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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: FD1919

2. Project title: Evaluation of the mapping and assessment of urban and suburban areas

3. Contractor organisation(s):
   Centre for Ecology & Hydrology
   Maclean Building
   Crowmarsh Gifford
   Wallingford
   Oxfordshire
   OX10 8BB

4. Total Defra project costs: £ 74,939

5. Project: start date .... 01 May 2003
   end date .... 31 March 2006

6. It is Defra's intention to publish this form.
Please confirm your agreement to do so...YES ☒ NO ☐

(a) When preparing SID 5s contractors should bear in mind that Defra intends that they be made public. They should be written in a clear and concise manner and represent a full account of the research project which someone not closely associated with the project can follow.

Defra recognises that in a small minority of cases there may be information, such as intellectual property or commercially confidential data, used in or generated by the research project, which should not be disclosed. In these cases, such information should be detailed in a separate annex (not to be published) so that the SID 5 can be placed in the public domain. Where it is impossible to complete the Final Report without including references to any sensitive or confidential data, the information should be included and section (b) completed. NB: only in exceptional circumstances will Defra expect contractors to give a "No" answer.

In all cases, reasons for withholding information must be fully in line with exemptions under the Environmental Information Regulations or the Freedom of Information Act 2000.

(b) If you have answered NO, please explain why the Final report should not be released into public domain

Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

The Flood Estimation Handbook (FEH) procedures have become standard practice for flood estimation in the UK. Catchment descriptors quantify physical and climatological characteristics and play a key role in the Handbook methodologies. Urbanisation will often have considerable effect on the downstream flood regime and the FEH catchment descriptor defining urban extent (*URBEXT*), provides a basis for taking account of this effect within the procedures. The land cover data used in the derivation of *URBEXT* during the FEH research programme were based on satellite imagery taken around 1990. The release of the CEH Land Cover Map 2000 (LCM2000) provided an opportunity to bring the indexing of catchment urbanisation up to date.

A two-stage research project (FD1919) was commissioned under the Defra/EA Fluvial, Estuarine and Coastal Processes R&D Theme. During Stage 1, the evaluation identified that three LCM2000 Subclasses; namely Suburban, Urban and Inland Bare Ground, were likely to be most appropriate in defining the extent of built-up areas. Subsequently however, it also found that there was exaggeration of the extent of Suburban and Urban land cover in rural areas that needed addressing before the data could be used. It also concluded that the Subclass Inland Bare Ground, mapped appropriate land cover in an urban context, but not elsewhere. Lastly, the evaluation determined that some Suburban areas had been misclassified as arable and horticultural land cover and suggested a reclassification procedure was required.

As a result of these findings procedures were developed to refine the LCM2000 land cover data that define built-up areas. Ordnance Survey settlement outlines provided the basis for a mask where Urban, Suburban and Inland Bare Ground land cover that fell outside the mask was rejected. A reclassification procedure was applied to Arable horticulture land cover where it fell within the mask. If the selected land cover parcels were shown to be predominantly Suburban or Urban areas by the 1990 Land Cover Map of Great Britain, then the reclassification from Arable horticulture to Suburban was 'approved'. Assessment of the result of the rejection and reclassification procedures showed that overall their application produced a refinement of the mapping of built-up areas by LCM2000.

The key recommendations from Stage 1 were that the refined land cover data be used to derive updated values of catchment urban extent, that this descriptor be known as $URBEXT_{2000}$, and that these new values be made available to FEH users through the release of a new version of the FEH CD-ROM. This would also present an opportunity to give users access to recent advances in the digital terrain model used to define catchment boundaries and drainage paths.

Following on from these recommendations, research carried out in Stage 2 saw the development and derivation of a new index describing urban extent based on these data (*$URBEXT_{2000}$*), the production of a new FEH CD-ROM, and the development of new FEH procedures based on *$URBEXT_{2000}$*. Additionally, the catchment descriptors *URBLOC* (describing the location of built-up areas within the catchment) and *URBCONC* (defining the concentration of catchment urbanisation) were also computed using the new data. Furthermore, the production of a new FEH CD-ROM provides an opportunity for FEH users to benefit from the improvements made to the Integrated Hydrological Digital Terrain Model (IHDTM) used to define catchment boundaries. Consequently, an important element of the work, conducted during Stage 2, was the recalculation of catchment values using newly-defined boundaries for all existing descriptors.

It is evident, therefore, that the work carried out under the Defra/EA funded R&D project FD1919 has brought improvement to the FEH procedures in a number of ways. Stage 1 of the project culminated in the provision of a land cover dataset that would allow key indices describing catchment urbanisation to be updated. Stage 2 of the research programme saw the development of indices describing the extent, location and concentration of catchment urbanisation based on the new data; know as *$URBEXT_{2000}$*, *$URBLOC_{2000}$*, and *$URBCONC_{2000}$*, respectively. Index values were subsequently derived for all UK catchments of at least 0.5 km^2. This fulfilled the primary objective of providing catchment descriptor values that define urbanisation and are based on the most recent national digital land cover data available.

The new urban descriptor values will be made available to FEH users through the release of a new FEH CD-ROM. The development of a new CD-ROM provided an opportunity to include recent advances to the IHDTM; which defines catchment boundaries and drainage paths, and is used to describe physical attributes of the catchment such as mean slope. Improvements to the IHDTM, made since version 1.0 of the FEH CD-ROM was launched in 1999, included; enhancing the quality of the data inputs, the application of the latest version of the IHDTM derivation software, and the provision of an IHDTM for all parts of the UK. Catchment values for new and existing descriptors have been derived using the improved IHDTM and are provided on the new FEH CD-ROM. Version 2.0 of the FEH CD-ROM also includes new and improved functionality.

Finally, the catchment descriptor *URBEXT* plays a key role in the FEH procedures. When using the FEH statistical procedures, it provides a basis for adjusting estimates of the median annual flood (*QMED*) and the flood growth curve, when the subject catchment is urbanised. These adjustment procedures, developed during the FEH research programme and published in Volume 3 of the Handbook, are centred on the use of the catchment descriptor *$URBEXT_{1990}$*. Values of *$URBEXT_{1990}$* are based on land cover data recorded around 1990, as indicated by the subscript. The new descriptor *$URBEXT_{2000}$* is not simply an update to *$URBEXT_{1990}$*, it is derived from data produced using different mapping techniques and typically the same level of catchment urbanisation will result in higher values of *$URBEXT_{2000}$* than *$URBEXT_{1990}$*. Consequently, *$URBEXT_{2000}$* values cannot be used with procedures designed for use with *$URBEXT_{1990}$*, and therefore, new procedures, based on models calibrated using *$URBEXT_{2000}$* values, were developed.

It is recommended that those using the FEH CD-ROM 1999 (version 1.0) upgrade to the new FEH CD-ROM (version 2.0). This will provide access to the improved IHDTM, new software functionality, and updated indices describing catchment urbanisation. It is also recommended that, when using the FEH statistical procedures, the urban adjustment procedures used are based on values of *$URBEXT_{2000}$* rather than *$URBEXT_{1990}$*. The FEH statistical procedures for flood frequency estimation are implemented through use of the software product WINFAP-FEH. The package is currently being upgraded to incorporate the recommended changes to the statistical procedures, for release later this year (2006).

