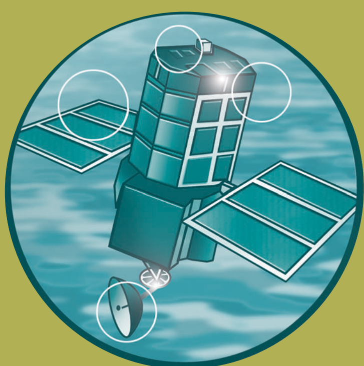
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

URBEXT$_{2000}$ - A new FEH catchment descriptor

Calculation, dissemination and application

R&D Technical Report FD1919/TR



Environment Agency

defra
Department for Environment Food and Rural Affairs

Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

$URBEXT_{2000}$ – A new FEH catchment descriptor

Calculation, dissemination and application

R&D Technical Report FD1919/TR

Produced: March 2006

Authors: A C Bayliss, K B Black, A Fava-Verde &
T R Kjeldsen

Statement of use

This document describes Stage 2 of a two-stage research project carried out under the Defra/EA Fluvial and Coastal Processes R&D Theme. This report provides new recommendations for the use of the FEH statistical procedures for flood frequency estimation and provides details of the research that underpins these changes. Consequently it is an important reference document for users of the Flood Estimation Handbook.

Dissemination status
Internal: Released internally
External: Released to public domain

Keywords: research; flood frequency estimation; FEH; catchment descriptor; IHDTM; urban extent; $URBEXT_{2000}$; urban adjustment; FEH CD-ROM

Research contractor: Centre for Ecology & Hydrology Wallingford

Defra project officer: Dr Paul Webster

Publishing organisation
Department for Environment, Food and Rural Affairs
Flood Management Division,
Ergon House,
Horseferry Road
London SW1P 2AL

Tel: 020 7238 3000 Fax: 020 7238 6187

www.defra.gov.uk/environ/fcd

Published by the Department for Environment, Food and Rural Affairs (March 2007). Printed on material that contains a minimum of 100% recycled fibre for uncoated paper and 75% recycled fibre for coated paper.

PB No. 12527 / 1

Acknowledgements

The authors wish to acknowledge the following people for the assistance they provided during the project.

The Defra Project Officer, Dr Paul Webster (Hydro-Logic Ltd), for his encouragement and his guidance on Defra's requirements.

Those who provided valuable feedback on the beta-test version of the new FEH CD-ROM (version 2.0), namely:

Richard Cole and David Tweedie, Rivers Agency, DARDNI
Duncan Faulkner and Chas Ward, JBA Consulting
David MacDonald, Black & Veatch
Duncan Reed, DWRconsult
Andrew Sloan, Kirk McClure Morton
Peter Spencer, Environment Agency
Manuela Toth and David Price, Jacobs Babtie
Paul Webster, Hydro-Logic Ltd

Helen Davies (CEH Wallingford) for carrying out many of the improvements made to the data inputs that led to an improved Integrated Hydrological Digital Terrain Model (IHDTM).

Particular thanks are due to David Morris (CEH Wallingford) for his work in producing a new IHDTM and for his most valuable advice on streamlining and running the catchment descriptor derivation programs.

Executive summary

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 and refinement of LCM2000 data defining built-up areas was carried out, resulting in a dataset that could be used to update $URBEXT_{1990}$.

The principal objectives of Stage 2 were; to develop and derive catchment values for a new index describing urban extent based on these data ($URBEXT_{2000}$), to make the values available by releasing a new FEH CD-ROM, and to provide 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 provided an opportunity for FEH users to benefit from the improvements made to the digital terrain model 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.

This report gives details of the work carried out under Stage 2. It begins by describing the importance of catchment descriptors in the FEH procedures (Chapter 1). They provide a method for estimating key variables at ungauged sites and in judging catchment similarity when ‘pooling’ flood peak data. Descriptors are also used to identify urbanised catchments, for which FEH provides additional procedures based on the catchment value of *URBEXT*. Following the Stage 1 recommendations, *URBEXT* will now be derived using data based on LCM2000 outputs.

The CEH Integrated Hydrological Digital Terrain Model (IHDTM) is pivotal to the derivation of descriptor values. Chapter 2 describes how improvements to the data inputs, and the ‘river to grid’ software, enables the new IHDTM to define catchment boundaries and drainage paths with greater accuracy. Additionally, coverage has now been extended to include the Scottish Islands, providing complete coverage of the UK.

In order that the FEH procedures benefit from the advances provided by the new IHDTM, it was necessary to recalculate all descriptor values previously provided on the FEH CD-ROM 1999, using newly defined drainage paths and catchment boundaries. Chapter 3 provides an outline of how the software, used to derive in excess of 90 million descriptor values, was improved to reduce 'run times'. The resolution to which values are held was increased for a number of descriptors and the increased coverage provided by the new IHDTM also allowed descriptor values to be derived for the Scottish Islands. The chapter also provides a summary of the procedures followed in order to check data integrity.

Built-up areas can now be defined using data based on outputs from LCM2000, providing an opportunity to bring the indexing of catchment urbanisation up to date. Chapter 4 presents details of the development of three new indices that describe catchment urbanisation ($URBEXT_{2000}$, $URBLOC_{2000}$ and $URBCONC_{2000}$) based on the new data. It begins by describing how the existing indices (derived using 1990 data), included weights, where appropriate, to reduce the influence of suburban areas, compared to urban development, on the final index value. The same philosophy is applied to the new indices, with the effect of suburban development and areas of 'Inland Bare Ground', reduced with weights of 0.5 and 0.8 respectively. It concludes by recommending that an $URBEXT_{2000}$ value of 0.03 be used to define the threshold at which urban adjustment procedures begin to be applied and provides a set of $URBEXT_{2000}$ values that can be used to describe different levels of urbanisation (e.g. moderately urbanised, heavily urbanised etc.).

$URBEXT_{2000}$ is not simply an update to $URBEXT_{1990}$, it is based on 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 it is necessary to define new models and adjustment procedures for use with $URBEXT_{2000}$. Chapter 5 begins by defining the relationship between $URBEXT_{2000}$ and the Flood Studies Report catchment characteristic *URBAN*. This allows $URBEXT_{2000}$ to be updated (or backdated) based on a value of *URBAN* derived manually from OS 1:50,000 mapping. It also describes how the FEH urban expansion model has been rescaled for use with $URBEXT_{2000}$, allowing users to estimate index values for a target year based on a national urban growth model. Most importantly, it defines equations for use with $URBEXT_{2000}$, in order that estimates of the index flood (*QMED*) and pooled flood growth curve factors can be adjusted based on the new index.

The benefits of the new FEH CD-ROM are summarised in Chapter 6. Descriptor values recalculated using an improved IHDTM are made available to users, along with values for the new urban descriptors. The new software also provides new and enhanced functionality.

Finally, in Chapter 7, the report concludes by summarising the research carried out under FD1919. It recommends the use of new indices describing catchment urbanisation that have been developed based on more up-to-date mapping, along with urban adjustment procedures designed for use with $URBEXT_{2000}$. A new FEH CD-ROM will be released to give users access to these descriptors, and its companion software WINFAP-FEH is being upgraded to include the new procedures.

Contents

List of figures

List of tables

Glossary

AREA	IHDTM-derived catchment area (km^2)
BFIHOST	Base Flow Index derived using HOST
DDF	Depth-Duration-Frequency
FARL	FEH catchment descriptor defining the Flood Attenuation from Reservoirs and Lakes
FEH	Flood Estimation Handbook
FEH CD-ROM	A software package that provides design rainfall estimates and catchment descriptor values
FSR	Flood Studies Report
HOST	Hydrology Of Soil Types classification
IBG	Inland Bare Ground
IHDTM	Integrated Hydrological Digital Terrain Model
LCM2000	Land Cover Map 2000
LCMGB	Land Cover Map of Great Britain
PRUAF	Percentage Runoff Urban Adjustment Factor
QMED	Median annual maximum flood
$QMED_{rural}$	As-rural median annual maximum flood
r^2	Coefficient of determination
SAAR	1961-90 Standard period Average Annual rainfall (mm)
SPRHOST	Standard Percentage Runoff derived using HOST
UAF	Urban Adjustment Factor
UEF	Urban Expansion Factor
URBAN	FSR catchment characteristic defining urban extent
$URBAN_{50k}$	FSR catchment characteristic URBAN defined using 1:50,000 mapping
$URBEXT_{1990}$	FEH catchment descriptor defining urban extent in 1990
$URBEXT_{2000}$	FEH catchment descriptor defining urban extent in 2000
$URBCONC_{1990}$	FEH catchment descriptor defining the concentration of urbanisation in 1990
$URBCONC_{2000}$	FEH catchment descriptor defining the concentration of urbanisation in 2000
$URBLOC_{1990}$	FEH catchment descriptor defining the location of urbanisation in 1990
$URBLOC_{2000}$	FEH catchment descriptor defining the location of urbanisation in 2000
WINFAP-FEH	Windows frequency analysis package used to implement the FEH statistical procedures
x_{1000}	Urban-adjusted growth factor for 1000-year return period
$xrural_t$	As-rural pooled growth factor for T-year return period
$xrural_{1000}$	As-rural pooled growth factor for 1000-year return period

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 (see Section 4.1).

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.

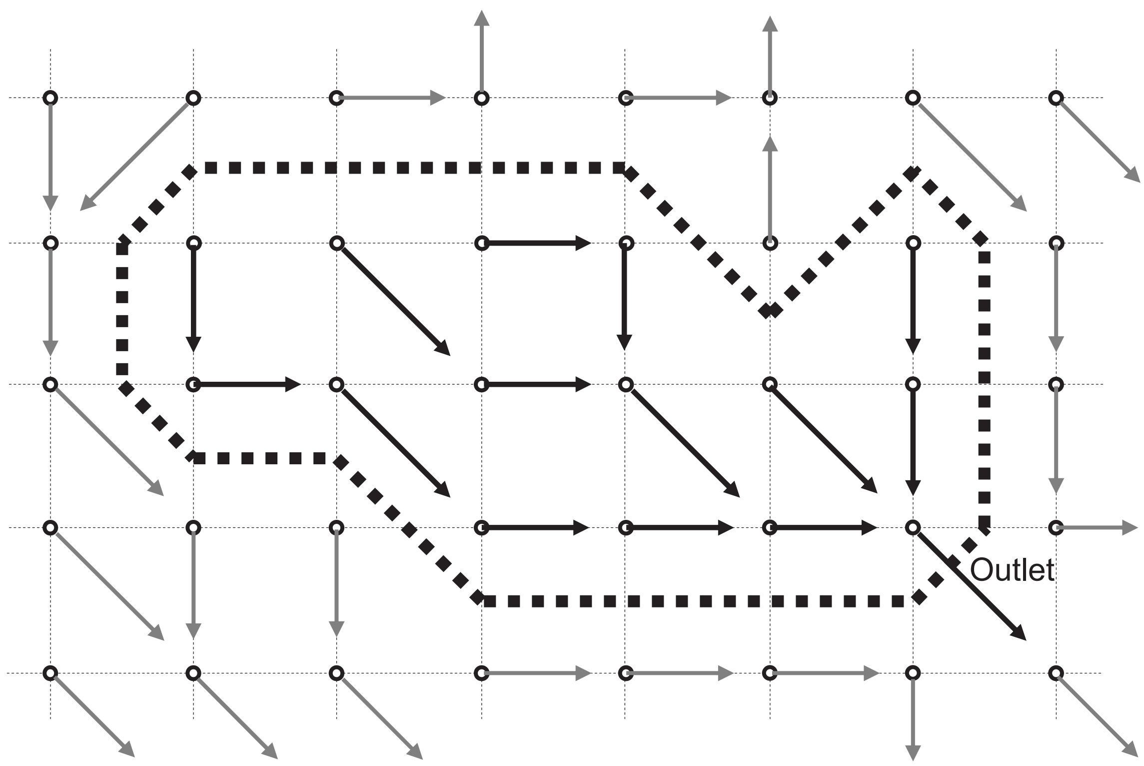


Figure 2.1 Derivation of an IHDTM catchment boundary (dashed line) using drainage paths (arrows)

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. Software development

River networks digitised from OS 1: 50,000 mapping are used, along with elevation data, to locate drainage paths correctly. Early IHDTM software 'guided' the placement of drainage paths, but improvement to the code now means that drainage paths are 'locked' in position so that they are entirely coincident with OS mapping of river networks. This is particularly advantageous in areas where the use of elevation data alone cannot position drainage paths accurately (e.g. The Fens).

