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Estimating flood peaks and hydrographs for small catchments: Phase 1

Project: SC090031

Flood and Coastal Erosion Risk Management Research and Development Programme

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Miranda Kavanagh

Director of Evidence

Executive summary

This report presents the results of Phase 1 of Project SC090031 'Estimating flood peaks and hydrographs for small catchments'. This work was jointly funded by the Environment Agency, the Centre for Ecology & Hydrology (CEH) and JBA Consulting. The objectives of the scoping study were:

- to review existing datasets and techniques available for flood estimation in small rural and urban catchments and to suggest a preferred technique;
- to assess a range of possible methods that could be applied to small catchment hydrology in the future;
- to recommend interim procedures if appropriate.

The study has focused on flood estimation in small rural and urban catchments in the UK. For the purposes of the study, a limit of 25 km^2 was selected as the maximum catchment area considered, although it is recognised that many flood risk assessments are required for much smaller areas, some of which may form only part of a catchment and may not contain a watercourse.

The scoping study has included a review of the sources of flow data in the UK for small catchments. The Environment Agency's HiFlows-UK dataset provides flood peak data for over 950 gauging stations, but less than 10% are from catchments smaller than 25 km^2 in area. A particular problem is the current lack of adequate flow data for small urban catchments. The prospects for augmenting the dataset have been explored and a number of sources of potential new data have been identified. It is proposed that the expansion of the flow data available for further analysis should form one of the early tasks of Phase 2 of this project.

Consideration of the types of process that give rise to floods in small catchments and plots highlights the fact that practical flood models rely on conceptual simplifications and empirical data on a range of scales. Every year, many flood risk assessments are carried out on small catchments in the UK, often to meet the requirements of planning guidance such as Planning Policy Statement 25 (PPS25), and for other reasons such as the design of storm sewers and road drainage. A review of the guidance available to practitioners has demonstrated that a number of different methods, some of which were developed more than 35 years ago, are recommended for different applications. In some cases, the guidance to use particular methods seems to be related more to the ease with which they can be applied, rather than to how appropriate individual methodologies are. The most up-to-date methods available are those from the *Flood Estimation Handbook* (FEH) and its subsequent updates, which are based on long, reliable gauging station records and were specifically developed to be applicable to a range of catchment sizes and types.

The report provides details of an analysis comparing the performance of a number of widely used flood estimation methods in small catchments. The results suggest that the FEH statistical method and the Revitalised Flood Hydrograph (ReFH) event-based method both outperform the older methods, although the former may be more uncertain on small catchments than on larger ones. While there is little evidence to suggest that the accuracy of the FEH methods when applied to ungauged catchments is particularly scale dependent, it is recommended that further flood peak data from small catchments, both rural and urban, should be analysed.

The conclusions of the scoping study are as follows:

- The FEH methods (both statistical and ReFH methods) are applicable across the range of catchment sizes used in their development and thus the continued recommendation of outdated methods such as IH 124 and ADAS 345 is inappropriate.
- Since small catchments are not well represented in HiFlows-UK, further flood peak data for small rural and urban catchments should be sought and analysed.
- Despite lack of bias, uncertainty in flood estimation remains high and there is a need to develop and test improved catchment descriptors, especially of soils and watercourse extent.
- There is a requirement for improved hydrological methods to support fluvial flood risk assessment in very small catchments and also to support drainage design.
- Estimates are required of both flood peaks and hydrographs to give flood volumes.

The following interim recommendations are made to practitioners:

Based on the results of the analysis in Section 6, it is recommended that flood estimates on small catchments should be derived from FEH methods in preference to other existing methods. The current versions of the FEH statistical approach or the ReFH rainfall-runoff model should be used except on highly permeable catchments (BFIHOST>0.65), where ReFH should be avoided, and possibly on urban catchments ($URBEXT_{2000}$>0.15), where the results of the ReFH model can be less reliable. Checks should be carried out to ensure that the flood estimates are within expected ranges based on what is known about the history of flooding and the capacity of the channel (including evidence from previous flood marks).

For catchments smaller than 0.5 km^2 and small plots of land, runoff estimates should be derived from FEH methods applied to the nearest suitable catchment above 0.5 km^2 for which descriptors can be derived from the FEH CD-ROM and scaled down by the ratio of catchment areas. The decision to translate FEH estimates from catchment scale to plot scale should be accompanied by an assessment of whether the study site is representative of the surrounding catchment area.

One of the outputs of the study is a proposal for further research within a second phase of the project, which is presented in a separate document. Following on from Phase 2, it is expected that a new software tool would be developed, which would form part of the FEH suite.

Contents

1 Introduction

1.1 Project background

This report describes the work undertaken during the first phase of Project SC090031 'Estimating flood peaks and hydrographs for small catchments'. The objectives of this scoping study are:

- To review existing datasets and techniques available for flood estimation (including flood peaks and hydrographs) in small rural and urban catchments and to suggest a preferred technique.
- To recommend interim procedures, if appropriate, and to assess a range of possible methods that could be applied to small catchment hydrology in the future. This is intended to inform a possible second phase of work.

A decision on whether to proceed with a second phase of work to analyse datasets, develop techniques and produce practical tools will be made at the end of Phase 1.

The current phase of the research is a collaborative project involving the Environment Agency, the Centre for Ecology & Hydrology (CEH) and JBA Consulting.

1.2 Scope of the project

In the UK, the most widely used methods of flood frequency estimation are presented in the *Flood Estimation Handbook* (FEH) (Institute of Hydrology 1999) and subsequent updates. The methods are applicable to catchments of at least 0.5 km^2, an arbitrary threshold reflecting the spatial resolution of the digital catchment descriptors which underlie the methods. In practice, many of the catchments for which flood estimates are required are 'small', a term which is defined in the FEH and its predecessor the *Flood Studies Report* (FSR) (NERC 1975), as less than about 20 to 25 km^2 in area. Gauged data for small catchments are generally sparse, making the estimation of flood frequency particularly uncertain because such small catchments are not well represented in the datasets on which the generalised methods have been calibrated.

However, small catchment hydrology is very important in the UK, as illustrated by Figure 1.1. This shows the digital river network in Wales, with rivers draining a catchment area of greater than 25 km^2 in blue and rivers draining areas of less than 25 km^2 in red. An additional consideration is that many small areas for which flood risk assessments are required do not contain a watercourse at all, and may or may not represent a contiguous catchment in the case of development sites for which estimates of greenfield runoff rates are required.

Because of the paucity of flow data in small catchments, especially in lowland and urban areas, at present, a large number of different methods are applied to flood estimation in small catchments, and these can give widely differing results. Many of the methods have not been thoroughly examined for scientific robustness, and current guidance on which method to apply is often contradictory.

This study focuses on flood estimation in small urban and rural catchments of less than 25 km^2. The project has links with current work to update the Defra/Environment Agency R&D report *Preliminary Rainfall Runoff Management for Developments* (Defra/EA 2005), which aims to provide a consistent methodology for computing pre-development (greenfield) site runoff for development control assessment.

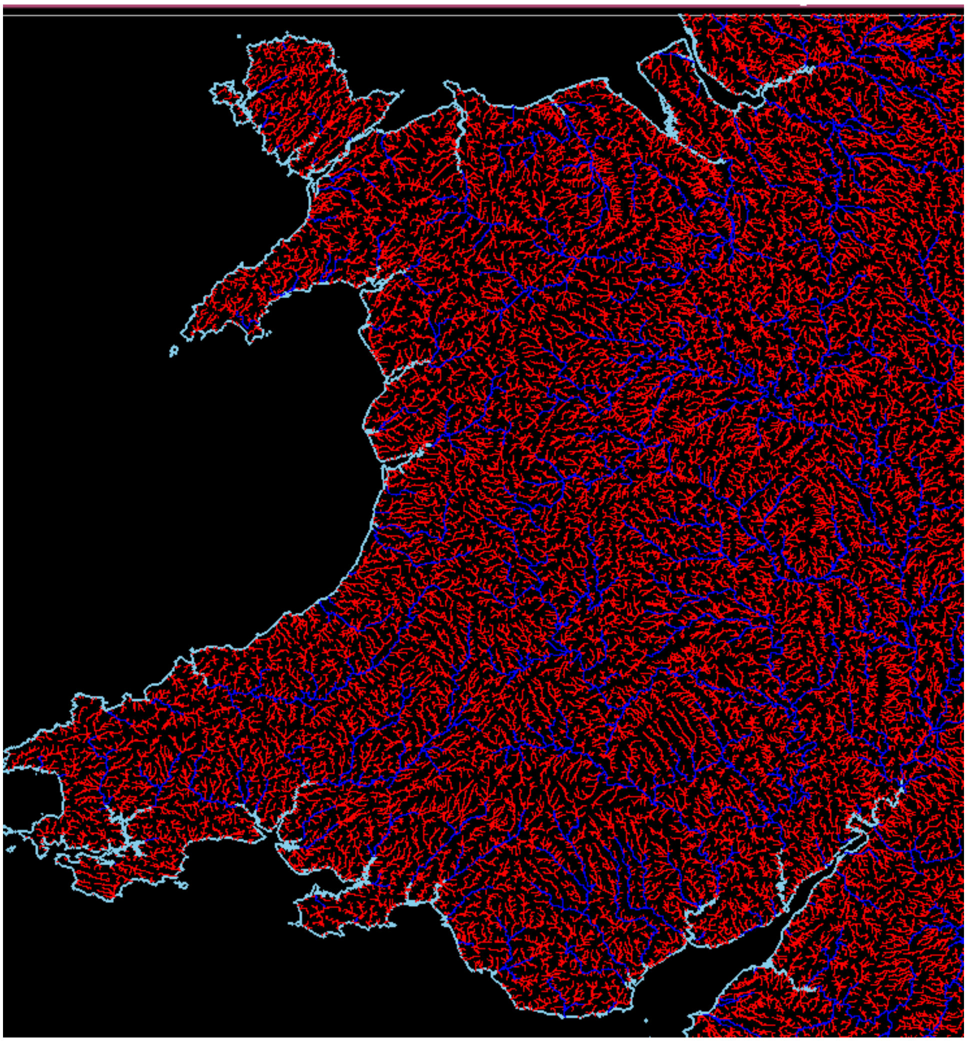


Figure 1.1 Map showing river catchments of less than 25 km^2 (red) and greater than 25 km^2 (blue) in Wales

1.3 Specification of Phase 1

The first phase of the project was divided into three tasks as follows:

Task 1: Identification of the types of catchment to be included in the study

- Review of user needs:
  - types of study that use small catchment methods and typical range of catchment sizes covered;
  - summary of existing guidance.
- Typical range of catchment sizes:
  - lower limit of catchment area;
  - whether greenfield sites are to be included.
- Catchment types and descriptors:
  - including applicability of methods to both rural and urban catchments;
  - catchment descriptors including spatial resolution of digital datasets.

Task 2: Review of current datasets, techniques and knowledge on small catchment processes

- Review of existing datasets (flood peaks and hydrographs) in small catchments including:
    - HiFlows-UK, CEH, Environment Agency, water companies, local authorities;
    - identification of short-term flow survey data as well as longer-established gauging stations;
    - level gauges with high flows rating equations;
    - datasets from plot-scale runoff measurement experiments;
    - any readily available quality assured datasets from overseas experiments (in areas of comparable climate and land use).
- Review of current methods used to estimate floods in small catchments including:
    - FEH methods, IH124, ADAS 345, rational method, hybrid models, continuous simulation models.
- Assessment of the uncertainties associated with both methods and datasets.

Task 3: **Recommendations on how best to go forward and highlight interim methodologies that could be applied until Phase 2 is completed**

- Production of a short report, including a write-up of Tasks 1 and 2, proposal of options including a costed methodology.

- Alternatively a recommendation may be made that Phase 2 of the project is postponed to enable more data to be collected, or that one of the existing methods is adequate and Phase 2 is not necessary.

1.4 Structure of the report

This report presents the findings of Tasks 1 and 2 as specified above and proposes a number of tasks for Phase 2. The second section identifies the needs of users, considering the most typical applications of small catchment and greenfield runoff methods and addressing the use of design flow estimates in flood risk assessments. Section 3 provides information about flow data for small UK catchments of potential use to Phase 2 of this study, and Section 4 presents an introduction to flood-generating processes in small catchments. Current methods of flood estimation in small catchments and in greenfield sites are discussed in Section 5, together with current guidance to UK practitioners. Section 6 presents the results of preliminary analyses of the performance of existing flood estimation techniques in small catchments. Finally, the conclusions of the first phase of the research are discussed in Section 7, and a number of interim recommendations are presented.

2 User needs

2.1 Typical applications of small catchment and greenfield runoff methods

Every year, thousands of flood studies are carried out across the UK on small catchments and on plots of land which form part of a catchment and may not contain a watercourse. Many of these are flood risk/consequence assessments carried out to meet the requirements of PPS25, TAN15 and equivalent planning guidance in Scotland and Northern Ireland. Section 2.2 below explains how design flood flows are used in many flood risk assessments.

Other uses of flood estimates on small catchments include:

- flood mapping studies, including those on larger catchments for which hydraulic model inflows are needed from multiple small catchments;
- flood warning studies;
- design of storm sewers;
- design of road drainage and culverts;
- design of pumping stations and other infrastructure;
- appraisal of options for flood alleviation;
- reservoir design.

2.2 Example: what are design flows used for in flood risk assessments?

Planning Policy Statement 25 (PPS25) requires consideration of the risk of flooding arising from a development in addition to the risk of flooding to the development. The latter often requires estimation of design flood flows on a watercourse or sewer that may act as a source of flooding. In many cases this is a small watercourse, typically with no flow data available. Various flood estimation methods, most often those from the FEH, are used in this situation.

However, the more difficult task can be the assessment of flood risk arising from the development, both on-site and off-site. For the latter it is necessary to estimate the present-day runoff from the site (which may be a greenfield or a brownfield, previously developed, site). This flow rate is the maximum that will be permitted from the developed site (PPS25 states that ‘Surface water arising from a developed site should, as far as is practicable, be managed in a sustainable manner to mimic the surface water flows arising from the site prior to the proposed development’). If the runoff is managed using sustainable urban drainage systems (SUDS) storage features such as attenuation ponds, storm tanks or site landscaping, the greenfield runoff rate is used to select the size of the flow restriction that controls the outlet of the storage feature. Greenfield runoff rates are commonly calculated using pre-FEH methods as discussed in Section 5.2.

The volume of storage needed is calculated from knowledge of the post-development runoff volume, for which a flood hydrograph is needed. This needs to account for the increased volume due to creation of impermeable surfaces. For consistency it is obviously desirable to use the same method to calculate both the pre- and post-development runoff volume, but this is not always feasible given the ranges of applicability of existing flood estimation methods.