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);

- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

Commercial Exploitation

Is there any Intellectual Property arising from this project which is suitable for commercial exploitation? (Question 10 Form SID5A).

Yes. Data arising from this project will be disseminated through the issue of a new version of the FEH CD-ROM.

Short Report

1. Introduction

1.1 FEH catchment descriptors

The Flood Estimation Handbook (FEH) procedures (IH 1999), have largely superseded those described in the Flood Studies Report (NERC 1975) as the standard methods for estimating flood frequency in the UK.

Derivation of catchment characteristics for use in the Flood Studies Report (FSR) procedures involved the time-consuming manual extraction of information from paper maps. An innovative approach to defining descriptor values for the FEH employed an Integrated Hydrological Digital Terrain Model (IHDTM) to define catchment boundaries automatically superimposed on digital spatial datasets. Descriptor values are supplied to users on the FEH CD-ROM along with a geographical interface to aid catchment selection. This approach is seen to be a major advance in flood frequency estimation.

Catchment descriptors quantify physical and climatological characteristics (Bayliss 1999) and play an important role in the Handbook methodologies. Relationships established between descriptors and key variables, such as the median annual flood (QMED), provide techniques for producing flood frequency estimates at ungauged sites. Descriptor values are used in the judgment of catchment similarity when, for example, there is a requirement to 'pool' flood peak data (Reed *et al*. 1999). They are also used to identify permeable and urbanised catchments for which the FEH provides additional steps to the procedures.

1.2 Indexing urban extent

Urbanisation will often have considerable influence on the downstream flood regime and, without amelioration, be likely to increase flood volumes and reduce response times. Consequently, consideration of this effect is an important part of flood frequency estimation procedures and definition of the extent of catchment urbanisation crucial to producing a 'best estimate'.

Guidance following publication of the FSR in 1975 advised users to estimate the urbanised fraction of the catchment using a hand-drawn catchment boundary overlain on an Ordnance Survey (OS) 1:50,000 scale map. The production of a digital Land Cover Map of Great Britain (LCMGB) that included classes defining urban and suburban areas (Fuller *et al*. 1994), by the then Institute of Terrestrial Ecology (now CEH Monks Wood), meant that the FEH could consider an automated approach to defining catchment urbanisation.

Data delineating urban and suburban areas, held as a regular 50 m grid, were supplied for the FEH research programme. An advantage of the digital LCMGB, is that it does discriminate between urban and suburban areas. The latter are defined to be a mixture of urban development and permanent vegetation, and in Volume 5 of the FEH, Bayliss and Scarrott (1999) describe how a composite index quantifying urban extent (*URBEXT*) was developed, that reduces the influence of the suburban element with a weight of 0.5.

The urban and suburban land cover data used in the derivation of *URBEXT* for the FEH are based on satellite imagery taken around 1990. Since the extent of catchment urbanisation is likely to change through time it is important that index values are 'dated'. *URBEXT* values given for gauged catchments in Volume 5 of the Handbook, and made available for over 4 million ungauged sites on the FEH CD-ROM, describe urban and suburban development around 1990. That is made clear by use of a subscript (i.e. $URBEXT_{1990}$).

The quantification of catchment urban extent given by index values of $URBEXT_{1990}$ is now clearly out of date. FEH users currently employ pragmatic solutions to update catchment values of $URBEXT_{1990}$ where necessary and reasonably expect that any new national land cover dataset be considered for use. The release of the CEH Land Cover Map 2000 (LCM2000) included classes defining urban and suburban areas (Fuller *et al*. 2002) and provided an opportunity to bring the indexing of catchment urbanisation up to date.

A two-stage research project (FD1919) was commissioned under the Defra/EA Fluvial, Estuarine and Coastal Processes R&D Theme. The primary objectives of Stage 1 were to thoroughly evaluate appropriate outputs from LCM2000, apply refinement procedures to the land cover data where necessary, and report on the suitability of the data in deriving an update to values of $URBEXT_{1990}$. Following the evaluation, the Stage 1 report (Bayliss and Davies 2003) made a number of recommendations (summarised below) that were approved by the Defra-appointed review group, and subsequently formed the basis of Stage 2 of the research project.

1.3 Recommendations from Stage 1 Report

The recommendations of the authors were that:

- Refined LCM2000 data described in the Stage 1 report be used to produce an update to the FEH catchment descriptor *URBEXT* to be known as $URBEXT_{2000}$.

and in Stage 2 that:

- Advances to the IHDTM used to define catchment boundaries are embraced when deriving values of $URBEXT_{2000}$ and that other descriptor values presented on the FEH CD-ROM are recalculated across the UK using the improved catchment definition. Improvements made to the IHDTM since the release of version 1.0 of the FEH CD-ROM will include:
    - The application of the latest methods, for 'locking in' IHDTM-derived drainage paths to the river networks shown on 1:50,000 OS maps, to many more regions of the UK.
    - Recognising the effect of some canals when generating IHDTM-derived drainage paths.
    - The provision of IHDTM grids for all islands in the UK (most notably in Scotland) not included on version 1.0 of the FEH CD-ROM, thereby extending the use of FEH procedures to these areas.

- Procedures used to compute catchment values of $URBEXT_{2000}$ are consistent with those used to produce values of $URBEXT_{1990}$ but that the programming code is reviewed in the light of recent advances in processing power and updates to database software.

- $URBEXT_{2000}$ will be a composite index based on catchment values of the refined land cover classes Suburban, $\text{Suburban}_{\text{Ah}}$, Urban and Inland Bare Ground.

- Analyses are carried out to determine the most appropriate weightings of the individual components of the composite index $URBEXT_{2000}$.

- In addition to calculating $URBEXT_{2000}$ for all catchments defined on the FEH CD-ROM, values for the catchment descriptors *URBLOC* (describing the location of built-up areas within the catchment) and *URBCONC* (defining the concentration of catchment urbanisation) are also computed based on the refined land cover classes taken from LCM2000. They will be known as $URBLOC_{2000}$ and $URBCONC_{2000}$ respectively.

- Since the use of a parcel-based approach in LCM2000 is likely to give different values of catchment urban extent to that derived from the pixel-based LCMGB data, the FEH models that include *URBEXT* as an input parameter should be revisited.

- Catchment values of $URBEXT_{2000}$ are disseminated to FEH users through the production and release of version 2.0 of the FEH CD-ROM. Values for $URBLOC_{2000}$ and $URBCONC_{2000}$ will also be provided.

- New functionality be included as part of upgrade to the FEH CD-ROM.

2. An improved IHDTM

2.1 Role of the IHDTM

The CEH Integrated Hydrological Digital Terrain Model (IHDTM), described by Morris and Flavin (1990), uses Ordnance Survey digital 1:50,000 contour and river centre-line data to define elevation information and drainage path directions over a regular 50 m grid. The model's use of digital river information to position river valleys accurately means that the IHDTM is better suited to hydrological applications than other digital terrain models. Using these drainage path directions a catchment boundary can be derived automatically at any node on the IHDTM (Figure 2.1). Subsequently, with appropriate software, the boundary can be applied to any gridded dataset to generate catchment values.

