09 - FLOOD ESTIMATION IN SMALL AND URBANISED CATCHMENTS IN IRELAND

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Abstract

OPW has coordinated a comprehensive research programme for the development of flood estimation methodologies in Ireland entitled the Flood Studies Update (FSU). This programme highlighted the absence of national guidance or policies in relation to peak flow estimation in urban and small rural catchments for effective design recommended the development of methodologies for small catchments calibrated to Irish conditions. A total of ten existing methodologies were selected for investigation, and after discounting some unsuitable methods, this number was reduced to four. The most commonly used of these ten methods is the IH124 method. The FSU 3-variable (Das and Cunnane, 2009), the FSU 7-variable (Murphy, 2009) and the FEH-statistical (Kjeldsen, Jones and Bayliss, 2008) equations were found to perform favourably even though they were not developed specifically for small catchments. A new regression equation was also developed and tested on 38 gauged small catchments (between 5 and 30km^2) and the results proved encouraging. The new regression equation for small catchments, however needs to be tested more rigorously using a greater number of gauging stations with good quality data before it can be recommended for widespread use.

Key words: peak flow, small rural catchment, urban catchment, physical catchment descriptors.

1. INTRODUCTION

This paper examines methods for small catchment flood estimation currently being applied in Ireland and abroad, and makes recommendations for the method that is the most suitable in an Irish context at this time.

Most small and urban catchments are ungauged. In practice, most hydraulic structures used to control runoff are installed in small catchments where flood estimation techniques are required for their design. Research performed under the OPW Flood Studies Update (FSU) programme highlighted a number of methods that are widely used in Ireland by Local Authorities and Consultants, and a further literature review indicated other widely used methods from other countries. These are discussed in the following sections, and the performance of a selection of these methods is assessed in this paper by comparison against observed data from gauging stations on small Irish catchments.

2. ASSESSMENT OF SMALL CATCHMENT FLOOD ESTIMATION METHODS

Initially a total of ten existing methods were considered, however after a detailed literature review and closer inspection, six of the methods/equations were removed from further analysis. The methods that were discounted were as follows:

(a) The Rational Method (Mulvaney, 1851) and the Modified Rational Method (HR Wallingford, 1981);
(b) USGS Regression Equations;
(c) The National Resources Conservation Service (NRCS) TRR-55 Method;
(d) The National Resources Conservation Service (NRCS) Unit Hydrograph Method;
(e) The Flood Studies Supplementary Report No. 6 (Institute of Hydrology, 1978);
(f) ADAS 345 and TRRL methods.

The traditional and modified Rational Methods, and the ADAS345/TRRL methods were removed from further analysis because there was insufficient evidence to support their use on catchments greater than 5km2 in area (Ponce, 1989, ASCE, 1992 and Pitt et. al. 2007). It is worth noting though that the Modified Rational Method was found in the literature to be the most suitable method for use in urban/urbanising catchments up to 5km^2 in area, and particularly suited to the design of drainage networks at the plot scale. The USGS regression equations are not applicable to Ireland because they were developed specifically for regions in North America (Koltun & Roberts, 1990). In addition, in the NRCS TRR-55, and NRCS Unit Hydrograph Methods, many of the parameters used are not directly transferable to Ireland (USDA-NRCS, 1986).

The FSSR No.6 method uses Irish soil mapping developed for the Flood Studies Report (NERC, 1975). This soil mapping was originally intended for large catchments, and the spatial resolution is not sufficient for use in smaller scale catchments. In addition, FSSR No.6 has now been superseded twice, first by the IH124 method in 1994, and more recently by the FEH Statistical method in 2008.

The remaining four methods that were retained for further investigation were as follows:
(i) Institute of Hydrology Report No. 124,
(ii) The FEH Statistical method (2008),
(iii) FSU 3-variable equation (from Work Package 2.2 of the FSU),
(iv) FSU 7-variable equation (from Work Package 2.3 of the FSU).

A brief summary of the four methods to be examined in this paper are summarised in the sections that follow.