Development includes buildings and paved surfaces, including transport infrastructure, but also more subtle increases in runoff such as those associated with the transition from agricultural land to quarries, open-cast mines or sports pitches. Runoff calculations are also needed for large-scale low-intensity development such as wind farms, with comparatively small increases in impermeable area.

Existing methods of flood estimation are not always adequate for some of these applications. For example, it is not straightforward to represent the change in runoff resulting from the transition from agricultural land to sports pitches or golf courses. None of the widely used flood estimation methods are suitable for representing effects such as the change from long grass to tightly mown playing surfaces and the installation of subsurface drainage. Similar comments apply to quarry developments, which typically involve stripping of soils and vegetation.

3 Sources of data

This section provides information about flow data on small UK catchments (less than 25 km^2) that could potentially be used in a future study.

3.1 HiFlows-UK

The Environment Agency's HiFlows-UK dataset (v3.1.1, released in July 2011) provides flood peak data, gauging station information and catchment descriptors for 953 gauging stations in the UK. Of these, 840 stations are considered 'suitable for QMED estimation' and have annual maximum records of at least four years in length. A total of 75 of these stations have catchments of less than 25 km^2 in area. Twenty-four have catchments smaller than 10 km^2.

Of the 75 catchments smaller than 25 km^2, the majority are essentially rural. Eleven are classed as heavily urbanised ($URBEXT_{1990}$>0.125).

The classification of stations in HiFlows-UK is indicative. In compiling the HiFlows-UK dataset, the general criterion for 'indicative suitability' for QMED (median annual maximum flood) estimation was to accept the station if QMED is likely to be within 30% of its true value. Sometimes it is found that more detailed reviews of gauging stations and ratings lead to the conclusion that additional stations are suitable for estimating QMED. Even for stations where the uncertainty in QMED may be greater than ±30%, it is sometimes decided that it is better to use the flood peak data than to rely on catchment descriptors to estimate QMED. With this in mind, and bearing in mind the typically large uncertainty in estimating design flows from catchment descriptors on small catchments, additional sources of flow data have been considered as part of this study. These include gauging stations that have been rejected from HiFlows-UK, and other stations that may never have been considered for inclusion in the dataset.

3.2 National River Flow Archive

Another source of flood peak data for UK catchments is the National River Flow Archive (NRFA) held at CEH Wallingford. The NRFA collates, quality controls and archives hydrometric data from gauging stations across the UK. A total of 127 catchments have an area of less than 25 km^2 and thus would potentially be of use to this project.

3.3 Other Environment Agency data

Environment Agency staff have suggested several gauging stations on small catchments that are not currently included in HiFlows-UK but may provide acceptably accurate estimates of QMED. Stations that have been suggested to date are:

- 18 stations with a gauging station data quality (GSDQ) class of good on catchments smaller than 30 km^2. Three were discounted as they were reservoir compensation gauges. Annual maximum flows for the remaining 15 stations have been supplied. Most are in South West, South East and Anglian Regions. Six of the stations have been included in the tests of existing methods described in Section 6.
- 15 stations in North West Region judged to have potential for producing useful high flow data on catchments smaller than 40 km^2. Nine of the

catchments are smaller than 25 km^2 and the smallest is 6 km^2. Not all of the stations currently have rating equations and some of those that do have ratings have no high flow gaugings. This list of stations was supplied towards the end of Phase 1 and so the data have not yet been requested.

Another possibility that has been investigated within the Environment Agency is the inclusion of level-only gauges for which rating equations may be available from hydraulic models or spot gaugings. Many water level recorders were installed in or near urban areas in the years following the Easter 1998 floods; thus they now have around 10 years of record. Where they are in engineered channels and free from variable backwater effects it should be possible to derive accurate rating equations up to bank-full conditions from hydraulic models. It is recommended that Phase 2 of this study includes a trawl for suitable gauging stations by asking staff in Environment Agency area teams, because they may help overcome the current shortage of flow data on small urban catchments.

3.4 Rivers Agency, Northern Ireland

A list of 39 stations was provided, with catchment areas up to 40 km^2. Thirty-six of the catchments are smaller than 25 km^2 and the smallest is 0.23 km^2. Nearly all the stations have ratings but not all are suitable for high flows. A few are short records from the 1970s and 1980s for which the data may no longer be available. Flow data from ten of the gauges on the smallest or most urban catchments has been obtained and used for the tests described in Section 6. Several other gauges may have records that are suitable for including in Phase 2.

3.5 International data

Given geographical and climatic similarities between part of the UK and Ireland, a search was made for small catchment flow data from Ireland. The quality of high flow ratings in Ireland was reviewed as part of the recent Flood Studies Update research programme (Hydro-Logic 2006). Of the gauging stations classed as suitable for estimating QMED, the smallest catchment area was 6.5 km^2 and there were nine catchments smaller than 25 km^2. Given the lack of very small catchments it was considered that this dataset was unlikely to add significant value to this study.

3.6 Plot-scale data

The sources below were approached to seek flow or runoff data from very small catchments or plots:

- Imperial College, Pontbren experimental catchment: Flow data was supplied for a 3 km^2 catchment and a 0.4 ha drained plot (Marshall *et al.* 2009). Both surface runoff and subsurface flow were supplied for the latter, but the period of record was short and discontinuous, with a total of 23 months of data. It is unlikely the data will be useful for constructing a flood peak series, but it may still provide useful evidence of scaling effects when compared with flow recorded downstream on the 3 km^2 catchment.

- Rothamsted Research, North Wyke: 24 months of flow data was provided for two small plots, including drain flow and subsurface lateral flow. Both plots have an area of 0.1 ha.

- ADAS: Runoff data is available for several plots smaller than 1 ha, both drained and un-drained. ADAS also hold streamflow data for a reasonable number of small catchments, some of which were used in the development of IH 124 (e.g. Cliftonthorpe, Lower Smithy, North Weald and Redesdale). None of this data has been supplied yet but it is expected to be available from ADAS, at a small charge, for use on Phase 2 of this study.

- United Utilities, SCaMP (Sustainable Catchment Management Plan) programme: Streamflow data are available from six small catchments or plots in the Forest of Bowland, Lancashire. An agreement has been drawn up to make these datasets available for Phase 2. The flow measurements were made by Penny Anderson Associates on behalf of United Utilities, for a period of around 5 years.

- Environment Agency Project SC060092 – 'Multiscale Experimentation, Monitoring and Analysis of Long-term Land Use Changes and Flood Risk': This project covered the same area as the SCaMP project, in the Forest of Bowland, but flows were measured at different locations, for a period of 3 years starting in early 2008. The data have been requested.

- Universities of Durham and Leeds, Moor House research site, Upper Teesdale: Flow was measured on four very small catchments in the 1950s to 1960s as part of an investigation of the impact of artificial drainage on peatland catchments (Conway and Millar 1960). More recently the University of Leeds has measured runoff at the plot scale from 2002 to 2004 (Holden *et al.* 2006) and the University of Durham is currently monitoring other plots. There are large gaps in recent data due to the failure of the equipment during most winters so it is unlikely the data will be useful for constructing a flood peak series. This upland peatland area is not typical of the locations where most small catchment design flows are needed and so it has been decided not to incorporate any additional data from Moor House in the present study.

In addition to the above, data were sought from local authorities and water companies but no suitable flow datasets were found. Other potential data providers, including Exeter University, will be approached during the proposed Phase 2 of the study.

4 Flood-generating processes in small catchments

4.1 What is a small catchment?

What constitutes a small catchment is unclear; it is a relative judgement dependent on the user. A UK hydrologist probably thinks of anything less than 25 km^2 as fairly small, and anything larger than 1000 km^2 as fairly large. These approximate limits are certainly reasonable given the catchments in the Environment Agency's HiFlows-UK dataset – where 72 of 848 are less than 25 km^2 and 66 greater than 1000 km^2. These limits also nicely match the range to which the Revitalised Flood Hydrograph (ReFH) model is best suited. The concepts in the FEH and ReFH can be applied outside this range (bearing in mind the implicit ReFH assumption of a uniform/consistent spatial rainfall distribution), but the problem is to select sensible values for the model parameters – ones that fall within the range of the standard estimation equations or can be corroborated by results from similar catchments. Thus the label 'small catchment' probably depends more on the availability of data to calibrate and validate a model than on any real limit on catchment area.

Yet, for many drainage engineers, 5 km^2 is already a large catchment, and small catchments go down to just a few hectares. Are 'all catchment' methods still applicable as we go ever smaller in size range? Are they focused sufficiently on small catchments? Is there a size at which the balance of flow processes within the catchment changes? The upland catchment area of a small reservoir may be as low as 1 km^2, but it may still have a clear topographic catchment boundary, a stream network and an associated mix of riparian areas, flood zones and hillslopes. Hydrographs, peaks and time to peaks could still be measured, and the methods could be applied. The main concern is how well the published regression equations would predict model parameters, given the susceptibility of small catchments to local conditions (e.g. intense rainfall cells, topographic and soil conditions, land use and flow path management/ maintenance – such as hedgerows, ditches and ponds, agricultural monocultures/cycles etc.) that would average out in larger catchments.

However, a lowland catchment area comprising farmland or forest may have no natural drainage system, or possibly a series of dug ditches along field or property boundaries, or maybe under-soil drainage. If there is no discernible stream, there can be no stream data with which to validate a model. The area may never produce local surface runoff into a stream, and clearly represents a different sort of (very) small catchment area. It may accept (subsurface) flow from a similar area upstream, and/or lie alongside a stream, becoming an internal contributing area to a larger downstream catchment. So what are the flood issues? How much will it contribute to downstream flooding, and by what method could this be estimated? Does the method include appropriate detail to model the relevant processes and conditions, and can the model parameters be reasonably estimated? In particular, are FEH methods suitable when they are based on a 50 m topographic grid, 1 km soils grid, and catchment parameters available only for areas above 0.5 km^2? To address these points we must consider the processes involved in flood generation.

4.2 Flow generation processes

In natural catchments, floodwater is generated by a combination of processes, including:

(i) Intense rainfall that exceeds the infiltration capacity of the soil – the excess forming surface runoff which accumulates down slope to form a dendritic network of rivulets, streams, ditches, watercourses and rivers. It should be noted that, unless they are near saturation, UK soils generally have sufficient infiltration capacity to absorb typical rainfall intensities. Extreme intensities may cause runoff but this is often of short duration, and the runoff generated may be trapped and absorbed further downslope.

(ii) Rainwater that infiltrates (vertically) and then flows laterally on meeting either the water table, a more impervious layer, a preferential flow path caused by geomorphology, plant or animal activities (e.g. pervious bands, root cavities and burrows), or a man-made drainage system (e.g. agricultural, urban). These lateral flows may pass along totally separate subsurface flow paths, or may accumulate in lowland areas close to the stream network, forming wet riparian areas of reduced infiltration capacity (encouraging future infiltration excess runoff) and either breaching the soil surface as springs or contributing directly to the stream via bed or bank flow. The 'surface runoff' seen in a stream system may well have begun as infiltration and subsurface flow.

(iii) Streamflow that concentrates and conveys runoff within a river network developed in sympathy with the scale of flow to be carried. Channel and banks are sufficient to contain normal flows (typically up to the 2-year flow rate), but may be overtopped by rarer/larger flows causing inundation of riparian floodplain areas. Given the general shortage of flow data from small catchments, the capacity and condition of any existing drainage system are vital guides towards assessing likely flood flows. This includes assessing drainage extent, density and evidence from previous flooding – taking due account of any artificial channel modifications and subsequent geomorphological adjustments.

From (i) and (ii) above, it is clear that soil properties, saturation state and water table depths are crucial in generating flood response, both overland and subsurface. Soils also control local (in-field) flow rates – typically of a few centimetres per second – that make up a large part of response lag in small catchments. Even upland catchments of a few hectares can show lags of several hours. Channel flow rates of some metres per second only begin to dominate with the long river reaches found in large catchments. Information on soils is considered the weakest link in current small catchment flood estimation: the HOST (Hydrology of Soil Types) classification, for example, is based on average breakdowns of soil types within 'soil associations', and further averages the associations over a 1 km grid. More specific assessment of soil properties at a smaller scale is required.

The effect of agriculture on soil properties is varied and the impacts on flood runoff uncertain. At the field scale, ploughing improves soil texture and infiltration capacity, yet provides ready sediment sources if storm rainfall occurs before the stabilising vegetation has grown. Soil capping and compaction, vehicle ruts and farm tracks can interrupt subsurface flow paths and provide new surface paths leading to flooding in low spots away from usual drainage paths. The net effect of such *ad hoc* changes is inconsistent, depending on the scale of the area affected and on how any runoff generated eventually reaches the established drainage system. Recent studies under the FRMRC (Flood Risk Management Research Consortium, http://www.floodrisk.org.uk) have found no consistent impacts at other than field scale.

The ‘muddy flood’ phenomenon in small upland catchments is recognised, but there is little data to assess its true likelihood at any particular site – does it depend on a rare synchronisation of agricultural circumstances and localised extreme storm conditions? Is any resultant flooding dependent as much on blockages caused (at culverts etc.) as on any perceived enhancement in flow rate?

Urban impacts on flood runoff are generally larger, involving additional processes – with impervious and semi-pervious areas (roofs, roads, yards etc.) that yield true surface runoff, connected to pipe and channel drainage systems (of finite capacity), or to SUDS (soakaways, ponds etc.). Soils are heavily modified (compressed, contaminated, replaced, gardened etc.) and subsurface flow paths disrupted (by foundations, service trenches etc.). Catchment boundaries are changed (diversions, overflows etc.), and urban water systems introduced (supply, sewerage, hosepipes). Surface flow paths are shorter and smoother, and catchments of a few hectares typically yield response lags of around 15 minutes. Existing river channels are altered (filled, culverted, embanked) and flood alleviation schemes developed (washlands, flood channels, storage etc.). Moreover, with less dependence on soil and antecedent conditions, urban flooding tends to be caused by summer thunderstorms rather than winter depressions. It is not surprising that flood estimation for small urban and rural catchments has largely developed separately, with sewer methods such as the rational method widely used, and rural/FEH methods only applied to larger catchments where local impacts have largely averaged out. Combining results for intermediate cases is still an uncertain area.

Despite a broad understanding of flood processes, large- and small-scale spatial variability mean that practical flood models depend on conceptual simplifications and empirical data. Indeed, not validating a model against observed data may mean the balance between flood processes is misrepresented.

Many frequently used concepts such as ‘surface runoff’, ‘surface water’, ‘overland flow’ and ‘pluvial flooding’ are misleading. They imply runoff generation by ‘infiltration excess’ alone (see (i) above). In the context of urban catchments, Defra (2009) describes surface water flooding as flooding from sewers, drains, small watercourses and ditches that occurs during heavy rain in urban areas. This goes beyond flooding due to local surface runoff alone, and includes overflows from sewers and watercourses due to inadequacy or raised water levels downstream, and also springflow and groundwater infiltration into urban drainage systems. Thus, thinking of runoff as ‘infiltration excess’ alone is not sufficient. Furthermore, even if an area does not appear to yield local surface runoff, it does not mean that it is not contributing to storm flow in the stream network further downstream (some CEH datasets do indeed show streamflow increasing while ‘contributing’ ditches remain dry, implying deeper flow paths into the stream bed).

