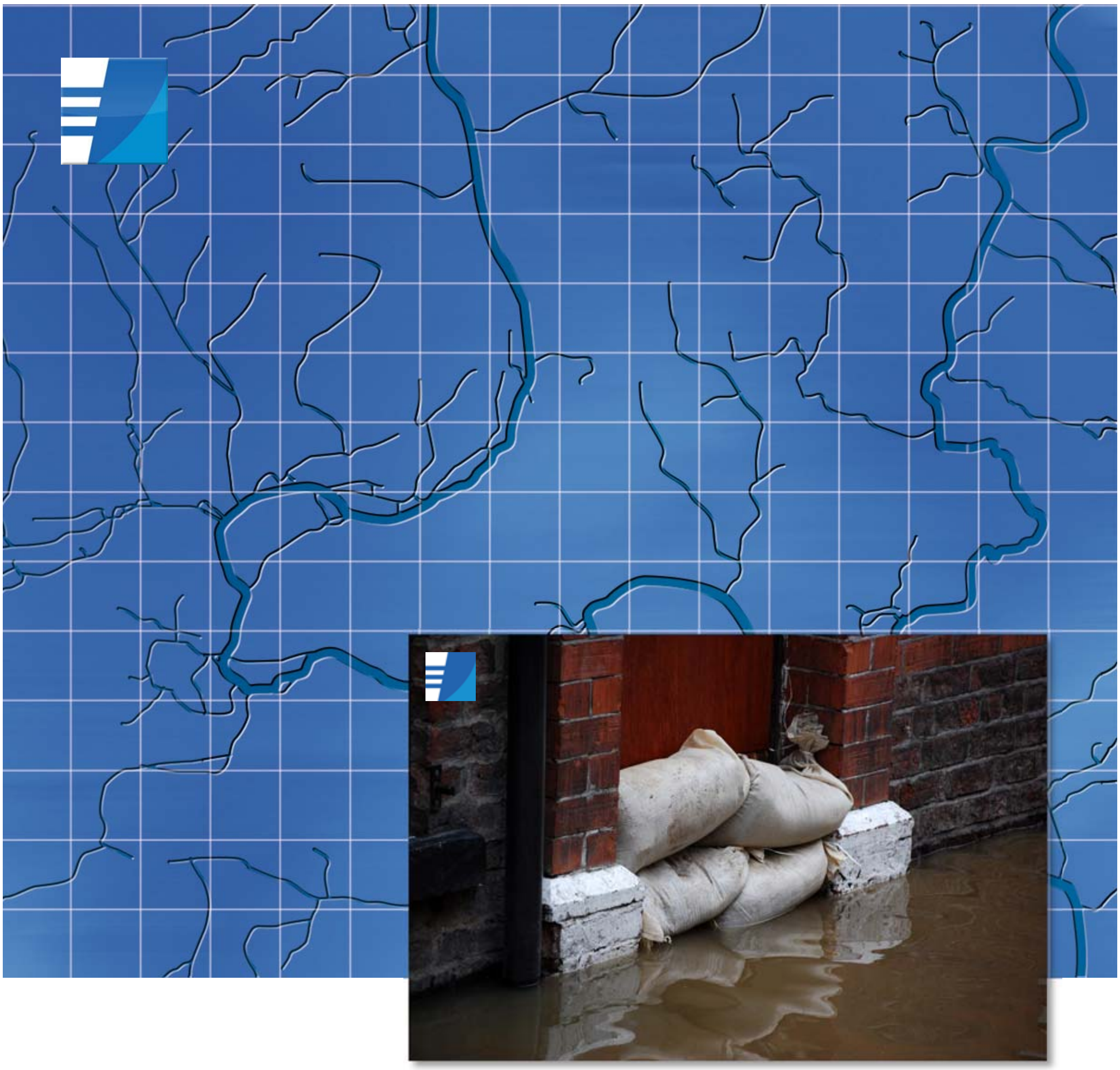
WINFAP 4 QMED Linking equation



Wallingford HydroSolutions Limited

WINFAP 4 QMED Linking equation

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1 Introduction

The basic FEH statistical method comprises a pooling method for estimating a growth curve coupled with the estimation of the index flood, the median annual flood (QMED). The QMED is the value of the annual maximum flood which may be expected to be equalled or exceeded once every two years on average. The flood frequency curve is given by the product of the two. This report focuses on the estimation of QMED and specifically the estimation from continuous gauged records that are not suitable for direct use within the estimation of QMED.