2.1 The Institute of Hydrology Report no. 124 (IH 124, 1994)

The IH 124 Report examined the response of small catchments, less than 25km^2, to rainfall and derived an improved flood estimation equation (Marshall & Bayliss, 1994). A total of 87 sites were used to develop the method. The report developed a new equation to estimate the mean annual flood, *QBAR* (in m^3/s), for small rural and urban catchments.

$$QBAR_{rural} = 0.00108\,\mathbf{AREA}^{0.89}\,\mathbf{SAAR}^{1.17}\,\mathbf{SOIL}^{2.17} \quad \text{and}$$
$$QBAR_{urban} = QBAR_{rural}\,(1 + \mathbf{URBAN})^{2NC}[1 + \mathbf{URBAN}\{(21/\mathbf{CIND}) - 0.31]$$

where: *NC* is “rainfall continentality factor”
$NC = 0.92 - 0.00024\mathbf{SAAR}$, for $500 \leq \mathbf{SAAR} \leq 1100$mm,
$NC = 0.74 - 0.000082\mathbf{SAAR}$, for $1100 \leq \mathbf{SAAR} \leq 3000$mm, and
CIND is a catchment index defined as a function of SOIL and catchment wetness index (CWI), both as in FSR (1975)
$CIND = 102.4SOIL + 0.28\,(CWI - 125)$,

QBAR has an estimated return period of 2.33 years. The estimated *QBAR* is then multiplied by the growth factors derived by the FSR to estimate design flows for specified return periods. For example QBAR is multiplied by 1.96 to get the 100-year peak flow.

The IH124 method described above was developed for UK catchments and has been in use in Ireland since its publication (O'Sullivan *et. al.,* 2010). The main reservation with IH 124 is that the catchment descriptors *SOIL* and *SAAR* were not represented proportionally in the number of catchments used during the research that lead to the report (Marshall & Bayliss, 1994).

The catchment descriptors used by the method to estimate peak flows are also available for Irish catchments. Balmforth *et. al.* (2006) recommends using IH 124 for catchments up to 25km^2 and the CIRIA culvert design report (Balkham *et. al.,* 2010) recommends it more for small rural (Greenfield) catchments. Thus, it is worth examining the applicability of this method in the Irish context.

2.2 The FEH Statistical Method

The improved UK database for gauged catchments provided by the HiFlows-UK Project and the feedback from users of FEH lead to research into how to improve the original FEH method. A total of 602 rural catchment in the UK were used in the development of this method, and it is applicable to catchments greater than 0.5km^2 (Kjeldsen *et. al*, 2008).

The method brought unto the FEH, the following key improvements:

- A new regression model for estimating the median annual maximum flood, *QMED*
- An improved procedure for the use of donor catchments, and
- An improved procedure for formation of pooling groups and estimation of pooled growth curves.

The method also introduced new catchment descriptors, and a technique of weighting donor catchments using geographical distance.

The final model for prediction of *QMED* at ungauged sites is given by (Kjeldsen *et. al.,* 2008):

$$QMED = 8.3062 AREA^{0.851} 0.1536^{(\frac{1000}{SAAR})} FARL^{3.4451} 0.046^{BFIHOST^2}$$

[*BFIHOST* is replaced by BFI_{soil}]

Some reports indicated conflicting opinions that this method may not be appropriate for heavily urbanised catchments. On the other hand, it produces results close to the actual measured *QMED* per the reported results. It is worth exploring on Irish catchments.

2.3 The FSU 3-variable equation

The FSU 3-variable equation was developed as part of the FSU. It was developed as a 'short-cut' equation for the estimation of flow in ungauged catchments and was used to test the applicability of different types of adjustments to statistical flood estimations. It is a simple equation and uses the size-wetness-permeability descriptors *AREA*, *SAAR*, and *BFI*:

$$QMED = 0.000302 AREA^{0.829} SAAR^{0.898} BFI^{1.539}$$

In the past, short cut equations of this form have proven useful on smaller catchments in Ireland.

