used to select input stations for modelling the ℓn(residuals). Figure 27 shows the interpolated residual map, areas of under-estimation are shown in red, while the grey areas represent over-estimation of ℓn(Qmed). Evidence of clustering of model error is evident with areas of overestimation (red) shown to occur in the south east, much of the north west, the mid west and the south west. On the contrary areas of underestimation (blue) are evident for much of the east and south of the country. In order to further refine models for these areas it is essential that monitoring of catchment hydrology is continued and where residuals are large that more monitoring stations are established.

In order to extract the correction values from the interpolated map, the points of interest (i.e. the validation stations) were overlaid and the interpolated ℓn(residuals) extracted. This error was then used to adjust the predictions from the rural ℓn(Qmed) model. The scatter plot showing the IDW adjusted ℓn(Qmed) V's observed ℓn(Qmed) is shown in Figure 28. The r^2 increases from 0.909 before IDW adjustment to 0.912 following adjustment.

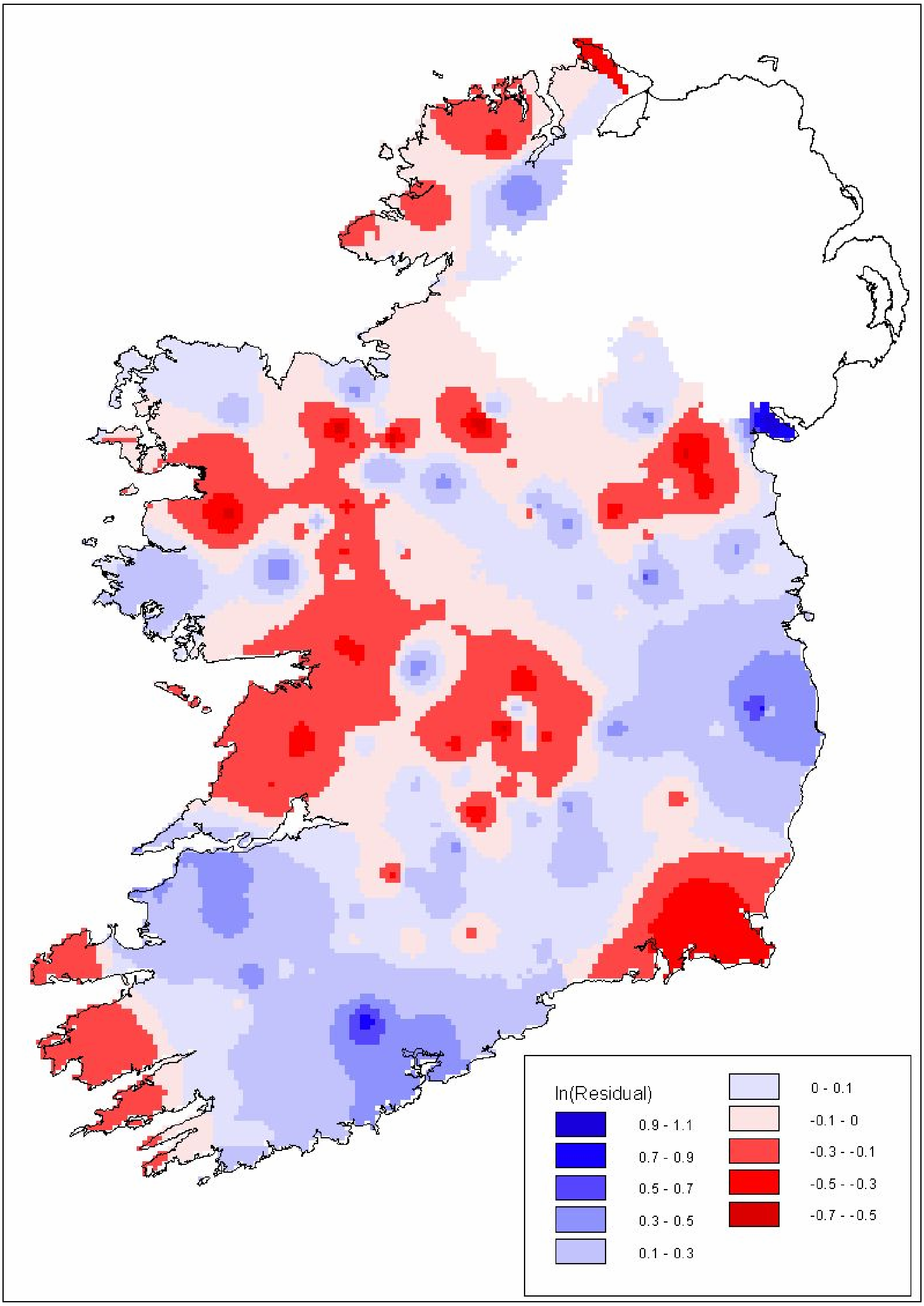

Figure 27: IDW interpolated residual map from the rural ℓn(Qmed) model.

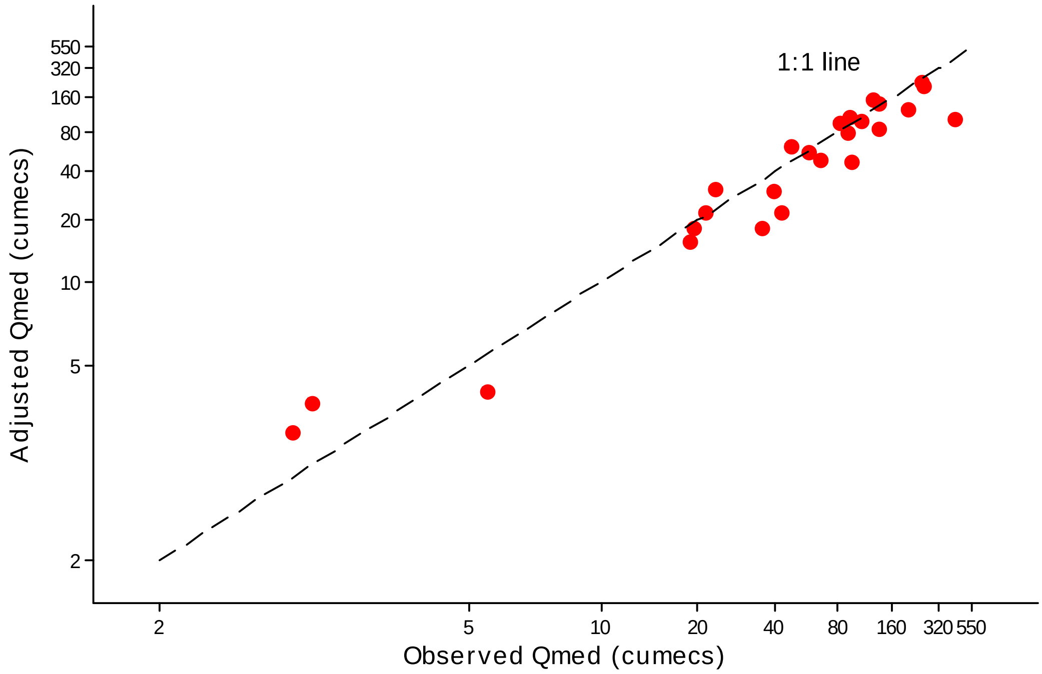

Figure 28: Relationship between IDW adjusted ℓn(Qmed) V's observed ℓn(Qmed)