Baseflow too is a misleading concept, often regarded as ‘groundwater’ flow. It is better thought of as the slow draining down of the combined catchment/stream system. It should be recognised that, given the flow time through a stream network, much of what may be interpreted as ‘baseflow’ lower down a catchment may well have originated as ‘storm runoff’ at the top of a catchment.

With the true source of observed streamflow undefined, and with the changing balance between in-field and in-channel processes, the extrapolation of flood estimation across catchment scales is uncertain. There is also a general lack of high flow data to support such extrapolation, especially for small, lowland, rural catchments. Flooding from such catchments has not attracted the same concern as wider scale, main river flooding – it is usually of low impact, and the cost of a structured flow monitoring programme has not appeared justified.

Recent flood events have highlighted the need for new guidance on small catchment flood estimation, both to estimate floods entering urban areas (from flat lowland and steep valley catchments), and to assess pre-development 'greenfield runoff rates' (so SUDs systems can be designed to avoid post-development increases in flooding downstream). Assessing how upstream response, or a change therein due to land use or drainage works, contributes to flooding downstream is a vague area, and more background data from nested catchment studies are required. Note also that the statistical assessment of downstream flows is needed (i.e. estimation of a flood flow with a given exceedance probability) and excessive focus on an individual storm may be misleading. Future research needs are discussed in Section 7, but this discussion suggests a greater focus on soil conditions and the balance between surface/subsurface and channel flow components is required.

5 Current methods and guidance

5.1 Review of current methods of flood estimation in small catchments

Simple flood formulae derive from two almost distinct approaches: the index flood approach, where an *association* is sought between flow of some specified severity and catchment/climate characteristics, and the rainfall-runoff approach, where the *causal relationship* is considered between rainfall, catchment characteristics and flow. The index approach includes simple factors, such as x cumecs/km^2 or y l/s/ha, and regression equations, such as those of the FSR and FEH (see below and Appendix A). Simple rainfall-runoff methods are usually related to the rational method (Q=CiA), where flow rate per unit area (Q/A) is set proportional to rainfall rate in some critical duration; the coefficient of proportionality and the critical duration are required.

Both approaches have their limitations. For example, an association of higher floods with high annual rainfall does not necessarily imply a causal relationship; high annual rainfall may imply high catchment slope or thinner soils, which could be truer causes of higher floods. On the other hand, an over-simplified causal relationship between rainfall and flow may be assumed, or a relationship derived from individual storms might not extend to statistically defined T-year rainstorms. In either case, relationships will be based on data from a limited number of catchments, and may not be generally applicable. A single universal formula cannot be recommended, but informed comparison of independent methods should be used.

The FEH statistical and hydrograph methods (see Section 5.1.5) are clearly the preferred methods for medium to large catchments, but are arguably less clearly suited to small catchments, particularly the very smallest (below 1 km^2) where catchment descriptors may not be defined. In such cases, the recommendation is to consider a larger downstream catchment and scale the results by the AREA (catchment drainage area) ratio – taking due account of any other significant differences between the upstream and downstream catchments (e.g. soil type, land use, topography). This approach can even be simplified to using standard runoff rates in ‘cumecs per sq km’ or ‘litres per second per hectare’, based on region and soil type (see Appendix A).

Evidence to support scaling any flood estimate by AREA is discussed further in Appendix B, but it is noted here that (a) it accords to some extent with unit hydrograph methods (ignoring rainfall areal reduction factors and changes in lag-time and critical storm duration/mean intensity with catchment size), and (b) it is reasonably in line with the AREA exponent in the QBAR (mean annual maximum flood) equations from FSR, FSSR6 and IH 124 (see Sections 5.1.2 and 5.1.4), and in the original FEH QMED equation. The AREA exponent of the improved FEH equation (0.851) does differ further from 1.0, but it should be recognised that regression coefficients define not causal relationships but associations between the descriptors used (and the development of the FSR equation showed how the AREA exponent grew from 0.73 to 0.95 as additional variables indexing stream density, soil type, climate etc. were introduced).

5.1.1 Transport and Road Research Laboratory (TRRL) LR 565 method

The LR 565 method (Young and Prudhoe 1973), developed to estimate flood flows on small natural catchments bordering motorways, is essentially a rational method:

$$Q = (F/3.6)*(P/T_c)*AREA$$

where F is a factor depending on standard average annual rainfall (SAAR, in mm), P is rainfall depth (mm) and T_c is the notional time of concentration in hours. The method was developed using data from five gauges on four catchments, each on heavy clay, and ranging in size from 2.8 to 21.3 km^2. Values of flow (Q) and P for individual storms were used to estimate T_c (with F set to 1). These T_c values were then related to catchment length (L) and slope (S) as

$$T_c = 2.48\ (L/S)^{0.39}$$

Note:

(i) The LR 565 equation contains no percentage runoff factor, and thus the derived T_c values may be elongated to reduce mean rainfall intensity. The FSR (see Section 5.1.2) used three of the LR 565 catchments, deriving time to peak (T_p) values of 4.5, 3.0 and 3.7 as against T_c values of 16.7, 27.5 and 23.7 h, respectively.
(ii) For design use, rainfall is estimated by the Bilham equation (the research predated the FSR/WASSP rainfall model). The F factor (based on just four catchments) accounts for differences between the T-year flow peak from frequency analysis and that derived from the equation using the Bilham rainfall in duration T_c.
(iii) Testing the method on 16 further catchments of size 10.4 to 88.7 km^2 suggested that catchment area should be substituted by the area covered by clay.

The LR 565 method is not as generally applicable or extensively founded as the FSR methods that followed soon after.

5.1.2 Methods of the *Flood Studies Report* (FSR)

In 1967, the Committee on Floods of the ICE (ICE 1967) recommended research into improved techniques of flood estimation, thereby initiating the research programme that eventually resulted in the publication of the five-volume *Flood Studies Report* (FSR) (NERC 1975). The FSR describes an extensive analysis of gauged flow data from the British Isles and presents two methods of design flood estimation: the statistical method and the rainfall-runoff method. In the statistical method, an index flood, the mean annual flood, QBAR, is derived from catchment characteristics and then multiplied by a growth factor to give an estimate of the flood peak with a return period of T years, Q_T. The rainfall-runoff method uses a unit hydrograph model whose parameters are estimated from catchment characteristics. Inputs and initial conditions for the model are then selected as a set to give an estimate of Q_T.

Within both methods there was scope for including local data, either from the site of interest itself or from nearby locations. This recommendation was crucial to improve the accuracy of the methods.

Until the publication of the FEH in 1999, the FSR provided the most widely based flood estimation methods available in the UK. However, the various model equations were based on data from large catchments, generally greater than 20 km^2. There has always been some concern over their suitability for small catchments, particularly with regard to the measurement of mainstream length and slope on the 1:25,000 map (small catchments may not have clearly defined drainage systems at this scale).

With this in mind, Flood Studies Supplementary Report (FSSR) 6 (Institute of Hydrology 1978) presented equations for QBAR, PR (percentage runoff) and T_p based on small catchments (below 20 km^2). The authors concluded that these equations gave results no better than the original FSR equations, but that a simpler QBAR equation:

$$QBAR = 0.00066\ AREA^{.92}\ SAAR^{1.22}\ SOIL^{2.0}$$

could be used if a quick answer was required (where SOIL is an index of winter rainfall acceptance potential). A quick solution to the rainfall-runoff model can be obtained by using the revised T_p and PR equations of FSSR16 (Institute of Hydrology 1985) with the rational formulation of FSSR9 (Institute of Hydrology 1979):

$$Q = RC*(PR/100)*(P/D)*AREA$$

where P and D are rainfall depth and duration, and RC is a routing factor depending on D and T_p. The database used to derive these equations is given as 531 catchments for the original FSR Q equations, 47 catchments for the small catchment Q equation, and 181 catchments for PR and T_p, with 37 below 20 km^2 (though most of the small catchments are steep upland catchments).

5.1.3 The ADAS 345 method

The ADAS 345 method (Bailey *et al.* 1980) is an amalgam of the LR 565 method and the FSSR6 QBAR equation (ADAS 1982). Concerned that slope was not associated with flow in the FSSR6 equation, and reasoning it was due to a limited dataset, the LR 565 form of equation was preferred. However, this did not account for various soil types, so the SOIL factor from FSSR6 was added to the LR 565 equation. This is highly suspect since both SOIL and SAAR imply slope. Moreover, the basis for the exponent of SOIL in the equation is not explained.

The LR 565 method requires rainfall depth, for which Reference Book 345 appears to have used the Holland version of the Bilham equation:

$$P = 25.4(T*D/10)^{0.32}$$

Substituting this together with the LR 565 T_c and F equations gives:

$$Q = SOIL^{2.0} * \left\{\frac{0.985*(0.00127*SAAR-0.321)*T^{0.32}}{(L/S)^{0.265}}\right\} * AREA$$

or $\quad Q = St * F * AREA$

Apparently putting return period T equal to 2, 5 and 10 years for grass, arable and horticultural catchments, they present a graphical solution for F (l/s/ha), with tabulated St values for different soils. The method is simple but suspect.

5.1.4 Institute of Hydrology Report 124 (IH 124) method

The IH 124 method (Marshall and Bayliss 1994) was the result of a study aiming to improve the characterisation of flood response on small catchments (of area less than

25 km^2), especially on relatively permeable, dry, partly urbanised catchments. IH 124 presented new equations for time to peak based on FSR catchment characteristics for both part-urban and rural catchments. The study also introduced a revised version of the FSR regression equation for the mean annual flood, QBAR, based on gauged records for 71 small rural catchments:

$$QBAR = 0.00108\ AREA^{0.89}\ SAAR^{1.17}\ SOIL^{2.17}$$

Where AREA, SAAR and SOIL are catchment descriptors available from the FSR maps. However, unlike the catchments used in the same study for the investigation of flood response, many of these 71 catchments were upland, relatively wet and impermeable. Only nine had SAAR values of under 800 mm, while 30 catchments were in high SAAR areas (over 1500 mm).

5.1.5 *Flood Estimation Handbook* (FEH) methods

Currently, the most widely used methods for flood frequency estimation for river catchments in the UK are based on the FEH (Institute of Hydrology 1999) and subsequent updates. The FEH methods and associated software offer two alternative approaches to flood frequency estimation:

- The FEH statistical method based on an index flood methodology and involving analysis of annual maximum peak flow series. The original procedures have been updated under Environment Agency Project SC050050 and are described by Kjeldsen *et al.* (2008).
- An event-based rainfall-runoff method which provides a design flood hydrograph. Again, the FEH rainfall-runoff method has been superseded by the ReFH method as presented by Kjeldsen *et al.* (2005) and Kjeldsen (2007).

The lower limit of catchment size to which the FEH is applicable is 0.5 km^2, which, in practice, is defined according to the spatial resolution of the digital catchment descriptors made available on the FEH CD-ROM (CEH 2009), and not due to scale limitations in the theoretical modelling principles underlying the FEH methods. However, as the FEH methods are calibrated to observed data, and these datasets contain a limited number of very small catchments, some degree of extrapolation is required when using the FEH on small catchments. A summary of the area of the catchments used in the calibration of the two FEH methods is shown in Table 5.1.

Table 5.1 Summary of catchment sizes used in the development of the FEH methods

	Statistical (updated)	**ReFH**
Number of gauges	602	101
Smallest catchment (km^2)	1.63	3.47
Largest catchment (km^2)	4586.97	511.33
Mean catchment area (km^2)	332.98	174.28

The improved FEH statistical method

The improved FEH statistical method was developed within Environment Agency Project SC050050 funded through the Defra/Environment Agency Joint Flood and Coastal Erosion Risk Management R&D Programme. It is an index-flood based method which allows hydrologists to estimate the complete flood frequency curve in any gauged or ungauged catchment in the UK. Details of the method can be found in Kjeldsen *et al.* (2008), and only a brief summary is presented here. The flood frequency estimation procedure consists of two stages. First, the index flood itself (defined as the median annual maximum flood) is estimated, either from AMAX (annual maximum) observations or from catchment descriptors. The catchment descriptor model is defined as:

$$QMED_{cds} = 8.3602 AREA^{\ 0.8510}\ 0.1536^{\ (1000/SAAR)}\ FARL^{\ 3.4451}\ 0.0460^{BFIHOST^{**}2}$$

where the subscript *cds* refers to an estimate obtained from catchment descriptors. The second step is to create a pooling-group of 'hydrologically similar' catchments, where similarity was defined by Kjeldsen *et al.* (2008) as similarity with regard to catchment area (AREA), standard annual average rainfall (SAAR), flood attenuation from reservoirs and lakes (FARL) and an index of flood plain extent (FPEXT). Weighted averages of second and third order L-moment ratios (L-CV and L-SKEW) are calculated from all the sites within the pooling-group and the model parameters of the dimensionless growth curve are estimated from a Generalised Logistic (GL) distribution using the method of L-moments. Finally, the full flood frequency curve is estimated as the product of the index flood and the dimensionless growth curve.

When conducting a flood frequency analysis in an ungauged catchment it is advised that data should be transferred from nearby gauged (donor) catchments. The method for data transfer presented by Kjeldsen *et al.* (2008) reduces the prediction uncertainty of the index flood (QMED) by compensating for local flood controlling factors not easily captured by lumped catchment descriptors such as those used in the equation above (Kjeldsen and Jones 2010). Thus, in this study estimates of the index flood obtained from the catchment descriptor equation were subsequently adjusted through data transfer from the nearest (geographically) suitable donor site.

The catchments included in this assessment include both rural and urban catchments. Initially, the method developed by Kjeldsen *et al.* (2008) only considered rural catchments. A subsequent CEH project considered how to include considerations of urban development into the method, and was reported by Kjeldsen (2010). Thus, in this study, where applicable, estimates of both QMED and the growth curves were adjusted for urbanisation using the $URBEXT_{2000}$ catchment descriptor.