The improved 'river to grid program' became available towards the end of the FEH research programme, but in sufficient time to be used in the production of an IHDTM (and subsequently in the derivation of the catchment descriptor values released on the FEH CD-ROM 1999) for the Nene and Great Ouse catchments in eastern England, the Scottish mainland, Northern Ireland, and the Isle of Wight (see Figure 2.2).

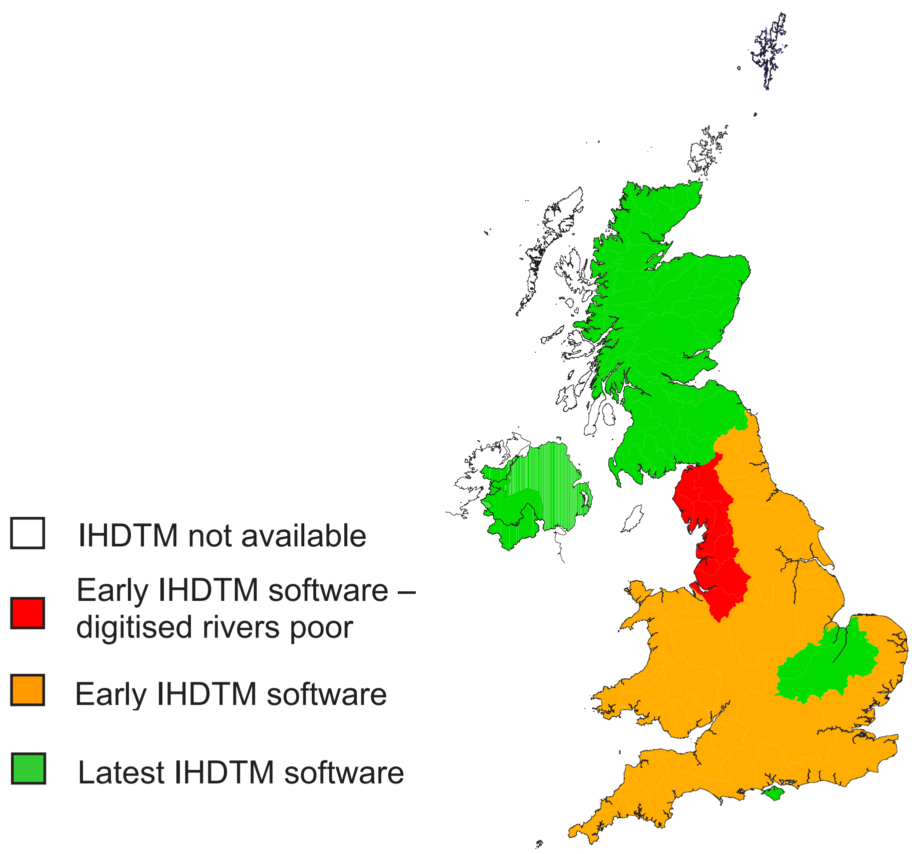


Figure 2.2 Regional variations in the quality of the IHDTM used to derive the catchment descriptor values presented on the FEH CD-ROM 1999

2.3 Improving data inputs

Since there is great reliance on OS river networks the quality of the digitised data is paramount. Work carried out on the IHDTM grids, following publication of the FEH CD-ROM 1999, has focused on improving the quality of the digitised river networks through review and editing. This improvement has, in the main, been driven by CEH research projects requiring an IHDTM for a specific river basin, rather than through a systematic programme. However, networks for much of the west side of England (hydrometric areas 43 – 76) and the Thames basin (areas 37 – 39) have been improved as a result.

More recently, the Defra/EA R&D project FD1919 has prompted further improvements. Funding from FD1919, and elsewhere, has enabled the review and editing of the river network for the Severn to be carried out. Additionally, networks for rivers draining to the North Sea between The Wash and the Humber estuary (the Welland through to the Ancholme), the Trent basin, and the south coast rivers of Kent, Sussex and Hampshire, have also have been subject to further quality control.

In addition to the systematic improvement of data quality for a number of hydrometric areas, attention has also been given to problems identified by users of the FEH CD-ROM version 1.0 since its release in 1999. In most cases the reported errors related to incorrectly located drainage paths resulting from the application of the 'early' IHDTM software. Other problems could be traced back to errors in the digitised rivers. Many of these issues were resolved by the data 'review and edit' programmes described above, or the application of the 'latest' IHDTM software. However, where reported errors remained, specific fixes were implemented where possible.

The IHDTM grids used to define catchment descriptor values for dissemination through the FEH CD-ROM 1999, were available for the UK mainland, Anglesey, and the Isle of Wight, but were not available for Scottish islands, the Isles of Scilly and the Isle of Man (Figure 2.2). However, since publication, digital elevation and river data have become available for these 'missing' areas, making it possible to include the Isle of Man (a UK Dependency) and provide complete coverage of the UK.

2.4 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 (Section 2.3) 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 2.3).

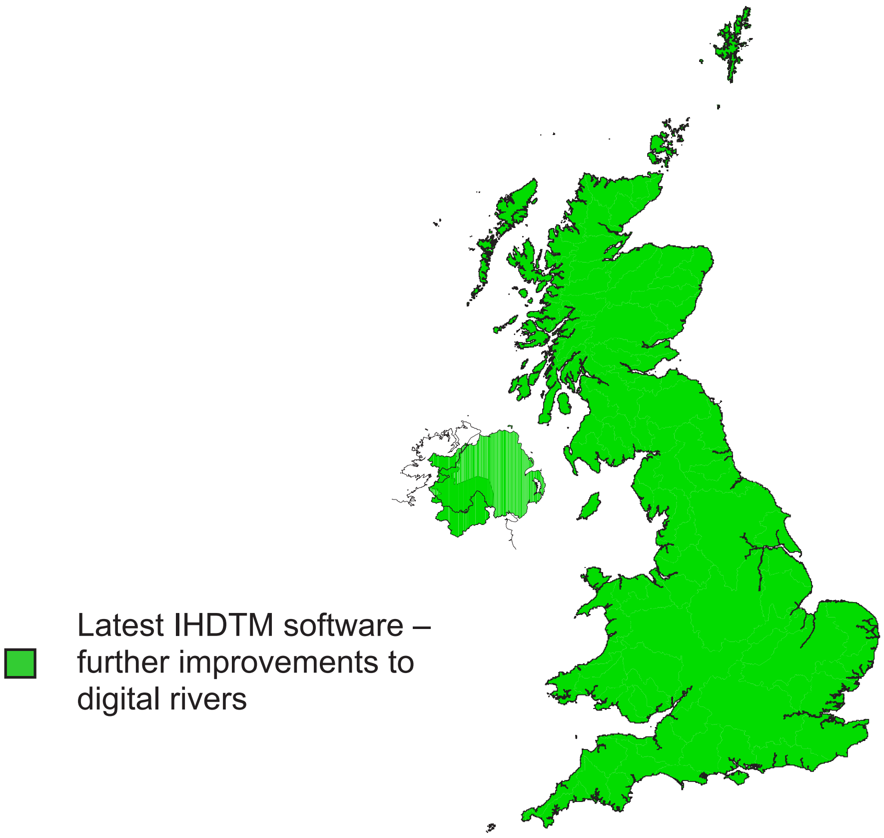


Figure 2.3 Coverage of the new IHDTM grids

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 (see Appendix A). 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. Computation and quality control of catchment descriptor values

3.1 Introduction

To ensure consistency throughout catchment descriptor datasets, and to benefit from the improvements in the IHDTM grids achieved since release of the FEH CD-ROM 1999 (see Chapter 2), it is necessary to recalculate all descriptor values computed at that time. The extended coverage provided by the new IHDTM also means that descriptor values can now be computed (where thematic data are available) for catchments in the Isles of Scilly, the Scottish Islands and the Isle of Man. In addition, new software is required to define descriptor values describing urbanisation based on data taken from Land Cover Map 2000 (see Chapter 4).

During the FEH research programme a suite of FORTRAN programs were written to define and store descriptor values for all points on the IHDTM drainage paths which had a catchment area of at least 0.5 km^2. These programs were complex, and since the number of catchments where computation was required exceeded four million, ‘run times’ were exceedingly long (calculating values for each descriptor typically took weeks rather than days or hours). These programs could again be used to compute descriptor values, but refinement was necessary to reduce run times and to ensure compliance with changes to the UNIX platform, on which the software is run, and updates to the relational database (ORACLE) on which the values are stored.

3.2 Outline of computation procedure

The structure of the FORTRAN programs is, by necessity, far from straightforward, and it is appropriate only for a brief outline of the computation procedure to be provided here. The software is provided with a list of drainage path sources, where the catchment area is equal to (or sometimes slightly above) 0.5 km^2. Beginning with the first source, the catchment boundary is defined using IHDTM drainage directions (see Figure 2.1). Having defined the boundary, relevant blocks of thematic data are ‘cached’, and the appropriate descriptor(s) value(s) computed. The software ‘migrates’ downstream from this source, repeating the process, until it reaches the sea (defined as the tidal limit), or in the case where subsequent sources are processed, when it reaches the sea or a reach where values have already been derived. As values are derived they are written to the relevant Oracle tables and, due to the volume of data involved, are stored in a compressed format.

Before the programs could be run to derive descriptor values, updating and improvement of the software was made to address the issues described in Section 3.1. Firstly, changes to the code were made to ensure compliance with the operating system and database. Secondly, since the available memory of workstations has improved dramatically since descriptor values were derived during the FEH research programme, the amount of data cached at any one time was increased to benefit from these improvements. The order in which the drainage path ‘sources’ were presented to the programs was also optimised to ensure the retrieval and caching of data was carried out efficiently. These improvements, combined with the increased processing power of workstations, resulted in much reduced ‘run times’ so that a typical set of descriptor values could be derived in a few days rather than weeks.

3.3 Data resolution

The CEH appraisal of the FEH statistical method (Morris 2003) revealed that when *QMED* is estimated from catchment descriptor values, spurious steps in these estimates can occur (as you move along a river reach), if the descriptor values have not been stored with sufficient resolution. The report concluded that in the main descriptor values were stored to sufficient accuracy, but in some locations insufficient resolution in *SPRHOST* and $URBEXT_{1990}$ values led to step changes in *QMED* estimates. The review recommended that the resolution of values held for these two descriptors should be increased by a factor of ten.

This recommendation was adopted for the storage of recalculated *SPRHOST* and $URBEXT_{1990}$ values carried out using the new IHDTM grids. For example, an *SPRHOST* value would now be stored as 4073, rather than 407, and be supplied as 40.73 rather than 40.7. Similarly, an $URBEXT_{1990}$ value would be stored as 258, rather than 26, and be provided as 0.0258 rather then 0.026. The resolution adopted for $URBEXT_{1990}$ values was subsequently applied to the new descriptor $URBEXT_{2000}$ (see Chapter 4).

In addition to catchment descriptors, the FEH CD-ROM provides depth-duration-frequency (DDF) parameters for a user-defined point or catchment in order that the design rainfall depth, or the rarity of an observed rainfall event, can be estimated (Faulkner 1999). It has become apparent that the resolution of the DDF parameters provided with the FEH CD-ROM 1999, can occasionally result in contradictions between durations, despite constraints to the DDF model intended to prevent this occurring. Consequently, as part of the recalculation of DDF parameters using the new IHDTM grids, the resolution of stored values has been increased by a factor of 100.

3.4 Data integrity

The volume of data required to provide catchment information at every 50 m point along IHDTM drainage paths, even when those with a catchment area of less than 0.5 km^2 are excluded, is immense. With the development of three new catchment descriptors describing catchment urbanisation (see Chapter 4), in total, in excess of 90 million values were calculated for 22 catchment descriptors (over 4 million for each). In addition to the descriptors, catchment values were also calculated for each of the six depth-duration-frequency parameters. Inevitably, ensuring data quality across such datasets is a demanding, but very necessary, task.