5.2 Discussion on Geostatistical Mapping for Qmed Adjustment

While they are becoming more common place in flood hydrology, one risk of the use of automated methods for adjusting Qmed is that it overwrites the use of experience and subjective, locally informed decision making in flood hydrology, where there is scope to consider many factors in deriving adjustments, e.g. the degree of similarity between the gauged and subject catchments, the likely quality of the gauged estimate of Qmed and the use of a single or indeed multiple donors based on combinations of selection procedures. Additionally, the automated method for adjusting Qmed using geostatistical mapping does not allow for residuals to be mapped up and down the river system which is in line with the 'nested' approach recommended from Chapter 4 in using downstream or upstream 'pivotal' gauges. That said, the inverse distance weighting is likely to weight nearby gauges on the same stream highly as the geographical distance between centroids of catchments located on the same river network are generally small. Finally, there is a need for further investigations into scale considerations when using automated approaches with a key question arising as to whether it is appropriate to use data from a small tributary to adjust Qmed values for a large main river and vice versa, such issues can arise when interpolating across land rather than up and down river networks.

In conclusion, the geostatistical approach offers the potential of investigating the spatial characteristics of model residuals and of adjusting Qmed estimates. The work described here is successful in improving model performance, however, it is *critical* that the user 'owns' the estimates of Qmed that they produce and as such it is advocated that the user adopt the most appropriate method for the situational context in order to adjust derived values of Qmed.

6. Example Application of FSU Methodology

In order to provide an example application of the methodology derived for index flood estimation in ungauged catchments st26002 The Suck at Rockwood was selected. This station has a Qmed of 56.56 cumecs and a polygon area of 641.45 km^2 but is treated as an ungauged location for illustrative purposes here. The following provides a step by step guide to deriving an estimate for the index flood at this location.

- **Step one: Derive coordinates for ungauged location:**

In this case the catchment centroid has an easting of 172050 and a northing of 270500.

- **Step two: Derive catchment descriptor information:**

Original Descriptor	Value	ℓn Transformed Descriptor	Value
POLYGON AREA	641.451	ℓn(Area)	6.464
DRAIND	0.799	ℓn(DRAIND)	-0.224
S1085	0.500	ℓn(S1085)	-0.693
SAAR	1067.030	ℓn(SAAR)	6.973
URBEXT	0.003	ℓn(1+URBEXT)	0.003
FARL	0.979	ℓn(FARL)	-0.021
BFIsoils	0.604	ℓn(BFIsoils)	-0.505
ARTDRAIN2	0.000	ℓn(1+ARTDRAIN2)	0.000

Table 16: Original and ℓn Transformed descriptors for st26002.

- **Step three: Apply the rural Qmed model using Equation 15 above:**

$$Qmed = 1.237X10^{-5} AREA^{0.937} BFIsoils^{-0.922} SAAR^{1.306} FARL^{2.217} DRAIND^{0.341}$$
$$S1085^{0.185}(1 + ARTDRAIN2)^{0.408}$$

The substitution of values from Table 16 into Equation 15 gives a Qmed value of 58.93 cumecs, an overestimation of 2.37 cumecs.

- **Step four: Apply the Urban Adjustment Factor using Equation 29 above**

$$UAF = (1 + URBEXT)^{1.482}$$

By substituting the relative information from Table 16 an Urban Adjustment Factor of 1.004 is returned giving a UAF adjusted Qmed value of 59.158 cumecs.

- **Step five: Transfer data from gauged locations to improve model prediction**

Transfer data from gauged locations to improve model prediction using the methods described in Chapter four or the geostatistical approach using Inverse Distance Weighting (IDW) described above. The approaches derived in Chapter 4 are used to modify the regression estimate at the subject site by the ratio of the observed Qmed at a donor or analogue site to the regression estimate of Qmed at the donor or analogue site. The equation for adjusting Qmed at the subject site is given as:

$$Qmed^s = Qmed^d \left(\frac{Qmed^s rural\ \mathrm{mod}\,el}{Qmed^d rural\ \mathrm{mod}\,el} \right) \qquad \text{(Eqn. 31)}$$

where $Qmed^s$ is Qmed at the subject site and $Qmed^d$ is Qmed at the donor site. Where an analogue catchment is used the superscript *d* is replaced by *a* for analogue. Table 17 provides the results of adjustment procedures.

Adjustment Approach	Station Number	Qmed (cumecs)	Adjusted Qmed	Factorial Difference
Qmed Rural Model		58.93		
Qmed UAF adjusted			59.16	1.05
Donor up_1	st26006	24.20	54.70	0.97
Donor down_1	st26005	93.20	53.90	0.95
Donor_down_2	st26007	88.20	59.70	1.06
Analogue	st30007	62.90	75.10	1.33
IDW Interpolated			56.95	1.01
Observed Qmed		56.56		

Table 17: Comparison of adjustment procedures for st26002. Donor up_1 and Donor down_1 etc. refer to the first or second station upstream or downstream.

For the particular example used the final modelled Qmed value of 56.95 cumecs is returned for the IDW interpolated adjustment procedure. The use of the next station upstream as a donor site is also very successful. Unfortunately in the real world situation the flood hydrologist will not be able to compare with observations and local hydrological experience should be used in deciding which adjustment method to use.

