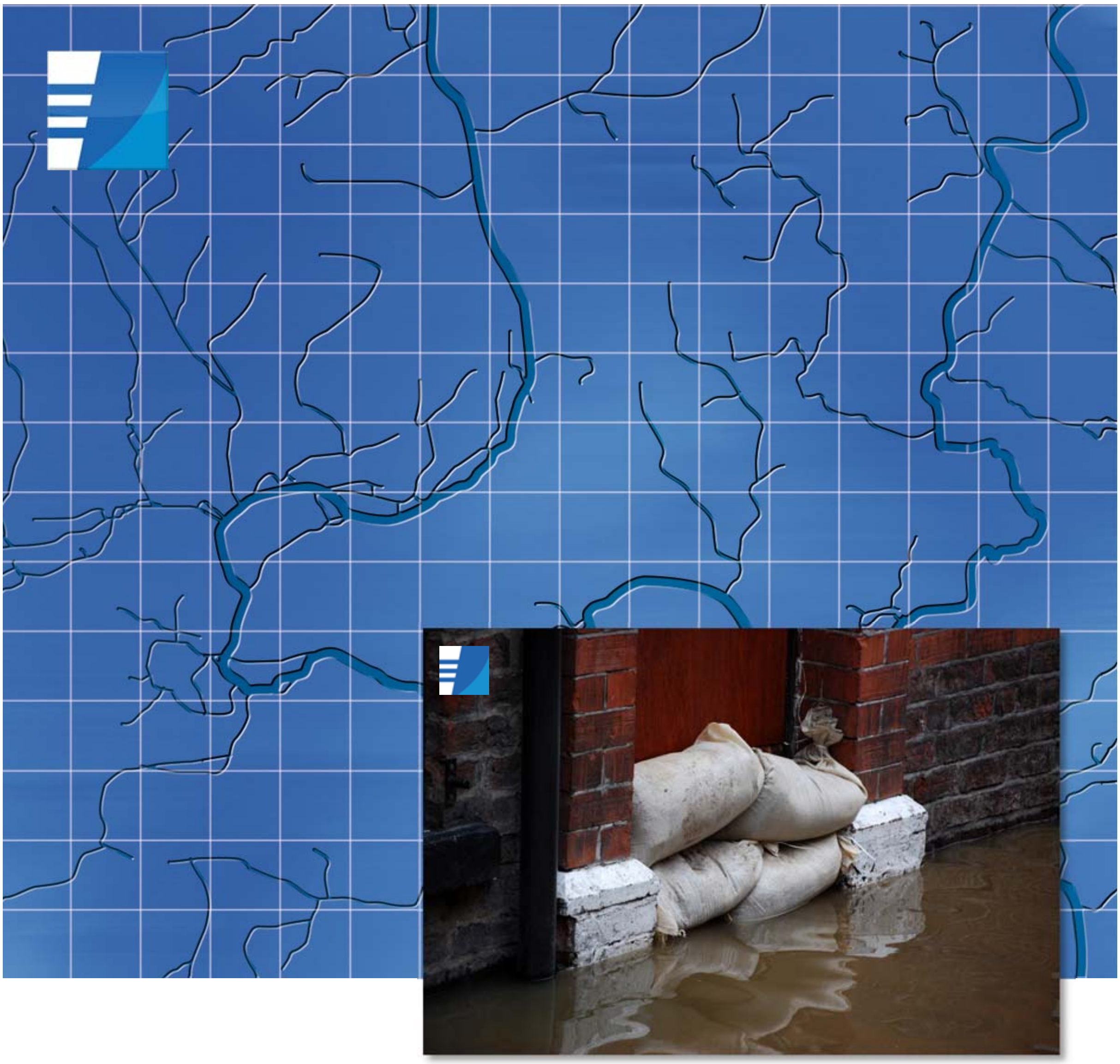
WINFAP 4 Urban Adjustment Procedures



WHS
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WINFAP 4 Urban adjustment procedures

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Contents

1 Introduction

In summary, the urban adjustment procedure for adjusting the as rural estimate of a flood frequency curve in WINFAP consists of the following steps:

- estimation of an QMED Urban Adjustment Factor (UAF);
- scaling of an as rural estimate of the QMED index flood by UAF;
- estimation of adjustment factors for scaling the pooled mean estimates of L-CV and L_skew for the as rural pooled growth curve; and
- computing the product of the urban adjusted QMED and the growth curve estimated from the urban adjusted L-CV and L-SKEW estimates.