If the catchment is gauged, of a suitable hydrometric quality and of a suitable record length the QMED can be estimated directly from Amax series and if the record length is relatively short it may be estimated from a Peaks Over Threshold analysis (POT). For the ungauged case QMED is estimated using a regression model[1] relating QMED to catchment descriptors ($\mathrm{QMED_{cds}}$):

$$\mathbf{QMED}_{cds} = \mathbf{8.3062AREA^{0.8510}0.1536^{\left(\frac{1000}{SAAR}\right)}FARL^{3.4451}0.0460^{BFIHOST^{2}}}, \qquad \text{Equation 1}$$

in which AREA is the topographic catchment area, SAAR is the catchment average annual rainfall for the period 1961-1990 and FARL is an index formulated to capture the attenuation influence of open water bodies on flood flows. BFIHOST is result of a regression model linking the empirical gauged flow record index of Base Flow Index (BFI) to the fractional extents of soil association classes within a catchment that underpins the Hydrology of Soil Types classification. BFI is a hydrograph separation algorithm developed by the Institute of Hydrology as a general catchment classification tool[2].

The f.s.e. for this model is 1.431, that is it can be said with a 68% level of confidence that the true value of QMED will lie within the interval [1/f.s.e, f.s.e]QMED where QMED is the estimated QMED obtained using the equation, assuming the estimates are unbiased. In practice estimates from observed data will be subject to both sampling error and measurement error, although sampling error rapidly reduces with record length. Thus the f.s.e. for the catchment descriptor model reflects both measurement and model error with model error being the dominant component.

Within the NRFA Peak Flows suitability indices the gauged flow record is deemed suitable for QMED estimation if the measurement error is not greater than 30%. This is a semi-qualitative measure as there is no level of confidence associated with it, and from a consideration of measurement error it might be expected that measurement errors at high flows across the gauging station network might be biased towards under-estimation. Nevertheless, a comparison of error terms demonstrates the value of using at site data.

In practice, most catchments are ungauged and WINFAP 4 incorporates the multiple donor adjustment procedure developed and evaluated by Kjeldsen et al 2014[3]. This procedure uses error correction terms based on the QMED model residuals for nearby gauged catchments. The evaluation of the procedure demonstrated that use of correction terms based on 6 donors reduced the f.s.e. of

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[1] Kjeldsen, T. R., Jones, D. A. and Bayliss, A. C., 2008. Improving the FEH statistical procedures for flood frequency estimation: Science Report: SC050050. Other. Environment Agency.

[2] Low Flows Studies. Institute of Hydrology 1980

[3] T. R. Kjeldsen, D. A. Jones,D. G. Morris. 2014. Using multiple donor sites for enhanced flood estimation in ungauged catchments. Water Resources Research, Vol 50, Issue 8,Pages 6646–6657

estimate across 602 catchments to 1.355, recognising that the biggest reduction in f.s.e. was obtained through the use of the first two donors.

The UK has a relatively dense gauging station network – currently comprising around 1500 flow-measurement stations augmented by a substantial number of secondary and temporary monitoring sites.

Within the NRFA[4] Peak Flows catchment dataset there are 838 catchments judged as being of suitable hydrometric quality for the estimation of QMED and 797 that meet the minimum record length criterion for estimating QMED directly from the AMAX series. Thus flow data from only about 50% of the UK network can be used to constrain uncertainty in the estimation of QMED within the current estimation methods.