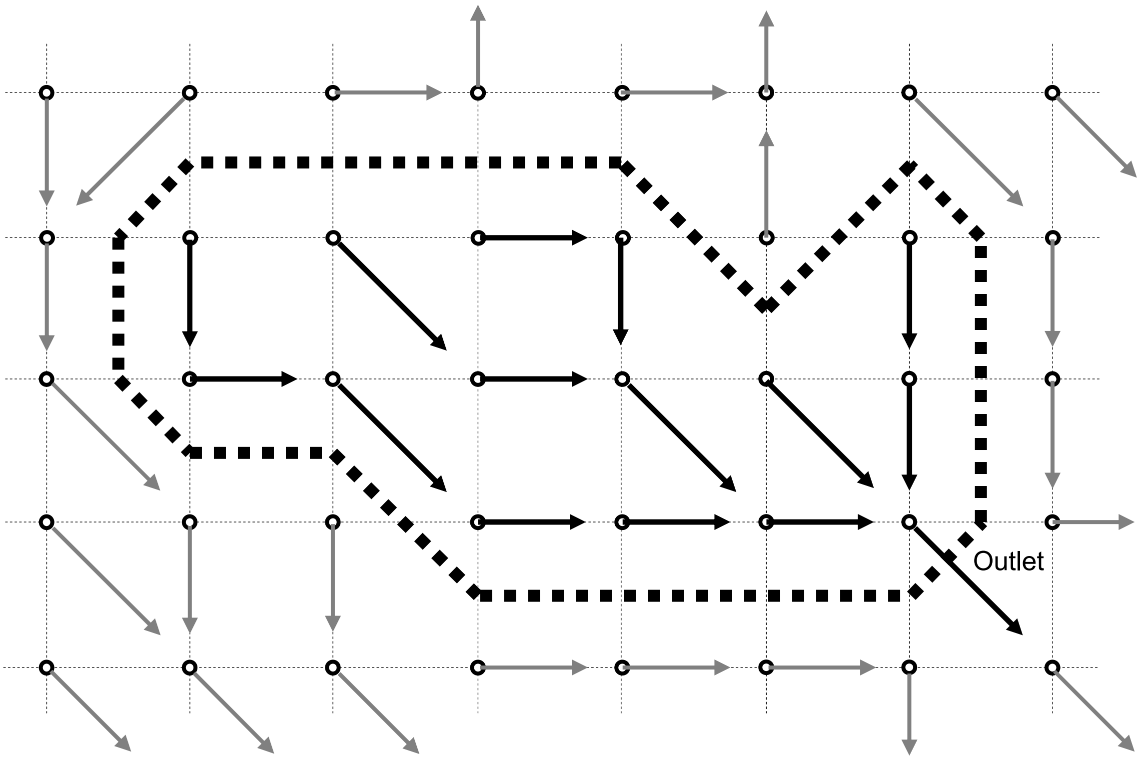

Figure 2.1 Derivation of an IHDTM catchment boundary (dashed line) using drainage paths (arrows)

The digital catchment descriptors are a vital component of the FEH procedures (see Section 1.1). The IHDTM is pivotal to deriving catchment values of these descriptors since the model is used to define watersheds and, additionally, the IHDTM grids themselves are used to define indices describing the physical and morphometric attributes of catchments – for example, catchment shape and slope. Given the key role that the IHDTM plays in defining descriptor values, it is important that drainage paths and catchment boundaries are defined accurately.

2.2 New IHDTM grids

The refinement of the IHDTM grids is an almost perpetual process and Project FD1919 sought to 'capture' as many of these improvements as possible without compromising the schedule. The quality of the data inputs to the model have been significantly improved since catchment descriptor values were defined in the late 1990s for the FEH research programme and subsequent release on the FEH CD-ROM 1999 (version 1.0). Additionally, the improved river to grid software had yet to be applied to all areas covered by the IHDTM. The development of new indices describing catchment urbanisation, and the requirement to disseminate these values with the publication of a new version of the FEH CD-ROM, also presented an opportunity to recalculate all catchment descriptor values based on improved IHDTM grids.

Consequently, new versions of the grids were derived to encapsulate all the current improvements to the input data and benefit from improvements to the IHDTM software by applying the latest version of the code. Furthermore, the IHDTM grids were also extended to provide complete coverage of the UK and the Isle of Man (see Figure 2.2).

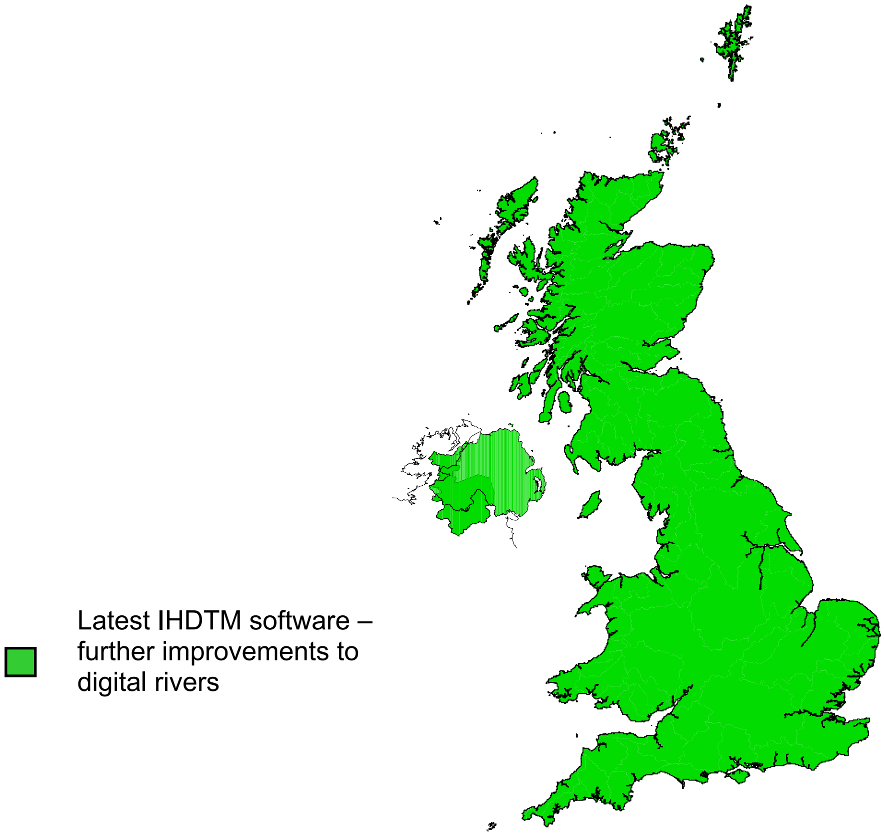

Figure 2.2 Coverage of the new IHDTM grids

Catchment areas were defined using the new IHDTM-derived drainage paths for 958 of the 962 gauging stations, listed, at the time of writing, on the HiFlows-UK website (www.environment-agency.gov.uk/hiflowsuk). A comparison with those provided by the gauging authorities, revealed that for 38 stations (4.0%) the areas differed by more than a factor of 1.1. A similar comparison carried out during the FEH research programme (Bayliss 1999), using the IHDTM drainage paths subsequently provided on the FEH CD-ROM 1999, showed that 5.2% of the 1000 sites compared, exceeded this threshold. This indicates that use of the new IHDTM grids has brought an improvement in catchment boundary definition.