For the 19 descriptors presented on the FEH CD-ROM 1999, FORTRAN programs to calculate catchment values had, of course, been developed at that time, but by necessity, a number of changes had been made to the software (Sections 3.2 and 3.3) before reuse here. For each FORTRAN program, to ensure the computation of descriptor values would be carried out as intended, tests were run on sample areas so that comparisons between the 'new values' and those computed previously, could be made. In order that these comparisons were meaningful, and solely for the purposes of these tests, new values were calculated using the 'old IHDTM'. With respect to the three new descriptors describing catchment urbanisation, checks were made by comparing with manually-calculated values.

Once it had been established that the software was computing descriptor values correctly, the programs were rerun using the new IHDTM grids and set up to derive values for the whole of the UK. These datasets were then subject to further checks. First, the 'completeness' of each set of descriptor values was checked both visually, by mapping stored values, and by using software to ascertain whether a value was present at each node where the catchment area is at least 0.5 km^2. It was apparent from this review that the datasets, from which the descriptor values are derived, do not always have complete UK coverage (e.g. SAAR 1941-70 data are not available for the Scottish island of St. Kilda), which resulted in some 'missing values'. [N.B. Underlying thematic data are incomplete for Fair Isle and St. Kilda in Scotland, the Isles of Scilly, and the Isle of Man (a UK Dependency). Catchment descriptor values are not provided for the Channels Islands (also a UK Dependency).]

The checks also identified that very occasionally descriptor values had not been calculated where the catchment shape was extremely unusual (e.g. at some sites within lakes, where the drainage paths often take on a 'herring bone' pattern, and catchments can be extremely long and narrow). Areas of incomplete descriptor values arising from 'quirks' in the data are very infrequent, extremely limited in area, and are most frequently found at sites where estimates are not required (e.g. within lakes). Consequently, since the problem was judged to be extremely minor, the large investment in time required to resolve this issue was not justified.

Secondly, descriptor values were checked to ensure that they fell within the expected range. For some descriptors the acceptable range is very apparent. For example, Standard Percentage Runoff (*SPR*) is estimated from the Hydrology of Soil Types (HOST) classification where the range of *SPRHOST* values is between 2.0 and 60.0. Consequently catchment values based on this source must lie in this range. For others, (e.g. mean drainage path length - *DPLBAR*) the acceptable range is less obvious and those with extreme values were checked to ensure computation had been correctly carried out.

4. Defining catchment urbanisation – the new descriptors

4.1 Existing descriptors

4.1.1 URBEXT$_{1990}$

The FEH index $URBEXT_{1990}$ reflects the extent of both urban and suburban land cover within a catchment. Rather then simply adding the two values together, intuitively, in the context of flood estimation, it is logical to give more weight to the urban fraction, since the types of development typically included in this land cover class (e.g. city centres, major industrial and commercial sites) tend to have a greater influence on the flood generation process than suburban areas.

In Chapter 6 of Volume 5 of the Flood Estimation Handbook, Bayliss and Scarrott (1999) describe in detail the rationale behind the weighting of 0.5 assigned to the extent of suburban land cover present in a catchment. To briefly summarise the reasoning here: the description of the suburban class given by the 1990 Land Cover Map of Great Britain (Fuller *et al*. 1994), defines suburban land cover as comprising a mixture of built-up land and permanent vegetation, so on average, you might expect urban development to occupy one-half of each pixel in the suburban land cover class. This suggested a weighting of 0.5 was appropriate. Additionally, an investigation into the relationship between the depiction of built-up areas on 1:50,000 Ordnance Survey maps, and that by the 1990 urban and suburban land cover mapping, supported this view. Consequently, the catchment descriptor $URBEXT_{1990}$, defining the extent of both urban and suburban areas (URB_{EXT} and $SUBURB_{EXT}$ respectively) in a single composite index, is given by:

$$URBEXT_{1990} = URB_{EXT} + 0.5\ SUBURB_{EXT} \tag{4.1}$$

4.1.2 URBLOC$_{1990}$

In addition to defining the extent of catchment urbanisation, the FEH also provides an index (*URBLOC*) describing the location of urban and suburban areas within the catchment, relative to its outlet (see Volume 5, Section 6.6.2). This descriptor is based on a refinement of the 1990 Land Cover Map of Great Britain (LCMGB), described above, denoted by the use of the subscript 1990 (i.e. $URBLOC_{1990}$).

A brief description only, of the derivation of $URBLOC_{1990}$, is given here. Firstly, the urban location parameter (URB_{LOC}) is calculated by computing the mean distance from the outlet to urban nodes within the catchment, expressed as a fraction of the mean distance to all nodes that lie within the catchment. Secondly, using the same procedure, the distance to suburban nodes is used to define $SUBURB_{LOC}$. Finally, in keeping with the indexing of the extent of urban and suburban land cover, a composite index, combining the urban and suburban parameters, is defined. The fraction of the catchment given to the respective land cover classes (URB_{EXT} and $SUBURB_{EXT}$) is used to weight the addition of the urban and suburban location parameters. Thus the composite index is given by:

$$URBLOC_{1990} = \frac{URB_{EXT}\ URB_{LOC} + 0.5\ SUBURB_{EXT}\ \ SUBURB_{LOC}}{URB_{EXT} + 0.5\ SUBURB_{EXT}} \tag{4.2}$$

where

$$URB_{LOC} = \frac{URBDIST_{MEAN}}{DIST_{MEAN}} \qquad SUBURB_{LOC} = \frac{SUBURBDIST_{MEAN}}{DIST_{MEAN}} \tag{4.3}$$

The urban and suburban parameters are not defined when the catchment is completely rural and poorly defined when it is nearly so. Therefore, the FEH recommends that the index $URBLOC_{1990}$ should not be computed when $URBEXT_{1990}$ is less than 0.005.

4.1.3 URBCONC$_{1990}$

A third index describing catchment urbanisation, based on a refinement of the urban and suburban LCMGB data, is provided by the FEH. The concentration index (*URBCONC*) quantifies the 'connectivity' of urban and suburban areas. The derivation of index values is described in detail in Volume 5 (Section 6.7.2) of the FEH and, again, only a brief description is provided here. Since it was based on 1990 data, the descriptor is shown with the relevant subscript i.e. $URBCONC_{1990}$.

For each grid node within the catchment the number of adjacent nodes flowing to the point under examination, along IHDTM-derived drainage paths, is computed ($INFLOW_{TOTAL}$). During this computation the number of inflowing nodes which are urban or suburban is also noted ($INFLOW_{URB/SUBURB}$). In this case it was judged to be inappropriate to differentiate between urban and suburban areas and hence when calculating index values, urban and suburban nodes are used in the same way. Consequently, $URBCONC_{1990}$ is defined as:

$$URBCONC_{1990} = \frac{\sum_{1}^{n} INFLOW_{URB/SUBURB}}{\sum_{1}^{n} INFLOW_{TOTAL}} \tag{4.4}$$

In keeping with the rationale applied to the computation of $URBLOC_{1990}$ (Section 4.1.2), the index is only calculated when $URBEXT_{1990}$ is at least 0.005.

4.2 New descriptors

4.2.1 Introduction

The CEH Land Cover Map 2000 (Fuller *et al*. 2002) also differentiates between the different types of development that form built-up areas. There was, therefore, an opportunity to develop a set of indices that followed the principles described above, but based on more 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.

4.2.2 $URBEXT_{2000}$

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:

$$URBEXT_{2000} = URB_{EXT} + 0.5\ SUBURB_{EXT} + 0.8\ IBG_{EXT} \tag{4.5}$$

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.

4.2.3 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 $URBLOC_{1990}$ (summarised in Section 4.1.2) 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:

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

where

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

$$IBG_{LOC} = \frac{IBGDIST_{MEAN}}{DIST_{MEAN}} \tag{4.7}$$

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.

4.2.4 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), and summarised here in Section 4.1.3, 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:

$$URBCONC_{1990} = \frac{\sum_{1}^{n} INFLOW_{URB/SUBURB/IBG}}{\sum_{1}^{n} INFLOW_{TOTAL}} \quad (4.8)$$

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

4.3 Comparison of URBEXT$_{2000}$ with URBEXT$_{1990}$

Following the assessment of the suitability of LCM2000 outputs for use in defining catchment urbanisation, Bayliss and Davies (2003) reported that inherent differences in the pixel-based and parcel-based approaches used to produce the Land Cover Map of Great Britain and the Land Cover Map 2000 respectively, would lead to values of $URBEXT_{2000}$ that would typically be higher than equivalent $URBEXT_{1990}$ values for the same level of urbanisation. Additionally, $URBEXT_{2000}$ values are also likely to be higher as a result of the significant urban development that has taken place in many areas of Great Britain since 1990.

A comparison of $URBEXT_{2000}$ and $URBEXT_{1990}$ for the same catchments is likely to be informative, but also necessary, in order that consistent guidance can be provided with respect to the application of the FEH urban adjustment procedures. Volume 3 of the FEH (Robson and Reed 1999) recommends that, when using the statistical method, these adjustment procedures are applied when $URBEXT_{1990}$ is 0.025 or greater. At this point the catchment is described by the FEH as 'slightly urbanised'. The FEH (e.g. Reed 1999) also warns that its procedures (with respect to both the statistical and rainfall-runoff methods) are not applicable if the catchment is 'extremely heavily urbanised (i.e. $URBEXT_{1990}$ is 0.5 or greater). In these circumstances detailed catchment modelling is often required, rather than the application of a set of generalised procedures, such as those described in the FEH. Given the differences in the land cover mapping referred to above, it is inappropriate to assume that the levels of urbanisation indicated by index values of 0.025 and 0.05, are the same for both $URBEXT_{2000}$ and $URBEXT_{1990}$.

Values of $URBEXT_{2000}$ and $URBEXT_{1990}$ were extracted from the descriptor tables (Chapter 3) for 877 gauged catchments, taken from the 962 sites listed on the HiFlows-UK website (www.environment-agency.gov.uk/hiflowsuk). Values for all 962 catchments were not used since 37 of those listed had values based on an IHDTM-derived catchment area that differed by more than a factor of 1.1 from the published area, four had a catchment area of less than 0.5 km^2, and 44 are in Northern Ireland, where $URBEXT_{1990}$ values are only estimated.

Figure 4.1 illustrates the relationship between $URBEXT_{2000}$ and $URBEXT_{1990}$ for those 877 catchments. In all but a small number of cases (where catchment values of *URBEXT* are very low), $URBEXT_{2000}$ values exceed those for $URBEXT_{1990}$. This is as expected, given the parcel-based approach used to derive the LCM2000 and subsequently the index $URBEXT_{2000}$, and additionally, the new index also takes account of urban development that has occurred since 1990.

The FEH uses an $URBEXT_{1990}$ value of 0.025 as the dividing point between what it describes as 'essentially rural' catchments and those which are urbanised and subject to additional procedures. It also suggests that where $URBEXT_{1990}$ equals 0.5 or more, that alternative methods be sought. In order to estimate corresponding thresholds for use with $URBEXT_{2000}$ values, regression analysis has been carried out to enable corresponding values of $URBEXT_{2000}$ to be identified for given values of $URBEXT_{1990}$. The regression line (solid line) and thresholds (dashed lines) are shown on Figure 4.1, to illustrate the estimation of equivalent $URBEXT_{2000}$ values for these thresholds, and the other categories of urbanisation defined using $URBEXT_{1990}$ in the FEH (Volume 5, Section 6.5.3).