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Appendix 1 Summary Statistics for the full dataset

CENTE: Catchment Centroid Easting

CENTN: Catchment Centroid Northing

AREA: Polygon Area

Qmedrural: Qmed as modeled by the all rural model (Equation 15)

UAF: Urban Adjustment Factor as modeled by Equation 29

AdjRural: UAF adjusted Qmedrural value

Station No.	CENTE	CENTN	Station Name	River Name	AREA	N	DRAIND	S1085	SAAR	(1+URBEXT)	FARL	BFIsoils	(1+ARTDRAIN2)	Qmed	Qmedrural	UAF	AdjRural
st01041	217110	401430	Sandy Mills	Deele	116.18	32	1.47	7.07	1329.37	1.01	1.00	0.38	1.00	82.61	51.28	1.01	51.94
st01055	205280	389760	Mourne Beg	Mourne Beg Weir	9.69	9	1.55	13.63	1975.76	1.00	0.74	0.51	1.00	2.70	3.75	1.00	3.75
st03051_post	265690	334737	Blackwater	Faulkland	143.19	11	1.39	7.58	1083.30	1.03	0.95	0.47	1.37	40.10	39.52	1.05	41.45
st03051_pre	265691	334738	Blackwater	Faulkland	143.19	16	1.39	7.58	1083.30	1.03	0.95	0.47	1.00	21.50	34.80	1.05	36.50
st06013_post	287730	287060	Charleville Weir	Dee	309.15	30	1.12	2.55	873.08	1.01	0.97	0.62	1.78	27.37	41.94	1.01	42.50
st06014_post	284150	302550	Tallanstown Weir	Glyde	270.38	30	0.87	3.07	927.45	1.01	0.93	0.63	1.66	21.46	33.08	1.02	33.65
st06025_post	282580	287060	Burley	Dee	175.98	30	1.00	3.64	908.31	1.00	0.96	0.61	1.83	18.69	26.40	1.00	26.49
st06026_post	282260	299880	Aclint	Lagan (Glyde)	148.48	46	1.02	4.72	940.87	1.01	0.92	0.62	1.67	12.30	21.68	1.01	21.97
st06030	314620	311980	Ballygoly	Big	10.40	30	2.22	19.31	1156.77	1.00	0.97	0.62	1.00	10.03	3.66	1.00	3.66
st06033_post	303320	285380	Coneyburrow Br.	White (Dee)	55.23	27	1.06	10.02	856.53	1.03	1.00	0.56	1.85	18.60	12.24	1.04	12.75
st07001_pre	267549	267632	Tremblestown	Tremblestown	151.31	18	0.84	2.16	913.24	1.00	1.00	0.73	1.00	11.29	14.52	1.01	14.62
st07002_post	257670	260750	Killyon	Deel	284.97	26	0.79	0.93	920.53	1.00	0.93	0.72	1.80	19.22	24.48	1.01	24.60
st07002_pre	257671	260751	Killyon	Deel	284.97	20	0.79	0.93	920.53	1.00	0.93	0.72	1.00	17.91	19.27	1.01	19.36
st07003_post	277087	239289	Castlerickard	Blackwater (Enfield)	181.51	29	0.80	0.85	809.22	1.01	1.00	0.65	1.76	21.87	17.14	1.01	17.28
st07003_pre	277088	239290	Coneyburrow Br.	White (Dee)	181.51	17	0.80	0.85	809.22	1.01	1.00	0.65	1.00	12.71	13.60	1.01	13.71
st07004_post	262570	292690	Stramatt	Blackwater (Kells)	245.74	49	1.09	2.12	1007.88	1.01	0.77	0.65	1.14	18.05	18.72	1.01	18.91
st07005_post	263021	253853	Trim	Boyne	1332.17	29	0.82	0.51	879.71	1.01	0.98	0.70	1.76	104.98	101.61	1.01	102.65
st07005_pre	263022	253854	Trim	Boyne	1332.17	17	0.82	0.51	879.71	1.01	0.98	0.70	1.00	86.10	80.65	1.01	81.48
st07006_post	274170	285621	Fyanstown	Moynalty	177.45	19	1.18	2.92	936.67	1.00	0.99	0.64	1.38	27.93	25.99	1.01	26.15
st07007_post	256860	239070	Boyne Aqueduct	Boyne	441.18	26	0.81	0.70	870.98	1.01	1.00	0.66	1.77	35.70	41.27	1.02	41.95
st07007_pre	256861	239071	Boyne Aqueduct	Boyne	441.18	8	0.81	0.70	870.98	1.01	1.00	0.66	1.00	37.15	32.71	1.02	33.25
st07009_post	269546	253853	Navan Weir	Boyne	1658.19	29	0.84	0.59	868.55	1.01	0.99	0.71	1.73	134.82	126.23	1.01	127.66
st07010_post	270730	283490	Liscartan	Blackwater (Kells)	699.75	18	0.98	1.71	948.29	1.01	0.91	0.62	1.36	70.72	68.97	1.01	69.57
st07010_pre	270731	283491	Liscartan	Blackwater (Kells)	699.75	29	0.98	1.71	948.29	1.01	0.91	0.62	1.00	32.87	60.92	1.01	61.44
st07011_post	262570	290470	O'Daly's Br.	Blackwater (Kells)	281.74	21	1.03	1.83	1003.32	1.01	0.80	0.68	1.15	35.06	21.07	1.01	21.25
st07012_post	269180	265280	Slane Castle	Boyne	2460.27	19	0.87	0.68	890.06	1.01	0.97	0.69	1.61	265.86	186.10	1.01	188.62
st07012_pre	269181	265281	Slane Castle	Boyne	2460.27	29	0.87	0.68	890.06	1.01	0.97	0.69	1.00	149.61	153.40	1.01	155.47
st07033_post	264950	295340	Virginia Hatchery	Blackwater (Kells)	124.94	25	1.04	2.23	1032.22	1.01	0.89	0.53	1.00	14.62	16.29	1.01	16.44
st07041	267210	252830	Ballinteer Br.	Boyne	1576.07	7	0.82	0.57	870.58	1.01	0.99	0.70	1.00	165.00	95.44	1.01	96.47
st08002	308680	260010	Naul	Devlin	33.43	22	0.79	4.06	791.12	1.01	1.00	0.58	1.00	5.41	4.00	1.01	4.03
st08003_post	303910	251620	Fieldstown	Broadmeadow	83.59	21	1.10	4.26	826.00	1.05	1.00	0.50	1.56	22.55	15.43	1.07	16.48
st08005	319280	243650	Kinsaley Hall	Sluice	9.17	24	0.91	6.80	710.76	1.25	1.00	0.64	1.00	2.32	1.09	1.39	1.52
st08007_post	301060	253190	Ashbourne	Broadmeadow	37.94	17	0.99	3.84	845.02	1.06	1.00	0.47	1.79	8.24	8.06	1.10	8.85