The urban adjustment procedures have been revised for the purposes of WINFAP 4. The purpose of the revisions has been to:

- enable the user to directly define the influence of urban surfaces through the specification of an impervious extent, achieved through reformulating and recalibrating the QMED Urban Adjustment Factor (UAF) and the growth curve adjustment factors; and
- to resolve a mathematical discontinuity issue within the definition of Percentage Runoff Urban Adjustment Factor (PRUAF) within the method as published by Kjeldsen (2010)[1].

The current estimation of UAF (identifying the discontinuity in PRUAF) and the origins of PRUAF are discussed within section 0.

Section 3 presents the specification of PRUAF in terms of impervious extent and the associated recalibration of UAF is presented in section 4. This section also presents a recast of the equations for adjusting the growth curve moments.

[1] Kjeldsen, T.K., 2010. Modelling the impact of urbanization on flood frequency relationships in the UK. *Hydrology Research*, volume 41, issue 5, pp391-405.

2 The estimation of the QMED Urban Adjustment Factor (UAF)

2.1 Background

For urban catchment where at site data are available the observed urban adjustment factor, UAF_{OBS}, is calculated as the ratio of the QMED estimated from observed data ($QMED_{OBS}$) and the $QMED_{CDS}$ estimated from catchment descriptors.

For ungauged catchments the urban-adjusted estimate of QMED, $QMED_{urban}$, is a product of the as-rural catchment descriptor estimate of QMED and an estimate of the UAF:

$$\mathbf{QMED_{urban} = QMED_{cds}UAF} \quad (1)$$

The UAF is estimated using an equation that was optimised to explain the variation in UAF_{obs} within urbanised gauged catchments across the UK. The original FEH derivation of UAF was re-calibrated by Bayliss *et al*. (2006) [2] FEH equation to utilise the, then, newly developed URBEXT2000 catchment descriptor as follows:

$$\mathbf{UAF = (1 + \mathit{URBEXT}_{2000})^{0.66}PRUAF,} \quad (2)$$

Where $URBEXT_{2000}$ is a composite index of urban and suburban extent (Bayliss *et al*., 2006). The percentage runoff urban adjustment factor *PRUAF* is an estimate of the increase in runoff volume that occurs as a consequence of urbanisation and is a function of urban extent and catchment type. Bayliss *et al.* also updated the derivation of *PRUAF* from the original FEH equation[3] yielding the equation:

$$\mathbf{PRUAF = 1 + 0.47URBEXT_{2000}\left(\frac{70}{SPRHOST} - 1\right)} \quad (3)$$

[2] Bayliss, A.C., Black, K.B., Fava-Verde, A. and Kjeldsen, T.R., 2006. *$URBEXT_{2000}$ – a new FEH catchment descriptor*. R&D Technical Report FD1919/TR, Department of Food, Agriculture and Rural Affairs (DEFRA), London.
Available at: http://randd.defra.gov.uk/Document.aspx?Document=FD1919_5228_TRP.pdf

[3] Robson, A. and Reed, D., 1999. Statistical procedures for flood frequency estimation, Flood Estimation Handbook Volume 3, Centre for Ecology and Hydrology, Wallingford, UK, pp338.

Where SPRHOST is the outcome of a regression model relating standard percentage runoff to hydrology of soil type (HOST) soil classes within UK gauged catchments[4].

This model was subsequently updated again by Kjeldsen (2010) to remove the dependency of PRUAF on the outdated SPRHOST catchment descriptor and to take advantage of the larger number of urban catchments and flood events in the HiFlows dataset available at that time. The use of the improved $QMED_{cds}$ equation published by Kjeldsen et al (2008)[5] to calculate UAF within the urbanised catchments within HiFlows also ensured compatibility with the new QMEDcds equation.

The final form of this equation was given by:

$$\mathbf{UAF} = (\mathbf{1} + \mathbf{URBEXT_{2000}})^{0.37}\mathbf{PRUAF}^{2.16} \qquad \mathbf{4}$$

Both UAF models (equations 2 & 4) include the PRUAF term. In Kjeldsen's 2010 update, *PRUAF* from Equation 3 had been recast in terms of *BFIHOST[4]* using the relationship specified within Equation 5 to substitute for SPRHOST in equation 3 to yield equation 6.

$$\mathbf{SPRHOST} = \mathbf{70}(\mathbf{1} - \mathbf{BFIHOST}) \qquad \mathbf{5}$$

$$\mathbf{PRUAF} = \mathbf{1} + \mathbf{0.47URBEXT_{2000}}\left(\frac{\mathbf{BFIHOST}}{\mathbf{1-BFIHOST}}\right) \qquad \mathbf{6}$$