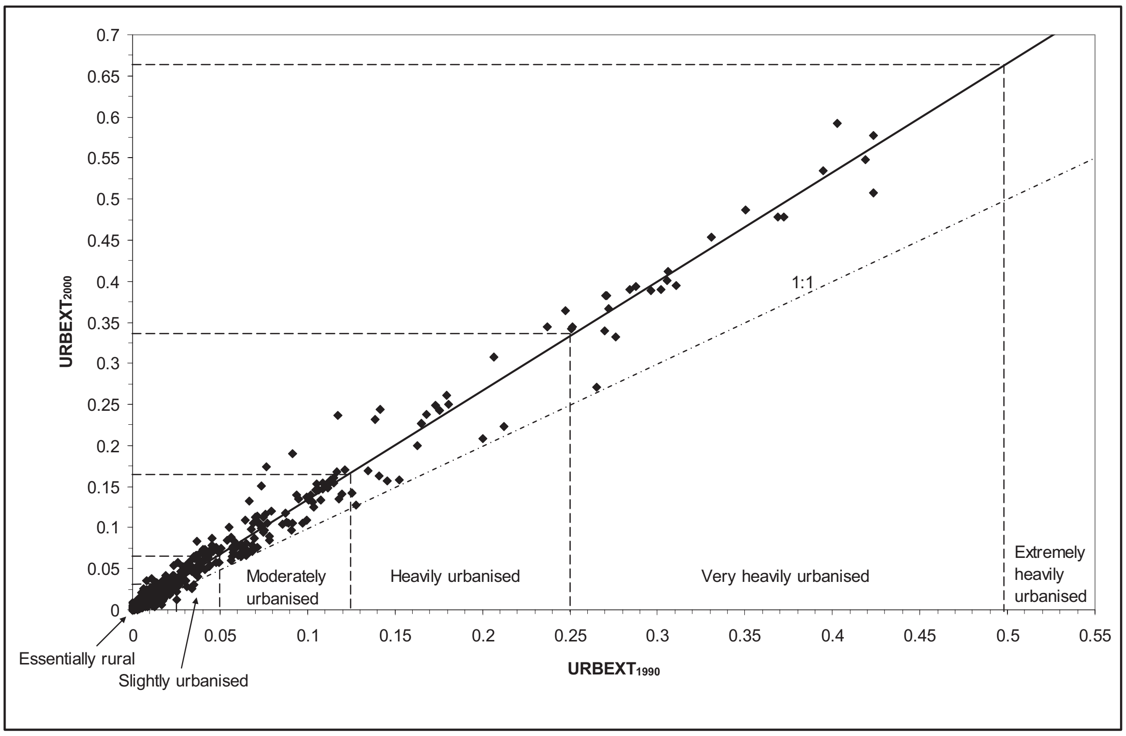


Figure 4.1 Relationship between $URBEXT_{2000}$ and $URBEXT_{1990}$

However, $URBEXT_{2000}$ values include new development carried out since 1990, making direct comparison difficult. To reduce the 'noise' introduced by comparing *URBEXT* index values defined for different target dates (i.e. 1990 and 2000), the equivalent $URBEXT_{2000}$ values, identified on Figure 4.1, were 'backdated' to 1990 using the urban expansion model (Equation 5.5) described in Section 5.3.

Equivalent values were also rounded since the definition of these categories is somewhat arbitrary. Although the lower and upper limits of $URBEXT_{2000}$ (0.03 and 0.6 respectively), are intended to guide regarding the applicability of the methods, the other categories are presented only to provide appropriate and consistent descriptions of the different levels of urbanisation. Equivalent $URBEXT_{2000}$ values have been selected with sufficient care to ensure that the new category limits are consistent with those used with $URBEXT_{1990}$, but attempting to provide exact category limits is inappropriate. Table 4.1 provides a restatement of the categories of urbanisation distinguished in the FEH according to their $URBEXT_{1990}$ values, together with 'equivalent' $URBEXT_{2000}$ values estimated using the procedure described above.

Table 4.1 Categories of catchment urbanisation

Category	$URBEXT_{1990}$	$URBEXT_{2000}$
Essentially rural	$0.000 \le URBEXT_{1990} < 0.025$	$0.000 \le URBEXT_{2000} < 0.030$
Slightly urbanised	$0.025 \le URBEXT_{1990} < 0.050$	$0.030 \le URBEXT_{2000} < 0.060$
Moderately urbanised	$0.050 \le URBEXT_{1990} < 0.125$	$0.060 \le URBEXT_{2000} < 0.150$
Heavily urbanised	$0.125 \le URBEXT_{1990} < 0.250$	$0.150 \le URBEXT_{2000} < 0.300$
Very heavily urbanised	$0.250 \le URBEXT_{1990} < 0.500$	$0.300 \le URBEXT_{2000} < 0.600$
Extremely heavily urbanised	$0.500 \le URBEXT_{1990} \le 1.000$	$0.600 \le URBEXT_{2000} \le 1.000$

5. FEH urban adjustment procedures

5.1 Introduction

The role of the catchment descriptor *URBEXT* in the FEH procedures is an important one. Where gauged data are available, the effect of urbanisation (albeit the net effect) is usually embraced by the observed data. However, in the majority of cases the subject site is ungauged, and where the catchment is judged to urbanised, there is a requirement to take account of the urban effect on the flood regime. Within the FEH procedures, the descriptor *URBEXT* is used in a number of ways.

The FSR/FEH rainfall-runoff method, published in Volume 4 of the FEH (Houghton-Carr 1999), employs *URBEXT* in the adjustment of percentage runoff and in the estimation of time-to-peak. The level of urbanisation, defined by *URBEXT*, is also used to guide the choice of storm profile. Recent research focused on improving the FSR/FEH rainfall-runoff method, resulted in the publication of the Revitalised Flood Hydrograph Model (Kjeldsen *et al*. 2005). The new model requires urban extent to be defined in order to estimate time-to-peak and baseflow lag. *URBEXT* is also used to determine appropriate design conditions (i.e. rainfall depth and profile, and initial soil moisture depth and baseflow values). Winter design conditions are recommended for use on essentially rural catchments and summer design conditions for use on urbanised catchments.

In the FEH statistical method, *URBEXT* is also used to differentiate between essentially rural and urbanised catchments (Section 4.3 discusses the choice of an *URBEXT* value to make that distinction). Where the site of interest is ungauged and urbanised, the FEH recommends a two-stage approach for estimating both the index flood (*QMED*) and the pooled flood growth curve (Reed 1999b). In the case of the former, firstly *QMED* is estimated from catchment descriptors as if the catchment was rural ($QMED_{rural}$). Secondly, following the adjustment of $QMED_{rural}$ by data transfer (using essentially rural donors and/or analogues), an urban adjustment factor (*UAF*), based on the subject catchment value of *URBEXT*, is applied. A similar procedure is adopted for estimating the pooled flood growth curve. In the first stage, the flood growth curve is estimated from a pooling-group made up of essentially rural catchments only, and in the second step, an adjustment for urbanisation is made to growth curve factors.

The urban adjustment procedures published in the FEH (IH 1999) are based on models calibrated using the descriptor $URBEXT_{1990}$. However, it is now recommended that the new catchment descriptor $URBEXT_{2000}$ be used to define catchment urban extent (see Section 1.3). $URBEXT_{2000}$ is not simply an update to $URBEXT_{1990}$, it is based on data produced using different mapping techniques and typically the same level of catchment urbanisation will result in higher values of $URBEXT_{2000}$ than $URBEXT_{1990}$ (Bayliss and Davies 2003). Consequently, $URBEXT_{2000}$ values cannot be used with procedures designed for use with $URBEXT_{1990}$ and new procedures, based on models calibrated using $URBEXT_{2000}$ values, are required.

The development of procedures for the use of $URBEXT_{2000}$ within the FEH statistical method is described in subsequent sections of this chapter (defining new procedures for use with the recently published revitalised FSR/FEH rainfall runoff-method is beyond the remit of this research project). In addition to new methodologies for the adjustment of $QMED_{rural}$ and pooled growth curve, the estimation of *URBEXT* using Ordnance Survey mapping (Section 5.2) and the adjustment of *URBEXT* to estimate the level of urbanisation relating to a particular year (Section 5.3), are also revisited and described below.

5.2 Relationship between URBEXT and URBAN

5.2.1 Introduction

Before describing the relationship between the digitally-derived catchment descriptor $URBEXT_{2000}$ and the manually-defined catchment characteristic *URBAN* (Section 5.2.3), it may be helpful to summarise the need for such a relationship and the preceding analyses relating to $URBEXT_{1990}$ (Section 5.2.2).

The Flood Studies Report (NERC 1975) catchment characteristic *URBAN* defines the fraction of the catchment that is urbanised. Subsequent guidance to Flood Studies Report (FSR) users recommended that this be calculated manually using the Ordnance Survey's representation of built-up areas on 1:50,000 maps.

With the development of catchment descriptors based on digital data for use within the FEH procedures, including a new index defining urban extent ($URBEXT_{1990}$), regression models were developed so that key flood estimation parameters could be estimated using the new descriptors. However, it became evident that it was occasionally necessary to 'substitute' *URBAN* values with the new $URBEXT_{1990}$ values – for example, in updating the FSR/FEH percentage runoff model (see Section 5.4.3) and in 'converting' $URBEXT_{1990}$ values to *URBAN* values for use in the software package Micro-FSR. Consequently, it was necessary to establish a relationship between *URBAN* and $URBEXT_{1990}$.

Before describing the investigation it is important to clarify the notation. The use of the subscripts 1990 and 2000 denote the source of the digital data used to define *URBEXT* (see Chapter 1), and with the development of these new indices, it is important that the origin of the catchment characteristic *URBAN* is also made clear. The *URBAN* index was developed for use with the FSR procedures and in the context of referring back to these procedures, is often used with the subscript FSR (i.e. $URBAN_{FSR}$). Catchment values of the index *URBAN* are derived from 1:50,000 mapping and can also be shown with the subscript 50k (i.e. $URBAN_{50k}$). This is perhaps a more appropriate subscript when comparisons are made with $URBEXT_{1990}$ and $URBEXT_{2000}$, since all the subscripts then denote the data source. However, the terms $URBAN_{FSR}$ and

$URBAN_{50k}$ do relate to the same index, they are calculated in an identical way, and they are interchangeable.

5.2.2 $URBAN_{50K}$ and $URBEXT_{1990}$

In Volume 5 of the FEH, Bayliss and Scarrott (1999) report how data for 25 urbanised catchments were assembled in order to investigate the relationship between $URBAN_{50k}$ and $URBEXT_{1990}$. Catchment values of $URBAN_{50k}$ were manually derived from Ordnance Survey (OS) 1:50,000 maps according to the FSR methodology. Since the $URBAN_{50k}$ values were to be compared with *URBEXT* values based on satellite imagery taken around 1990, then OS maps of a corresponding era were used where possible. The extent of urbanisation for the chosen catchments was wide ranging (with $URBAN_{50k}$ values between 0.053 and 0.850). $URBEXT_{1990}$ values were computed automatically using the composite index described here in Section 4.1.

Initial analysis provided a regression equation with an intercept that was very close to zero. Consequently, the intercept was suppressed (set to zero) and the relationship subsequently published in Volume 5 (page 48) was:

$$URBAN_{50k} = 2.05\, URBEXT_{1990} \qquad (5.1)$$

This relationship provided a basis for substituting $URBAN_{50k}$ values with the new $URBEXT_{1990}$ values where required (see Section 5.2.1).

Volume 5 (page 50) also describes how the above equation was simply reversed to give:

$$URBEXT_{1990} = \frac{URBAN_{50k}}{2.05} \qquad (5.2)$$

This second equation was given, since it became apparent that being able to estimate $URBEXT_{1990}$ from $URBAN_{50k}$ values would provide a practical way of 'updating' $URBEXT_{1990}$. For example, in the case where the extent of catchment urbanisation has increased significantly post-1990, it is important to adjust the $URBEXT_{1990}$ value if possible. To adjust $URBEXT_{1990}$ directly is difficult, but using the relationship between $URBAN_{50k}$ and $URBEXT_{1990}$, it is possible to do this indirectly. The suggested procedure is to obtain post-1990 OS mapping, or to manually add new developments to an existing map, and then calculate $URBAN_{50k}$ using the FSR methodology. A new $URBEXT_{1990}$ value can then be estimated from the 'updated' $URBAN_{50k}$ value.

5.2.3 $URBAN_{50k}$ and $URBEXT_{2000}$

With the introduction of the new index $URBEXT_{2000}$ it is necessary to revisit the modelling with $URBAN_{50k}$ to develop regression equations for use with $URBEXT_{2000}$. $URBAN_{50k}$ values for 25 urbanised catchments had been derived for the regression analysis described in Section 5.2.2, based on OS mapping published around 1990. Since it is very time consuming to derive $URBAN_{50k}$ values, it was decided to 'update' these existing values for use here. Consequently, the $URBAN_{50k}$ data were updated by referring to more recent OS mapping, so that the values more closely matched the extent of urbanisation present in 2000. In addition, the revision of the $URBAN_{50k}$ data included any adjustments necessary as a result of the use of catchment boundaries defined by the new IHDTM. Following these revisions, the $URBAN_{50k}$ values used were consistent with the $URBEXT_{2000}$ data, both in relation to the year to which they refer, and in the boundaries used to define the catchments.