3 Defining catchment urbanisation - new descriptors

3.1 Introduction

The CEH Land Cover Map 2000 (Fuller *et al*. 2002) differentiates between the different types of development that form built-up areas. There was, therefore, an opportunity to develop a set of indices based on recent data. The evaluation of LCM2000 outputs, carried out in the first stage of this research project, described by Bayliss and Davies (2003), recommended that the refined LCM2000 data depicting areas of Suburban and Urban land cover could be used to define built-up areas. The types of development classified as Urban and Suburban areas were consistent with those defined by LCMGB classes of the same name, and which were subsequently used to define $URBEXT_{1990}$, $URBLOC_{1990}$ and $URBCONC_{1990}$. They also described how in an urban context, the data based on the LCM2000 class Inland Bare Ground, depicted gravel car parks, railway sidings, derelict industrial land, and misclassified urban and suburban development. Consequently, they concluded that any new composite indices describing catchment urbanisation, and based on LCM2000 outputs, should also include refined Inland Bare Ground data. The development of three new catchment descriptors, based on LCM2000 data and given the subscript 2000, is described below.

3.2.1 $URBEXT_{2000}$

Stage 1 of the research project produced refined data, based on outputs from LCM2000, for the classes Urban, Suburban (including areas reclassified as Suburban) and Inland Bare Ground (IBG). The report recommended that these data be used to produce a composite index describing catchment urban extent.

The Stage 1 report concluded that both LCM2000 and LCMGB assign the same types of development to their Urban and Suburban classes. Consequently, since the LCM2000 class Suburban most often comprised areas with a mixture of the urban and vegetated areas often found in residential areas dominated by detached and semi-detached housing, a weighting of 0.5 again seemed appropriate.

The report also recommended the inclusion of IBG (when found within a settlement) in the depiction of built-up areas and in the subsequent definition of urban extent. However, assigning a weighting to the extent of IBG found in a catchment is more difficult. The refined LCM2000 data used here only includes IBG where it is found in an urban context. Bayliss and Davies (2003) found that in a rural context the land cover assigned to the class IBG is dominated by quarries or naturally exposed rock surfaces, but in the urban environment, IBG represents the wide range of developments often found within built-up areas. These developments ranged from suburban residential to industrial, but were more commonly found to represent land cover types that were equivalent to those assigned to the Urban class (weighting of 1.0), rather then the Suburban class (weighting of 0.5). Consequently, a weighting for the IBG component of the composite index of 0.8 was judged to be appropriate.

The composite index $URBEXT_{2000}$ is defined as:

$$URBEXT_{2000} = URB_{EXT} + 0.5\ SUBURB_{EXT} + 0.8\ IBG_{EXT} \qquad (3.1)$$

where URB_{EXT}, $SUBURB_{EXT}$ and IBG_{EXT} represent the extent within the catchment of the three refined land cover classes Urban, Suburban and Inland Bare Ground.

3.2.2 $URBLOC_{2000}$

The availability of refined LCM2000 data that defines built-up areas also led to the development of a new urban location index ($URBLOC_{2000}$). The principles used to define $URBLOC_{1990}$ were followed, but in keeping with approach used to define $URBEXT_{2000}$, the new index also takes account of areas of Inland Bare Ground (IBG) within the catchment, as well as Urban and Suburban areas. Consequently, the location of areas of IBG is included within the composite index $URBLOC_{2000}$ which is defined as:

$$URBLOC_{2000} = \frac{URB_{EXT}\ URB_{LOC} + 0.5\ SUBURB_{EXT}\ SUBURB_{LOC} + 0.8\ IBG_{EXT}\ IBG_{LOC}}{URB_{EXT} + 0.5\ SUBURB_{EXT} + 0.8\ IBG_{EXT}} \qquad (4.6)$$

where

$$URB_{LOC} = \frac{URBDIST_{MEAN}}{DIST_{MEAN}} \qquad SUBURB_{LOC} = \frac{SUBURBDIST_{MEAN}}{DIST_{MEAN}}$$

$$IBG_{LOC} = \frac{IBGDIST_{MEAN}}{DIST_{MEAN}} \qquad (3.2)$$

The location parameters URB_{LOC}, $SUBURB_{LOC}$ and IBG_{LOC} are not defined when the catchment is completely rural and poorly defined when nearly so. In order to avoid the computation of misleading values of *URBLOC*, the FEH (Volume 5, Section 6.6.2) recommends that the index $URBLOC_{1990}$ is not calculated when $URBEXT_{1990}$ is less than 0.005. This threshold was intended to be an approximation of the point at which the urban extent value is more likely to be based on settlements, rather than isolated dwellings. Its choice, however, is somewhat arbitrary and consequently the same threshold is recommended here for use with $URBEXT_{2000}$ and $URBLOC_{2000}$. Therefore, when $URBEXT_{2000}$ is less than 0.005, $URBLOC_{2000}$ should not be defined.

3.2.3 $URBCONC_{2000}$

A new urban concentration index to be derived using refined data for the LCM2000 land cover classes Urban, Suburban and Inland Bare Ground, was also developed. The derivation procedure follows the principles described in the FEH (Volume 5, Section 6.7.2) for the definition of $URBCONC_{1990}$ values. The new procedure does, however, take account of the 'connectivity' of areas of IBG, as well as those defined to be urban or suburban, in the definition of $URBCONC_{2000}$. Accordingly, the new index is defined as:

$$URBCONC_{1990} = \frac{\sum_{1}^{n} INFLOW_{URB/SUBURB/IBG}}{\sum_{1}^{n} INFLOW_{TOTAL}} \tag{3.3}$$

$URBCONC_{2000}$ values are calculated only when $URBEXT_{2000}$ is at least 0.005.

4. FEH urban adjustment procedures

4.1 Adjusting $QMED_{rural}$

4.1.1 Introduction

Reed and Robson (1999) discus in detail in the FEH (Volume 3, Chapter 18) the need to adjust the estimate of *QMED* when the subject catchment is ungauged and urbanised, and also describe the rationale for an urban adjustment model. The key points are summarised here to provide the background for a new adjustment procedure designed for use with $URBEXT_{2000}$.

When an urban catchment is gauged, the observed data include the effect resulting from urbanisation. However, it is important to note that, since most gauged catchments in the UK have some flood alleviation measures in place (e.g. storage ponds), the observed data typically include the net effect only (i.e. the effect of urbanisation on flood flow that has not been offset by the flood mitigation works in place). Similarly, the ungauged urbanised catchments for which flood estimates are frequently required, also typically include these works. It is evident therefore, that the gauged records provide appropriate data on which to base an adjustment model for use in the ungauged case.

The urban adjustment factor (*UAF*) describes the proportional increase in *QMED* attributable to the net effect of urbanisation, relative to the rural state. The *UAF* can be determined for gauged urbanised catchments since it is defined as the ratio of *QMED* based on observed data, to the as-rural *QMED* ($QMED_{rural}$) estimated using catchment descriptors i.e.

$$UAF = \frac{QMED}{QMED_{rural}} \tag{4.1}$$

where $QMED_{rural}$ is given by:

$$QMED_{rural} = 1.172\ AREA^{AE} \left(\frac{SAAR}{1000}\right)^{1.560} FARL^{2.642} \left(\frac{SPRHOST}{100}\right)^{1.211} 0.0198^{RESHOST} \tag{4.2}$$

Here, *AE* denotes the *AREA* exponent given by:

$$AE = 1 - 0.015 \ln\left(\frac{AREA}{0.5}\right) \tag{4.3}$$

The variable *RESHOST* is a residual soils term obtained from HOST data and defined by

$$RESHOST = BFIHOST + 1.30\left(\frac{SPRHOST}{100}\right) - 0.987 \tag{4.4}$$

In cases where the subject site is gauged, the flood peak series include the effect of urbanisation and no adjustment of *QMED* is needed. However, in the vast majority of cases the subject site is ungauged and an adjustment to $QMED_{rural}$ is required. Hence, it is necessary to define a model that allows the estimation of the *UAF* from catchment descriptors.