WINFAP 3 was released in 2009 during the development of the Kjeldsen (2010) UAF model and represents an interim position combining the definition of PRUAF from Equation 3 within the Urban Adjustment Factor (UAF) model within Equation 4. Thus the key catchment descriptor in WINFAP-FEH is still *SPRHOST* whilst Kjeldsen (2010) uses *BFIHOST* as the key descriptor. The equation for *PRUAF* though is fundamentally unchanged. In practice the substitution of *BFIHOST* within PRUAF using equation 5 has subsequently been shown to cause issues in very highly permeable catchments with a *BFIHOST* value of one resulting in an infinite value of *PRUAF*.

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[4] Institute of Hydrology Report No. 126, 1995. Hydrology of soil types: a hydrologically based classification of the soils of the United Kingdom

[5] Kjeldsen, T.R., Jones, D.A. and Bayliss, A.C., 2008. Improving the FEH Statistical Index Flood method and Software, Environment Science Report SC050050, pp137.
Available at: http://www.defra.gov.uk/environ/fcd/research/default.htm

2.2 Origins of PRUAF

PRUAF is the ratio of the percentage runoff from an urban catchment to as rural percentage runoff for a catchment, defined as:

$$\boldsymbol{PRUAF} = \frac{\boldsymbol{PR}}{\boldsymbol{PR_{RURAL}}}\text{ ,} \quad \text{7}$$

where PR is Percentage Runoff, the percentage of rainfall that forms runoff. The re-stated FSR rainfall runoff method6 defines percentage runoff from an urban areas as:

$$\boldsymbol{PR} = (\boldsymbol{1} - \boldsymbol{URBAN})\boldsymbol{PR_{RURAL}} + \boldsymbol{IF.URBAN.PR_{IMP}} + (\boldsymbol{1} - \boldsymbol{IF}).\boldsymbol{URBAN.PR_{RURAL}} \text{ ,} \quad \text{8}$$

where URBAN is the urban extent as mapped on the Ordnance Survey 1:50:000 map series. This extent does not consider the differences between urban and sub-urban land cover classes embodied within the URBEXT2000 catchment descriptor data sets.

This equation states that the percentage of rainfall that forms runoff from a catchment with an urban extent (defined by URBAN) is a sum of the percentage runoff from the rural part of the catchment, (PR_{RURAL}) the percentage runoff from the Impervious Fraction (IF) of the URBAN extent, PR_{IMP}, and the runoff from the pervious fraction of the URBAN extent which assumed to also be PR_{RURAL}. This expression of percentage runoff is common with the core definition of runoff within the ReFH 2. Dividing equation 8 through by PRRURAL yields PRUAF as:

$$\boldsymbol{PRUAF} = (\boldsymbol{1} - \boldsymbol{URBAN}) + \frac{\boldsymbol{IF.URBAN.PR_{IMP}}}{\boldsymbol{PR_{RURAL}}} + (\boldsymbol{1} - \boldsymbol{IF}).\boldsymbol{URBAN}\text{ ,} \quad \text{9}$$

which simplifies to:

$$\boldsymbol{PRUAF} = \boldsymbol{1} + \boldsymbol{IF.URBAN}.\left(\frac{\boldsymbol{PR_{IMP}}}{\boldsymbol{PR_{RURAL}}} - \boldsymbol{1}\right) \quad \text{10}$$

Bayliss et al [2] published a mapping relationship between URBAN and $URBEXT_{2000}$ as:

$$\boldsymbol{URBAN} = \boldsymbol{1.567URBEXT_{2000}} \quad \text{11}$$

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[6] Houghton-Carr, H. (1999) Restatement and application of the Flood Studies Report rainfall-runoff method. Flood Estimation Handbook, Vol. 4, Institute of Hydrology, Wallingford, UK.

The Bayliss definition of PRAUF is derived by setting PR_{RURAL} equal to SPRHOST following the principles of the FSR rural Percentage Runoff equations and ignoring the dynamic runoff terms of this equation. Assuming that IF=0.3 and PRIMP=70% then using the relationship between URBAN and URBEXT2000 to substitute for URBAN in equation 10 yields the Bayliss definition of PRUAF, equation 3.