The challenge for establishing any gauging station is to establish a location or structure that can measure over the full range of flows (typically 3 to 4 orders of magnitude variation between the highest and lowest flows) whilst maintaining sensitivity of stage to flow, particularly at low flows. Low Flows are characterised by long recessions in which the rate of change in flow with time is low. Thus high flows are problematic to measure due to the constraints of having independent measurement of flow for empirically rated sections and/or maintaining flows within formal structures or rated sections. Low flows are difficult to measure from the perspective of measurement sensitivity.

Furthermore, the low flow regime may be very heavily modified by anthropogenic water use and return. The higher flows will generally not be so influenced as abstraction and discharge limits are predominately set to limit abstraction at low flows and maintain effluent dilution at low flow. The only significant exception to this are impounding reservoirs the influence of which will be across the entire flow regime.

The purpose of this research has been to develop a linking equation to enable the gauged records for within bank, non-flood flows to be used for estimating QMED. A linking equation of this nature offers the potential for significantly increasing the set of gauged catchments that can be used as local data to inform the estimation of QMED in practice.

2 Datasets

This study has used readily available catchment datasets. All gauged flow records held by the NRFA were evaluated by WHS in 2009 for both low flow hydrometric quality and the degree of artificial influence. This exercise was conducted as part of the 2010 revisions to the hydrology models and methods that underpin the LowFlows Enterprise software using the methods originally defined by Gustard et al. 1992[5]. The methods for estimation and classification of the impact of artificial influences on the flow regime were refined both through the use of improved datasets representing the influence of abstractions, discharges and impounding reservoirs and the development of uncertainty measures to quantify the uncertainty of the estimates of nett influence.

A set of 549 stations currently meet the requisite hydrometric quality and naturalness criteria for inclusion within the LowFlows estimation methods. For each catchment the water resources flow regime descriptors of gauged BFI and gauged estimates of the Daily Mean Flows (DMF) that are equalled or exceeded for 5% of the time ($Q5_{DMF}$) and 10% of the time ($Q10_{DMF}$) were selected. The

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[4] National River Flows Archive (http://nrfa.ceh.ac.uk/)

[5] Gustard, A.; Bullock, A.; Dixon, J. M.. 1992 Low flow estimation in the United Kingdom. Wallingford, Institute of Hydrology, 88pp. (IH Report No.108)

flow estimates were selected from the long term flow duration curved for these catchments and were selected on the basis that experience has shown that the 15-minute flow measurements that underpin the derivation of the DMF for flows at these exceedance probabilities predominantly lie within the limits of the verified rating relationship for a gauging station and certainly within bank.

The common set of catchments between this data set and the catchments from the NRFA peak flows dataset that are considered as suitable for QMED estimation were selected for use within the study. This resulted in a set of 387 catchments being identified. The standard set of FEH Web Service catchment descriptors were also selected in addition to the flow regime descriptors. Summary catchment descriptor and QMED statistics are presented within Table 1.

Table 1 Summary catchment descriptor and QMED statistics for the catchment datasets

	QMED	AREA	BFIHOST	FARL	SAAR	URBEXT2000
Maximum	816.92	4399.7	0.97	1	2913	0.58
Minimum	0.61	7.9	0.18	0.73	558	0.000
Median	45.25	139.4	0.47	0.99	1077	0.004

Within this catchment dataset 27 of the catchment have URBEXT2000 values of greater than 0.06 (6%) which is the lower boundary of the moderately urbanised class and a total of 31 catchments have lake attenuation indices (FARL) of less than 0.95. The 336 catchments with URBEXT2000 values of less than 0.06 and FARL>0.95 were selected for method development. The resultant method was also tested against the urbanised catchment set (URBEXT2000>0.06) and the catchments with significant lake attenuation potential. The purpose of this was to test whether the method is sensitive to the degree of urbanisation or attenuation potential.