The revitalised FSR/FEH rainfall-runoff (ReFH) method

The revitalised FSR/FEH rainfall-runoff method was developed as an event-based approach to design flood estimation and replaced the existing FSR/FEH method (Kjeldsen *et al.* 2005). Details of the method can be found in Kjeldsen *et al.* (2005) and only a brief summary is presented here. The method uses an event-based rainfall-runoff model, the Revitalised Flood Hydrograph (ReFH) model, to convert design storm events of appropriate duration and rarity into a corresponding design flood event of similar rarity. The ReFH model has four model parameters controlling hydrological losses (maximum soil capacity, C_{max}), routing using a unit hydrograph (time to peak, T_p) and two baseflow parameters (recharge and lag-time, BR and BL). The four parameters can be estimated using catchment descriptors available from the FEH CD-ROM (CEH 2009). The design storms are generated using the FEH depth-duration-frequency (DDF) model (Faulkner 1999). In its present form, the ReFH method is not recommended for use in catchments defined as permeable (BFIHOST>0.65) or urban ($URBEXT_{2000}$>0.1500). Further work to improve its structure and performance for such catchments is ongoing at CEH.

5.1.6 Comments by MacDonald and Fraser (2009)

MacDonald and Fraser (2009) made an unpublished presentation on the estimation of design floods in small UK catchments. A new regression equation was introduced based on annual maximum data from 127 gauged sites draining an area of less than 25 km^2. The equation relates QMED to four standard catchment descriptors derived from the FEH CD-ROM (CEH 2009).

5.1.7 Other methods

There are several other methods that are used for flood estimation on small catchments in addition to those listed above. These include rules of thumb, for example drainage rates used to specify sizes for pumping stations, and local approaches or variants on standard techniques. Examples include:

- The Poots and Cochrane equation (Civil Engineering Branch, Department of Finance, Northern Ireland 1980), which is a variant of the FSR statistical method.
- The Devon Hydrology Strategy (Haskoning 2007), which includes regional equations for different parts of Devon in which the 100-year flood is estimated on the basis of catchment area.
- Work by Colin Clark (e.g. Clark 2007) on flood estimation using a method intended for application over a range of catchment sizes.

Review of these methods, which are not published in peer-reviewed journals, is considered to be outside the scope of this study. However, the fact that such methods have been developed indicates that there is an appetite for improving small catchment methods and a perception that standard methods are not always appropriate.

5.2 Review of guidance on small catchment and greenfield runoff flood estimation

There is a wide range of UK guidance documents touching on flood estimation in small catchments or development sites. This section reviews some of the key references and mentions others.

5.2.1 Defra/EA (2005)

This guidance considers the IH 124 and ADAS 345 methods, recommending IH 124 for use on catchments under 2 km^2 because it is simpler to apply, based on a larger number of catchments and aimed at predicting extreme runoff conditions. The report does not claim that IH 124 gives more accurate results than other methods; rather, the recommendation was aimed largely at meeting the pragmatic needs of the industry. For larger catchments, FEH methods are recommended. For development sites smaller than 0.5 km^2, the report recommends applying IH 124 with an area of 0.5 km^2 and scaling down the peak flows by area.

The report recommends that the IH 124 estimate of QBAR should be combined with regional growth curves from FSSR2 and FSSR14 to obtain a peak flow of the chosen return period. This recommendation has the advantage, for a 'back of envelope' calculation, that the relevant FSR growth curves are fixed and available in tables. However, the FSR curves do not incorporate up-to-date information and lack the flexibility of FEH growth curves. The FEH pooled analysis is able to incorporate information preferentially from sites similar to the place for which an estimate is needed, rather than mixing in information from much larger catchments.

The recommendation to use IH 124 for rural runoff estimation in small catchments is repeated in several subsequent guidance documents, including:

- *Design Manual for Roads and Bridges* (Highways Agency 2004);
- *Exceedance in Urban Drainage* (Balmforth *et al.* 2006);
- *SUDS Manual* (Woods-Ballard *et al.* 2007);
- *Code for Sustainable Homes Technical Guide* (Department for Communities and Local Government 2009);
- *Drainage Manual* (Network Rail 2010).

5.2.2 Highways Agency (2004)

This recommends IH 124 for catchments larger than 0.4 km^2 and ADAS 345 for smaller catchments, the justification being that smaller areas are unlikely to contain watercourses and thus IH 124 is not appropriate. It discounts FEH methods because they were 'developed for pre-defined river catchments of a certain dimension and cannot deal with smaller catchments'. Arguably the same point could be made about IH 124. The manual states that 'the FEH approach also requires the use of a software package and considerable knowledge of hydraulics'.

5.2.3 Balmforth *et al.* (2006)

This includes a brief comparison of 11 possible methods of estimating peak flows or runoff volumes on small rural catchments, with some useful interpretations of their strengths and weaknesses. As well as those covered by the present study, it also lists Poots and Cochrane (1979), the US Soil Conservation Service (SCS) method, FSR, FSSR6 and FSSR16. It recommends IH 124 for estimating peak flows for stormwater management, possibly supplemented by another method for design of structures whose failure may have damage implications.

The report compares results from seven methods on one example catchment and, from comparing the predictions, states 'It is clear that for this type of catchment that the FEH methods would appear to be seriously under predicting the peak flow for extreme events'. This conclusion seems hard to justify given the fact that, in the absence of any flow data for the catchment, there is no information available on the true nature of the flood frequency relationship.

5.2.4 Runoff estimation for quarry projects

A rather different range of methods is recommended by guidance on runoff estimation for quarry projects by MIRO, MIST and Geoffrey Walton (undated)**.** The handbook recommends the rational method or alternatives including water balance calculations, PDM (using a probability distribution of infiltration capacity rather than storage capacity). FEH methods are also suggested, but only for areas larger than 0.5 km^2.

5.2.5 Environment Agency (2009)

The Environment Agency's guidelines on flood estimation review the pros and cons of four small catchment methods: rational, the IH 124, ADAS 345 and FEH methods. They stress that there is no ideal method for small catchments, apart from in extremely rare cases that offer ample flood peak data, and urge users to critically consider the merits of the various methods available. The FEH statistical or ReFH methods are recommended as the best choices for small catchments. For greenfield runoff estimation the guidelines do not recommend any particular method, mentioning options including application of runoff rates calculated from FEH methods or using IH 124 or ADAS 345.

5.2.6 CIRIA (2010)

This document reviews a range of flow estimation methods for small catchments including FEH statistical, ReFH, IH 124 and ADAS 345. It suggests that there is little reason to prefer the IH 124 formula for QBAR over the FEH formula for QMED and recommends scaling FEH estimates down by catchment area as a first choice when estimates are needed for rural catchments smaller than 0.5 km^2. In suggesting scaling of flow estimates, the CIRIA hydrology guidance also recommends users to consider how well the study area is represented by the information used in the wider catchment estimate; its recommendation is to carry out a hydrological assessment, not simply a mechanistic procedure. The guidance also sets out recommended methods according to whether the study area is rural or urban and whether a peak flow or hydrograph is needed. It suggests both methods based on modelling and data analysis and also methods suitable for 'hand calculation' as a fall-back position, noting that there is a concern from users for estimation procedures that are proportionate to the requirements of a given study.

5.2.7 Summary of guidance

To summarise the documents mentioned above, many of them recommend using IH 124 for catchments up to 2 km^2, sometimes with a lower limit of 0.4 km^2 (below which ADAS 345 is recommended). Most recommend FEH methods for catchments over 2 km^2, and some for smaller catchments down to the plot scale.

5.3 Review of previous comparisons of small catchment methods

There have been relatively few other published studies comparing the merits of different small catchment flood estimation methods. This section briefly reviews three such papers from the UK and Ireland.

Hall (1996) compared a version of the rational method with the short-cut version of the FSR rainfall-runoff method (Institute of Hydrology 1979). The rational method uses a technique proposed by Richards in the 1930s in which the time of concentration is varied inversely with the average rainfall intensity, and is estimated iteratively as part of the computation. Comparisons were made on 31 catchments, four of which are smaller than 10 km^2. The paper concludes that the Richards version of the rational method offers no advantages over the short-cut version of the FSR rainfall-runoff method.

Gardner and Wilcock (2000) reviewed six alternative regression equations for QBAR and tested them on small catchments in Northern Ireland. The best equation was found to be one developed for large catchments in Northern Ireland. The equation was developed nearly 30 years ago (Hanna and Wilcock 1984), from flow records just 10–12 years long. The Poots and Cochrane equation (Civil Engineering Branch, Department of Finance, Northern Ireland 1980), which is still commonly used by the Rivers Agency in Northern Ireland, was found to be less satisfactory.

Cawley and Cunnane (2003) pointed out some disadvantages of the QBAR regression equation from IH 124 in greenfield runoff estimation. Of the catchments used in development of the regression, 75% have soil types 4 or 5 (the least permeable soils), so estimation of QBAR on soil types 1 to 3 is questionable. The authors suggest that the MAFF Report 5 method should be considered more seriously for greenfield runoff assessment. They also point out the mismatch between the scale and nature of the catchments used in the derivation of the methods and the much smaller scale of the plots (generally not complete catchments) for which greenfield runoff estimates are needed. They stress that flow attenuation measures such as SUDS are generally required to avoid flood impacts at a point somewhere downstream of the development site. Using a runoff value applicable to the local area for all development sites within that area promotes a strategic approach to runoff management.

6 Performance of existing methods

6.1 Introduction

As summarised in the previous section, a range of methods are currently used for flood estimation in ungauged catchments. Although there are various sources of guidance on the choice of method, these tend not to be based on any scientific comparison of performance in terms of accuracy and uncertainty. In the following section a two-stage process of assessing the predictive ability of methods is presented. First, in Section 6.2, the ability of various methods to predict flood peaks of low return period (the 2-year flood or QMED) is assessed, together with a brief comparison of growth factors estimated by the different methods. This investigation shows that, in general, the FEH suite of methods performs better than both the ADAS and the IH 124 methods. The second part of the analysis provides a comprehensive assessment of the ability of both the improved FEH statistical and ReFH methodologies to predict design floods for a range of return periods (T = 2, 5, 30 and 100 years). The results show that the performance of the FEH methodology is not scale dependent, and also provide a useful indication of the level of uncertainty involved in flood frequency estimation at ungauged sites.

6.2 Comparison of the performance of different methods

One challenge in assessing the performance of flood estimation methods is that it is not possible to know the true value for a design flow (i.e. the flow of a given return period). However, it is usually possible to estimate design flows for relatively short return periods with a high level of confidence when there is an ample record of good quality flood peak data at the site of interest.

A number of tests were carried out to compare the ability of the various methods to estimate QMED on small gauged catchments, where QMED can be estimated with some confidence from flood peak data. The typical length of flood peak records on small catchments is 20–30 years, and the mean 68% confidence interval for QMED when estimated from the flood peak data was found to be 0.87 to 1.11 times the best estimate. This magnitude of uncertainty is much smaller than that associated with estimates derived from methods applied to ungauged catchments.

There are very few, if any, flood peak records long enough to enable estimation of, say, the 100-year return period flood with high confidence. However, some additional comparisons of flood growth curves were carried out, and these are described in Section 6.2.4.

The tests described here are a continuation of work described in Faulkner *et al.* (2011), which covered catchments up to 10 km^2.

6.2.1 Selection of catchments

The tests were carried out on 73 gauged catchments across England, Wales, Scotland and Northern Ireland, all smaller than 25 km^2. These are shown in Figure 6.1 and listed in Appendix C.

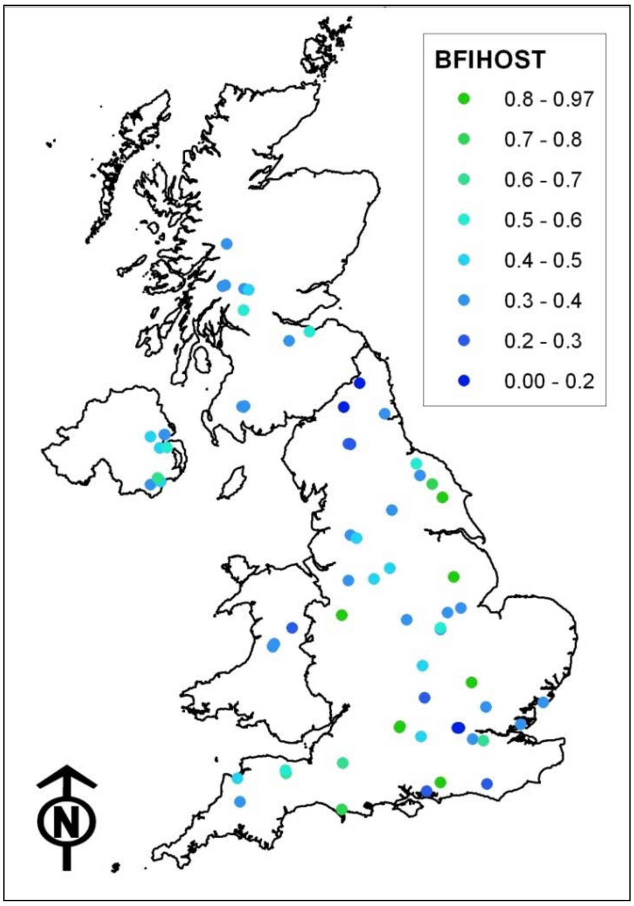


Figure 6.1 Sites used in comparison of all methods

The catchments were selected from the following sources:

- *HiFlows-UK*: all 25 catchments classed as suitable for QMED estimation and under 10 km^2 from the dataset, along with a selection of 15 catchments between 10 and 25 km^2. All of the additional catchments selected had values of SAAR under 1000 mm in order to focus on the type of catchment where flood studies were likely to be carried out, and to exclude some upland experimental catchments which were already well represented in the sample of catchments smaller than 10 km^2.

- *National River Flow Archive (NRFA)*: 23 additional urban catchments or catchments under 10 km^2, to improve the number of very small or urban catchments in the sample. Some of these were recommended by the Environment Agency as providing reliable high flow measurements (indicated by a high flow class of 'Good' in the GSDQ classification) even though they are not currently included in HiFlows-UK. Others were selected on the basis of station descriptions in the Hydrometric Register.

- *Environment Agency*: three additional gauging stations thought to give reliable high flow measurements but not currently included in HiFlows-UK or the NRFA.

- *Rivers Agency*: six gauging stations thought to give reliable high flow measurements but not currently included in HiFlows-UK, again selecting primarily very small and/or urban catchments.

- One small catchment at Pontbren in Wales, for which flow data were supplied by Imperial College.

Several potential catchments were excluded where one was nested within another, to avoid including similar data twice. Approximately two-thirds of the catchments chosen for the tests had been used in the development of the FEH methods.

Figure 6.1 shows the 73 small catchments which were used in the final comparison, and also illustrates the range of soil permeability as indexed by BFIHOST (a baseflow index derived using the HOST classification).