The representation of the generation of urban net rainfall within ReFH2 follows the same general form of equation 8 but where PRIMP is referred to as the Impervious Runoff Factor (IRF) with a default of 0.7 (range [0,1]) and the rural percentage runoff component is the net rainfall generated by the ReFH loss model divided by the total rainfall. The empirical catchment evaluation of the model retained these default values. A subsequent generalisation of the model across all urbanised catchments within the HiFlows data based identified that 70 and 0.3 were the optimal values and a good working set of defaults[7].

3 Specifying UAF in terms of impervious extent, URBAN and choice of PRUAF

3.1 Expressing UAF in terms of URBAN

The current form of UAF, given by equation 4, is the outcome of a logarithmic multivariate regression in which the log residuals in the estimation of $QMED_{cds}$ for urbanised catchments are related to $URBEXT_{2000}$ and PRUAF. The (1+$URBEXT_{2000}$) term is to prevent the log equation failing for the case $URBEXT_{2000}$ =0 thus enabling the log model to be fitted to an [$URBEXT_{2000}$, PRUAF] coordinate pair [0,1]; i.e. enabling a zero value of URBEXT2000 to be set in the regression model.

The direct use of $URBEXT_{2000}$ means it is both difficult to interpret the UAF model in terms of actual urban extents and prevent the model being used to estimate the influence of urbanisation in very urbanised catchments. Based on Equation 11 an URBEXT2000 value of 1 (completely urbanised) corresponds to an URBAN value of 0.64; that is a maximum of 64% of a catchment surface can be URBAN as mapped on 1:50K maps.

Ultimately it is the extent of the urban surface that is impervious and that is positively drained that is of interest. Positive drainage may be directly through the surface water drain network or indirectly though combined sewer overflows. It is these runoff mechanisms that results in enhanced runoff response within urbanised catchments.

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[7] WHS, 2016. Revitalised Flood Hydrograph Model ReFH2: Technical Guidance, pp 67. Available at: http://files.hydrosolutions.co.uk/refh2/ReFH2_Technical_Report.pdf

Within the ReFH2 software the area of impervious surface within a catchment is based upon the urban fraction (URBAN), the total catchment area (AREA) and the fraction of the URBAN area that is defined as impervious (the impervious fraction IF). A default value of URBAN is estimated from $URBEXT_{2000}$ using the relationship between URBAN and URBEXT2000 (Equation 11).

A similar approach has been adopted in WINFAP 4 to enable the user to interpret the value of URBEXT2000 as an impervious area and to enable values of URBAN > 64% to be used within the method. This approach has necessitated changing the formulation of the UAF to:

$$\boldsymbol{UAF = (1 + IF.URBAN)^n PRUAF^m} \qquad \mathbf{12}$$

An exploratory analysis shows that an adequate UAF model can be constructed from PRUAF as the only term. This is not a surprising outcome given that PRUAF in essence is an extension of the (1+IF.URBAN) term where the influence of the URBAN component is moderated by underlying catchment type (moderating factor less than 1 for impermeable catchment and greater than 1 for permeable catchment). However, it was judged to be important to maintain the link back to earlier work and hence the current form of UAF has been retained

PRUAF is defined from equation 6 (after Kjeldsen, 2010) in which urbanisation is expressed through substitution of $URBEXT_{2000}$ in terms of URBAN and allowing the PR_{IMP}, and IF to be variables yielding:

$$\boldsymbol{PRUAF = 1 + IF.URBAN.\left(\frac{PR_{IMP}}{70(1-BFIHOST)} - 1\right)} \qquad \mathbf{13}$$

Default values for PR_{IMP} and IF are 70 and 0.3 respectively.

3.2 Resolving the discontinuity within the BFIHOST based PRUAF equation

The relationship between SPRHOST and BFI is plotted in Figure 1 for catchments within the NRFA Peak Flows dataset together with a line of best fit (defined though linear regression). The simplified, approximate relationship between SPRHOST and BFIHOST, Equation 5, defined by Kjeldsen in his 2010 paper is also plotted on the figure as a separate red line. Whilst the attractiveness of the equation is simplicity it can be observed that the equation does lead to an underestimation in high BFI catchments in practice.

The linear regression of SPRHOST on BFIHOST for this dataset yields:

$$\mathbf{SPRHOST = 69.4 - 65.7BFIHOST} \qquad \mathbf{14}$$

Substituting this equation within the Bayliss definition of PRUAF and plotting the ratio of PRUAF derived using this equation and PRAUF as defined by Kjeldsen's equation yields the relationship presented within Figure 2. This illustrates the sensitivity of PRUAF to the relationship between SPRHOST and BFIHOST. The very large UAFs observed for Kjeldsen's equation in permeable catchments with extensive urban areas are a consequence of the fact that the value of PRUAF approaches a discontinuity for a value of BFIHOST =1.