3 Deriving the QMED linking equation

3.1 Method

The relationships between the dependent variable observed QMED and “within rating” flow regime measures were explored through a combination of graphical review and multi-variate regression analysis (bi-directional elimination, stepwise regression). In the development of this linking equation the additional explanatory power of catchment descriptors was explored with the exception of the topographic area. Data transformations were applied, as required, to linearise these relationships. Five sets of random numbers were used for testing the validity of significance criteria.

The topographic area was exluded for two reasons. Firstly, as all flow statistics were entered with dimensions of L^3T^{-1} the scale effect of catchment size are captured within the flow statistics used. Furthermore, the FEH QMED catchment descriptor equation has the limitation that it is sensitive to the estimate of contributing catchment area. It is an assumption that the contributing catchment area can be approximated through the use of the topographic catchment area. This is also generally true of any catchment model although models such as the ReFH and PDM models allow for an expanding contributing area bounded at a maximum by the topographic area. This assumption of a closed, fully contributing topographic catchment area can be quite flawed in both small and permeable catchments. A data based method that does not depend on explicit or implicit assumption of a closed catchment water balance is thus desirable as the method will be entirely independent of the catchment descriptor method for QMED.

3.2 Results

Within the final equation QMED is estimated as a function of:

- $Q5_{DMF}$ – the gauged daily mean flow that is equalled or exceeded for 5% of the time;
- $GRADQ5_{DMF}$ – gradient of the gauged flow duration curve between $Q5_{DMF}$ and $Q10_{DMF}$ (dQx/dPx) under the assumption of a log -normal approximation. This adoption of this approximation seeks to linearises the empirically derived gradient. These values are negative, and within the UK gauging station lie within the interval [0,-1]. The values were therefore increased by 1 to allow the variable to be log transformed within the regression modelling;
- DPSBAR – the average slope along the drainage paths within the CEH DTM for the catchment; and
- BFI – the value of Base Flow Index calculated directly from the daily mean flow series for a gauging station and not to be confused with HOSTBFI.

The final model is summarised within Table 2 and expressed algebraically by Equation 2. Note that the model is a log transformed regression of QMED and thus the standard error of the model has been expressed as a factorial standard error.

Table 2 Summary statistics for the QMED linking model.

Variable	Coefficient	Std Error	t-value	p-value
CONSTANT	0.246	0.108	2.277	0.023
$Log[Q5_{DMF}]$	0.866	0.014	61.487	0
$Log[GRADQ5_{DMF}]$	-0.775	0.153	-5.055	0
Log[DPSBAR]	0.265	0.035	7.637	0
BFI^2	-0.622	0.065	-9.554	0
	f.s.e=1.31		Adj. R^2=0.96	

$$\mathbf{QMED} = \mathbf{1.762Q5_{DMF}}^{\mathbf{0.866}}(\mathbf{1} + \mathbf{GRADQ5_{DMF}})^{-\mathbf{0.775}}\mathbf{DPSBAR}^{\mathbf{0.265}}\mathbf{0.2388}^{\mathbf{BFI^2}} \qquad \textbf{Equation 2}$$

The f.s.e compares favourably with those reported for the catchment descriptor equation and the outcomes of donor adjustment. The dominant term in the equation is $Q5_{DMF}$. As the equation is a product of terms the other terms would suggest that for a given value of $Q5_{DMF}$ the resultant QMED will be higher for catchments with higher flow variability, steeper catchments and for less permeable catchments (lower values of BFI). This interpretation is intuitively attractive.

4 Comparisons of the QMED Linking and catchment descriptor equations and implications for use.

The residuals from both the QMED linking equation and the FEH QMED catchment descriptor equation have been considered across the following sub-sets:

- development catchment set;
- all catchments;
- the urbanised catchments only (Urbext2000 >0.06); and
- catchments in which the flood response may be significantly attenuated by the presence of surface water bodies (FARL<0.95).

Four catchments were both urbanised and had low FARL values. The f.s.e. and model bias values were evaluated for each class and the arithmetic difference calculated between the f.s.e. for the FEH CD equation and the linking equation. These results are presented within Table 3 together with the number of catchments within each class.