The range of catchment types is illustrated in Figure 6.2. In terms of average annual rainfall, the distribution is very different from what would be expected on the sort of catchments for which design flows are usually needed. Although there are a large number of catchments with low to moderate SAAR (500–1000 mm) there are also many upland catchments with high or very high SAAR. In particular, there are 11 catchments where SAAR is 2300–2600 mm. Most of these are upland catchments from research studies: at Plynlimon (mid-Wales), Loch Dee (Galloway) and Balquhidder in the Scottish Highlands. The highest value of SAAR is 3131 mm at 89008, Eas Daimh, which drains the slopes of Ben Lui, whose summit is at 1130 m. Results from the comparisons of methods are presented both for all catchments and for a subset of catchments with low to moderate rainfall (using a threshold of 1200 mm, chosen because it is likely that the majority of flood risk assessments will be for lowland areas where SAAR is under 1200 mm).

In terms of soils, there is a good range of BFIHOST values, from below 0.2 (highly impermeable) to above 0.8 (highly permeable). The majority (58%) are moderately impermeable (0.2–0.4).

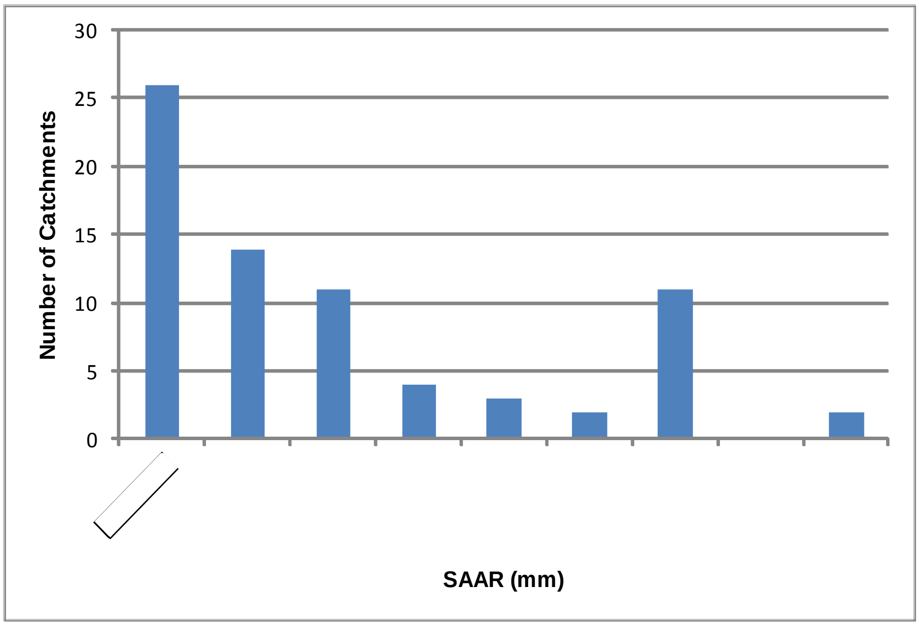
In terms of reservoir influence, all but one of the catchments had a value of FARL very close to 1, indicating very little attenuation due to reservoirs and lakes. The exception is 19009, Bog Burn at the outlet of Cobbinshaw Reservoir, where FARL is 0.61. The results on this catchment will be less reliable for methods that do not account for the presence of lakes or reservoirs (i.e. all except the FEH statistical method).

Most of the catchments are essentially rural, but nine are heavily urbanised with an $URBEXT_{2000}$ value greater than 0.15. These catchments have been left in the dataset, because the study is concerned with the full range of small catchment types, but some of the summary results are presented with and without urban catchments, as it is recognised that some of the flood estimation methods (e.g. ADAS 345) are designed solely for rural areas.

6.2.2 Methods used in the comparison

The following methods have been compared:

- FEH statistical method, using the revised QMED formula from Kjeldsen *et al.* (2008). An urban adjustment was applied using the formula based on $URBEXT_{2000}$ (Bayliss *et al.* 2007). No attempt was made to adjust the initial estimate of QMED using nearby gauging stations (donor sites) because in practice it is very rare to find a nearby donor station on a suitably small-sized catchment.



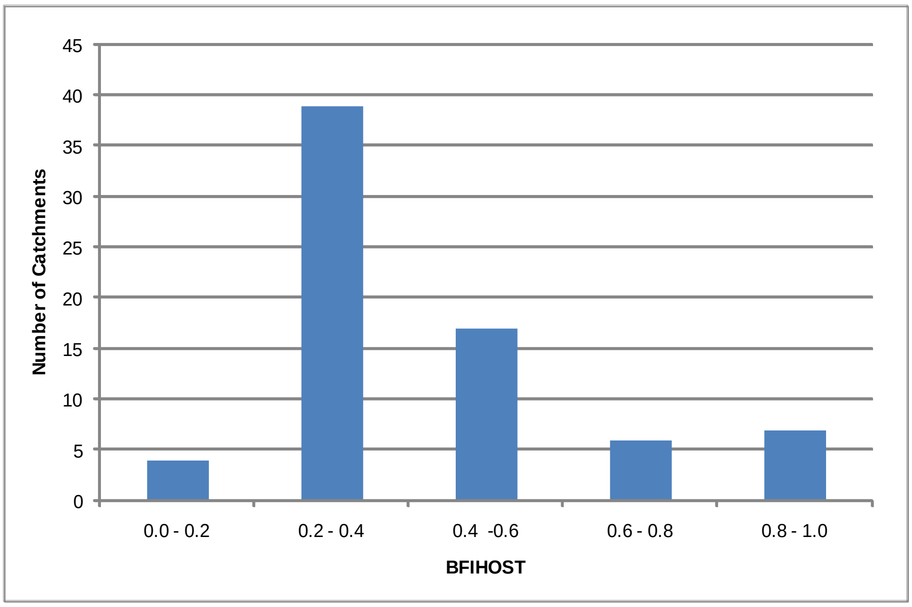


Figure 6.2 Ranges of catchment descriptors for sites used in comparison of all methods

- ReFH (Kjeldsen 2007), using catchment descriptors to estimate all model parameters and the default design storm duration.
- IH 124 (Marshall and Bayliss 1994), with an urban adjustment applied taken from the CIRIA guide to the design of flood storage reservoirs (1993), as presented in IH 124.
- ADAS Report 345 culvert design method (ADAS 1982 and Bailey *et al.* 1980). The crop type needed for the solution chart in the ADAS method was set to

grass, which from comparison with Figure 4 of Bailey *et al.* (1980) represents a return period of 2 years.[1]

The FSR/FEH rainfall-runoff method was not included because this has been superseded by ReFH. The rational method was not applied because it is rarely recommended or used for greenfield runoff estimation or small natural catchments in the UK, apart from in its modified form presented in ADAS 345.

QMED was estimated using each method. For IH 124, QBAR was converted to QMED using the regional growth curve factors provided in IH 124. The estimated QMED was compared with the value calculated from flood peak data. The performance of the methods across all sites was summarised by calculating the root mean square error (for log QMED), and the bias, which was taken as the geometric mean of the ratios between predicted and observed QMED.

6.2.3 Results – comparison of QMED estimates

This section compares the results from various methods with estimations of QMED calculated from flood peak data, referred to for brevity as 'observed QMED' although it is recognised that there will be errors in these estimates too, due to natural variability and uncertainty in measurement of high flows. Dependent on the length of record, the 'observed QMED' was calculated from AMAX or peaks-over-threshold (POT) data.

The figures that follow show the results in various different ways. Firstly, Figures 6.3 and 6.4 are scatter plots comparing predicted QMED from each method with observed QMED. Figure 6.3 shows all catchments and Figure 6.4 makes the plot rather clearer by removing the results on high-rainfall catchments (SAAR>1200 mm). Most of the high-rainfall catchments are located in remote upland areas; these have been removed from Figure 6.4 as most flood studies are likely to be carried out on catchments with lower average annual rainfall. The second figure adds some explanation of the ReFH results by highlighting permeable catchments (BFIHOST>0.65), as the ReFH method is not recommended for application on such catchments.

Note the logarithmic scale on both graphs. This is intended to illustrate the factorial differences between predicted and observed QMED, rather than the additive differences. It also helps distinguish between the results for some of the smallest catchments, where flows are very low.

[1] Note that the labelling of the lines on ADAS 345 Appendix 6 (which enables calculation of the factor F used in the method) appears to be misleading. The three lines labelled Grass, Arable and Horticulture can be compared with the lines on MAFF Report 5 Figure 4, where the lines are labelled with return periods rather than crop types. It can be seen that these three lines correspond to return periods of 2, 5 and 10 years. Since MAFF Report 5 is earlier, presumably these return periods are the correct ones for the lines. Yet in MAFF Report 5 it is stated that the correspondence between return periods and land uses is:

1 year: Grassland
2 years: Intensive grass and cereals
5 years: Roots
10 years: Horticultural

So the three lines in ADAS 345 labelled Grass, Arable and Horticulture should actually be labelled Intensive grass and cereals, Roots and Horticulture. But more simply, they can be treated as being labelled 2, 5 and 10 years.

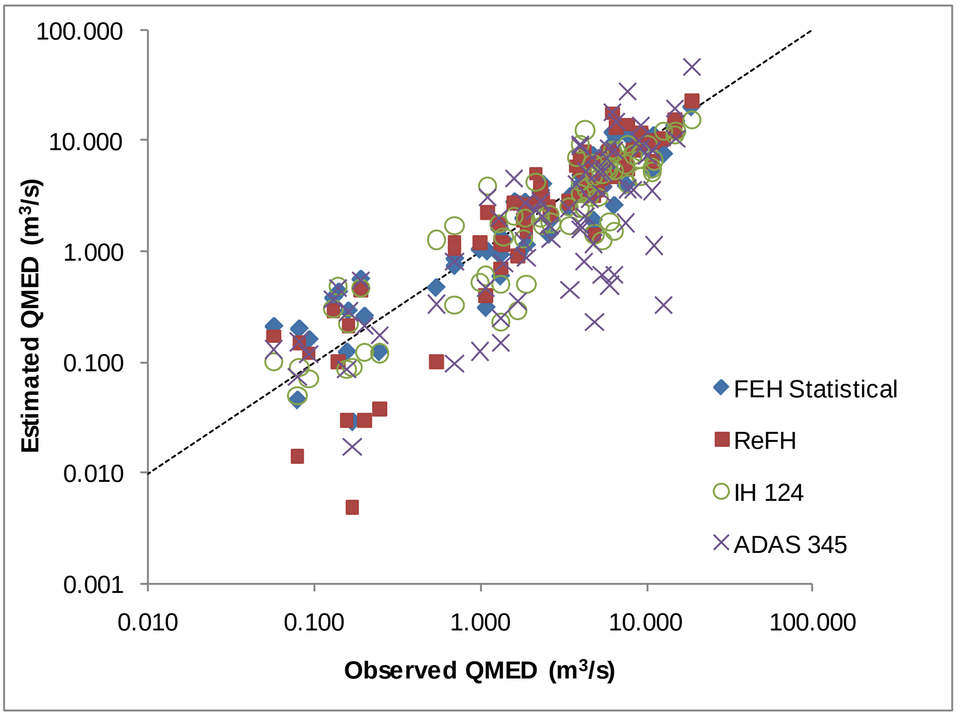


Figure 6.3 Scatter plot of results at all sites against observed QMED

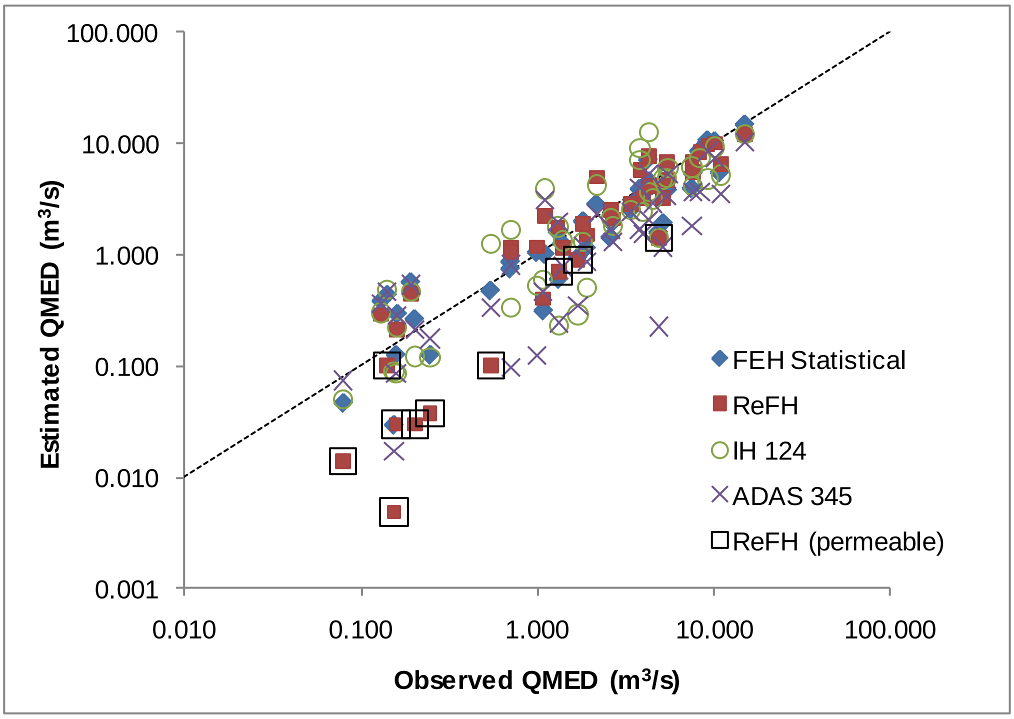


Figure 6.4 Scatter plot of results at low to moderate rainfall sites (SAAR <1200 mm)

Some observations on these plots are:

- The FEH statistical method generally shows close agreement with observed QMED values, over the full range of flow rates.
- The ReFH method shows close agreement for catchments with high flows, particularly for higher rainfall catchments. The similarity between observed and estimated flows on catchments with high flows is comparable to that of the statistical method. However, it substantially underestimates QMED for several of the catchments with lower flows. Many of these are highly permeable catchments, as illustrated in Figure 6.4.
- IH 124 shows a good fit for many catchments, although shows rather more scatter than FEH statistical. Despite the close match in places, the method underestimates by at least 10% on 60% of the catchments sampled. If the high-rainfall catchments (which formed a large part of the dataset from which the method was developed) are ignored, IH 124 can be seen to underestimate QMED on most catchments.
- ADAS 345 has a larger scatter than the other methods, sometimes giving a close match, sometimes overestimating but more commonly underestimating. If the high-rainfall catchments are removed, ADAS 345 underestimates QMED on a large majority of catchments, particularly on those with moderate to low flows (which are generally the permeable ones).