Initial regression analyses, showed the intercept to be close to zero, both where $URBAN_{50k}$ is predicted from $URBEXT_{2000}$ (intercept = -0.002) and where $URBEXT_{2000}$ is predicted from $URBEXT_{50k}$ (intercept = 0.009). In both cases the intercept was judged not to be significant and in subsequent analyses set to zero.

Figure 5.1 indicates that there is a strong relationship between $URBAN_{50k}$ and $URBEXT_{2000}$ and further regression analyses confirmed that to be the case (r^2 values are greater than 0.95 - see Table 5.1).

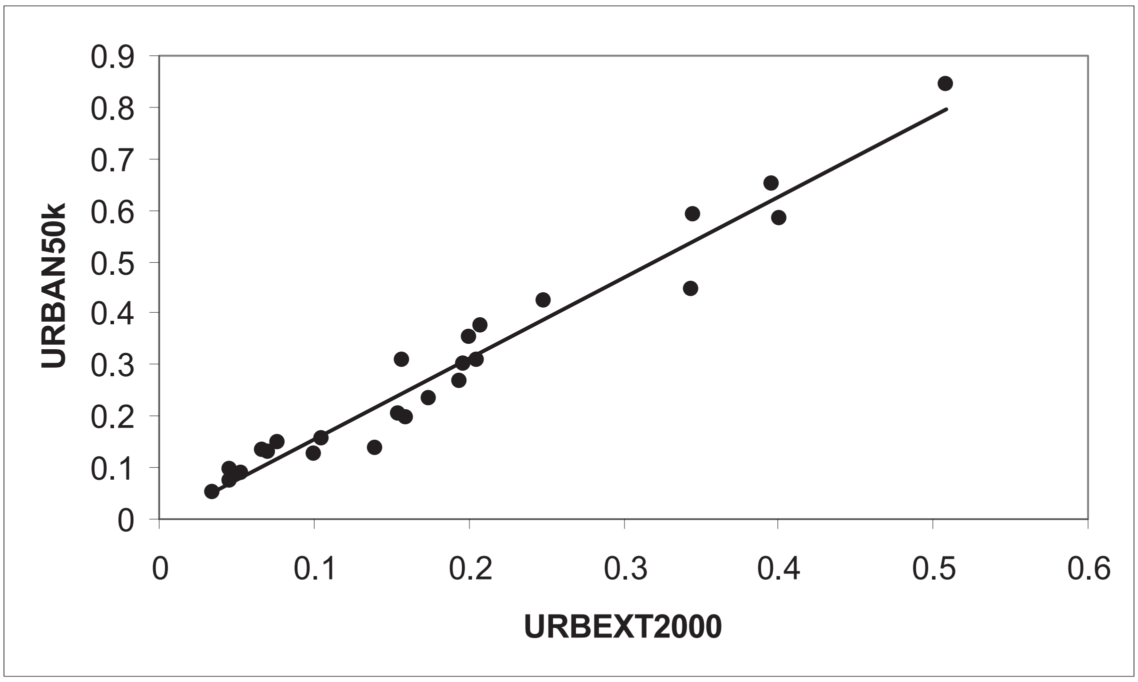


Figure 5.1 Relationship between $URBAN_{50k}$ and $URBEXT_{2000}$

Table 5.1 $URBAN_{50k}$ and $URBEXT_{2000}$ – regression analysis results

Model	r^2	No. of values	Standard error
Equation 5.3	0.957	25	0.038
Equation 5.4	0.955	25	0.027

Following these analyses the equation recommended for use in estimating $URBAN_{50k}$ from $URBEXT_{2000}$ is:

$$URBAN_{50k} = 1.567\,URBEXT_{2000} \quad (5.3)$$

The line of best fit is shown in Figure 5.1

Rather than rearranging this equation in order that $URBEXT_{2000}$ can be estimated from $URBAN_{50k}$, the relationship established by regression analysis is provided here and is given as:

$$URBEXT_{2000} = 0.629\,URBAN_{50k} \quad (5.4)$$

The provision of Equation 5.3 allows the 'substitution' of $URBAN_{50k}$ with the $URBEXT_{2000}$ values when required (see Section 5.4.3) and additionally, use of Equation 5.4 allows $URBEXT_{2000}$ to be updated (or backdated) based on a manually defined value of $URBAN_{50k}$.

5.3 Urban Expansion Factor (UEF)

The index $URBEXT_{1990}$ describes the extent of catchment urbanisation around 1990. However, many of the flood peak records available are 'centred in time' earlier than 1990. In some circumstances it is desirable to relate the *URBEXT* value in use, more closely to the period of record being used. For example, in the calibration of an urban adjustment factor model, Reed and Robson (1999) adjusted $URBEXT_{1990}$ values to be more consistent with the flood record used to define *QMED*. This adjustment was carried out using a model of urban expansion, described in Volume 5 of the FEH by Bayliss and Scarrott (1999). The model was based on data published by the Council for the Protection of Rural England (CPRE 1993). These data provided a way defining the urban area in England as a fraction of the 1990 value, known as the urban expansion factor (*UEF*). Where the 'target year' is pre-1990, applying a *UEF* has the effect of reducing the $URBEXT_{1990}$ value. Additionally, the model could also be used to estimate post-1990 urban expansion and the result of applying a *UEF* in these circumstances would be to increase the value of $URBEXT_{1990}$.

With the development of $URBEXT_{2000}$, it became necessary to update the urban expansion model. The model was based on 'urban area' values presented by the CPRE as five-yearly snapshots during the period 1945 to 1990 inclusive and the factors provided are relative to the urban area in 1990 (i.e. the *UEF* for 1990 is 1.0). In order to develop a model for the adjustment of $URBEXT_{2000}$, urban area data are required for a period that included the year 2000, to enable factors relative to the urban area in 2000 to be provided. Land use change tables published by the Office of the Deputy Prime Minister (ODPM 2004) give details of the total area of land in England that 'changed to developed use', in each of the years from 1991 to 1998 inclusive.

Figure 5.2 illustrates that use of the data provided by the ODPM, gives considerable reassurance that the existing model (based on an inverse tan function) is providing reasonable expansion factors beyond 1990, and can be used as a basis for determining *UEF*s appropriate for use with $URBEXT_{2000}$ values. [It should be noted that although the ODPM data did not include a value for 2000, data for the period 1991 to 1998 gave sufficient confidence in the existing model such that the model itself could been used to provide the necessary 'urban area' value for year 2000].

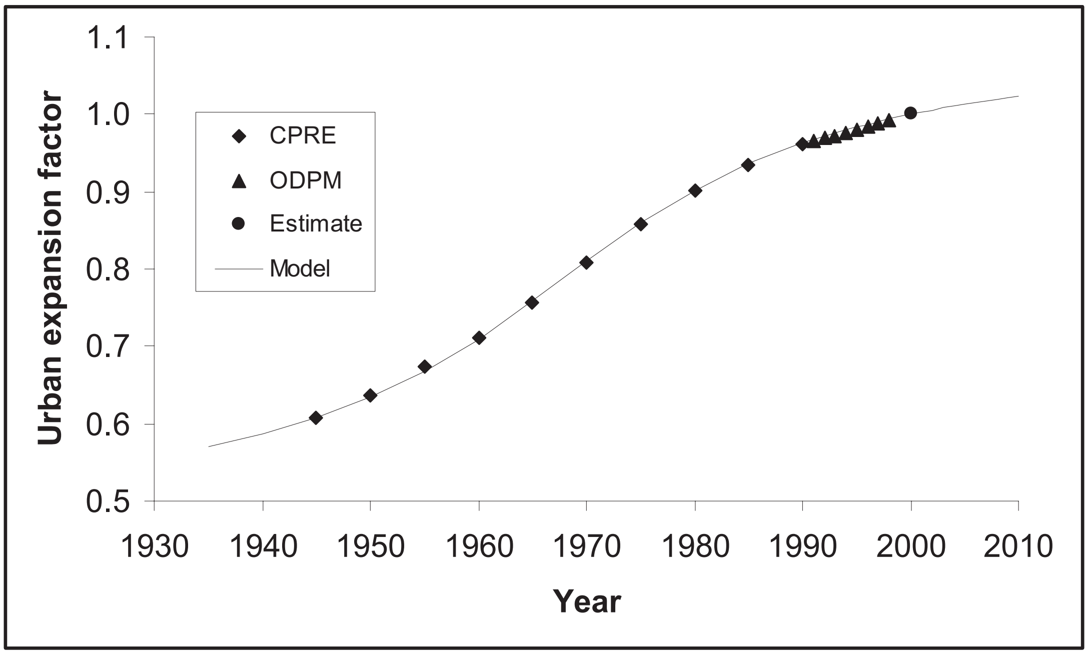


Figure 5.2 Urban expansion model based on data published by CPRE (1993) and ODPM (2004) and rescaled for use with $URBEXT_{2000}$

Although the model published in Volume 5 of the FEH was again used here, it was necessary to rescale the model so that the urban expansion factor for the year 2000 is 1.0 (see Figure 5.2). New model parameters have been estimated to provide the equation given below:

$$UEF = 0.7851 + 0.2124 \tan^{-1}\left(\frac{Year - 1967.5}{20.32}\right) \quad (5.5)$$

[The term within the parentheses is in radians.]

The use of Equation 5.5 will, therefore, provide urban expansion factors appropriate for 'backdating' $URBEXT_{2000}$, or for use in estimating the $URBEXT_{2000}$ value beyond the year 2000.

5.4 Adjusting $QMED_{rural}$

5.4.1 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.

$$UAF = \frac{QMED}{QMED_{rural}} \tag{5.6}$$

where $QMED_{rural}$ is given by:

$$QMED_{rural} = 1.172\ AREA^{AE} \left(\frac{SAAR}{1000}\right)^{1.560} FARL^{2.642} \left(\frac{SPRHOST}{100}\right)^{1.211} 0.0198^{RESHOST} \tag{5.7}$$

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

$$AE = 1 - 0.015 \ln\left(\frac{AREA}{0.5}\right) \tag{5.8}$$

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

$$RESHOST = BFIHOST + 1.30\left(\frac{SPRHOST}{100}\right) - 0.987 \tag{5.9}$$

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 5.4.2) 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 5.4.3).

[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.]

5.4.2 Adjusting $\mathbf{QMED_{rural}}$ using $\mathbf{URBEXT_{1990}}$

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:

$$UAF = (1 + URBEXT)^{g} \; PRUAF \qquad (5.10)$$

where

$$PRUAF = 1 + 0.615\, URBEXT \left(\frac{70}{SPRHOST} - 1 \right) \qquad (5.11)$$

[*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 (see also Section 5.3 above). *UAF* values were defined using the ratio of *QMED* estimated from gauged data, to $QMED_{rural}$ estimated using catchment descriptors (Equation 5.7).

The calibrated model

A logarithmic transformation was applied to Equation 5.10 to give the linear model form below:

$$\ln UAF = g \ \ln\left(1 + URBEXT_{1990}\right) + \ln PRUAF \quad (5.12)$$

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:

$$UAF = \left(1 + URBEXT_{1990}\right)^{0.83} \ PRUAF \quad (5.13)$$

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

Model structure

An identical approach to that described in Section 5.4.2 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:

$$UAF = \left(1 + URBEXT\right)^{g} \ PRUAF \quad (5.14)$$

This is identical to the model structure described in Section 5.4.2. 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 5.11). 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 (see Section 5.2) that allows $URBAN_{FSR}$ ($URBAN_{50k}$) to be estimated from $URBEXT_{1990}$ values (Equation 5.1). 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 $URBEXT_{2000}$ (Equation 5.3), 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:

$$PRUAF = 1 + 0.47\, URBEXT_{2000} \left(\frac{70}{SPRHOST} - 1 \right) \qquad (5.15)$$

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 (see Chapters 2 and 3). *URBEXT* values were again adjusted to the midpoint of the flood record, but since $URBEXT_{2000}$ values are now being adjusted, rather than $URBEXT_{1990}$ values, the new urban expansion factor (*UEF*) model described in Section 5.3 (Equation 5.5) was used.