2.4 The FSU 7-variable equation

The FSU 7-variable equation was also developed as part of the FSU. The analysis used to derive the FSU 7-variable equation used 216 Irish gauging stations, of which 10 of these had a contributing catchment area of less than 30km^2. The 7-variable equation gives an initial estimate of the index flood for a catchment on the assumption that it is 100% rural.

$$QMED_{rural} = 1.237\text{x}10^{-5}\ AREA^{0.937}\ BFIsoils^{-0.922}\ SAAR^{1.306}\ FARL^{2.217}\ DRAIND^{0.341}\ S1085^{0.185}\ (1+ ARTDRAIN2)^{0.408}$$

The rural estimate for *QMED* is further adjusted to obtain an estimate for urban/urbanised catchments as follows:

$$QMED_{urban} = QMED_{rural}(1+URBEXT)^{1.482}$$

Upon the release of the Flood Studies Update research, this will become the preferred method for flood estimation in Ireland.

3. APPLICATION OF SELECTED METHODS

3.1 Data Collection and Screening

Annual Maximum series data for all Irish catchments up to 50km^2 in area were collected from the hydrometric sections of the OPW, EPA and Rivers Agency of Northern Ireland.

The 2011 EPA Hydrometric register of gauging stations was used as a starting point, as well as five stations from Northern Ireland. This resulted in a dataset comprised of 86 stations. Following a statistical analysis on gauged catchments, an area of 30km^2 was chosen as the threshold between small and large catchments.

In the second phase of screening, a number of stations were removed from further analysis as follows:

- Stations with a period of record less than 7 years were removed. A period of record adjustment was applied to stations with record greater than 7 years;
- Stations that were immediately upstream/downstream of another gauge were removed and the station with the superior record was retained.
- Where catchments were the subject of arterial drainage, the pre-drainage record was removed.

After the second phase of screening was complete, the dataset reduced to 42 stations with an area of less than 30km^2, 37 with an area of less than 25km^2 and 16 stations with an area less than 10km^2.

3.2 Catchment Descriptors

The final dataset of 42 gauging stations consisted of catchments as small as 2.80km^2 and as large as 28.63km^2, the average being 13.57km^2. About 25 of the stations have *URBEXT* value of zero and the remaining 16 stations had an *URBEXT* value between 0.004 and 0.683. Over

90% of the stations have an *URBEXT* value of less than 0.025 which makes them predominantly rural catchments.

Catchment Descriptor	Minimum	Maximum	Average
AREA (km^2)	2.8	28.63	13.57
Mainstream Slope *S*1085 (m/km)	1.2	90.1	26.1
SAAR (mm)	475	2583	1243
FARL	0.63	1.0	0.96
BFIsoil	0.28	0.72	0.51
URBEXT	0	0.683	0.05

Table 1: *Range of values of each Physical Catchment Descriptor used in the analysis*

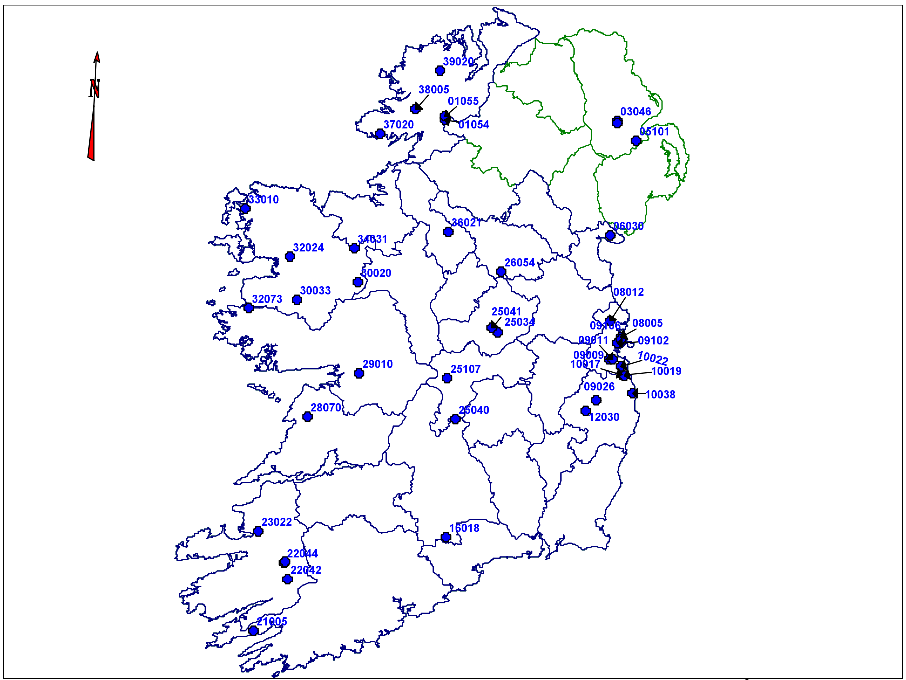


Figure 1: *The 42 gauging stations with catchment areas less than 30km^2 included in the study.*