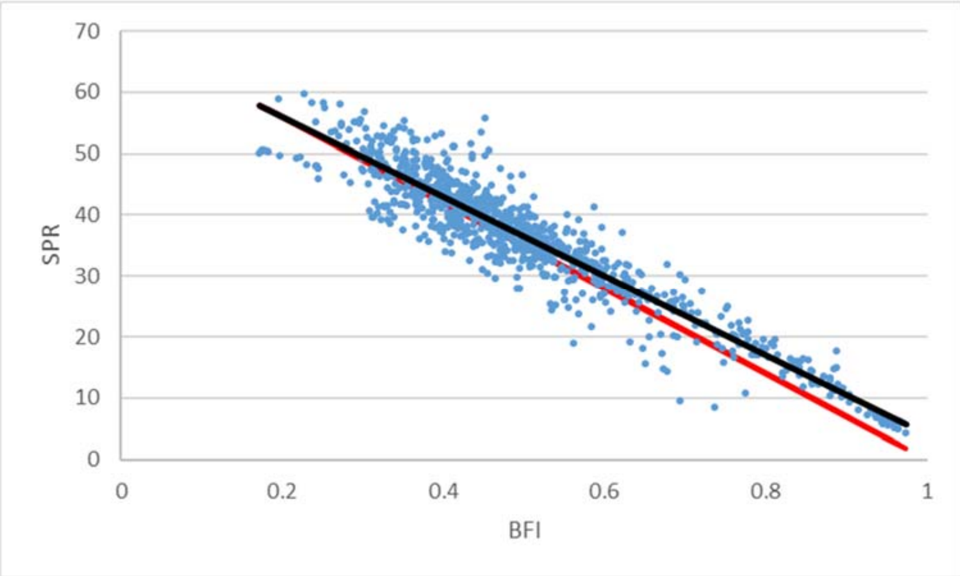

Figure 1 Relationships between SPRHOST and BFIHOST over the HiFlows dataset

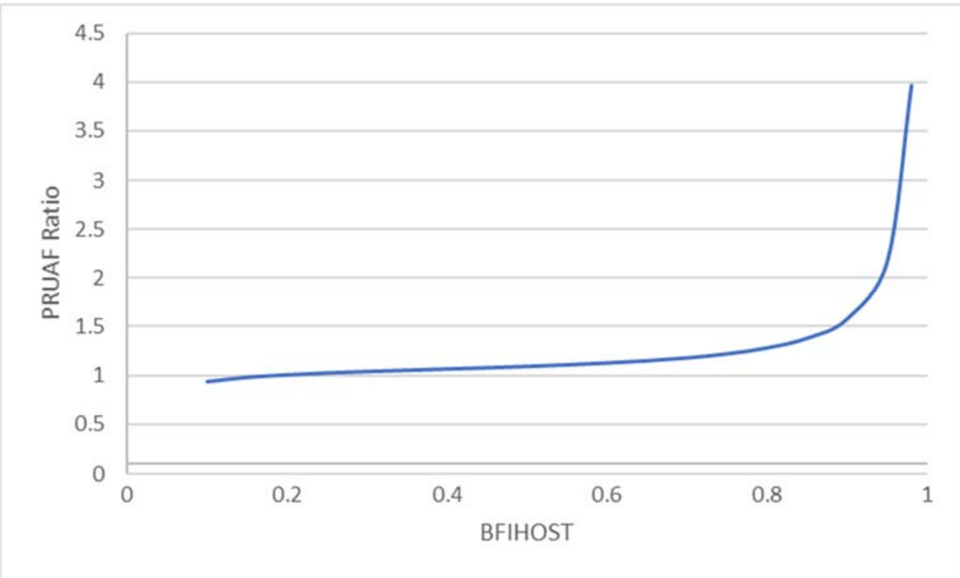

Figure 2 Influence of the choice of SPRHOST-BFIHOST relationship on the value of PRUAF

4 Recalibrating the QMED and growth curve Adjustment Factors

4.1 The QMED urban adjustment factor UAF

The revised formulation of UAF was fitted to the urbanised catchments ($URBEXT_{2000}$>0.03) within the NRFA Peak Flows dataset following the procedure previously used by Kjeldsen. URBAN was estimated using the reported values of $URBEXT_{2000}$ and the values for IF and PR_{IMP} were retained as the default values of 0.3 and 70%. This procedure yielded the following relationships for implementation within WINFAP 4.