The *UAF* Equation (9.3) published in Volume 3 of the FEH (Robson and Reed 1999), was based on a model calibrated using $URBEXT_{1990}$ values (albeit adjusted to the midpoint of the flood data record). The equation was provided for use with $URBEXT_{1990}$ values and remains unchanged. The model calibration and results are summarised again here (Section 4.1.2) to provide appropriate background and to demonstrate that the same model structure and calibration procedures have been adopted for use in defining a *UAF* equation for use with $URBEXT_{2000}$ (Section 4.1.3).

[With the development of the descriptor $URBEXT_{2000}$ it is important to use the subscripts 1990 and 2000 to avoid confusion. Subsequent sections of this report use the generic term *URBEXT* when referring to model structure but use the *URBEXT* subscripts to identify, where appropriate, the data used in calibrating the model. The use of the subscript also clarifies which *URBEXT* value is required when the calibrated model is used within the procedures.]

4.1.2 Adjusting $QMED_{rural}$ using $URBEXT_{1990}$

Model structure

The urban adjustment model described in Volume 3 of the FEH includes terms that reflect the faster response times and increased percentage runoff associated with urbanisation. The model is given as:

$$UAF = (1 + URBEXT)^{g} \ PRUAF \qquad (4.5)$$

where

$$PRUAF = 1 + 0.615\, URBEXT \left(\frac{70}{SPRHOST} - 1 \right) \qquad (4.6)$$

[*SPRHOST* is the standard percentage runoff estimated using the Hydrology Of Soil Types (HOST) classification (Bayliss and Morris 1999)].

The first term $(1+URBEXT)^{g}$ reflects the faster response times and increased *QMED* that comes with increased urbanisation, relative to the rural case. The second term, the percentage runoff urban adjustment factor (*PRUAF*), provides an estimate of the increase in percentage runoff due to urbanisation. The choice of the coefficient 0.615 is discussed in Volume 3 of the FEH (Section 18.3.2), and summarised in Table B.2 (page 240) in Volume 4.

Data for calibration

The calibration of this urban adjustment model, described in detail in Section 18.3.3 of Volume 3 of the FEH, used flood data from 115 urbanised catchments for which $URBEXT_{1990}$ was 0.05 or greater. For each catchment, the $URBEXT_{1990}$ values used in this calibration were adjusted to reflect the level of urbanisation that corresponded to the midpoint of the flood record, using the urban expansion factor (*UEF*) given in Volume 5 of the FEH. *UAF* values were defined using the ratio of *QMED* estimated from gauged data, to $QMED_{rural}$ estimated using catchment descriptors (Equation 4.2).

The calibrated model

A logarithmic transformation was applied to Equation 4.5 to give the linear model form below:

$$\ln UAF = g \ \ln(1 + URBEXT_{1990}) + \ln PRUAF \qquad (4.7)$$

A weighted least – squares regression model was fitted, with weights proportional to $URBEXT_{1990}$, so that greater weight was given to data from the most urbanised catchments. The resulting *UAF* equation recommended for use with $URBEXT_{1990}$ is:

$$UAF = (1 + URBEXT_{1990})^{0.83} \ PRUAF \qquad (4.8)$$

4.1.3 Adjusting $QMED_{rural}$ using $URBEXT_{2000}$

Model structure

An identical approach to that described in Section 4.1.2 was used to identify an urban adjustment equation for use with $URBEXT_{2000}$ values. The form of the model to be used to estimate *UAF* is:

$$UAF = (1 + URBEXT)^{g}\ PRUAF \tag{4.9}$$

This is identical to the model structure described in Section 4.1.2. However, the urban extent coefficient within the *PRUAF* term is dependent on the source of the mapping used to define urban extent (i.e. Ordnance Survey 1:50,000 maps, Land Cover Map of Great Britain 1990 or Land Cover Map 2000). Volume 4 of the FEH summarises the origins of the *PRUAF* term, and this coefficient, succinctly in Table B.2 (page 240). However, it is important to restate here the process by which the coefficient is defined, since the same approach is used to determine a *PRUAF* term for use with $URBEXT_{2000}$.

The *PRUAF* term given in the FEH for use with $URBEXT_{1990}$ values has an *URBEXT* coefficient of 0.615 (shown here as Equation 4.6). The coefficient derives from substituting a value of 0.3, that was intended for use with values of urban extent defined using Ordnance Survey mapping ($URBAN_{FSR}$), with one which was appropriate to use with values derived from digital data based on the LCMGB ($URBEXT_{1990}$). This was achieved by reference to the regression model that allows $URBAN_{FSR}$ ($URBAN_{50k}$) to be estimated from $URBEXT_{1990}$ values. It is now necessary to provide a coefficient that can be used with $URBEXT_{2000}$ values. Accordingly, based on the relationship established between $URBAN_{FSR}$ ($URBAN_{50k}$) and $URBEXT_{2000}$, the FSR coefficient of 0.3 has been substituted with value of 0.47. Thus, the *PRUAF* term for use with $URBEXT_{2000}$ values is:

$$PRUAF = 1 + 0.47\, URBEXT_{2000} \left(\frac{70}{SPRHOST} - 1 \right) \tag{4.10}$$

Data for calibration

Data for the 115 catchments used to calibrate the $URBEXT_{1990}$ model are again used here, allowing the direct comparison of results. It is important to use flood peak records that are consistent with those used to calibrate the $QMED_{rural}$ equation itself. Consequently, the *QMED* values based on gauged data, remain the same. Catchment descriptor values, including those for $URBEXT_{2000}$ rather than $URBEXT_{1990}$, were taken from the new datasets defined using the improved IHDTM. *URBEXT* values were again adjusted to the midpoint of the flood record.

Results

In keeping with the approach described in Volume 3 of the FEH and summarised here in Section 4.1.2, a logarithmic transformation was applied to Equation 4.9 to give the model form:

$$\ln UAF = g \ln(1 + URBEXT) + \ln PRUAF \tag{4.11}$$

Reed and Robson (1999) also calibrated a simpler model for comparative purposes which took the form:

$$\ln UAF = g \ln(1 + URBEXT) \tag{4.12}$$

The second model does not include the *PRUAF* component so that the effect of this term, on the prediction of *QMED* for urban catchments, can be assessed. Again, the same approach was applied here.

A weighted least – squares regression model was fitted in both cases, with weights proportional to catchment values of $URBEXT_{2000}$. Calibration results for both *UAF* models are presented in Table 4.1. The table also includes the results taken from Volume 3 of the FEH (Table 18.1, page 198) so that comparisons between models based on $URBEXT_{1990}$ and those based on $URBEXT_{2000}$, can be easily made.