The FEH Statistical method uses the BFI_{HOST} descriptor. Although there is no BFI_{HOST} map for Ireland, the BFI_{SOIL} descriptor was taken to be analogous to BFI_{HOST} as it is also limited to the range 0 to 1. Large variations between the two classifications are unlikely to occur.

3.3 Data Analysis

Each method under investigation was used to estimate *QMED* at each station. The IH 124 method produces estimates of the average annual maximum flow (*QBAR*) and this was converted to *QMED* using a conversion factor of 0.96. The estimated value for *QMED* was compared to the observed *QMED* values, four resulting outliers were removed and the results of this analysis on 38 small catchments are shown in Figure 2 below.

The values of coefficient of determination (R^2), root mean squared error (*RMSE)*, Nash-Sutcliff Efficiency (*NSE*), *mean bias* and factorial standard error (*fse)* are shown on Table 2 below. Accordingly, the FEH-Statistical and FSU-7v methods seem to perform better than the IH124 method and the FSU 3-variable equation.

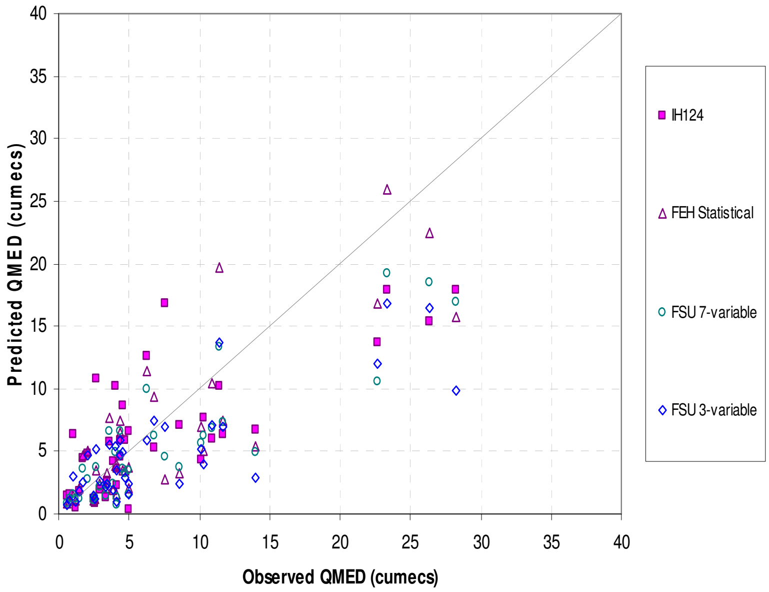


Figure 2: *Estimates of QMED Vs Observed QMED, after large outliers removed – 38 Stations.*

Table 2: *Statistical measures using 38 stations*

Flow (*QMED*) estimation methods (Area≤30km^2 & record≥7yrs)	**Coefficient of determination (R^2)**	**Std. dev. of error**	**RMSE**	**NSE**	**Mean Bias**	**FSE**
IH124	0.574	4.792	0.352	0.560	-0.300	1.975
FEH - Statistical	0.713	**3.985**	**0.246**	**0.696**	**-0.024**	**1.823**
FSU (7 variables)	**0.791**	4.164	0.267	0.668	0.130	1.858
FSU (3 variables)	0.666	5.077	0.287	0.506	0.083	2.025

IH124 and the FSU 3-variable equation were removed from the analysis at this stage. It was decided to develop and test a new regression equation that would sit somewhere between FEH-Statistical and FSU 7-variable, which takes into account BFI_{soil}, *S1085* and *FARL* in conjunction with the descriptors already contained in the two methods.