Results

In keeping with the approach described in Volume 3 of the FEH and summarised here in Section 5.4.2, a logarithmic transformation was applied to Equation 5.14 to give the model form:

$$\ln UAF = g \ln(1 + URBEXT) + \ln PRUAF \qquad (5.16)$$

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

$$\ln UAF = g \ln(1 + URBEXT) \qquad (5.17)$$

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 5.2. 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 5.2 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. 5.7)	1.84	0.801		
Simplified urban model (Eq. 5.17)	1.78	0.820	0.118	1.18 (0.22)
Urban model (Eq. 5.16)	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 5.2 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 (see Chapter 6) 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:

$$UAF = \left(1 + URBEXT_{2000}\right)^{0.66} \; PRUAF \qquad (5.18)$$

where

$$PRUAF = 1 + 0.47 \, URBEXT_{2000} \left(\frac{70}{SPRHOST} - 1 \right) \qquad (5.19)$$

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 5.13 and 5.18. Since, $URBEXT_{2000}$ and $URBEXT_{1990}$ values are based on land cover data produced using different mapping procedures (see Sections 4.2 and 4.1 respectively) they should not be compared directly. Consequently, rather than compare *UAF*s for a defined value of $URBEXT_{2000}$ and $URBEXT_{1990}$, Table 5.3 compares adjustment factors for the lower limit of each category of catchment urbanisation (e.g. slightly urbanised, moderately urbanised etc.). These categories are described in Section 4.2 for $URBEXT_{2000}$ and in Volume 5 of the FEH (Bayliss 1999) for $URBEXT_{1990}$. 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 5.3 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 5.3 provides examples of the *UAF* factors obtained by using Equation 5.18, 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 5.3 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.

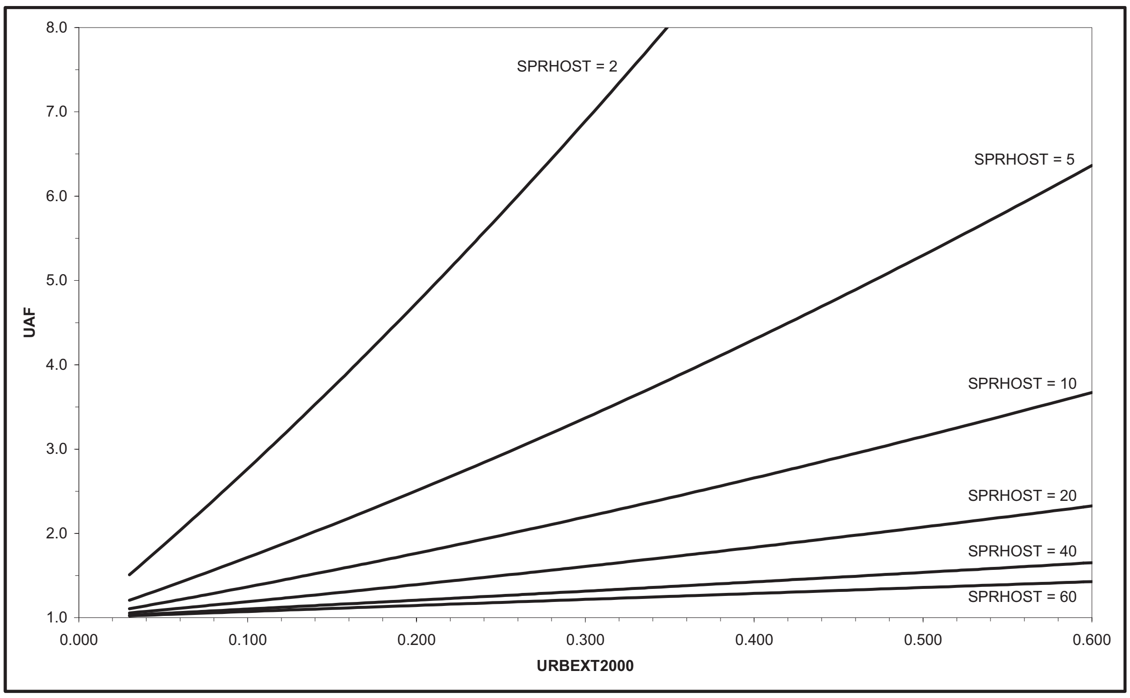


Figure 5.3 Relationship between UAF and $URBEXT_{2000}$ for selected values of SPRHOST

5.5 Adjusting pooling-group growth curve factors

5.5.1 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:

$$x_T = UAF^{-\left(\frac{\ln T - \ln 2}{\ln 1000 - \ln 2}\right)} xrural_T \qquad 2 \leq T \leq 1000 \qquad (5.20)$$

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 5.20) 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 5.21 and 5.22).

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

$$x_{1000} = UAF^{-1}\ xrural_{1000} \qquad (5.21)$$

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:

$$\begin{aligned} Q_{1000} &= QMED\ x_{1000} \\ &= (UAF\ QMED_{rural}) \times (UAF^{-1}\ xural_{1000}) \\ &= QMED_{rural}\ xrural_{1000} \qquad (5.22) \end{aligned}$$

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

5.5.2 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 5.21, 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 5.20.

The review identified that T-incoherence typically occurs where the catchment is extremely heavily urbanised (see Table 4.1) 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 5.20, 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:

$$x_T = 1 + \frac{\left(xrural_T - 1\right)\left(\frac{xrural_{1000}}{UAF} - 1\right)}{\left(xrural_{1000} - 1\right)} \qquad 2 \le T \le 1000 \qquad (5.23)$$

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 5.23, 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.

6. The new FEH CD-ROM

6.1 Introduction

The development of three new catchment descriptors defining catchment urbanisation (Chapter 4), 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 (Chapter 2). 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 6.2.

6.2 Improved and new functionality

6.2.1 Introduction

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. The list is extensive so, for brevity, only major features that are new to the product are described below.

6.2.2 Geographical interface

The FEH CD-ROM displays IHDTM-derived drainage paths and catchment boundaries along with a number of geographical layers to assist the user in locating the site of interest (Figure 6.1).

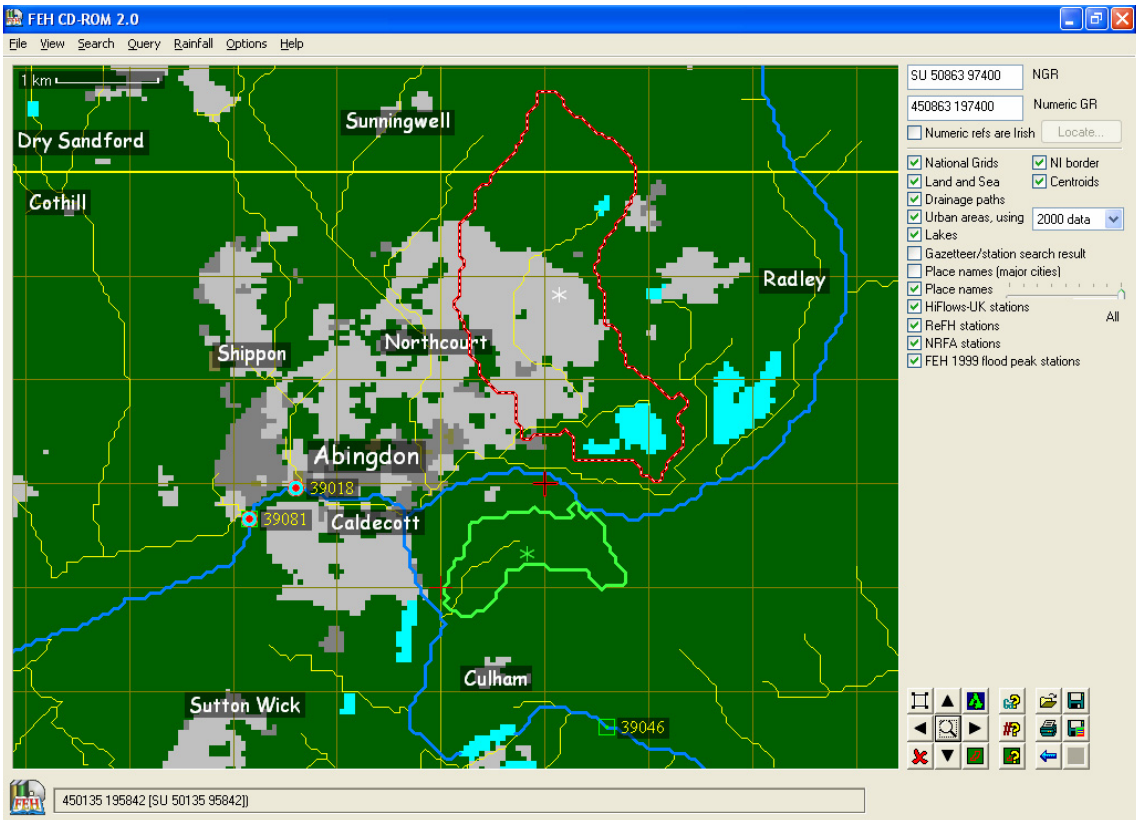


Figure 6.1 Geographical interface

Urban areas

In addition to displaying built-up areas defined using data based on the Land Cover Map of Great Britain (1990), the user can now display settlements defined using data based on the Land Cover Map 2000 (the latter are used to compute values of $URBEXT_{2000}$, $URBLOC_{2000}$ and $URBCONC_{2000}$). The new CD-ROM allows the user to toggle between the ‘1990 data’ and the ‘2000 data’.

Catchment centroids

Catchment centroids are computed by version 2.0 of the software. Figure 6.1 illustrates that by enabling the tick box, the centroid is displayed both for the catchment currently defined by the pointer (in green), and for the ‘selected’ catchment (red boundary) where the centroid is shown in white.

Gauging stations

The locations of river flow gauging stations are important if a station is the site of interest, or in judging the proximity of potential 'donor' and 'analogue' stations when the subject site is ungauged. The location of many more gauging stations can now be displayed by the new software. These include the 962 stations listed at the time of writing on the HiFlows-UK website (http://www.environment-agency.gov.uk/hiflowsuk/), the 101 stations used in the Revitalised Flood Hydrograph (ReFH) research programme and for which ReFH rainfall-runoff model parameters are published (Kjeldsen *et al*. 2005), and 1921 stations listed by the National River Flow Archive. It is also possible to display the location of the 1000 gauging stations whose flood peak records were used in the FEH research programme. Different symbols are used when gauging stations are displayed, to identify the dataset(s) to which they belong (see Legend).

In addition to enabling the location of gauging stations to be shown, a 'station register search' facility is provided (Figure 6.2). This allows the user to locate gauging stations by providing the gauge number, river name or station name.