Station No.	CENTE	CENTN	Station Name	River Name	AREA	N	DRAIND	S1085	SAAR	(1+URBEXT)	FARL	BFIsoils	(1+ARTDRAIN2)	Qmed	Qmedrural	UAF	AdjRural
st08008_post	306730	251490	Ashbourne	Broadmeadow	107.92	27	1.31	3.96	810.61	1.04	1.00	0.49	1.44	40.90	19.97	1.06	21.19
st08009_post	309930	245300	Balheary	Ward	61.64	15	1.32	3.78	767.09	1.08	1.00	0.55	1.55	5.00	10.14	1.11	11.29
st08011_post	301314	262945	Duleek	Nanny	181.77	24	1.11	3.05	819.49	1.01	1.00	0.54	1.02	32.22	23.60	1.01	23.84
st08012_post	310510	255580	Ballyboghill	Stream	25.95	17	1.04	5.45	798.70	1.01	1.00	0.46	1.07	4.56	4.65	1.01	4.69
st09001_post	290450	239260	Leixlip	Ryewater	209.63	49	0.83	2.30	783.26	1.03	1.00	0.44	1.14	35.46	27.39	1.04	28.58
st09002	301850	229020	Lucan	Griffeen	34.95	27	0.88	9.11	754.75	1.21	1.00	0.61	1.00	5.25	4.49	1.33	5.96
st09010	311930	222750	Waldrons Br.	Dodder	94.26	19	1.47	20.93	955.04	1.24	0.96	0.53	1.00	47.05	22.33	1.38	30.73
st09011	317260	226240	Frankfort	Slang	5.46	20	1.40	30.77	772.95	1.68	1.00	0.55	1.00	2.34	1.32	2.16	2.86
st09035	305440	228630	Kileen Rd.	Cammock	37.14	10	1.29	13.73	794.21	1.33	0.99	0.61	1.00	11.70	6.15	1.53	9.43
st10002	313780	200640	Rathdrum	Avonmore	230.89	55	1.03	7.16	1530.19	1.00	0.93	0.52	1.00	81.84	66.99	1.00	67.16
st10004	310710	201780	Laragh	Glenmacnass	30.57	22	0.94	24.98	1700.39	1.00	0.99	0.52	1.00	33.90	15.96	1.00	15.96
st10021	321200	223480	Commons Rd.	Shanganagh	32.51	26	1.16	11.37	799.07	1.24	1.00	0.65	1.00	7.26	4.89	1.38	6.74
st10022	319740	224210	Carrickmines	Cabinteely	12.94	23	1.67	10.16	821.92	1.30	1.00	0.66	1.00	3.70	2.34	1.47	3.45
st10028	309850	180440	Knocknamohill	Aughrim	202.92	16	1.06	7.93	1396.92	1.00	1.00	0.69	1.00	46.95	48.17	1.01	48.51
st11001_post	312800	151570	Boleany	Owenavorragh	155.11	33	1.13	1.58	931.07	1.02	1.00	0.60	1.36	47.17	21.84	1.02	22.38
st12001	295230	173740	Scarawalsh	Slaney	1030.75	50	1.07	2.10	1167.31	1.01	1.00	0.72	1.00	157.40	132.93	1.01	134.11
st12013	293760	194090	Rathvilly	Slaney	204.39	30	0.99	3.83	1383.48	1.00	1.00	0.71	1.00	43.55	40.10	1.01	40.38
st13002	284630	124020	Foulks Mills	Corock	62.96	19	1.04	5.49	1043.79	1.00	1.00	0.66	1.00	7.01	10.74	1.00	10.74
st14004	258386	227571	Clonbulloge	Figile	268.85	48	0.60	0.64	838.67	1.00	1.00	0.53	1.00	21.05	21.13	1.00	21.23
st14005	243520	203470	Portarlington	Barrow	405.48	50	1.00	5.70	1014.90	1.02	1.00	0.59	1.00	38.27	65.44	1.04	67.79
st14006	257050	211810	Pass Bridge	Barrow	1063.59	51	0.69	3.11	899.07	1.02	1.00	0.60	1.00	80.52	105.85	1.03	108.54
st14007	255452	193866	Derrybrock	Stradbally	118.59	25	0.55	3.92	814.07	1.01	1.00	0.64	1.00	15.61	10.83	1.01	10.94
st14009	248360	219050	Cushina	Cushina	68.35	25	0.64	2.34	831.24	1.00	1.00	0.61	1.00	6.79	6.64	1.00	6.66
st14011	275664	221578	Rathangan	Slate	162.30	24	0.40	0.99	806.97	1.01	1.00	0.60	1.00	14.00	10.62	1.01	10.75
st14013	279048	167789	Ballinacarrig	Burren	154.40	50	1.16	3.22	887.98	1.00	1.00	0.70	1.00	15.67	17.79	1.00	17.79
st14018	259960	194170	Royal Oak	Barrow	2419.40	65	0.72	0.45	857.46	1.02	1.00	0.66	1.00	148.03	140.20	1.03	143.83
st14019	257150	209950	Levitstown	Barrow	1697.28	64	0.59	0.70	861.46	1.02	1.00	0.63	1.00	99.94	106.65	1.03	109.55
st14029	259960	188020	Graiguenamanagh	Barrow	2778.15	51	0.75	0.53	876.50	1.02	1.00	0.65	1.00	160.74	173.25	1.02	177.32
st14033	239200	202590	Mountmellick	Owenass	78.89	28	1.12	11.49	1145.22	1.01	1.00	0.44	1.00	19.50	25.45	1.01	25.77
st14034	259960	205330	Bestfield	Barrow	2057.36	17	0.63	0.48	856.05	1.02	1.00	0.65	1.00	117.00	117.58	1.02	120.33
st15001	239650	146230	Annamult	Kings	444.35	43	1.10	3.57	935.24	1.00	1.00	0.51	1.00	88.31	68.65	1.00	68.87
st15002	237100	177630	Johns Bridge	Nore	1644.07	36	0.91	0.78	945.44	1.01	1.00	0.63	1.00	198.00	139.52	1.01	141.55