4. DEVELOPMENT OF A NEW EQUATION FOR SMALL CATCHMENTS

In order to select the best catchment descriptors to establish a new *QMED* model, the *Pearson correlation* coefficient (***r***) was determined. Table 3 shows correlation strength (*r*) between the observed *QMED* and each catchment descriptor. The same table also indicates correlations between individual descriptors (PCDs).

While developing a new *QMED* model, a combination of up to nine log-transformed PCDs were used with a number of iterations. The earlier research carried out in FSU WP2.3 already showed that the addition of more PCDs did not bring significant change in the efficiency of the model developed in that study. Hence this research confined itself to considering no more than nine PCDs.

Table 3: *Matrix of Pearson correlation coefficient (r) and scatter plot between catchment descriptors ln(PCDs) and ln(QMED) for 42 stations*

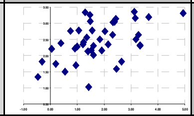
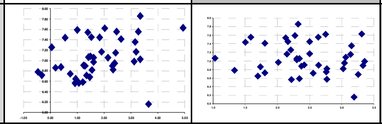
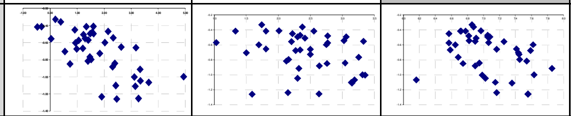
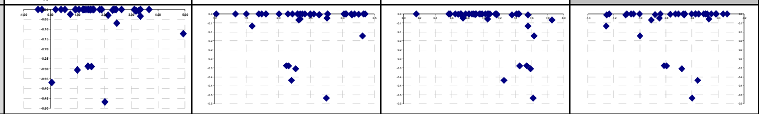
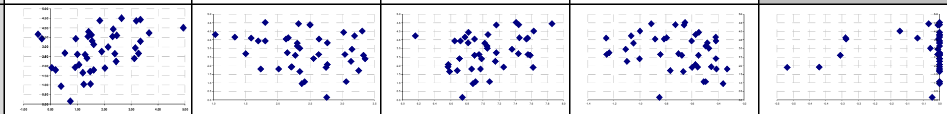
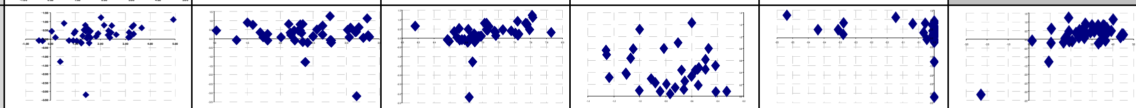
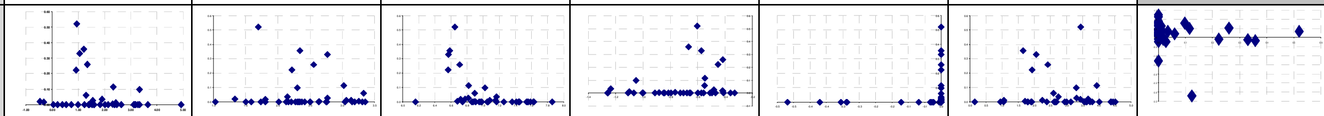
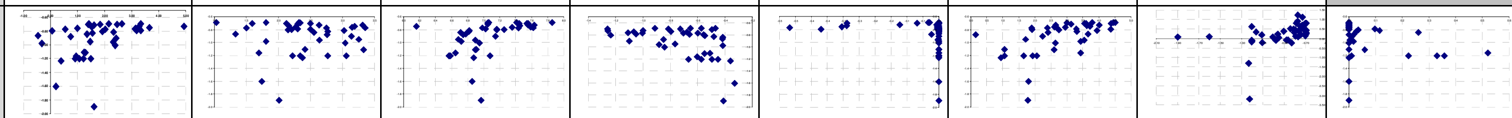
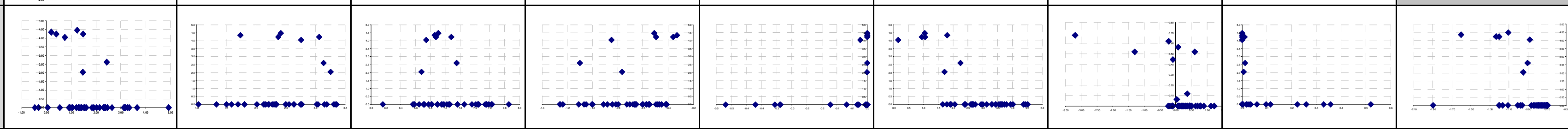
PCDs, *r*	**ln(*QMED*)**	**ln(*AREA*)**	**ln(*SAAR*)**	**ln(*BFI*)**	**ln(*FARL*)**	**ln(*S*1085)**	**ln(*DRAIND*)**	**ln (1+*URBEXT*)**	**ln(*SOIL*)**	**ln (*ARTDRAIN*2)**
ln(*QMED*)		**0.478**	**0.337**	**-0.669**	0.079	**0.377**	**0.329**	**-0.201**	**0.400**	**-0.291**
ln(AREA)			-0.138	**-0.238**	0.047	**-0.283**	-0.127	-0.063	0.018	0.126
ln(*SAAR*)				**-0.373**	**-0.505**	**0.317**	**0.376**	**-0.470**	**0.465**	-0.197
ln(*BFI*)					0.020	**-0.303**	**-0.393**	**0.216**	**-0.496**	**0.336**
ln(*FARL*)						-0.018	**-0.299**	0.195	**-0.275**	0.170
ln(*S*1085)							**0.639**	-0.127	**0.537**	**-0.737**
ln(*DRAIND*)								-0.157	**0.432**	**-0.590**
Ln (1+*URBEXT*)									**-0.305**	-0.101
ln(*SOIL*)										**-0.463**
ln (*ARTDRAIN*2)										