Table 4.1 UAF model calibration results giving (in brackets) standard errors for the coefficients

Model	f.s.e.	r^2 of ln*QMED*	r^2 of ln*UAF*	*g* (s.e.)
URBEXT$_{1990}$ (FEH Volume 3)				
Rural model	1.74	0.835		
Simplified urban model	1.70	0.852	0.092	1.49 (0.30)
Urban model	1.66	0.862	0.194	0.83 (0.28)
URBEXT$_{2000}$				
Rural model (Eq. 4.2)	1.84	0.801		
Simplified urban model (Eq. 4.12)	1.78	0.820	0.118	1.18 (0.22)
Urban model (Eq. 4.11)	1.75	0.831	0.216	0.66 (0.21)

It is evident that, in keeping with the results taken from the FEH, the use of an urban adjustment factor gives a small, but significant improvement, compared to using the rural model alone. It is also apparent, that the addition of the *PRUAF* term has again proved worthwhile, with the r^2 increasing from 0.118 to 0.216 when the *PRUAF* term is included.

Comparison of the two sets of results indicates that there is some improvement in the urban model when it is calibrated using *URBEXT*$_{2000}$ data. However, the r^2 remains small (0.216). In discussing the r^2 of the *URBEXT*$_{1990}$ urban model, Reed and Robson (1999), suggest that this is principally because the errors in the *QMED*$_{rural}$ model are large compared to the urban effect. The errors, of course, lead to considerable uncertainty in the 'observed' *UAF* data used in calibration. That same explanation is offered in respect of the urban model calibrated using *URBEXT*$_{2000}$ data – the *QMED*$_{rural}$ model has not changed and estimated values used to define the 'observed' *UAF* are subject to the same uncertainty.

Table 4.1 also reveals that the r^2 values of the new *QMED* models are lower than those achieved when the original models were developed. Although the same 115 catchments were used in both sets of models, the catchment descriptor values used here are those based on the improved IHDTM. These were taken from the new catchment descriptor datasets that are provided on version 2.0 of the FEH CD-ROM and include, and are consistent with, the supplied *URBEXT*$_{2000}$ values. These new catchment descriptor values were not used in the calibration of the *QMED*$_{rural}$ model, carried out during the FEH research programme, so it is unsurprising that r^2 values are now slightly lower.

It is concluded that, where the subject catchment is ungauged and urbanised, the use of an urban adjustment factor calibrated for use with *URBEXT*$_{2000}$ values, leads to an improved estimate of *QMED*. The results have also demonstrated that the inclusion of a *PRUAF* term, that reflects soil permeability, contributes to improving model performance.

Thus the *UAF* recommended for use with *URBEXT*$_{2000}$ is:

$$UAF = \left(1 + URBEXT_{2000}\right)^{0.66}\ PRUAF \qquad (4.13)$$

where

$$PRUAF = 1 + 0.47\,URBEXT_{2000}\left(\frac{70}{SPRHOST} - 1\right) \qquad (4.14)$$

Discussion

To illustrate the effect of using *URBEXT*$_{2000}$, rather than *URBEXT*$_{1990}$, it is useful to compare the urban adjustment factors resulting from the use of Equations 4.8 and 4.13. Since, *URBEXT*$_{2000}$ and *URBEXT*$_{1990}$ values are based on land cover data produced using different mapping procedures they should not be compared directly. Consequently, rather than compare *UAF*s for a defined value of *URBEXT*$_{2000}$ and *URBEXT*$_{1990}$, Table 4.2 compares adjustment factors for the lower limit of each category of catchment urbanisation (e.g. slightly urbanised, moderately urbanised etc.). For this comparison the *PRUAF* term has been calculated assuming soils have an average response (i.e. *SPRHOST* has been set to 37.0)

Table 4.2 Comparison of UAFs resulting from use of the $URBEXT_{1990}$ and $URBEXT_{2000}$ procedures

Category	$URBEXT_{1990}$	$URBEXT_{2000}$	UAF_{1990}	UAF_{2000}
Slightly urbanised	0.025	0.030	1.035	1.033
Moderately urbanised	0.050	0.060	1.070	1.065
Heavily urbanised	0.125	0.150	1.178	1.166
Very heavily urbanised	0.250	0.300	1.369	1.339
Extremely heavily urbanised	0.500	0.600	1.784	1.707

Given that the category limits chosen to describe the same levels of urbanisation in both $URBEXT_{1990}$ and $URBEXT_{2000}$ are somewhat approximate, it is reassuring that the *UAF*s are very similar. This indicates that the use of $URBEXT_{2000}$ is providing an adjustment to $QMED_{rural}$, that is consistent with that originally developed for use with $URBEXT_{1990}$ - indeed further comparisons beyond the sample shown here, established that consistency was apparent across a wide range of *SPRHOST* and *URBEXT* values. However, it should not be forgotten that $URBEXT_{2000}$ is based on more up-to-date data and, for many catchments, provides a more accurate picture of urban extent. Its use, therefore, results in the application of a more appropriate *UAF*.

The final column of Table 4.2 provides examples of the *UAF* factors obtained by using Equation 4.13, which was developed for use with $URBEXT_{2000}$ values. For the purposes of that illustration, *UAF* values have been provided for one value of *SPRHOST* only (i.e. 37.0), but it is important to examine the *UAF*s that will be estimated using the new equation for a range of soil types.

Figure 4.1 illustrates the relationship between *UAF* and $URBEXT_{2000}$ for selected values of *SPRHOST*, ranging from the most permeable (*SPRHOST* = 2) to the most impermeable (*SPRHOST* = 60). In the most extreme case, where the *SPRHOST* value is 2.0, and the catchment is very heavily urbanised, *UAF*s can be very high (intended to reflect the very significant impact that urbanisation has on a permeable catchment). However, for the most part, the data suggest that the effect of urbanisation on *QMED* is relatively modest. For example, on a heavily urbanised catchment with an $URBEXT_{2000}$ value of 0.225, and with average soils (say an *SPRHOST* value of 30.0), the *UAF* is 1.31. Reed and Robson (1999) noted that experimental studies have suggested that the result of urbanisation was to increase flood peaks 'several-fold', which contrasts with the relatively small adjustment of 31% estimated by the model used here. However, this is understandable since the observed flood peak data used to define *UAF* in the model calibration, typically includes the net effect of urbanisation (i.e. after flood mitigation works have reduced flood flows), rather than the direct effects reported by experimental studies.