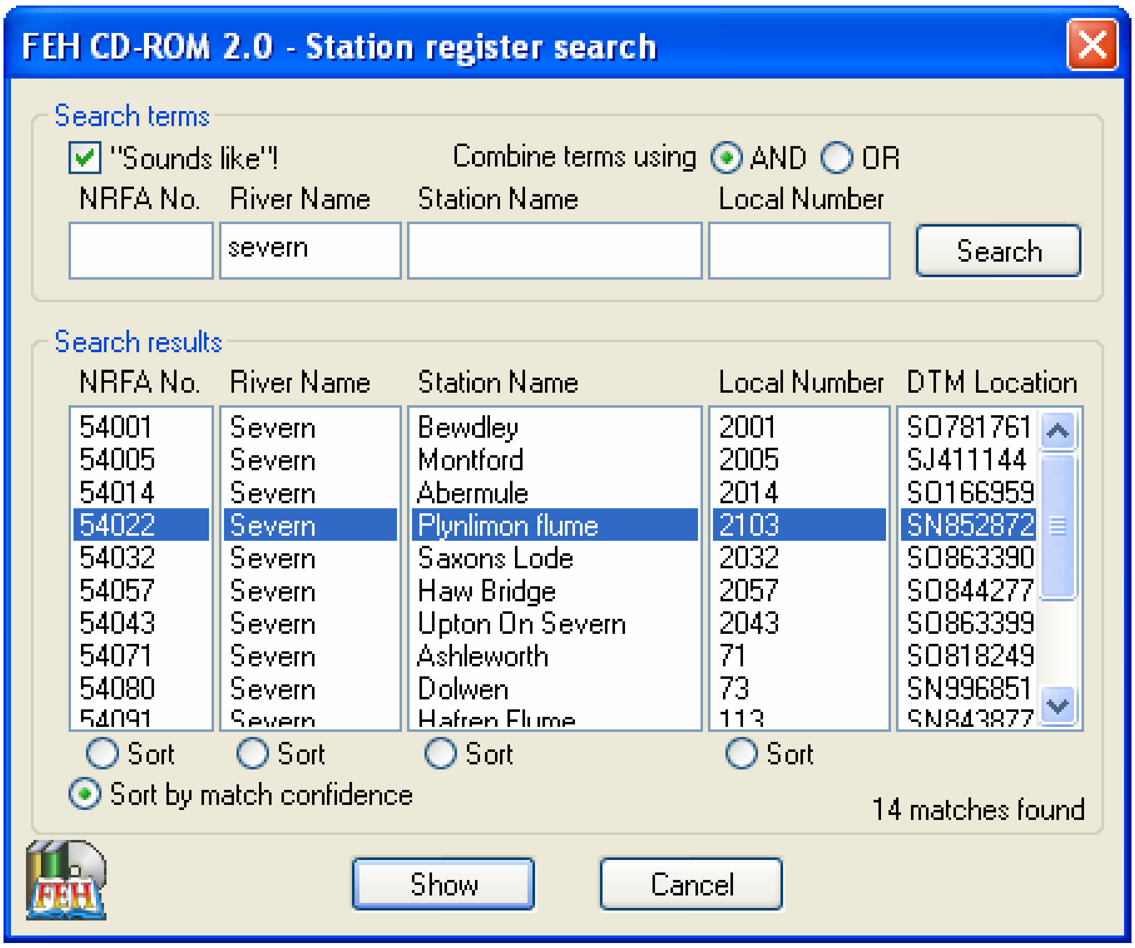


Figure 6.2 Gauging station register search facility

Legend

A legend can be enabled by the user to explain the colours and symbols used in the geographical interface (Figure 6.3).

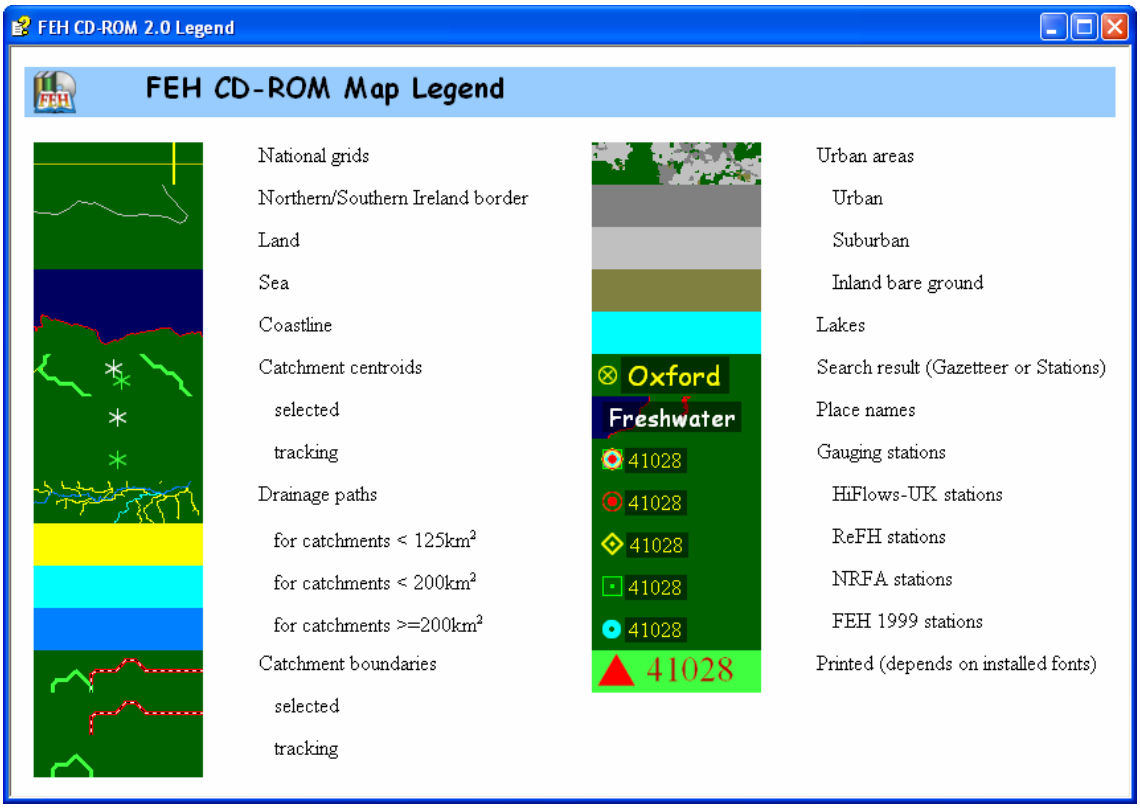


Figure 6.3 Legend

6.2.2 Map view

A major improvement to the software allows users to save, load, print and export the map view (the area selected by the user to be displayed by the software). Additionally, a 'history' button is now also provided. Brief details of these new features are provided below.

Saving and loading

The selection of the required map view is straightforward. However, the view may have been customised (e.g. to show a reduced number of place names) and it may be important to store a number of different views during a study, so that they can be returned to at a later data. The feature gives users the capability to store, load and return to a saved view or views.

Printing

Printing the map view to a standard scale (e.g. 1:50,000), that can be selected by the user, rather than the software, is now provided. Additionally, map scales, other than those provided as 'standard', can be entered by the user.

Exporting (saving) as an image

There is often a requirement to produce catchment maps for inclusion in project reports and presentations. The software now allows users to save a view as a digital image (Figure 6.4), and additionally gives the user control over image resolution and format.

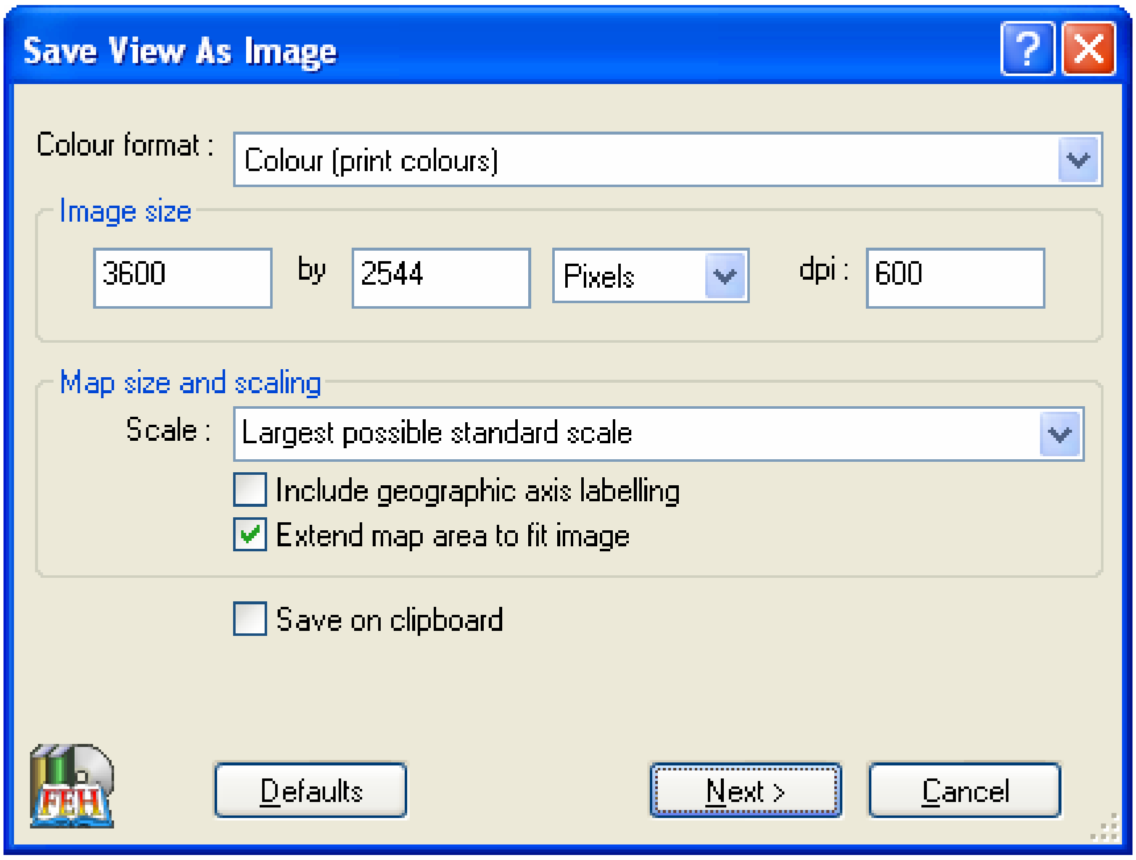


Figure 6.4 Exporting the view as an image

History buttons

The addition of this feature allows users to go back and forward through the 'view history' so that a view can be revisited without having to repeat the view selection process.

6.2.3 Exporting catchment descriptor values

WINFAP-FEH format

It is a requirement of the new software that values for the three new catchment descriptors ($URBEXT_{2000}$, $URBLOC_{2000}$ and $URBCONC_{2000}$) can be included in the exported files. The software achieves this by providing a new format, identified by the extension ‘cd2’, which includes values for these new descriptors (Figure 6.5). WINFAP-FEH is currently being upgraded so that users can ‘import’ cd2 files from the new FEH CD-ROM to enable them to implement the new urban adjustment procedures designed for use with $URBEXT_{2000}$ (Chapter 5).

```
[FILE FORMAT]
TYPE,CD2
VERSION,2.0
[END]

[CDS DETAILS]
NAME,GB 450500 197250 (SU 50500 97250)
LOCATION,Not known
NOMINAL AREA,7.22
NOMINAL NGR,4505,1972
[END]

[COMMENTS]
SOURCE, Data exported from FEH CD-ROM version 2.0 at 16:18:12 GMT on
Fri 18-Nov-2005
[END]

[DESCRIPTORS]
IHDTM NGR,GB,450500,197250
DTM AREA,7.22
ALTBAR,62
ASPBAR,160
ASPVAR,0.46
BFIHOST,0.683
DPLBAR,3.18
DPSBAR,16.7
FARL,0.925
LDP,6.45
PROPWET,0.31
RMED-1H,9.9
RMED-1D,31.1
RMED-2D,38.2
SAAR,600
SAAR4170,626
SPRHOST,26.84
URBCONC1990,0.801
URBEXT1990,0.1363
URBLOC1990,0.814
URBCONC2000,0.902
URBEXT2000,0.1588
URBLOC2000,0.792
[END]
```

Figure 6.5 Catchment descriptor file - cd2 format

The new FEH CD-ROM also provides a file format (a ‘cd’ file) that is identical to that used by the FEH CD-ROM 1999, ensuring that the software also complies with the requirements of existing versions of its companion software WINFAP-FEH. As a result, users of version 1.0 and version 1.1.002 of WINFAP-FEH can benefit from the improvements brought by the new IHDTM (Chapter 2), but will require the WINFAP-FEH upgrade to implement the new urban adjustment procedures.

Generic formats

The FEH CD-ROM 1999 allows users to export depth-duration-frequency (DDF) parameters and catchment descriptor values in a comma separated variable (csv) format. The new FEH CD-ROM also provides that same functionality, but additionally gives users the option of including catchment centroid coordinates and $URBEXT_{2000}$, $URBLOC_{2000}$ and $URBCONC_{2000}$ values, by enabling the appropriate tick boxes.

There is an increasing use of files in eXtensible Mark-up Language (XML) format, so to meet those demands, the new software also provides users with the facility to export DDF parameters and catchment descriptor values in that form.

7. Conclusions and recommendations

7.1 Conclusions

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 are to 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.