Table 4: *Best combinations of two to nine log-transformed PCDs in terms of fse on 38 stations*

No. of PCDs	Ln(*AREA*)	Ln(*SAAR*)	Ln(*BFI*)	Ln(*FARL*)	Ln(*S*1085)	Ln(*SOIL*)	ln(1+*ARTDRAIN*2)	ln(1+*URBEXT*)	ln(*DRAIND*)	R^2 (CoD)	SE	FSE
2	**X**	**X**								0.526	0.685	1.983
3	**X**	**X**		**X**						0.660	0.589	1.802
4	**X**	**X**	**X**	**X**						0.705	0.558	1.746
5	**X**	**X**	**X**	**X**			**X**			0.761	0.513	1.670
6	**X**	**X**	**X**	**X**	**X**			**X**		0.767	0.512	1.669
7	**X**	**X**	**X**	**X**	**X**	**X**		**X**		0.770	0.518	1.678
8	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		0.777	0.519	1.680
9	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	0.777	0.529	1.696

The lowest factorial standard error (*fse*) in the combinations in Table 4 above is 1.67 from using a total of five PCDs. However, the *p*-value for that combination at 95% confidence level for *ln*(*BFI*) is 0.152, larger than the desired critical value of $p = 0.05$ significance level, a cut off point usually adopted in statistical analysis. A *p*-value of 0.210 (approx 0.2) tells that there is a 1 in 20 chance that BFI_{soil} might not explain well the estimated value of *QMED*.

Table 5: *Outputs from regression analysis at 38 stations*

Coefficients	*Parameter*	*Standard Error*	*t-Stat*	*p-value*	Lower 95%	Upper 95%
Intercept	-12.742	2.562	-4.974	**0.000**	-17.981	-7.503
Ln[AREA]	0.866	0.172	5.026	**0.000**	0.514	1.219
Ln[SAAR]	1.716	0.371	4.630	**0.000**	0.958	2.474
Ln[BFI_{soil}*]*	-0.585	0.456	-1.281	**0.210**	-1.518	0.349
Ln[FARL]	3.303	0.930	3.553	**0.001**	1.402	5.204
Ln[ARTDRAIN2]	-1.295	0.503	-2.575	**0.015**	-2.324	-0.267

The regression equation developed with the above parameters and used on 38 stations has an overall $R^2 = 0.761$*, standard error of estimate (see) = 0.513, fse = 1.670 and df = 5; note the p-values for Ln[*BFI_{soil}*].*

However it has to be noted that significance tests do not usually tell us whether the difference is of practical importance. More importantly the regression equation considered does not include the variable slope (*S*1085) which the earlier models lacked. The next combination of five PCDs with $fse = 1.68$, row labelled light green was selected. More over, Figure 3 also shows that the use of more than five PCDs does not greatly improve the R^2 value. Hence, a final model with five descriptors *AREA*, *SAAR*, BFI_{soil}, *FARL* and *S*1085 was selected (See Table 5 above and Table 6).