Station No.	CENTE	CENTN	Station Name	River Name	AREA	N	DRAIND	S1085	SAAR	(1+URBEXT)	FARL	BFIsoils	(1+ARTDRAIN2)	Qmed	Qmedrural	UAF	AdjRural
st15004	228610	191660	McMahon's Br.	Nore	491.38	29	1.07	0.83	1067.46	1.01	1.00	0.59	1.00	41.10	59.09	1.01	59.87
st15005	228820	169830	Durrow Foot Br.	Erkina River	379.37	51	0.72	1.90	884.96	1.00	1.00	0.69	1.00	27.44	32.29	1.01	32.51
st15006	237100	165180	Brownsbarn	Nore	2418.27	50	0.91	0.94	941.92	1.01	1.00	0.63	1.00	289.14	204.05	1.01	206.72
st15007	223020	192070	Kilbricken	Nore	339.76	13	1.17	1.05	1123.04	1.01	1.00	0.59	1.00	53.45	47.88	1.01	48.40
st15012	231620	179260	Ballyragget	Nore	1056.80	7	0.92	0.70	974.00	1.01	1.00	0.61	1.00	75.82	96.09	1.01	97.23
st16001	223160	159560	Athlummon	Drish	135.05	33	0.94	0.92	916.42	1.00	1.00	0.62	1.00	15.66	13.64	1.00	13.70
st16002	217030	164680	Beakstown	Suir	485.69	51	0.89	1.27	932.15	1.01	1.00	0.62	1.00	52.66	48.00	1.02	48.79
st16003	201490	161560	Rathkennan	Clodiagh	243.20	51	1.13	5.26	1192.01	1.00	1.00	0.60	1.00	29.98	50.60	1.00	50.75
st16004	214810	170380	Thurles	Suir	228.74	49	0.92	1.80	941.36	1.01	1.00	0.64	1.00	21.37	25.22	1.02	25.62
st16005	197370	150610	Aughnagross	Multeen	84.00	30	1.41	6.56	1153.57	1.00	1.00	0.54	1.00	21.79	21.96	1.00	22.07
st16006	193810	148540	Ballinaclogh	Multeen	75.80	33	1.58	5.89	1115.82	1.00	0.99	0.59	1.00	27.87	17.72	1.00	17.72
st16007	189160	128650	Killardry	Aherlow	273.26	51	1.34	2.84	1330.55	1.01	1.00	0.63	1.00	75.84	58.33	1.01	58.91
st16008	209000	158030	New Bridge	Suir	1090.25	51	0.99	1.04	1029.63	1.01	1.00	0.62	1.00	92.32	116.08	1.01	117.23
st16009	202800	150350	Caher Park	Suir	1582.69	52	1.00	1.00	1078.57	1.01	1.00	0.62	1.00	162.21	174.36	1.01	176.36
st16011	203990	144850	Clonmel	Suir	2143.67	52	1.05	0.95	1124.95	1.01	1.00	0.67	1.00	247.00	229.03	1.01	231.52
st16012	199460	116370	Tar Br.	Tar	229.63	28	1.35	5.47	1320.79	1.00	1.00	0.53	1.00	57.68	65.34	1.00	65.60
st16013	223980	113400	Fourmilewater	Nire	93.58	33	1.58	24.80	1471.29	1.00	0.99	0.53	1.00	93.21	44.57	1.00	44.57
st16051	219279	167216	Clobanna	Suir	34.19	14	0.76	1.72	895.27	1.00	1.00	0.59	1.00	2.85	3.95	1.00	3.95
st18001	179800	90990	Mogeely	Bride	334.08	49	0.85	3.77	1156.40	1.00	1.00	0.70	1.00	62.18	48.35	1.00	48.35
st18002	156370	104360	Ballyduff	Blackwater	2333.69	50	0.96	1.34	1200.37	1.01	1.00	0.62	1.00	351.09	299.61	1.01	302.32
st18003	137680	102000	Killavullen	Blackwater	1256.70	33	1.01	1.66	1298.98	1.01	1.00	0.46	1.00	285.11	259.94	1.01	262.79
st18004	154460	113230	Ballynamona	Awbeg	310.30	47	0.94	1.48	985.41	1.00	1.00	0.68	1.00	31.20	32.31	1.00	32.47
st18005	176900	112220	Downing Br.	Funshion	378.47	50	0.98	2.45	1190.37	1.00	1.00	0.65	1.00	53.05	58.81	1.01	59.18
st18006	133320	102000	CSET Mallow	Blackwater	1054.78	28	1.03	2.01	1331.55	1.00	1.00	0.46	1.00	286.00	237.22	1.01	238.87
st18016	115890	99050	Duncannon	Blackwater	116.73	24	1.03	4.93	1440.95	1.01	1.00	0.35	1.00	79.65	51.27	1.01	51.86
st18048	129000	102000	Drumcommer	Blackwater	867.74	24	1.07	2.51	1382.88	1.00	1.00	0.47	1.00	220.00	213.92	1.01	215.44
st18050	118450	97670	Duarrigle	Blackwater	248.83	24	1.19	3.27	1469.42	1.00	1.00	0.32	1.00	124.50	111.37	1.01	111.96
st19001	162050	61780	Ballea	Owenboy	103.28	49	1.05	3.74	1175.68	1.02	1.00	0.68	1.00	15.42	17.95	1.03	18.46
st19020	183810	81380	Ballyedmond	Owennacurra	73.95	28	0.99	11.28	1179.07	1.00	1.00	0.69	1.00	22.40	15.79	1.00	15.79
st19046	159350	82170	Station Rd.	Martin	63.21	10	1.06	10.14	1196.46	1.00	1.00	0.70	1.00	29.95	13.75	1.00	13.80
st20002_post	132680	54500	Curranure	Bandon	423.74	31	1.20	2.23	1668.87	1.01	0.99	0.59	1.01	126.28	112.66	1.01	114.01
st21001	60600	71360	Cummeragh Weir	Cummeragh	47.23	39	1.57	15.04	2274.91	1.00	0.67	0.60	1.00	10.75	13.82	1.00	13.82
st22003_post	100970	107320	Riverville	Maine	271.29	9	1.15	5.00	1349.29	1.02	1.00	0.47	1.19	98.01	87.52	1.03	89.76