$$\mathbf{PRUAF = 1 + IF.URBAN.}\left(\frac{\mathbf{PR_{IMP}}}{\mathbf{69.366-65.686\times BFIHOST}} - \mathbf{1}\right) \qquad \textbf{15}$$

$$\mathbf{UAF = (1 + IF.URBAN)^{1.25}\ (PRUAF)^{1.33}} \qquad \textbf{16}$$

The new UAF model (NEW) and original Kjeldsen model (TRK) estimates are presented as a function of $URBEXT_{2000}$ for different values of BFIHOST within Figure 3. The observed UAF values within the development catchment dataset are also presented with the permeable catchments within the dataset highlighted.

This figure demonstrates that the new model is consistent with the observations and particularly so for the higher permeability urbanised catchments.

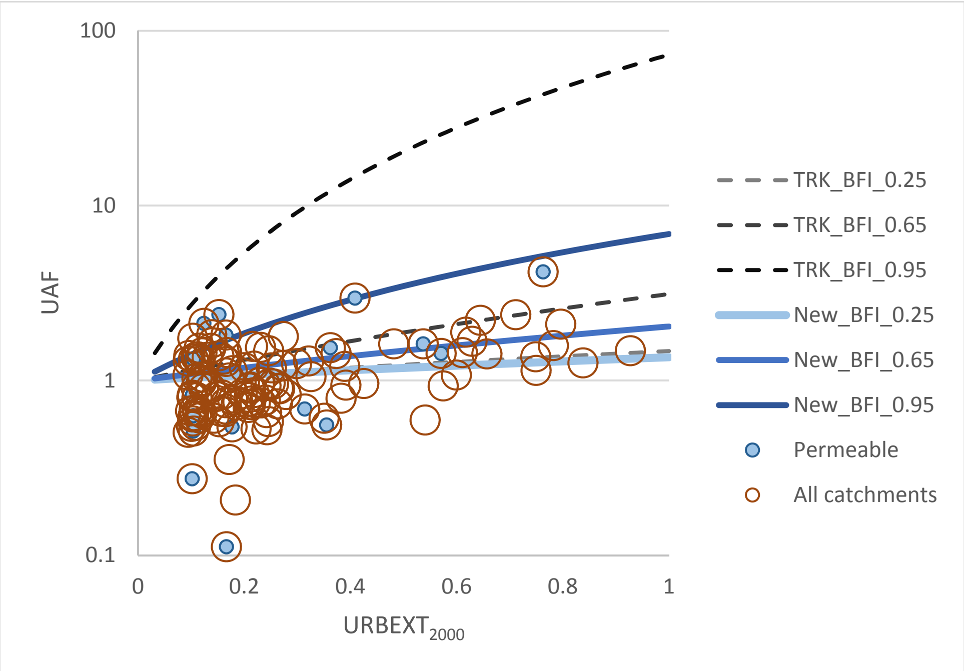

Figure 3 Comparisons of estimated UAF and observed UAF as a function of $URBEXT_{2000}$.

4.2 Re-casting of growth curve urban adjustment factors for L_cv and L_skew

Kjeldsen published the following revised adjustment equations for adjusting the growth curve through the adjustment of the rural pooled L-CV and pooled L-SKEW moment estimates to account for the degree of urbanisation:

$$\boldsymbol{LCV_{URBAN} = LCV_{POOLED} \times 0.5547^{URBEXT2000}} \quad \mathbf{17}$$

$$\boldsymbol{LSKEW_{URBAN} = [(LSKEW_{POOLED} + 1) \times 1.1545^{URBEXT2000}] - 1} \quad \mathbf{18}$$

These adjustment equations are based solely on the value of $URBEXT_{2000}$. Specifying these equations in terms of URBAN and recalibrating the coefficients yields the same relationship between adjustment coefficient and URBEXT2000 as defined by Kjeldsen 2010 (with URBAN estimated from URBEXT2000). The recast growth curve adjustment equations are:

$$\boldsymbol{LCV_{URBAN} = LCV_{POOLED} \times 0.68654^{URBAN}} \quad \mathbf{19}$$

$$\boldsymbol{LSKEW_{URBAN} = [(LSKEW_{POOLED} + 1) \times 1.096017^{URBAN}] - 1} \quad \mathbf{20}$$