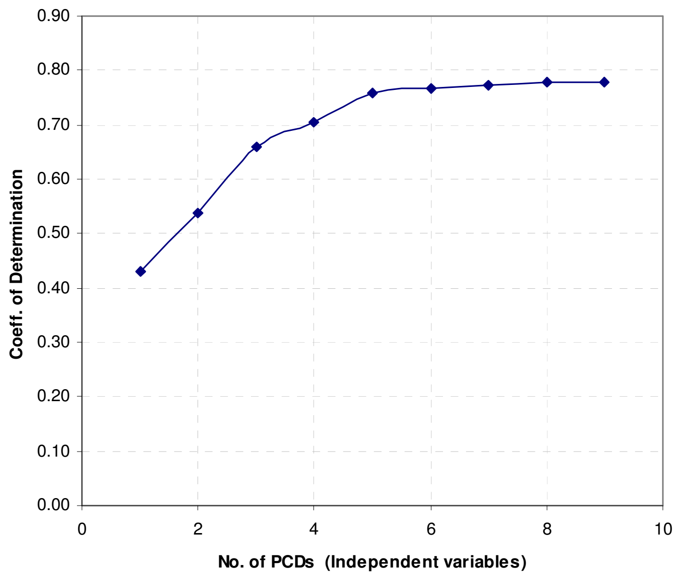


Figure 3: *Change in* R^2 *using combinations of between one and nine PCDs in the regression analysis.*

The new fitted model gives the following out put as shown in Table 6.

Table 6: *Outputs from regression analysis of 38 stations*

PCDs	Parameters	Standard Error	*t*-Stat	*p*-value	Lower 95%	Upper 95%
Intercept	-10.7733	2.6551	-4.0576	**0.0003**	-16.204	-5.343
$Ln[AREA]$	0.9245	0.1796	5.1469	**0.0000**	0.557	1.292
$Ln[SAAR]$	1.2695	0.4013	3.1637	**0.0036**	0.449	2.090
$Ln[BFI_{soil}]$	-0.9030	0.4390	-2.0569	**0.0488**	-1.801	-0.005
$Ln[FARL]$	2.3163	0.9497	2.4390	**0.0211**	0.374	4.259
$Ln[S1085]$	0.2513	0.1007	2.4965	**0.0185**	0.045	0.457

The FSU4.2a regression equation redeveloped with the above parameters used on 38 stations has R^2 = 0.758, standard error of estimate (see) = 0.521, df = 5 and fse = 1.684.

The final form of the small catchment regression equation is as follows:

$$QMED = 2.3848 * 10^{-5} AREA^{0.9245} SAAR^{1.2695} BFI^{-0.9030} FARL^{2.3163} S1085^{0.2513}$$

The exponents applied to *AREA*, *SAAR*, *BFI* and *S*1085 are quite similar to those for the FSU 7-variable equation. The performance of this new equation was compared with that of the FEH statistical and the FSU 7-variable equations, and the results are as outlined in Table 7 below:

Table 7: *Comparing the new regression equation with FEH and FSU-3v applied to 38 stations.*

Flow (*QMED*) estimation methods ($\leq$**30**km^2 & $\geq$7yrs)	Coeff. of determination (R^2)	Std. dev of errors	RMSE	NSE	Mean Bias	FSE
FEH Statistical	0.713	3.98	0.250	0.698	0.042	1.846
FSU 7-variable	0.791	4.16	0.245	0.672	0.141	1.879
New small catchments equation	0.802	3.27	0.219	0.808	-0.305	1.674

The equation has an R^2 value of 0.80, and *fse* of less than 2.00 for the 38 stations. The new equation compared well to the FEH –Statistical and FSU 7-variable methods. Thus, while it takes more *PCDs*, it performs relatively well, with a factorial standard error of 1.674.