Summary statistics were calculated in order to demonstrate the performance of each method. The results of these tests are shown in Figure 6.5 (bias) and Figure 6.6 (root mean square error, RMSE). The statistics are shown for four subsets of catchments. The numbers in brackets indicate the number of catchments within each subset.

a. All catchments (73).

b. Heavily urbanised catchments only, where $URBEXT_{2000}>0.15$ (9).

c. Excluding urban and permeable catchments (where BFIHOST>0.65), on which some methods cannot be expected to perform well (54).

d. Excluding high-rainfall catchments (where SAAR>1200 mm), which are atypical of the majority of populated locations where the largest number of flood risk studies for small catchments are carried out (44). The vast majority of the population of England and Wales live in areas where SAAR is below 1200 mm. The main reason for creating this subset was to remove the bias introduced by the inclusion of the large number of upland experimental catchments which form a major component of the small catchment dataset.

Summary statistics are shown in Table 6.1.

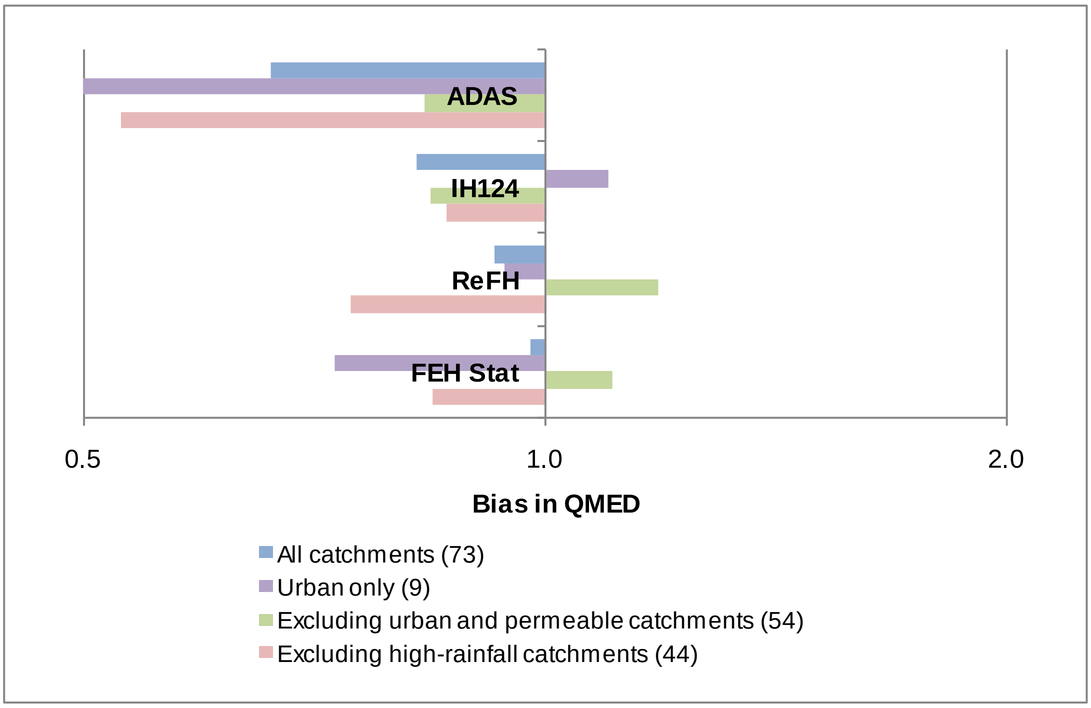


Figure 6.5 Mean bias in estimating QMED from each method

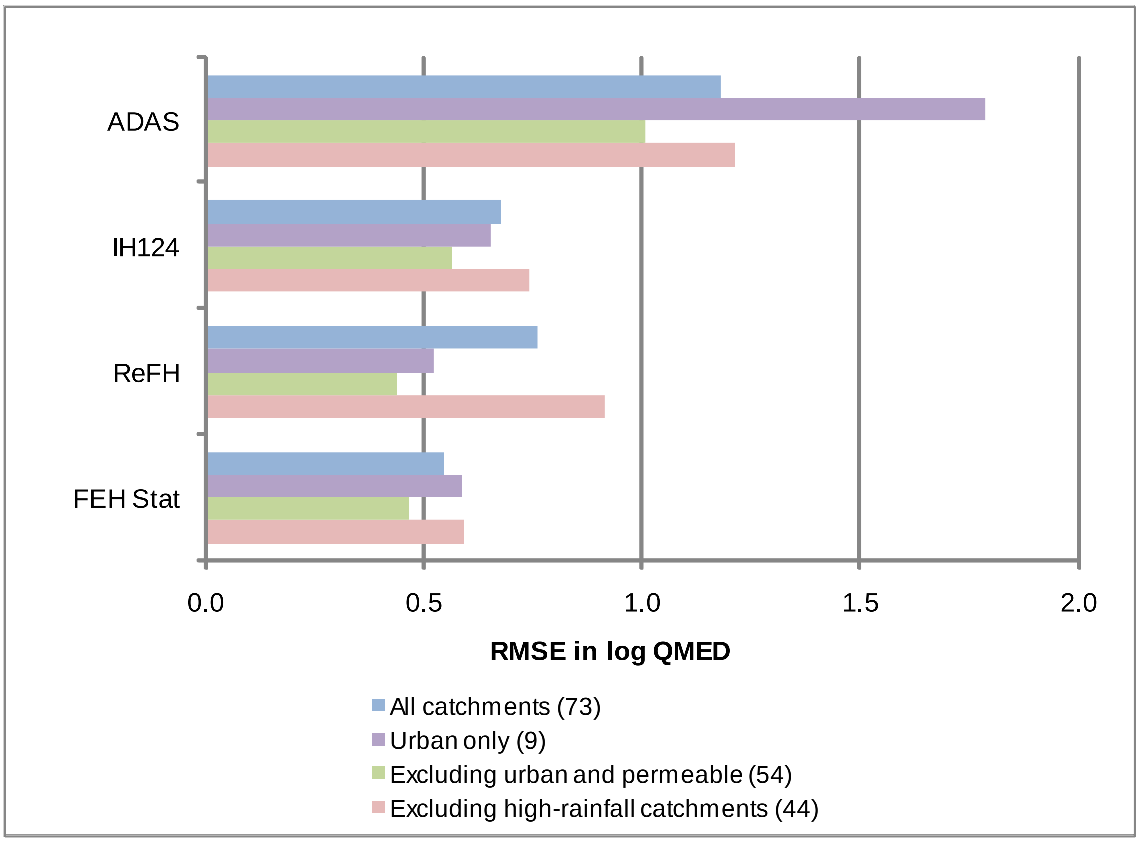


Figure 6.6 Root mean square error in estimating QMED from each method

Table 6.1 Summary statistics from tests (best performing methods shown in bold)

	All catchments (73)		Urban catchments only (9)		No urban or permeable catchments (54)		No high-rainfall catchments (44)	
	RMSE	Bias	RMSE	Bias	RMSE	Bias	RMSE	Bias
ADAS 345	1.180	0.662	1.787	0.258	1.006	0.834	1.212	0.529
ReFH	0.759	0.925	**0.523**	**0.941**	**0.438**	1.185	0.912	0.747
IH 124	0.675	0.823	0.651	1.100	0.566	0.841	0.739	**0.862**
FEH statistical	**0.547**	**0.977**	0.588	0.729	0.464	**1.107**	**0.593**	0.844

Some observations on the plots in Figures 6.5 and 6.6 are:

- There is a general tendency for all methods to underestimate QMED for small catchments. This occurs both on the full dataset and also on the set of low to moderate rainfall catchments.
- Overall, the FEH statistical method gives the least biased results, especially when the whole sample of catchments is used. The bias is also low when urban and/or permeable catchments are removed from the dataset, showing a slight overestimation. When these are included, it tends to underestimate, particularly on low to moderate rainfall catchments. FEH statistical also has the lowest error (RMSE) overall and the error is similar for the various subsets of catchment types. Interestingly, the error increases only slightly from rural to urban catchments.
- The ReFH method also has a fairly low bias when considering the entire dataset. This is marginally higher than that of the FEH statistical method, but significantly lower than IH 124 and ADAS. However, this overall average masks the fact that it tends to underestimate on permeable catchments and overestimate on less permeable and wet catchments, as can be seen from the results from the subsets. It has a particularly large bias when wet catchments are excluded. It seems that this is almost entirely due to the poor performance of ReFH on highly permeable catchments.

  Surprisingly, it is apparent that ReFH has low bias and low RMSE when only urbanised catchments are included in the analysis, despite advice that ReFH in its original form is not well suited to assess the effects of urbanisation on flood peaks and volumes (Kjeldsen 2007). However, the validity of the finding is limited by the small sample size of nine urbanised catchments.
- IH 124 tends to underestimate for all types of catchments, apart from urban only. The bias decreases slightly when high-rainfall catchments are removed. Error from IH 124 is higher than that from FEH statistical for all subsets.
- ADAS 345 also tends to underestimate significantly for all catchment subsets. When the high-rainfall catchments are removed it has a spectacular mean bias, underestimating QMED by nearly 50%. However, the only subset that is a fair test of the method is the one from which urban and permeable catchments have

been removed. For these the method gives less biased results, but the mean error is still much higher than that of any other method.

- For the whole dataset, the best performing method in terms of both bias and RMSE is FEH statistical. In terms of bias, IH 124 performs best when considering only low to moderate rainfall catchments, closely followed by FEH statistical.

As is clear from the comments above, the performance of the various methods appears to be strongly affected by the permeability and rainfall of the catchments. This is illustrated further in Figures 6.7 and 6.8, which show how the ratio of predicted to observed QMED varies with BFIHOST and SAAR.

Figure 6.7 shows a general trend towards underestimation of QMED on more permeable catchments. This is apparent even in the results of the FEH statistical method, although it is far more pronounced in results from the ReFH method. Once BFIHOST exceeds 0.65, ReFH and ADAS 345 underestimate QMED, and IH 124 underestimates for the majority of catchments. However, it is also obvious that ADAS 345 generally underestimates across the full range of BFIHOST values, which is in agreement with Figure 6.5.

The result that shows the furthest deviation from the observed QMED is from the ReFH method on a catchment where BFIHOST is 0.9. QMED estimated by ReFH is 31 times smaller than the observed value. This is the Rhee at Ashwell, a 0.75 km^2 chalk catchment which is also urbanised: $URBEXT_{2000}$ is 0.149, very close to the threshold that defines heavy urbanisation. The combination of high permeability and urbanisation appears to result in a particularly poor performance from ReFH. The Rhee was also the catchment on which FEH statistical underestimated by the largest amount (a factor of 5). The results on this catchment suggest that the uncertainty in design flows for permeable urban catchments is much higher than might be expected from consideration of standard error from the FEH QMED regression model. They also serve to further emphasise the unsuitability of ReFH for such catchments.

For more moderate permeability, most methods seem to give a better fit to the observed QMED, although there is possibly a tendency towards overestimation for both ReFH and FEH statistical. This may well be due to the association between low BFIHOST and high rainfall, because there is a clear tendency towards overestimation in high-rainfall catchments for all methods except IH 124 (Figure 6.8). The better performance of IH 124 may be explained by the large number of upland high-rainfall catchments used in the development of the regression for QBAR.

An interesting finding was that when soil type is ignored in the ADAS 345 method; its results are greatly improved on average. The overall bias for all catchments was 0.662 if using the soil type, and 1.098 if this was ignored; a substantial improvement. The RMSE also indicated a better match when soil type is ignored, decreasing from 1.180 to 0.810. This is mainly due to the removal of the underestimation of flows on more permeable catchments.

In conclusion, it appears that the FEH statistical method gives the best performance of all the methods tested for most subsets of catchments. The ReFH method underestimates QMED by a long way on average, although its performance is much improved when permeable catchments are excluded (for which it is already known to be unsuitable). Perhaps surprisingly, it appears that this performs well on small urban catchments – although this conclusion would greatly benefit from the inclusion of more catchments in the analysis. IH 124 tends to underestimate QMED, and ADAS 345 underestimates even more. All methods tested were found to underestimate QMED substantially on lower rainfall catchments.