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st22006	109850	89040	Flesk	Flesk/Laune	328.81	51	1.27	9.42	1819.32	1.01	0.96	0.41	1.00	169.09	172.86	1.01	174.24
st22009	99783	94399	White Bridge	Deenagh/ Laune	35.40	24	1.08	10.74	1172.49	1.06	1.00	0.58	1.00	11.47	9.36	1.09	10.16
st22035	100940	89040	Laune Bridge	Laune	559.66	14	1.36	7.56	2009.91	1.01	0.73	0.65	1.00	116.40	115.73	1.01	117.40
st22071	100940	89040	L. Leane	Tomies Pier	557.70	33	1.36	7.76	2010.83	1.01	0.73	0.64	1.00	104.10	115.77	1.01	117.43
st23001_post	109100	138950	Inch Br.	Galey	191.74	33	1.39	3.55	1084.01	1.00	1.00	0.33	1.19	99.05	66.50	1.00	66.80
st23002_post	109130	122100	Listowel	Feale	646.85	45	1.11	4.28	1345.00	1.00	1.00	0.32	1.00	368.19	248.52	1.01	249.84
st23012	89370	113730	Ballymullen	Lee (Kerry)	61.63	18	1.65	11.80	1264.00	1.02	1.00	0.43	1.00	15.66	27.11	1.04	28.10
st24001_post	161150	133340	Croom	Maigue	770.23	27	1.10	1.96	941.30	1.01	1.00	0.53	1.51	114.59	119.89	1.01	121.07
st24001_pre	161151	133341	Croom	Maigue	770.23	22	1.10	1.96	941.30	1.01	1.00	0.53	1.00	80.84	101.26	1.01	102.25
st24002	169878	138456	Gray's Br.	Camoge	229.40	27	1.14	1.68	917.14	1.00	1.00	0.59	1.60	23.49	33.89	1.01	34.11
st24004_post	156830	124940	Bruree	Maigue	242.13	18	1.16	3.52	974.53	1.01	1.00	0.52	1.34	62.41	46.32	1.02	47.24
st24004_pre	156831	124941	Bruree	Maigue	242.13	20	1.16	3.52	974.53	1.01	1.00	0.52	1.00	39.27	41.06	1.02	41.87
st24008_post	161151	133340	Castleroberts	Maigue	806.04	32	1.08	2.04	939.47	1.01	1.00	0.55	1.52	119.13	120.63	1.01	121.87
st24011_post	135390	125090	Deel Bridge	Deel	281.23	33	1.09	2.23	1058.19	1.01	1.00	0.49	1.42	104.55	58.02	1.02	59.07
st24012_post	134040	126890	Grange Bridge	Deel	366.28	36	1.23	2.17	1073.02	1.02	1.00	0.47	1.36	133.24	80.04	1.02	81.93
st24013_post	134040	128250	Rathkeale	Deel	438.79	52	1.19	2.06	1071.60	1.02	1.00	0.47	1.39	101.76	93.41	1.02	95.63
st24022_post	175880	137280	Hospital	Mahore	41.21	20	1.05	3.28	942.31	1.00	1.00	0.62	1.70	9.80	7.56	1.00	7.59
st24030_post	135391	125092	Danganbeg	Deel	258.88	25	1.10	2.40	1051.24	1.01	1.00	0.44	1.40	52.00	59.50	1.02	60.45
st24082_post	161155	133340	Islandmore Weir	Maigue	762.84	28	1.10	1.96	941.70	1.01	1.00	0.53	1.51	140.01	118.24	1.01	119.36
st25006_post	227880	230990	Ferbane	Brosna	1162.76	48	0.73	0.88	931.99	1.02	0.96	0.76	1.51	81.67	83.70	1.03	86.05
st25011_post	226360	230990	Moystown	Brosna	1180.21	49	0.72	0.83	930.98	1.02	0.96	0.71	1.51	82.02	89.95	1.03	92.54
st25014_post	219498	211667	Millbrook	Silver	164.41	48	0.91	5.83	1007.65	1.00	1.00	0.64	1.37	17.25	28.39	1.01	28.59
st25016_post	235934	217013	Rahan	Clodiagh	275.17	47	0.65	5.94	947.09	1.03	1.00	0.66	1.53	23.08	38.42	1.04	40.00
st25017_post	203250	270010	Banagher	Shannon	1920.00	34	0.81	0.25	1024.05	1.01	0.79	0.65	1.21	414.17	84.58	1.01	85.61
st25017_pre	203251	270011	Banagher	Shannon	2280.00	23	0.81	0.25	1024.05	1.01	0.79	0.65	1.00	414.17	91.94	1.01	93.06
st25020_post	178566	218020	Kileen	Killimore	197.09	35	0.97	1.84	1014.70	1.00	1.00	0.67	1.78	43.65	29.79	1.01	29.98
st25021	211310	194230	Croghan	Little Brosna	479.25	44	0.77	1.47	927.77	1.01	0.99	0.58	1.00	28.58	48.30	1.02	49.18
st25022	217414	202616	Syngefield	Camcor	161.34	22	0.80	9.83	984.46	1.00	1.00	0.59	1.00	31.20	27.13	1.00	27.21
st25023	205270	187570	Milltown	Little Brosna	113.86	52	0.84	2.64	922.49	1.00	1.00	0.71	1.00	11.22	12.03	1.00	12.07
st25025_post	193649	188116	Ballyhooney	Ballyfinboy	161.20	33	0.64	2.60	904.54	1.01	1.00	0.70	1.01	10.18	14.90	1.01	15.10
st25027_post	197180	177220	Gourdeen	Ollatrim	118.86	39	0.94	3.93	1021.15	1.01	1.00	0.62	1.48	22.10	21.27	1.01	21.47
st25029_post	195290	174780	Clarianna	Nenagh	292.67	33	0.89	4.83	1108.68	1.01	1.00	0.62	1.41	56.48	54.87	1.02	55.97
st25030	158770	188420	Scarriff	Graney	280.02	48	1.22	3.69	1183.81	1.00	0.85	0.59	1.00	40.64	38.60	1.00	38.67