As there were an insufficient number of urban gauging stations available for the small catchment analysis, the adjustment for urbanisation is the same as that used for the FSU 7-variable equation:

$$QMED_{urban} = QMED\,(1 + URBEXT)^{1.482}$$

The decision to use the adjustment for urbanisation as quoted above is backed up in part by research that was carried out in Work Package 4.3 of the FSU, where the proposed adjustment for urbanisation was estimated using hydrological modelling applied to three Irish urbanised catchments. This found that the urban adjustment closely followed that put forward by Naden and Polarski (1990) which proposed an adjustment factor of $(1+URBEXT)^2$.

The performance of the model across the 38 stations used in the analysis is shown in Figure 4 below:

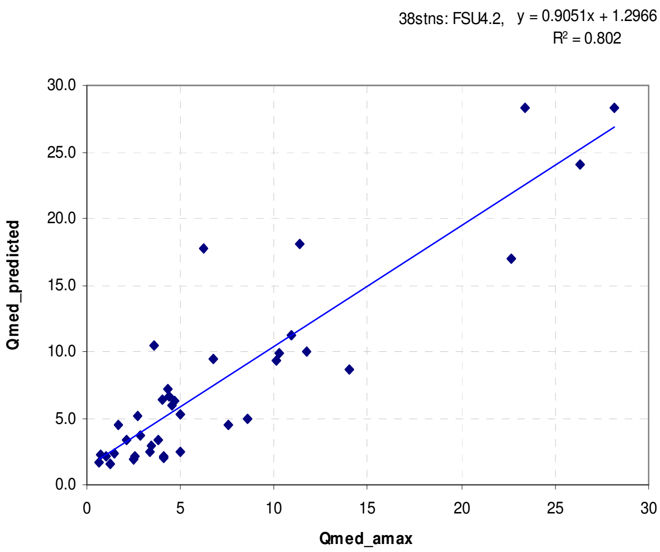


Figure 4: *Plot of observed QMED Vs estimated QMED using the new small catchment equation.*

While the new small catchment equation slightly outperforms the FSU 7-variable equation, the dataset on which it was based is still very small in terms of the number of catchments that would be required to develop a robust method that could be firmly recommended. There would also be the possibility that by using two different methods for catchments with areas in the region of 30km^2 that very different QMED estimates could be obtained for two adjacent points on the same river that had respective contributing areas of 29km^2 and 31km^2.

It is for these reasons that the FSU 7-variable equation is preferred for all catchments with an area of greater than 5km^2. The benefit of using a single equation outweighs those obtained by using a second equation for catchments between 5 and 30km^2.

5. CONCLUSIONS AND RECOMMENDATIONS

Ten existing methods were investigated. Some of the methods were found to overestimate significantly, the most notable being the IH124 method which is widely used in Ireland. The FEH-statistical method slightly overestimates and the FSU 7-variable equation slightly underestimates, however both of these methods perform comparatively well according to this research. As a further option a new regression equation was developed using five variables, *AREA*, *SAAR*, *BFI*, *FARL* and *S1085* to attempt to improve on the estimates obtained from the FEH and FSU methods. The results from the new method are encouraging. However it is only based on a set of 38 catchments and would need to be tested rigorously at more gauging stations with good quality data before it may be designated the preferred option.

In the Irish context, the FSU 7-variable equation is preferred over the FEH statistical method for flood estimation in small catchments, mainly because the physical catchment descriptors used in the 7-variable equation have already been derived for approximately 134,000 ungauged locations in Ireland.

The number of small catchments being monitored in Ireland is dwindling and consideration should be given to retaining as many of these as possible for the sake of improving the research into flood estimation for small and urban catchments.

6. ABBREVIATIONS

PCD:	Physical catchment descriptors,
AREA:	Catchment area,
SAAR:	Standard period average annual rainfall, (1961 to 1990),
BFIsoil:	Base flow index derived from soils,
FARL:	Flood attenuation by reservoirs and lakes,
FLATWET:	Index of catchment wetness,
DRAIND:	Drainage density,
S1085:	Mainstream slope,
ARTDRAIN2:	Percentage of the catchment river network that is included in the drainage schemes,
URBEXT:	Index of urban extent,
SOIL:	Soil index from winter rain acceptance potential,

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