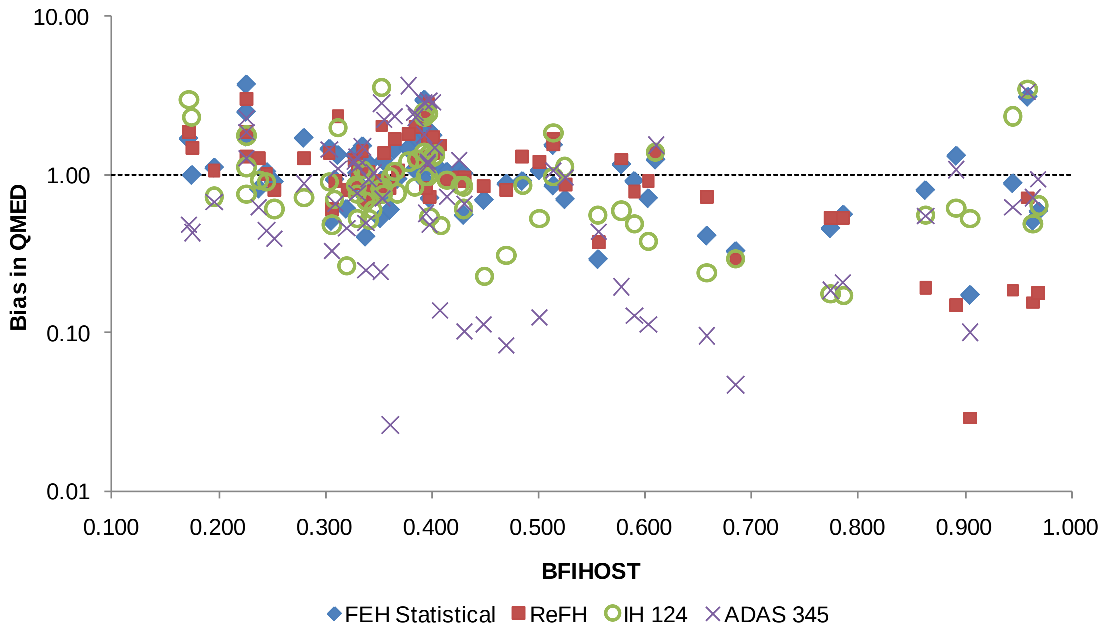


Figure 6.7 Ratio of predicted to observed QMED plotted against BFIHOST

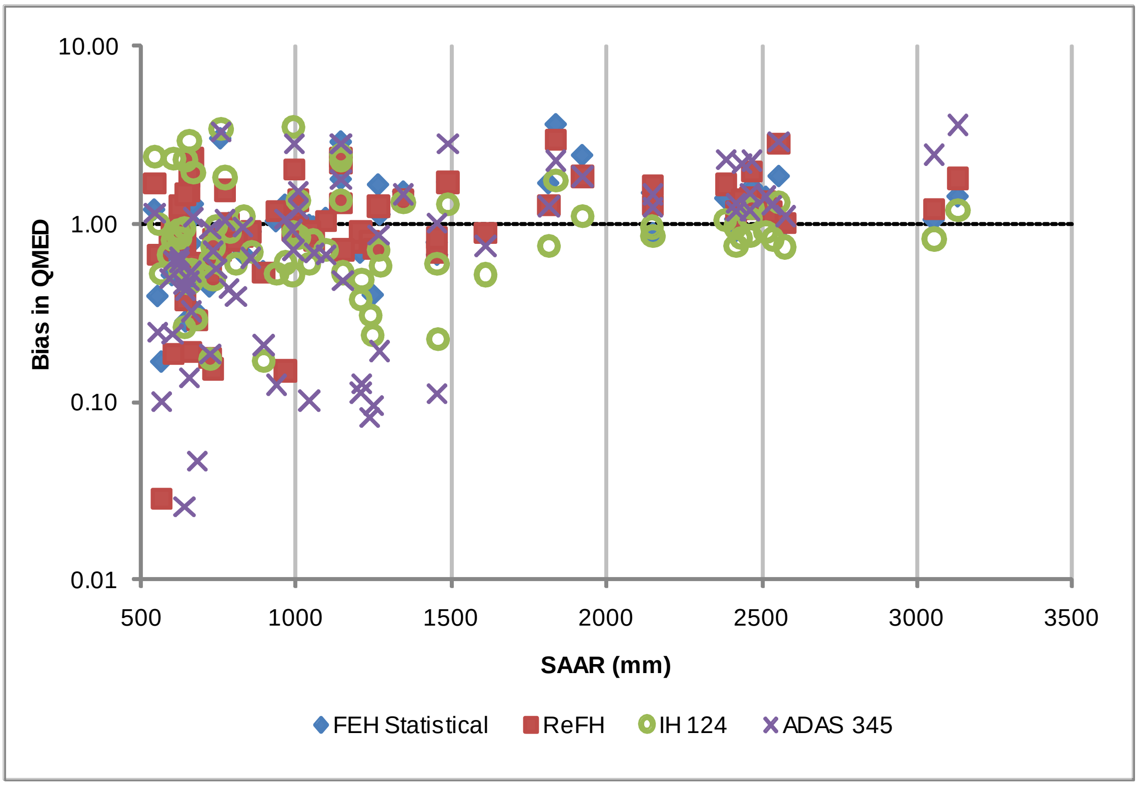


Figure 6.8 Ratio of predicted to observed QMED plotted against SAAR

6.2.4 Comparison of growth factors

The tests described above focused on estimation of QMED because it is possible to estimate QMED with reasonable confidence on many gauged small catchments. When estimating higher return period flows it is more difficult to be confident about the magnitude of the true value because of the uncertainty in estimating flood growth curves from records of limited length.

However, it will be of interest to compare the magnitude of flood growth factors used in the various different small catchment methods. There are three main ways in which growth factors are derived for the methods commonly in use for small ungauged catchments:

- FSR regional growth curves, commonly used in conjunction with the QBAR equation from IH 124 and often for ADAS 345. The latest revision of the FSR growth curves is contained in FSSR14 (Institute of Hydrology 1983), although no changes were made for return periods up to 100 years.
- FEH statistical growth curves derived from a pooling-group selected on the basis of similarity in four catchment descriptors: AREA, SAAR, FARL and FPEXT.
- ReFH, in which growth factors are affected by FEH rainfall growth curves and by the structure of the ReFH model, including a calibration factor which was introduced during the development of the design event to ensure that flood frequency curves from ReFH matched those from the FEH statistical method, on average.

In these three approaches, flood growth rates will be influenced by different factors:

- The FSR growth curves are fixed within a given region and are identical for large and small catchments.
- The FEH pooled curves vary with catchment descriptors, one of which is AREA. For many small catchments FARL will be 1 (i.e. indicating no reservoir influence) and FPEXT will typically take a fairly low value apart from in flat areas, as extensive floodplain areas are associated more with large watercourses (see Table 6.2: 75% of small catchments in HiFlows-UK have FPEXT<0.073). So the main sources of variation in FEH growth factors for small catchments may be the catchment area and the annual average rainfall.
- The ReFH growth factors will vary with geographical location (as extreme rainfall statistics show pronounced regional patterns) and with catchment properties.

In order to provide an indicative illustration of the typical variations between growth curves from these different methods, Figures 6.9 and 6.10 plot the 100-year return period growth factor for a selection of small catchments.

- The FSR growth factors are summarised by displaying their maximum and minimum values in England and Wales. The maximum is 3.99 for Region 5 (East Anglia) and the minimum is 2.22 for Region 2 (North East).
- The FEH pooled growth factors have been obtained by creating pooling-groups for idealised small catchments, with FARL set to 1.00 and FPEXT to 0.050. For Figure 6.9, SAAR was varied from 600 to 1200 mm with AREA set to 10 km^2. For Figure 6.10, AREA was varied from 0.5 to 25 km^2 with SAAR set to 800 mm, a typical value representative of many lowland areas. The analysis used version 3.02 of the HiFlows-UK dataset. It can be seen from Figure 6.9 that the pooled growth factor varies little with SAAR for a typical small catchment. On Figure 6.10, some variation with AREA can be seen, with growth factors rising up

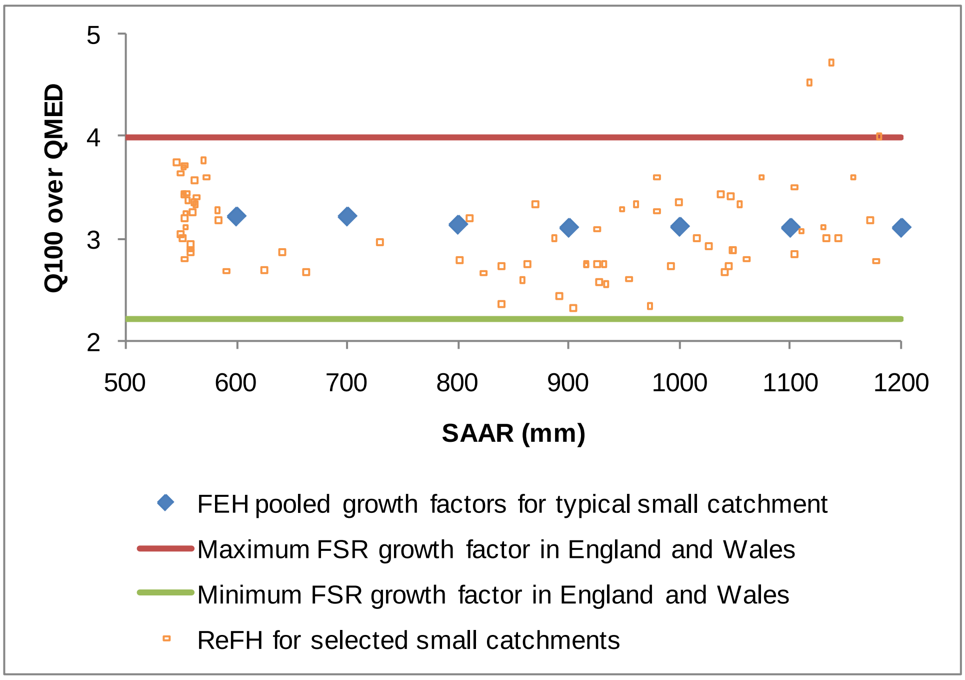


Figure 6.9 100-year growth factors for small catchments, plotted against SAAR

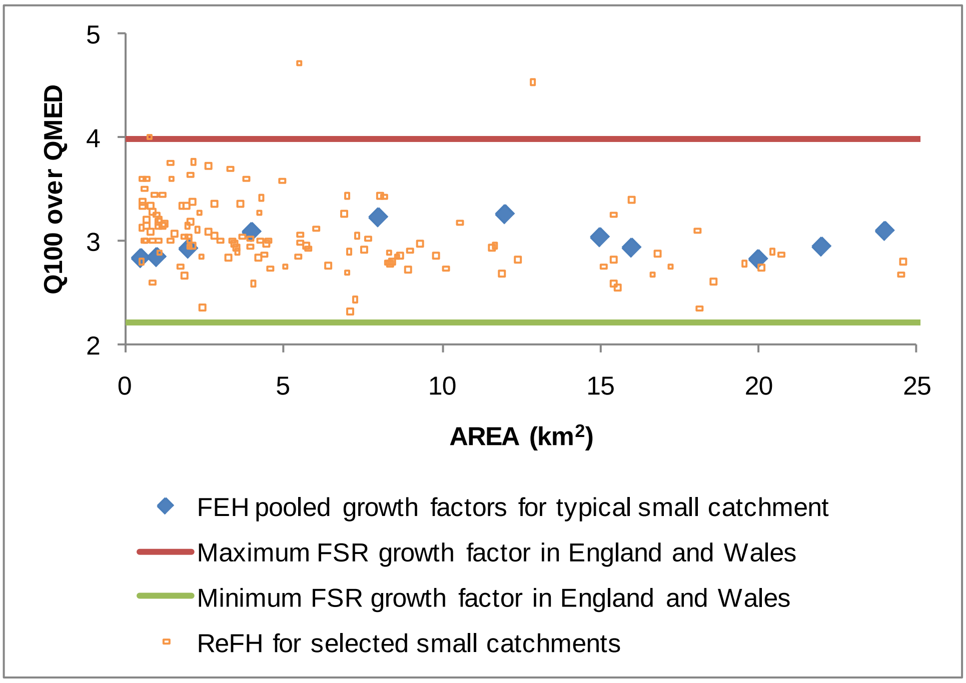


Figure 6.10 100-year growth factors for small catchments, plotted against AREA

to an area of around 10 km^2 and then falling as the area approaches 20 km^2, after which another slight rise is evident. However, the range of FEH growth factors is small compared with that of the FSR results. The range of FEH 100-year growth factors, from the catchments investigated, was 2.83 to 3.26.

- The ReFH growth factors have been obtained from analysing results taken from several flood studies carried out at JBA Consulting, including catchments in South Yorkshire, Lincolnshire, Essex, Greater Manchester and Cumbria. The range of growth factors appears to be similar to that shown in the FSR regional growth curves, although there are a small number of catchments for which ReFH produces higher growth factors. On average, the magnitude of ReFH growth factors appears to be broadly comparable with FEH pooled results.

In summary, it appears that estimated flood growth factors for small ungauged catchments vary widely, according to geographical location, when older methods of flood estimation are used (IH 124 and ADAS 345). When the FEH statistical method is used there is little variation for most typical small catchments, with the 100-year growth factor generally around 2.8 to 3.3. When ReFH is used there is more scope for variation, both with geographical location and catchment properties.

6.2.5 Discussion

The tests described above have revealed considerable variation between the performance of the various methods. The results can help guide the selection of an appropriate method from those currently available. If the primary desire is for accurate design flows, it appears there is little reason to continue using older methods (IH 124 and ADAS 345) on small catchments. They do have the advantages of simplicity and the fact that they can be applied without the need for specialist software. However, they do not appear to give results that are any more accurate than those from FEH methods. In addition to the findings from the tests there are other reasons to prefer FEH methods over the alternatives:

- ADAS 345 is based on a very small dataset of limited length. The formula for QMED in IH 124 is based on a larger dataset of small catchments but it is at least 19 years out of date now.
- The factorial standard error of the QBAR regression equation in IH 124 is 1.65 (Marshall and Bayliss 1994), considerably higher than the factorial standard error of 1.43 for the revised FEH QMED equation (Kjeldsen *et al.* 2008).
- IH 124, and often ADAS 345, rely on coarse-resolution soil maps with only five classes. These are less likely to be representative of local soil conditions than the HOST mapping, which is available at a 1 km grid size and allows 29 different soil classes. (A possible way round this might be to explore the use of HOST data within IH 124.)
- There are likely to be benefits associated with using flood growth curves derived from FEH methods which draw on much longer flood peak datasets than those available for earlier methods. The FSR growth curves that are typically used in conjunction with IH 124 and ADAS 345 are based on datasets that miss out on the last 40 years of flood peak data.

The results of the tests suggest that the results of the FEH statistical method may be more uncertain on small catchments than on other types of catchments. Considering just rural catchments ($URBEXT_{2000}<0.03$), the predicted QMED was outside the 95% confidence limits for the regression equation quoted in Kjeldsen *et al.* (2008) on 12.5% of the catchments tested. This result cannot be explained by the inclusion of catchments for which the data quality is less certain: considering just HiFlows-UK catchments, the proportion outside the 95% confidence limits increases to 17.5%. This is considerably larger than the 5% that would be expected for a typical catchment.

A feature of small catchments is that they are more likely to be dominated by unusual characteristics that tend to be averaged out in larger catchments. For example, most highly urbanised catchments will probably also be small. There has been recent research into improving flood estimation methods on urban catchments (Kjeldsen 2009,2010).

Another unusual characteristic of some small catchments in the set used for the tests described above is a high level of permeability. Five were chalk or limestone catchments with BFIHOST greater than 0.90. All methods showed some very large deviations from observed QMED values on these watercourses. For example, the FEH statistical method overestimated by a factor of 3.1 for 26802, the Gypsey Race at Kirby Grindalythe (a rural catchment on the Yorkshire Chalk), and underestimated by a factor of 5.9 for 33040, the Rhee at Ashwell (a part-urban chalk catchment near Cambridge with large groundwater abstractions). Another example of overestimation can be found on the South Winterbourne at Winterbourne Steepleton (a small chalk catchment in Dorset, not included in the tests described above) where QMED estimated from catchment descriptors is 5.5 times that estimated from annual maxima.

There appears to be a particular need to improve the estimation of design flows on small highly permeable catchments, although it is recognised that any generalised method may not be able to represent local hydrogeological features that may have a large influence on river flows. However, it would at least be advisable to develop guidance on the limits of applicability of generalised methods on unusual catchments and point users to alternative approaches.

6.3 Performance of FEH methods on small catchments

The previous section compared the performance of a range of methods currently used for flood estimation in small catchments only. In this section, the predictive ability of the two primary UK design flood estimation tools as described in the FEH and its subsequent updates is assessed using all the suitable annual maximum peak flow (AMAX) series available from the HiFlows-UK dataset version 3.02.

The two methodologies considered here are:

- SC050050 The improved FEH statistical method (Kjeldsen *et al.* 2008)
- FD1913 The revitalised FSR/FEH rainfall-runoff (ReFH) method (Kjeldsen *et al.* 2005, Kjeldsen 2007)

The HiFlows-UK database v3.02 contains AMAX series from 955 gauging stations located throughout the UK, and has been made available through the Environment Agency's HiFlows-UK website. For each gauging station, the relevant gauging authority has made an assessment of the data quality and indicated if the data are suitable for the estimation of QMED and for inclusion in a pooled analysis, respectively. For the purpose of this study, only gauges with a minimum of 4 years of AMAX data, and considered as a minimum 'suitable for QMED' were included in the analysis, thus reducing the sample of gauges from 955 to 848. For each gauged catchment, a set of catchment descriptors have been extracted from the FEH CD-ROM 3 (CEH 2009).