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st25034_post	243720	246350	Rochfort	L. Ennel Trib	10.77	24	0.27	3.61	968.60	1.00	1.00	0.70	1.68	1.46	1.28	1.00	1.28
st25038_post	192810	170840	Tyone	Nenagh	136.10	18	0.92	7.23	1249.29	1.00	1.00	0.59	1.27	39.30	34.31	1.00	34.42
st25040	216420	191040	Roscrea	Bunow	28.02	25	1.20	13.87	989.64	1.06	1.00	0.58	1.00	3.59	6.61	1.09	7.23
st25044	178910	172740	Coole	Kilmastulla	92.55	44	1.37	3.02	1186.86	1.00	1.00	0.57	1.00	22.85	20.16	1.00	20.16
st25124_post	239010	247730	Ballynagore	Brosna	215.45	19	0.64	0.95	954.84	1.04	0.78	0.81	1.56	13.65	10.67	1.05	11.23
st25158_post	185860	157640	Cappamore	Bilboa	109.55	18	1.52	7.02	1376.62	1.00	1.00	0.51	1.05	43.88	39.44	1.00	39.44
st26002	172050	270500	Rockwood	Suck	641.45	53	0.80	0.50	1067.03	1.00	0.98	0.60	1.00	56.56	58.93	1.00	59.16
st26005	172610	263220	Derrycahill	Suck	1085.38	51	0.76	0.41	1054.40	1.00	0.98	0.63	1.00	93.21	87.10	1.00	87.39
st26006	165610	281700	Willsbrook	River Suck	184.76	53	0.94	0.96	1120.64	1.01	0.97	0.49	1.00	24.23	27.82	1.01	28.05
st26007	174320	261260	Bellagill	Suck	1207.22	53	0.75	0.39	1045.62	1.00	0.98	0.58	1.00	88.15	101.62	1.00	101.93
st26008	214680	295900	Johnston's Br.	Rinn	280.31	50	1.13	1.02	1035.47	1.00	0.86	0.59	1.00	22.66	25.38	1.00	25.48
st26009	217577	290512	Bellantra Br.	Black	98.22	35	0.96	2.99	1018.79	1.00	0.94	0.54	1.00	13.22	14.32	1.00	14.32
st26012_post	165950	293770	Tinacurra	Boyle	519.92	12	0.89	0.26	1142.97	1.00	0.82	0.69	1.53	47.68	34.87	1.00	35.04
st26012_pre	165955	293775	Tinacurra	Boyle	519.92	25	0.89	0.26	1142.97	1.00	0.82	0.69	1.00	29.61	29.32	1.00	29.46
st26014_post	157530	291010	Banada Br.	Lung	215.14	16	0.96	0.36	1198.70	1.00	0.94	0.63	1.50	42.82	25.64	1.00	25.76
st26018_post	188764	288892	Bellavahan Br.	Owenure	119.48	49	0.83	0.43	1043.90	1.00	0.76	0.65	1.00	8.95	6.16	1.01	6.19
st26019	221830	276930	Mullagh	Camlin	252.96	52	0.91	0.63	979.62	1.01	0.99	0.60	1.00	21.18	24.54	1.02	25.01
st26020	225110	280300	Argar	Camlin	122.44	34	0.97	7.48	1003.36	1.00	1.00	0.56	1.00	11.12	22.84	1.00	22.86
st26021_post	236700	272650	Ballymahon	Inny	1098.78	30	0.74	0.27	945.25	1.00	0.81	0.75	1.63	66.34	47.29	1.01	47.58
st26022	212141	268048	Kilmore	Fallan	61.88	33	0.39	3.55	915.82	1.01	1.00	0.60	1.00	6.49	6.41	1.01	6.46
st26058_post	254630	277880	Ballinrink Br.	Inny Upper	59.98	24	0.49	4.68	973.50	1.01	1.00	0.70	1.71	5.35	8.21	1.02	8.34
st26108_post	165951	293771	Boyle Abbey Br.	Boyle	527.32	15	0.88	0.24	1142.66	1.00	0.83	0.73	1.53	57.32	32.83	1.01	33.04
st27001	123550	173520	Inch Br.	Claureen	46.70	31	1.79	4.56	1476.89	1.00	0.99	0.33	1.00	20.10	27.18	1.00	27.18
st27002	134102	190475	Ballycorey	Fergus	564.27	51	0.54	1.26	1336.35	1.00	0.84	0.65	1.00	32.60	47.50	1.00	47.56
st27003	123980	194590	Corrofin	Fergus	166.42	48	0.49	3.89	1567.43	1.00	0.92	0.64	1.00	22.92	28.30	1.00	28.36
st27070	123980	196210	L. Inchiquin	Baunkyle	143.58	29	0.33	4.65	1592.48	1.00	0.91	0.64	1.00	16.30	22.11	1.00	22.11
st29001	162710	227980	Rathgorgin	Raford	115.48	44	1.04	2.22	1089.74	1.01	1.00	0.61	1.00	13.46	18.06	1.01	18.24
st29004_post	151120	226961	Clarinbridge	Clarinbridge	121.44	32	0.57	2.70	1107.47	1.01	0.99	0.63	1.00	11.30	15.71	1.02	16.02
st29007_post	161760	222800	Craughwell	Dunkellin	271.48	22	0.93	2.07	1094.35	1.01	0.97	0.66	1.00	26.49	33.44	1.02	34.08
st29011_post	156900	222750	Kilcolgan	Dunkellin	354.14	22	0.77	1.85	1079.37	1.01	0.98	0.63	1.00	28.89	41.54	1.02	42.20
st29071	156120	200260	Cutra	L. Cultra	123.84	29	1.25	5.13	1212.48	1.00	0.80	0.56	1.00	15.40	18.36	1.00	18.36
st30001_pre	105970	276980	Cartronbower	Aille	121.02	18	1.42	5.46	1787.00	1.00	0.94	0.44	1.00	32.63	55.80	1.00	55.80
st30004_post	151460	262200	Corrofin	Clare	699.25	39	0.80	0.99	1103.65	1.01	0.99	0.60	1.70	90.34	96.96	1.01	98.01