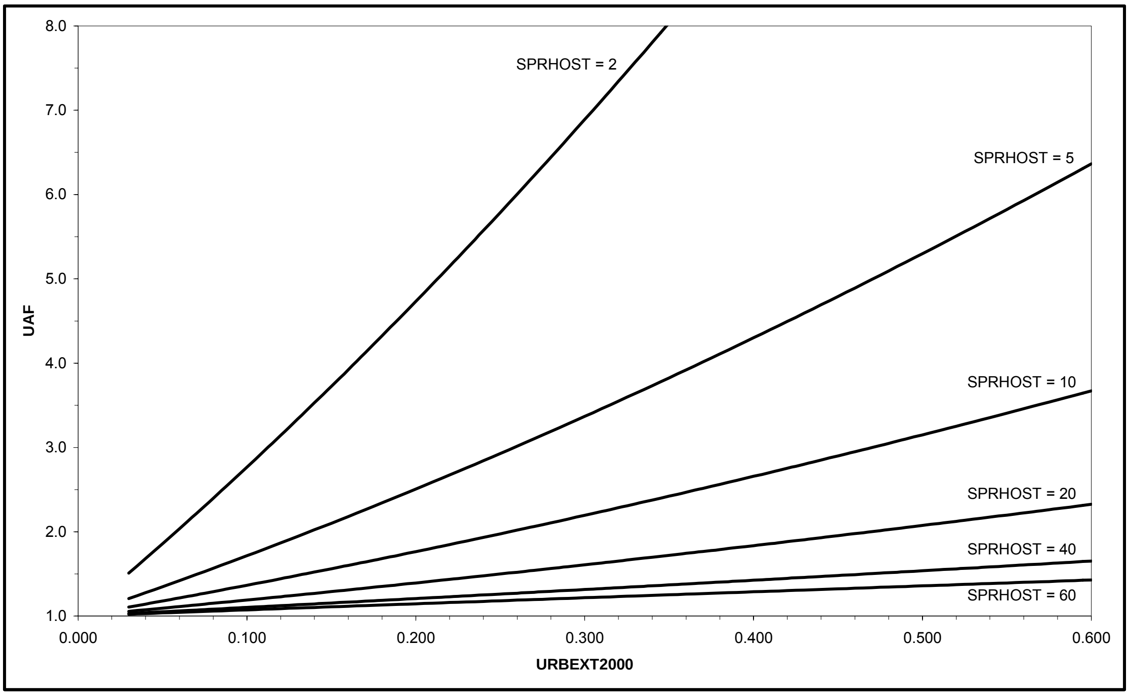

Figure 4.1 Relationship between UAF and $URBEXT_{2000}$ for selected values of SPRHOST

4.2 Adjusting pooling-group growth curve factors

4.2.1 Introduction

Where the subject site is gauged and the catchment is urbanised, the net effect of urbanisation is embraced by the observed data, consequently no adjustment for urbanisation is required. However, in nearly all cases, either the record is too short or the subject site is ungauged and a pooling-group approach is needed. Where the catchment is urbanised the procedure is in two stages. First the as-rural growth curve is estimated by pooling records from essentially rural catchments only. In the second stage the growth curve is adjusted for urbanisation. The adjustment procedure is defined in the FEH (Volume 3 Section 18.4) as:

$$x_T = UAF^{-\left(\frac{\ln T - \ln 2}{\ln 1000 - \ln 2}\right)} xrural_T \qquad 2 \leq T \leq 1000 \qquad (4.15)$$

where *UAF* is the urban adjustment factor, *T* is the return period in years and $xrural_T$ is the as-rural pooled growth curve factor.

The adjustment to the rural pooled growth curve is based on the perception that urbanisation has the greatest effect on short return period floods and little impact on very long return period floods (Reed and Robson 1999). The adjustment procedure defined above (Equation 4.15) is designed so that the growth curve factor for the 2-year return period flood (*QMED*) is unchanged. However, the effect of the adjustment procedure, when the return period is greater than 2 years and less than, or equal to, 1000 years, is to reduce growth curve factors. As a consequence, the 'urban growth curve' is always flatter than the corresponding as-rural growth curve.

Following the assumption that urbanisation has little or no effect on floods with a very long return period, the adjustment of growth curve factors is designed so that after the urban adjustment procedure has been applied, the resultant 1000-year flood flow is the same as the as-rural 1000-year flood flow (see Equations 4.16 and 4.17).

For the 1000-year return period the growth curve factor is:

$$x_{1000} = UAF^{-1}\ xrural_{1000} \qquad (4.16)$$

i.e. the $xrural_{1000}$ growth factor is simply divided by the same factor (the *UAF*) that has been applied to increase $QMED_{rural}$.

The estimated 1000-year flood is therefore:

$$\begin{aligned} Q_{1000} &= QMED\ x_{1000} \\ &= (UAF\ QMED_{rural}) \times (UAF^{-1}\ xrural_{1000}) \\ &= QMED_{rural}\ xrural_{1000} \qquad (4.17) \end{aligned}$$

i.e. the urban adjustment factor has no effect when T=1000 years.

4.2.2 Refinement of the procedure

It is essential that at the chosen subject site, following the application of the urban adjustment procedures, the growth curve factors increase with return period. Following publication of the FEH, a review of the statistical method by CEH (Morris 2003) found that this was not always the case. In some circumstances the adjustment of as-rural growth curve factors, using the procedures described above, produced inconsistencies in flood estimates for a selected site (referred to as T-incoherence).

An examination of growth curve factors, automatically produced for over 2.5 million subject sites (Morris 2003), revealed that at a small proportion of sites (between 0.1 and 0.2%), T-incoherence was being generated by the urban adjustment factor. This occurred when the UAF was close to, or greater than, the as-rural growth curve factor for the 1000-year return period ($xrural_{1000}$). For example, if $xrural_{1000}$ is 3.0 and the *UAF* is 3.5, the adjusted growth curve factor (x_{1000}), defined using Equation 4.16, will be 0.86 (i.e. the estimated 1000-year flood will be 86% of the estimated 2-year flood). The report determined that T-incoherence can also arise when the *UAF* is less than $xrural_{1000}$ because of the differing behaviour, as return period increases, of the *UAF* and $xrural_T$ components of Equation 4.15.

The review identified that T-incoherence typically occurs where the catchment is extremely heavily urbanised and permeable (*SPRHOST* is less than 20%), since this leads to high *UAF* values. This type of catchment occurs very infrequently (see preceding paragraph) and is also unlikely to present a problem to FEH users (when the catchment is defined as extremely heavily urbanised it is recommended that users seek alternative methods). However, since the automation of the statistical method resulted in flood estimates being produced for all catchments (of at least 0.5 km^2), the review recommended some modifications to the adjustment of growth curve factors to avoid T-incoherence.

Firstly, Morris (2003) recommended that a minimum urban-adjusted growth curve factor for the 1000-year return period be imposed, and that the *UAF* used for adjusting growth factors be made smaller than the *UAF* used for adjusting $QMED_{rural}$, when necessary, to prevent the urban-adjusted x_{1000} going below this limit. For the purposes of automating the statistical method, and until further research could be conducted, the lower limit for x_{1000} was set to 1.4 (i.e. $UAF = \min[UAF, xrural_{1000} / 1.4]$).

The choice of this lower limit is arbitrary and is set unnecessarily high if the sole objective is to avoid T-incoherence (a value greater than 1.0 is all that is required). Rather than impose an arbitrary value that would be applied in a relatively large number of cases, the judgement here is that a limit closer to 1.0 is preferable. This will result in x_{1000} being determined from flood data and catchment information on the vast majority of these 'problem catchments', rather than using an arbitrary value. In accordance with this philosophy, it is recommended that a minimum value of 1.1 be imposed when determining x_{1000} (i.e. $UAF = \min[UAF, xrural_{1000} / 1.1]$).

Secondly, the review noted that the form of Equation 4.15, used for applying an urban adjustment to growth curve factors, could result in T-incoherence, particularly at high return periods. To avoid this problem, an alternative equation was presented in the form:

$$x_T = 1 + \frac{\left(xrural_T - 1\right)\left(\dfrac{xrural_{1000}}{UAF} - 1\right)}{\left(xrural_{1000} - 1\right)} \qquad 2 \le T \le 1000 \qquad (4.18)$$

Following the recommendation here that x_{1000} is not allowed to fall below 1.1, *UAF* is defined as being that which is used to adjust $QMED_{rural}$, or $xrural_{1000}$ divided by 1.1, whichever is the smaller (see preceding paragraph). For return periods less than 1000 years the growth curve factors are scaled accordingly.