Table 3 factorial Standard Errors (f.s.e.) and bias by catchment class.

Catchment class	N	FSE			BIAS	
		LINK	CD	CD-LINK	LINK	CD
Rural high FARL	336	1.31	1.44	0.13	0.00	-0.03
All	387	1.34	1.46	0.12	0.00	-0.04
UrbExt2000>0.06	27	1.54	1.61	0.07	-0.09	-0.10
FARL<0.95	31	1.47	1.58	0.11	0.05	-0.10

The spatial patterns in the percentage difference between the QMED linking equation estimates and the $QMED_{cds}$ equation estimates are presented for the 336 rural, high FARL catchments within Figure 1 together with the model residuals for the QMEDcds equation. Negative percentage values indicate that the QMED Linking equation estimates are lower and positive values that the QMED linking equation estimates are higher.

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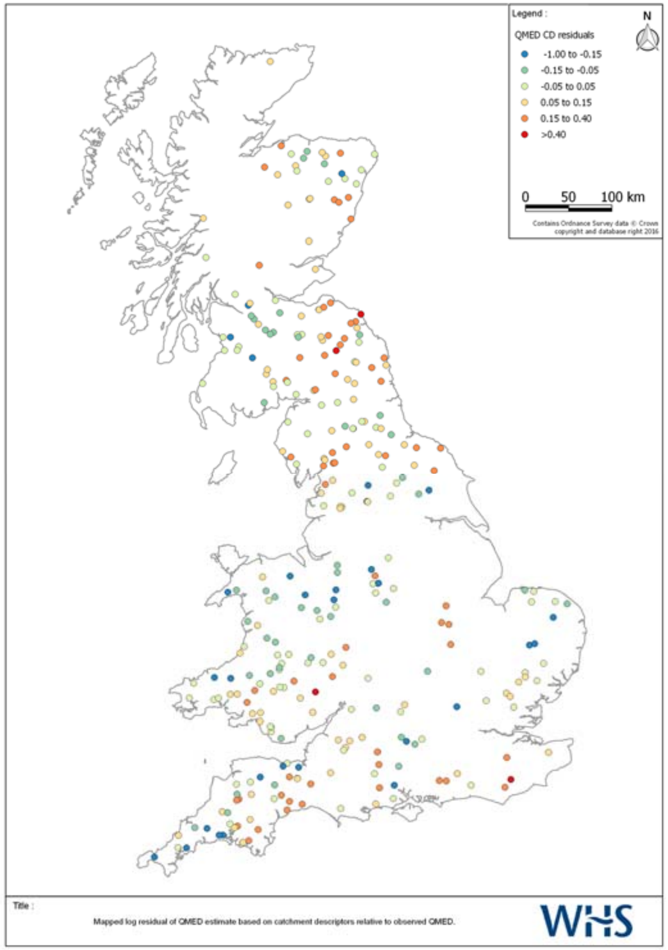
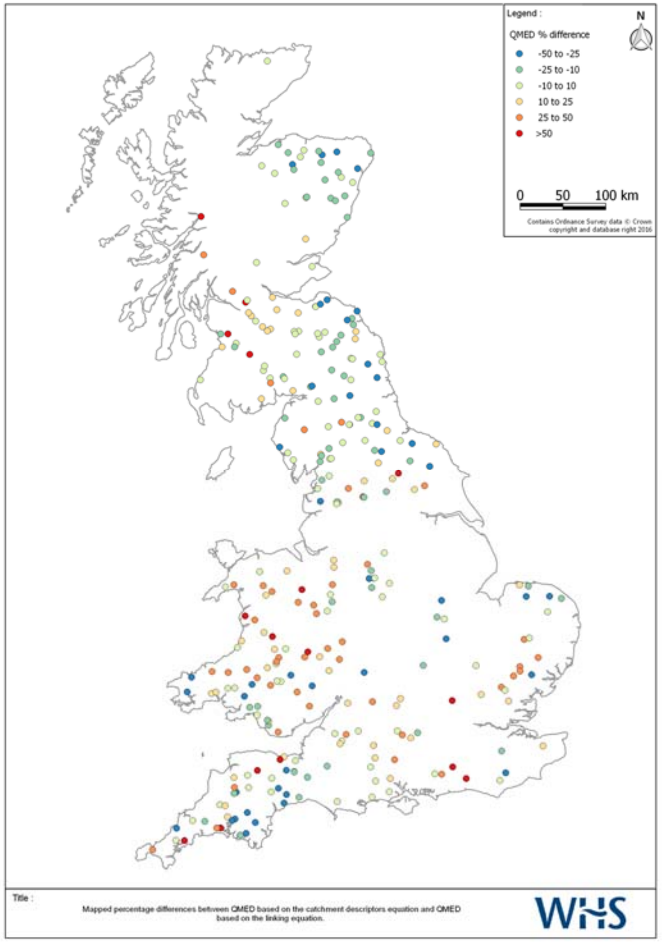
<td> </td>
<td> </td>
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<td>QMEDcds residuals</td>
<td>Percentage differences between the $\mathrm{QMED}_{\mathrm{link}}$ and $\mathrm{QMED}_{\mathrm{cds}}$ equations</td>
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Figure 1 Spatial variation in model differences