Station No.	CENTE	CENTN	Station Name	River Name	AREA	N	DRAIND	S1085	SAAR	(1+URBEXT)	FARL	BFIsoils	(1+ARTDRAIN2)	Qmed	Qmedrural	UAF	AdjRural
st30004_pre	151461	262201	Corrofin	Clare	699.25	7	0.80	0.99	1103.65	1.01	0.99	0.60	1.00	42.30	78.05	1.01	78.90
st30005_post	134860	270970	Foxhill	Robe	237.82	18	0.94	1.04	1172.46	1.01	0.99	0.56	1.69	36.78	43.10	1.01	43.63
st30005_pre	134861	270971	Foxhill	Robe	237.82	24	0.94	1.04	1172.46	1.01	0.99	0.56	1.00	22.88	34.82	1.01	35.24
st30007_post	151460	267470	Ballygaddy	Clare	469.90	31	0.81	1.13	1115.06	1.01	0.99	0.61	1.69	62.98	68.76	1.01	69.27
st30012_post	151460	254920	Calergalway	Clare	1072.88	9	0.66	0.77	1099.13	1.01	0.99	0.59	1.71	126.00	132.04	1.01	133.06
st30020_post	152090	279590	Ballyhaunis	Dalgan	21.41	29	1.85	3.21	1190.71	1.01	1.00	0.61	1.68	4.62	6.77	1.01	6.87
st30021_post	140280	273950	Christinas Br.	Robe	103.63	29	1.10	1.41	1168.14	1.00	0.99	0.57	1.67	27.20	21.76	1.00	21.81
st30061_post	126370	255730	Corrib Estuary	Wolfe Tone Bridg	3136.08	10	0.94	0.57	1422.43	1.01	0.66	0.81	1.41	250.07	151.19	1.01	152.65
st30061_pre	126371	255731	Corrib Estuary	Wolfe Tone Bridg	3136.08	46	0.94	0.57	1422.43	1.01	0.66	0.81	1.00	247.97	131.36	1.01	132.63
st31002	102270	234080	Cashla	Cashla	71.35	27	1.75	9.29	1530.25	1.00	0.63	0.50	1.00	12.02	12.13	1.00	12.13
st31072	86360	251550	Derryclare	Derryclare L	111.83	27	2.64	3.21	2464.73	1.00	0.64	0.51	1.00	43.20	32.79	1.00	32.79
st32011	84680	275510	Louisberg Weir	Bunowen	70.10	26	1.95	13.35	1612.95	1.00	0.99	0.34	1.00	64.87	54.95	1.00	55.07
st32012	105650	301310	Newport Weir	Newport	146.16	24	1.91	4.26	1784.36	1.00	0.84	0.65	1.00	29.85	38.95	1.00	38.95
st33001	95480	333070	Glenamoy	Glenamoy	76.12	25	1.56	10.64	1466.61	1.00	1.00	0.29	1.00	59.30	54.34	1.00	54.34
st34001_post	129200	299360	Rahans	Moy	1974.76	33	1.35	0.74	1322.66	1.01	0.83	0.76	1.34	177.00	178.57	1.01	180.77
st34003_post	129205	299365	Foxford	Moy	1802.38	29	1.38	0.98	1339.66	1.01	0.82	0.75	1.34	178.00	176.36	1.01	178.51
st34007	103940	313410	Ballycarroon	Deel	151.71	33	1.74	4.58	1590.04	1.00	0.98	0.35	1.00	81.98	83.52	1.00	83.52
st34009_post	154326	303354	Curraughbonun	Owengarve	117.11	33	1.18	3.26	1256.71	1.01	1.00	0.44	1.33	27.48	37.52	1.02	38.12
st34010	148930	309360	Cloonacannana	Moy	484.35	12	1.42	3.96	1385.67	1.01	0.99	0.40	1.00	95.42	169.15	1.01	171.28
st34011	124046	281900	Gneeve Br.	Manulla	143.01	30	1.16	0.63	1247.57	1.01	0.87	0.57	1.69	18.73	20.84	1.01	21.11
st34018_post	112610	289240	Turlough	Castlebar	95.40	27	1.60	3.06	1554.59	1.06	0.73	0.75	1.42	11.28	14.21	1.08	15.39
st34024_post	138010	283810	Kiltimagh	Pollagh	127.23	28	1.36	1.48	1177.46	1.01	0.92	0.52	1.60	20.80	26.15	1.01	26.44
st34029_post	109080	314880	Knockadangan	Deel	226.83	9	1.68	2.94	1468.42	1.00	0.98	0.42	1.11	110.00	88.59	1.00	88.94
st35001	165390	311220	Ballinacarrow	Owenmore	299.45	29	1.19	0.30	1172.84	1.00	0.92	0.64	1.00	31.16	28.26	1.00	28.40
st35002	155855	323805	Billa Br.	Owenbeg	88.82	34	1.70	13.51	1380.56	1.00	0.99	0.52	1.00	50.48	35.73	1.00	35.73
st35004	169526	306122	Big Bridge	Owenmore	116.96	15	1.18	2.28	1103.39	1.00	0.99	0.48	1.00	12.78	24.04	1.00	24.14
st35005	165930	315240	Ballysadare	Ballysadare	639.66	58	1.31	1.06	1198.32	1.00	0.90	0.62	1.00	75.42	75.21	1.00	75.44
st35011_post	184960	336256	Dromahair	Bonet	293.23	9	1.45	4.08	1534.30	1.00	0.98	0.53	1.19	132.23	98.61	1.00	98.85
st35011_pre	184961	336251	Dromahair	Bonet	293.23	17	1.45	4.08	1534.30	1.00	0.98	0.53	1.00	86.71	91.78	1.00	91.99
st36010	261170	313180	Butler's Br.	Annalee	771.73	50	1.01	1.58	967.55	1.00	0.86	0.63	1.00	66.80	59.49	1.01	59.88
st36011	235683	291581	Bellahillan	Erne	320.55	50	1.01	1.19	979.63	1.01	0.79	0.66	1.00	18.23	20.19	1.01	20.34
st36012	235580	290610	Sallaghan	Erne	262.04	47	0.92	1.53	985.45	1.00	0.76	0.77	1.00	14.12	13.40	1.01	13.50
st36016	267430	314260	Rathkenny	Annalee	506.95	14	0.96	2.25	975.34	1.01	0.82	0.69	1.00	50.98	34.99	1.01	35.35

Station No.	CENTE	CENTN	Station Name	River Name	AREA	N	DRAIND	S1085	SAAR	(1+URBEXT)	FARL	BFIsoils	(1+ARTDRAIN2)	Qmed	Qmedrural	UAF	AdjRural
st36018	267501	320821	Ashfield	Dromore	234.40	50	0.92	1.14	950.12	1.01	0.85	0.65	1.00	16.25	16.36	1.01	16.53
st36019	249750	304810	Belturbet	Erne	1491.76	47	1.01	1.30	971.21	1.01	0.76	0.63	1.00	89.95	81.68	1.01	82.49
st36021	207960	316710	Kiltybardan	Yellow	23.41	27	1.47	18.67	1569.64	1.00	1.00	0.33	1.00	23.37	19.11	1.00	19.11
st36031	243540	302970	Cavan	Lisdarn	63.77	22	1.12	4.25	910.43	1.06	0.96	0.50	1.00	6.55	10.48	1.09	11.42
st36071	203230	311760	Gowly	L. Scur	68.03	20	1.23	13.75	1314.65	1.00	0.82	0.64	1.00	6.42	12.95	1.00	12.95
st38001	185550	394980	Clonconwal	Owenea	111.25	33	2.37	6.15	1753.20	1.00	0.92	0.31	1.00	70.63	80.75	1.00	81.10
st39001	206170	409110	New Mills	Swilly	50.71	18	2.08	12.36	1764.48	1.00	0.99	0.32	1.00	47.80	48.34	1.00	48.34
st39009	208950	418480	Aghawoney	Fern O/L	206.83	33	1.81	5.17	1570.26	1.00	0.82	0.40	1.00	45.72	66.41	1.01	66.80