It is the recommendation of this report that Equation 4.18, with the *UAF* amended where necessary, be used for adjusting pooling-group growth curve factors to take account of the effect of urbanisation. It is also recommended that this issue be revisited, when further research on the derivation of pooling-group growth curve factors is carried out.

5. The new FEH CD-ROM

5.1 Introduction

The development of three new catchment descriptors defining catchment urbanisation, and the subsequent derivation of descriptor values, requires that these values be made available to FEH users, if FEH estimates of flood frequency are to benefit from the improvements these new indices bring. Catchment values for the descriptors developed during the FEH research programme were made available to users through the FEH CD-ROM 1999 (version 1.0). The software was well received by those engaged in flood frequency estimation and it is logical, therefore, that the new descriptor values be made available in the same way.

The release of a new FEH CD-ROM (version 2.0) also provides an opportunity to make available the improvements in drainage path and catchment boundary definition provided by the latest version of the IHDTM. Consequently, all descriptor values (those recalculated and those for the three new indices) have been derived using the improved IHDTM.

Furthermore, the release of new software allows new functionality to be included. The FEH CD-ROM provides a geographical interface that allows the user to identify their site of interest. Once the catchment is located and defined then the relevant catchment descriptors can be viewed and exported. New and improved functionality has been provided in many areas and the principal features that are **new** to version 2.0 are outlined below in Section 5.2.

5.2 Improved and new functionality

5.2.1 Summary

In the six-year period since the release of the FEH CD-ROM 1999 a small number of minor issues relating to the software were identified. The vast majority of these have been resolved as part of the software improvements carried out during this project. Additionally, feedback from users, and ideas from the project team, led to the introduction of a number of new features (e.g. exporting the view as an image file for inclusion in reports). Review of a beta-test version of the product led to further refinements and requests for additional features (e.g. access to a map legend when required). Many small, but important, enhancements to the software were made. For example, gauging station numbers are now shown in yellow rather than red (on a dark background) to improve map clarity.

6. Recommendations

6.1.1 Introduction

It is the recommendation of the authors that those currently using the FEH CD-ROM 1999 (version 1.0) upgrade to the new FEH CD-ROM (version 2.0). This will provide access to the improved IHDTM, new software functionality, and updated indices describing catchment urbanisation.

It is also recommended that urban adjustment procedures be based on values of $URBEXT_{2000}$ rather than $URBEXT_{1990}$. For use within the FEH statistical method, new equations have been developed for the adjustment of $QMED_{rural}$ and the as-rural pooled growth curve factors ($xrural_T$) (defining new procedures for use with the recently published revitalised FSR/FEH rainfall runoff-method was beyond the remit of this research project). These new equations are given in subsequent sections, along with a brief description of their role in the statistical procedures.

The use of a blue text box in subsequent sections highlights those equations that are provided for use with $URBEXT_{2000}$ and are new to the FEH statistical procedures. It is recommended that they supersede equations published for use with $URBEXT_{1990}$, in Volumes 3 and 5 of the FEH.

6.1.2 Adjusting $QMED_{rural}$

When the subject catchment is ungauged and urbanised, a two-stage approach is required to produce an estimate of *QMED* that includes the net effect of urbanisation. Firstly, *QMED* is estimated as if the catchment was rural. The equations provided for the estimation of $QMED_{rural}$ using catchment descriptors are unchanged and are given as:

$$QMED_{rural} = 1.172\ AREA^{AE} \left(\frac{SAAR}{1000}\right)^{1.560} FARL^{2.642} \left(\frac{SPRHOST}{100}\right)^{1.211} 0.0198^{RESHOST} \quad (6.1)$$

Here, *AE* denotes the *AREA* exponent given by:

$$AE = 1 - 0.015 \ln\left(\frac{AREA}{0.5}\right) \quad (6.2)$$

The variable *RESHOST* is a residual soils term obtained from HOST data and defined by

$$RESHOST = BFIHOST + 1.30 \left(\frac{SPRHOST}{100}\right) - 0.987 \quad (6.3)$$

In a subsequent step, the estimate of $QMED_{rural}$ should, wherever possible, be improved by data transfer from one or more suitable donor or analogue catchments.

When the catchment is urbanised, the second stage requires an urban adjustment factor (*UAF*) to be applied to $QMED_{rural}$ to provide an estimate of *QMED* that includes the urban effect i.e.

$$QMED = UAF\ QMED_{rural} \quad (6.4)$$

The research carried out within this project has produced new recommendations for the calculation and application of the *UAF*. It is suggested that a catchment can be considered to be urbanised if its $URBEXT_{2000}$ value is equal to, or exceeds, 0.03. It is recommended that the *UAF* be computed using the $URBEXT_{2000}$ and *SPRHOST* values and the equations given below:

$$UAF = \left(1 + URBEXT_{2000}\right)^{0.66} PRUAF \qquad (6.5)$$

where

$$PRUAF = 1 + 0.47\, URBEXT_{2000} \left(\frac{70}{SPRHOST} - 1\right) \qquad (6.6)$$

6.1.3 Adjusting pooling-group growth curve factors

The FEH also presents a two-stage approach for estimating the flood growth curve when the catchment is ungauged and urbanised. First, the as-rural growth curve is estimated by pooling records from essentially rural catchments only. Second, it recommends that a *UAF* based on the subject catchment value of *URBEXT* (Equation 6.5), should be used to adjust the pooled growth curve.

Following his review of the FEH statistical method, Morris (2003) presented the estimation of the pooled growth curve factor x_T in the alternative form given below:

$$x_T = 1 + \frac{\left(xrural_T - 1\right)\left(\dfrac{xrural_{1000}}{UAF} - 1\right)}{\left(xrural_{1000} - 1\right)} \qquad 2 \le T \le 1000 \qquad (6.7)$$

where *UAF* is the urban adjustment factor, *T* is the return period in years and $xrural_T$ is the as-rural growth curve factor. It is the recommendation of the authors that the alternative form given above (Equation 6.7) is used for adjusting as-rural pooled growth curve factors and that this adjustment procedure is applied when the $URBEXT_{2000}$ value for the subject catchment is equal to, or exceeds, 0.03.

The review also suggested that a minimum urban-adjusted growth curve factor for the 1000-year return period be imposed, and that the *UAF* used for adjusting growth factors be made smaller than the *UAF* used for adjusting $QMED_{rural}$, when necessary, to prevent the urban-adjusted x_{1000} going below this lower limit. It is recommended here that 1000-year growth curve factor (x_{1000}) is not allowed to fall below 1.1 and the *UAF* is defined as being that which is used to adjust $QMED_{rural}$, or $xrural_{1000}$ divided by 1.1, whichever is the smaller i.e.

$$UAF = \min\left(UAF, \frac{xrural_{1000}}{1.1}\right) \qquad (6.8)$$

For return periods less than 1000 years the growth curve factors are scaled accordingly using Equations 6.7 and 6.8.

6.1.4 WINFAP-FEH

The FEH statistical procedures for flood frequency estimation are implemented through use of the software product WINFAP-FEH. The package is currently being upgraded to incorporate the changes to the procedures recommended by this report for release later this year (2006).

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References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

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