The following observations can be made:

- The FEH catchment descriptor equation has a small nett bias across both the dataset used to develop the linking model and all catchments within the data set. In contrast the linking equation is unbiased, although acknowledging that the model was developed across the first of these datasets which comprises the majority of catchments within the full dataset.
- The catchment descriptor equation has a significant spatial bias across the catchment dataset whereas the linking equation does not have the same spatial bias.
- The f.s.e of the FEH catchment descriptor equation is comparable to the original published f.s.e. for this model over the development dataset and all catchments dataset. The f.s.e for the linking equation is approximately 25% smaller than the catchment descriptor equation f.s.e.
- The f.s.e. for both equations are higher for the urban catchments this is a consequence of the increase in bias; both equations tend to under-estimate the influence of urbanisation by approximately 10% on average. The f.s.e. for the linking equation is smaller although the difference in f.s.e. between methods is smallest in this class.
- The FEH urban adjustment procedure has not been applied to either equation for application within the urbanised catchments. Further graphical inspection of the residuals shows that the magnitude of the equation residuals is strongly correlated with UrbExt2000 for both equations. These result would suggest that the influence of enhanced urban runoff on the $Q5_{DMF}$ flow is not significant and hence not accounted for in the linking equation. Given the strong correlation with urbanisation and comparable bias it is reasonable to suggest that the application of the FEH urban adjustment procedure to the estimates from the linking equation would also reduce the bias in the estimates from the linking equation within urban catchments.
- The f.s.e. for catchments with significant surface water bodies (lakes or reservoirs) is lower by approximately 20% for the linking equation. However, the linking equation is biased towards over estimation by 5% whereas the QMED catchment descriptor equation tends to under-estimate by 10%. This suggests that the linking equation over compensates for the associated attenuation effects of these features but still has a lower f.s.e. and lower bias modulus than the catchment descriptor QMED equation for low FARL catchments.
- The QMED catchment descriptors equation accounts for the influence of surface water bodies through the FARL term. Research, deployed through the LowFlows Enterprise software, has clearly demonstrated that the $Q5_{DMF}$ flow statistic is influenced by the presence of upstream water bodies. However, the bias term would suggest that extreme flows are lesser greater extent, which is intuitively reasonable.

5 Conclusions

The QMED Linking equation has been incorporated within the WINFAP-FEH V4. The software requires the user to supply the following:

- Q5 flow m^3s^{-1}
- Q10 flow m^3s^{-1}
- Base Flow Index (from gauged data)

The software extracts the catchment value of DPSBAR from the CD3 file for the location to enable the equation to be applied. The QMED estimate is regarded as an as rural flow statistic as the flows used within the equation are not sensitive to the influence of urbanisation.