The catchment descriptor *URBEXT* plays a key role in the FEH procedures. In particular it provides a basis for adjusting the as-rural median annual flood ($QMED_{rural}$) estimated using catchment descriptors, and the as-rural pooled growth curve, when the subject catchment is urbanised. The 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 $URBEXT_{1990}$ (see Table 4.1). 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.

7.2 Recommendations

7.2.1 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 example, a relationship between $URBAN_{50k}$ and $URBEXT_{2000}$ has been established and the urban expansion model presented in the FEH has been rescaled for use with $URBEXT_{2000}$. Additionally, 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.

7.2.2 Relationship between URBEXT_{2000} and URBAN_{50k}

The FEH catchment descriptor $URBEXT_{2000}$ is based on data defining the land cover present around the year 2000. If the level of catchment urbanisation is known to have changed significantly over time, it may be considered desirable to update the $URBEXT_{2000}$ value to reflect the current situation or, in some circumstances, to backdate to a chosen year.

It is difficult to update (or backdate) $URBEXT_{2000}$ values directly, so a relationship between $URBEXT_{2000}$ and $URBAN_{50k}$ has been established. In order to adjust the $URBEXT_{2000}$ value, so that it more closely relates to the level of urbanisation in the chosen year, it is first necessary to obtain (or manually amend) a relevant OS 1:50,000 map. Second, the fraction of the catchment that is urbanised should be derived manually from the map ($URBAN_{50k}$), based on the extent of the built-up areas shown (in accordance with the techniques described in the Flood Studies Report, where the manual derivation includes both urban and suburban areas, but does not distinguish between them).

Finally, an adjusted $URBEXT_{2000}$ value can be estimated from a manually-derived $URBAN_{50k}$ value using the relationship:

$$URBEXT_{2000} = 0.629\, URBAN_{50k} \qquad (7.1)$$

7.2.3 Urban Expansion Factor (UEF)

A national model of urban growth was published in Volume 5 of the FEH. It provides an Urban Expansion Factor (*UEF*) that can be used to update or backdate a catchment value of $URBEXT_{1990}$, in order that it more accurately represents the level of urbanisation relating to the selected year. The model has been rescaled for use with $URBEXT_{2000}$, and provides a *UEF* through use of the equation given below:

$$UEF = 0.7851 + 0.2124 \tan^{-1}\left(\frac{Year - 1967.5}{20.32}\right) \quad (7.2)$$

[The term within the parentheses is in radians.]

The application of a UEF to the catchment value of $URBEXT_{2000}$ provides an alternative procedure to that summarised in Section 7.2.2.

7.2.4 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:

$$QMED_{rural} = 1.172\ AREA^{AE}\left(\frac{SAAR}{1000}\right)^{1.560} FARL^{2.642}\left(\frac{SPRHOST}{100}\right)^{1.211} 0.0198^{RESHOST} \quad (7.3)$$

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

$$AE = 1 - 0.015 \ln\left(\frac{AREA}{0.5}\right) \quad (7.4)$$

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

$$RESHOST = BFIHOST + 1.30\left(\frac{SPRHOST}{100}\right) - 0.987 \quad (7.5)$$

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.

$$QMED = UAF\ QMED_{rural} \tag{7.6}$$

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 (see Section 4.3). It is recommended that the *UAF* be computed using the $URBEXT_{2000}$ and *SPRHOST* values and the equations given below:

$$UAF = \left(1 + URBEXT_{2000}\right)^{0.66}\ PRUAF \tag{7.7}$$

where

$$PRUAF = 1 + 0.47\ URBEXT_{2000}\left(\frac{70}{SPRHOST} - 1\right) \tag{7.8}$$

7.2.5 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 7.7), 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:

$$x_T = 1 + \frac{\left(xrural_T - 1\right)\left(\dfrac{xrural_{1000}}{UAF} - 1\right)}{\left(xrural_{1000} - 1\right)} \qquad 2 \le T \le 1000 \tag{7.9}$$

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 7.9) 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.

$$UAF = \min\left(UAF, \frac{xrural_{1000}}{1.1}\right) \tag{7.10}$$

For return periods less than 1000 years the growth curve factors are scaled accordingly using Equations 7.9 and 7.10.

7.2.6 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).

8. References

Bayliss A. C., 1999. *Catchment descriptors.* Vol. 5, Flood Estimation Handbook. Wallingford: Institute of Hydrology.

Bayliss A. C. and Davies H. N., 2003. *Evaluation of the mapping and assessment of urban and suburban areas: Stage 1 – Evaluation of mapping*. FD1919 Report to Defra/Environment Agency. Wallingford: Centre for Ecology & Hydrology. 35pp.

Bayliss A. C. and Morris S. E., 1999. *Climate and soils.* Chapter 5, Vol. 5, Flood Estimation Handbook, pp.27-38. Wallingford: Institute of Hydrology.

Bayliss A. C. and Scarrott R. M. J., 1999. *Urban and suburban land cover.* Chapter 6, Vol. 5, Flood Estimation Handbook, pp.39-63. Wallingford: Institute of Hydrology.

CPRE, 1993. *The regional lost land – land use change in England's regions and counties 1945-1990*. Report to CPRE prepared by Environment Information Services.

Faulkner D. S., 1999. *Rainfall frequency estimation*. Vol. 2, Flood Estimation Handbook. Wallingford: Institute of Hydrology.

Fuller R. M., Groom G. B. and Jones A. R., 1994. *The Land Cover Map of Great Britain: an automated classification of Landsat Thematic Mapper data*. Photogrammetric Engineering and Remote Sensing, 60, 553-562.

Fuller R. M., Smith G. M., Sanderson J. M. Hill R. A., Thomson A.G., Cox R., Brown N. J., Clarke R. T., Rothery P. and Gerard F. F., 2002. *Countryside Survey 2000 Module 7 – Land Cover Map 2000.* Final Report to LCM2000 Consortium. Monks Wood: Centre for Ecology and Hydrology. 100pp.

Houghton-Carr H. A., 1999. *Restatement and application of the Flood Studies Report rainfall-runoff method*. Vol. 4, Flood Estimation Handbook. Wallingford: Institute of Hydrology.

IH, 1999. *Flood Estimation Handbook*. 5 Volumes and associated software. Wallingford: Institute of Hydrology.

Kjeldsen, T. R., Stewart, E. J., Packman, J. C., Folwell, S. S. and Bayliss, A. C., 2006. *Revitalisation of the FSR/FEH rainfall-runoff method*. Technical Report FD1913/TR, Department of the Environment, Food and Rural Affairs. 133 pp.

Morris, D. G., 2003. *Automation and appraisal of the FEH statistical procedures for flood frequency estimation*. FD1603 Report to Defra. Wallingford: Centre for Ecology & Hydrology.

Morris D. G. and Flavin R. W., 1990. *A digital terrain model for hydrology*. Proceedings of the fourth International Symposium on Spatial Data Handling. Zurich, **1**, 250-262.

NERC, 1975. *Flood Studies Report*. Natural Environment Research Council.

ODPM, 2004. *Land use change in England to 2003: Additional tables*. London: Office of the Deputy Prime Minister.

Reed D. W., 1999. Overview. Vol. 1, Flood Estimation Handbook. Wallingford: Institute of Hydrology.

Reed D. W., 1999b. *Adjusting for urbanisation (A)* Chapter 9, Vol. 3, Flood Estimation Handbook. Wallingford: Institute of Hydrology.

Reed D. W., Jakob D. and Robson A. J., 1999. *Selecting a pooling-group (A)* Chapter 6, Vol. 3, Flood Estimation Handbook. Wallingford: Institute of Hydrology.

Reed D. W. and Robson A. J., 1999. *Adjusting for urbanisation (B)* Chapter 18, Vol. 3, Flood Estimation Handbook. Wallingford: Institute of Hydrology.

Robson A. J. and Reed D. W., 1999. *Statistical procedures for flood frequency estimation*. Vol. 3, Flood Estimation Handbook. Wallingford: Institute of Hydrology.

Appendix A IHDTM-derived catchment boundaries – problem catchments

A comparison of the IHDTM-derived catchment area with the corresponding published catchment area (taken principally from those provided by the gauging authority to the NRFA) was carried out for 958 of the 962 gauging stations, listed, at the time of writing, on the HiFlows-UK website. [An IHDTM-derived catchment area was not derived at four gauging stations where the published catchment area is less than 0.5 km^2].

The percentage difference between catchment areas was defined as:

$$\frac{IHDTM\ AREA - NFRA\ AREA}{NRFA\ AREA}\ \%$$

Where the ratio of larger area to smaller area exceeded 1.1 (i.e. was outside the range -9.09% < Percentage difference < 10.0%) the catchment descriptors defined using the IHDTM-derived boundary were deemed to be unreliable. This comparison identified 38 gauging stations in the HiFlows-UK dataset (listed below) where the IHDTM-derived catchment area differed by more than a factor of 1.1 when compared with the published catchment area.

NRFA No.	Name	IHDTM-derived area (km^2)	Published area (km^2)	Percentage difference
20006	Biel Water at Belton House	57.55	51.8	11.1
23018	Ouseburn at Woolsington	10.48	9.0	16.4
25004	Skerne at South Park	224.58	250.1	-10.2
26009	West Beck at Snakeholme Lock	195.61	242.2	-19.2
26010	Driffield Canal at Snakeholme Lock	49.47	24.66	100.7
27073	Brompton Beck at Snainton Ings	8.06	12.9	-37.5
27206	Esk at Briggswath	325.25	370.0	-12.1
28017	Devon at Cotham	340.94	284.0	20.0
28052	Sow at Great Bridgford	141.77	163.0	-13.0
28060	Dover Beck at Lowdham	62.75	69.0	-9.1
28086	Sence at Wigston	126.04	113.0	11.5
30013	Heighington Beck at Heighington	24.03	21.2	13.3
30015	Cringle Brook at Stock Rochford	41.33	50.5	-18.2
31002	Glen at Kates Bridge	159.09	341.9	-53.5
31026	Egleton Brook at Egleton Gwash	1.92	2.5	-23.2
32029	Flore at Experimental Catchment	8.34	7.0	19.1
33023	Kennett at Beck Bridge	131.56	101.8	29.2
33048	Larling Brook at Stonebridge	27.96	21.4	30.7
33052	Swaffham Lode at Swaffham Bulbeck	21.33	36.4	-41.4
34008	Ant at Honing Lock	44.48	49.3	-9.8
39005	Beverley Brook at Wimbledon Common	39.49	43.5	-9.2
39017	Ray at Grendon Underwood	21.15	18.8	12.5
39031	Lambourn at Welford	159.00	176.0	-9.7
39057	Crane at Cranford	52.83	61.7	-14.4
40033	Dour at Crabble Mill	44.93	49.5	-9.2
41026	Cockhaise Brook at Holywell	29.80	36.1	-17.5

44009	Wey at Broadwey	7.95	7.0	13.6
44809	Piddle at Little Puddle	31.27	34.8	-10.1
52017	Congresbury Yeo at Iwood	55.40	66.6	-16.8
53023	Sherston Avon at Fosseway	77.73	89.7	-13.3
54026	Chelt at Slate Mill	31.31	34.5	-9.2
54052	Bailey Brook at Ternhill	38.38	34.4	11.6
54060	Potford Brook at Sandyford Bridge	22.37	25.0	-10.5
69011	Micker Brook at Cheadle	58.85	67.3	-12.6
70003	Douglas at Central Park Wigan	67.62	55.3	22.3
73015	Keer at High Keer Weir	30.06	48.0	-37.4
83004	Lugar at Langholme	203.70	181.0	12.5
90003	Nevis at Claggan	69.21	76.8	-9.9

The following HiFlows-UK gauging stations have a published catchment area of less than 0.5 km^2 and consequently catchment descriptor values have not been calculated these sites.

NRFA No.	**Name**	**Published area (km^2)**
25808	Burnt Weir at Moorhouse	0.05
25809	Bog Weir at Moorhouse	0.05
25810	Syke Weir at Moorhouse	0.04
205999*	Woodburn at Control	0.30

* Station 205999 was previously incorrectly numbered 206999.

PB12527 / 1

Nobel House
17 Smith Square
London SW1P 3JR

www.defra.gov.uk

Department for Environment
Food and Rural Affairs