Summaries of the AMAX dataset and the associated catchment descriptors are shown in Tables 6.2 and 6.3.

Table 6.2 Summary of AMAX dataset (number of years of data) from HiFlows-UK

	All catchments	Area <25 km^2
Number of gauges	848	72
Shortest record length (years)	4	9
Longest record length (years)	125	58
Mean record length (years)	37.3	30.9
Total number of AMAX	31,609	2,225

Table 6.3 Range of catchment descriptor values (numbers in parentheses show equivalent values for catchments below 25 km^2)

Descriptor	Range	Min.	25%	50%	75%	Max.
AREA	[0;∞]	1.63 (1.63)	64.57 (9.80)	144.70 (15.06)	354.90 (21.15)	9931.00 (24.92)
SAAR	[0;∞]	555 (555)	743 (767)	977 (1030)	1294 (1517)	2913 (2555)
FARL	[0;1]	0.6450 (0.7270)	0.9810 (0.9828)	0.9648 (0.9980)	0.9960 (1.000)	1.000 (1.000)
BFIHOST	[0;1]	0.172 (0.172)	0.401 (0.320)	0.470 (0.413)	0.567 (0.580)	0.974 (0.959)
FPEXT	[0;1]	0.0015 (0.0015)	0.0370 (0.0150)	0.0560 (0.0323)	0.0850 (0.0729)	0.2951 (0.2373)
PROPWET	[0;1]	0.21 (0.21)	0.34 (0.34)	0.45 (0.43)	0.59 (0.55)	0.85 (0.83)
DPLBAR	[0;∞]	1.3 (1.3)	9.9 (3.1)	15.5 (4.5)	24.6 (5.5)	139.9 (9.3)
DPSBAR	[0;∞]	8.80 (8.80)	47.48 (47.15)	81.05 (81.10)	123.40 (124.5)	441.80 (407.50)
$URBEXT_{2000}$	[0;1]	0.0000 (0.0000)	0.0019 (0.0000)	0.0086 (0.0022)	0.0306 (0.0149)	0.5917 (0.5347)

From Table 6.2, it is clear that the majority of catchments are larger than the 25 km^2 adopted in this study as the upper limit for small catchments.

6.3.1 Methods

The improved FEH statistical method (see Section 5.1.5) was applied to the data from the 848 gauging stations selected using the method of data transfer described by Kjeldsen and Jones (2010). Since the catchments analysed in this assessment included both rural and urban catchments, estimates of QMED and the growth curves were adjusted for urbanisation as appropriate using the method presented by Kjeldsen (2010).

The revitalised FSR/FEH rainfall-runoff (ReFH) method (see Section 5.1.5) was applied to the data from the 848 catchments (both rural and urban) as described by Kjeldsen *et al.* (2005), although the model equations were updated to include $URBEXT_{2000}$.

6.3.2 Predictive ability

The predictive ability of the FEH methods was assessed by visual inspection of plots of log-residuals defined as:

$$\log.res = \ln Q_T - \ln \widehat{Q}_T$$

where Q_T is the design peak flow value with a T-year return period obtained by fitting a Generalised Logistic (GL) distribution directly to the at-site data, and $\widehat{Q}_T$ is the corresponding estimate obtained using the FEH methodology (either statistical pooling-group method or ReFH) as if the site were ungauged. In addition to the residual plots, the factorial standard error (fse) was used as a numerical performance measure. To enable comparison of performance across return periods, the sampling variance of the at-site estimate was filtered from the calculated sum of squares estimate.

6.3.3 Results

FEH statistical method

The first assessment considered the performance of the improved FEH statistical method when applied to all 848 catchments in the dataset. Comparisons between design flood estimates obtained from observations and from treating each site as ungauged were made for return periods of 2, 5, 30 and 100 years. Figure 6.11 shows the residuals plotted against catchment area for each return period.

The two sets of residuals show a reasonably even spread of the residuals (i.e. a homogeneous variance) across all ranges of catchment area, and there is no immediately apparent difference in behaviour between small and larger catchments. This suggests that the FEH statistical method can reasonably be expected to perform as well (or as poorly) in small catchments as in larger catchments. However, there are a few outliers among the residuals with values of around 2 or -2, which are mainly associated with catchments smaller than 100 km^2. Given the overall size of the dataset and the influence of record length at each site, it is not obvious if these residuals represent a set of catchments where systematic failure of the FEH method is encountered, whether the peak flow datasets are problematic in these cases, or if they are merely a representation of the level of uncertainty expected in a large dataset.

The corresponding factorial standard errors for the two sets of residuals and for each of the return periods considered are shown in Table 6.4.

Table 6.4 Factorial standard error (fse) for regression and regression with donor adjustment

Return period	fse (regression only)	fse (regression + donor)
2	1.51	1.43
5	1.52	1.45
30	1.56	1.49
100	1.60	1.54

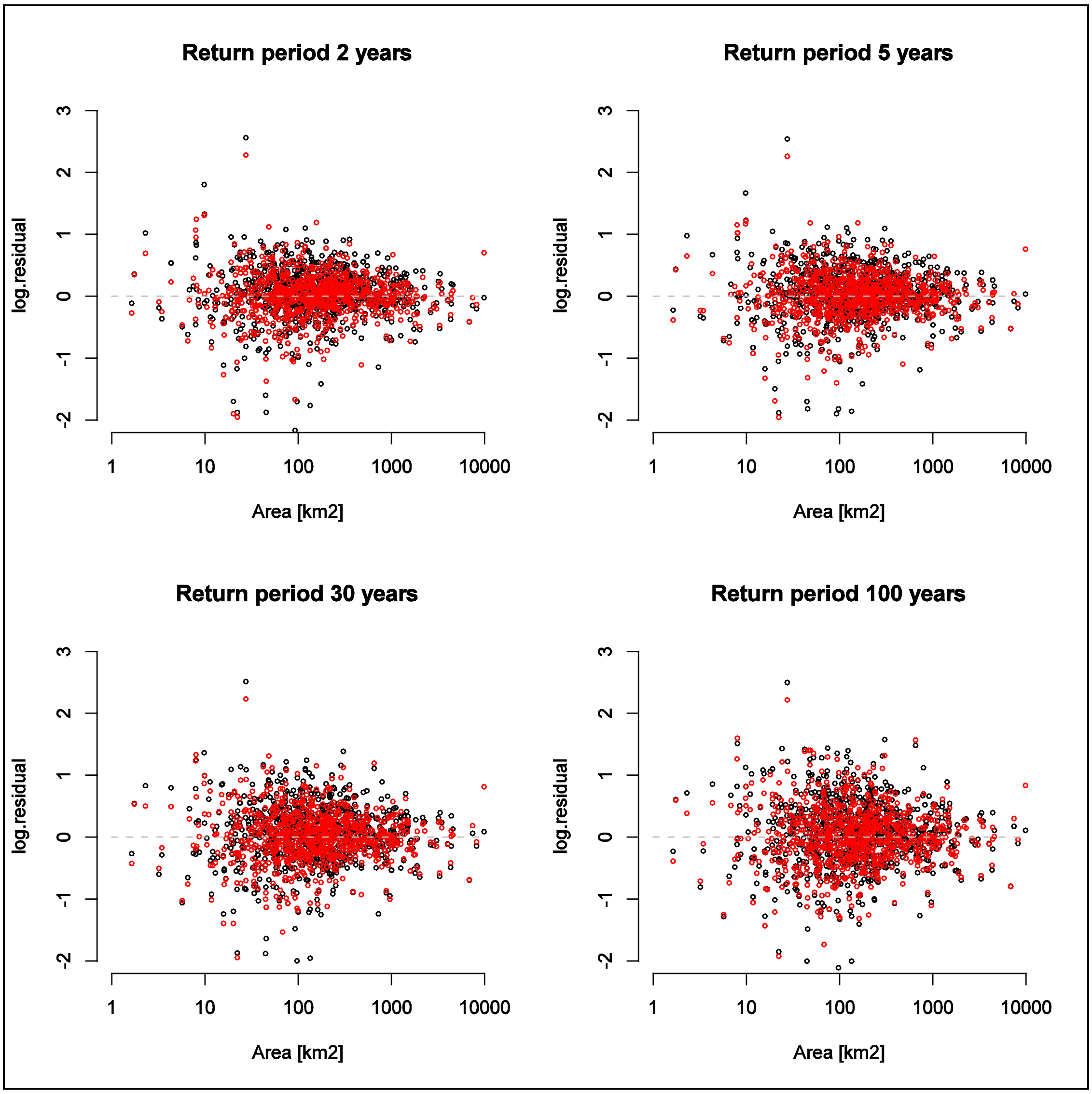


Figure 6.11 Comparison of log-residuals for return periods of 2, 5, 30 and 100 years (black dots represent cases where QMED is estimated using catchment descriptors only, and red dots are the corresponding estimates but with QMED enhanced through donor transfer)

The factorial standard errors reported in Table 6.4 show that the use of donor adjustment greatly reduces the prediction uncertainty when compared to using catchment descriptor-only methods when estimating the flood frequency curve at ungauged sites. Kjeldsen and Jones (2010) argued that the donor transfer could be interpreted as using local data to compensate for the inability of the existing set of FEH catchment descriptors to capture all local factors controlling the catchment flood response.

Considering only catchments smaller than 25 km^2, the log-residuals of the design peak flow estimates for the four selected return periods, derived using data transfer, are plotted against catchment area in Figure 6.12. This subset of small catchments consists of 72 catchments from the HiFlows-UK database. To aid the interpretation of the residual plots, the catchments were divided into five bins containing an equal number of catchments. Within each bin, the average and the standard deviation of the residuals were estimated and plotted on each diagram as the mean together with the 95% confidence interval (± 2 times standard deviation).

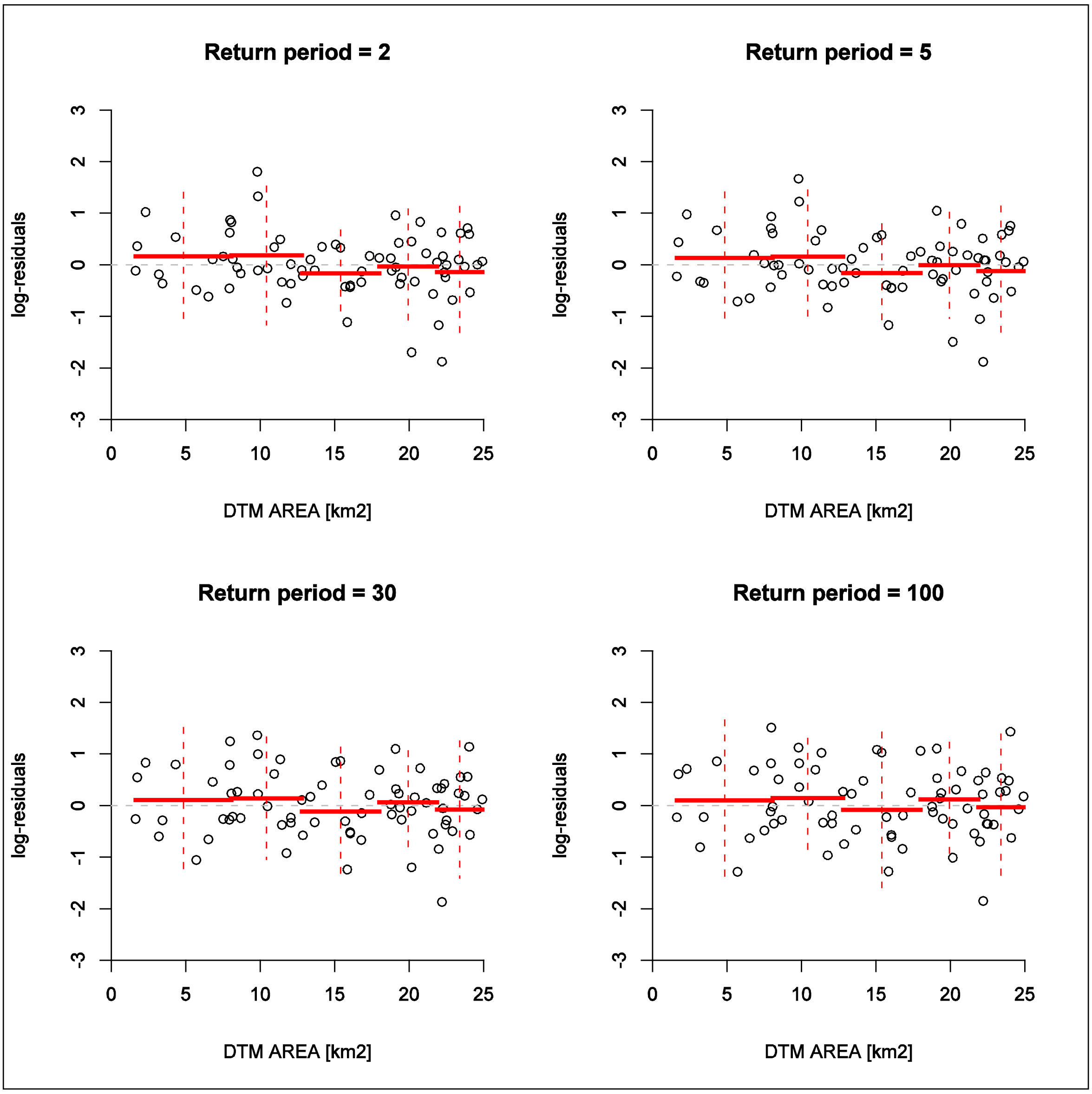


Figure 6.12 Log-residuals of design peak flow estimates. Red lines indicate average residual value within bin plus the 95% confidence interval (dashed red lines)

Assuming the residuals to be normally distributed (an underlying assumption justified for QMED by Kjeldsen *et al.* 2008), the t test indicated that the average of the residuals is not significantly different from zero for any of the area intervals for any return period. This suggests that, when considering the inherent uncertainty in flood prediction, the FEH statistical method does not give answers for small catchments which are statistically different from the at-site sample values.

ReFH

The ReFH model was applied to the same 848 catchments used in assessing the FEH statistical method above. The version of ReFH used in this study varies slightly from the version published by Kjeldsen *et al.* (2005) as the model equations involving $URBEXT_{1990}$ have been updated to include $URBEXT_{2000}$. This includes the regression model linking the ReFH model parameters T_p and BL to catchment descriptors, and the threshold for determining summer or winter design conditions. The residual plots shown in Figure 6.13 suggest that, for higher return periods, the ReFH model will yield estimates of the design peak flow which are, in general, higher than the peak flow values obtained from the at-site analysis of the AMAX series. However, as for the statistical method, there appears little or no evidence of a systematic difference in performance between small and larger catchments.

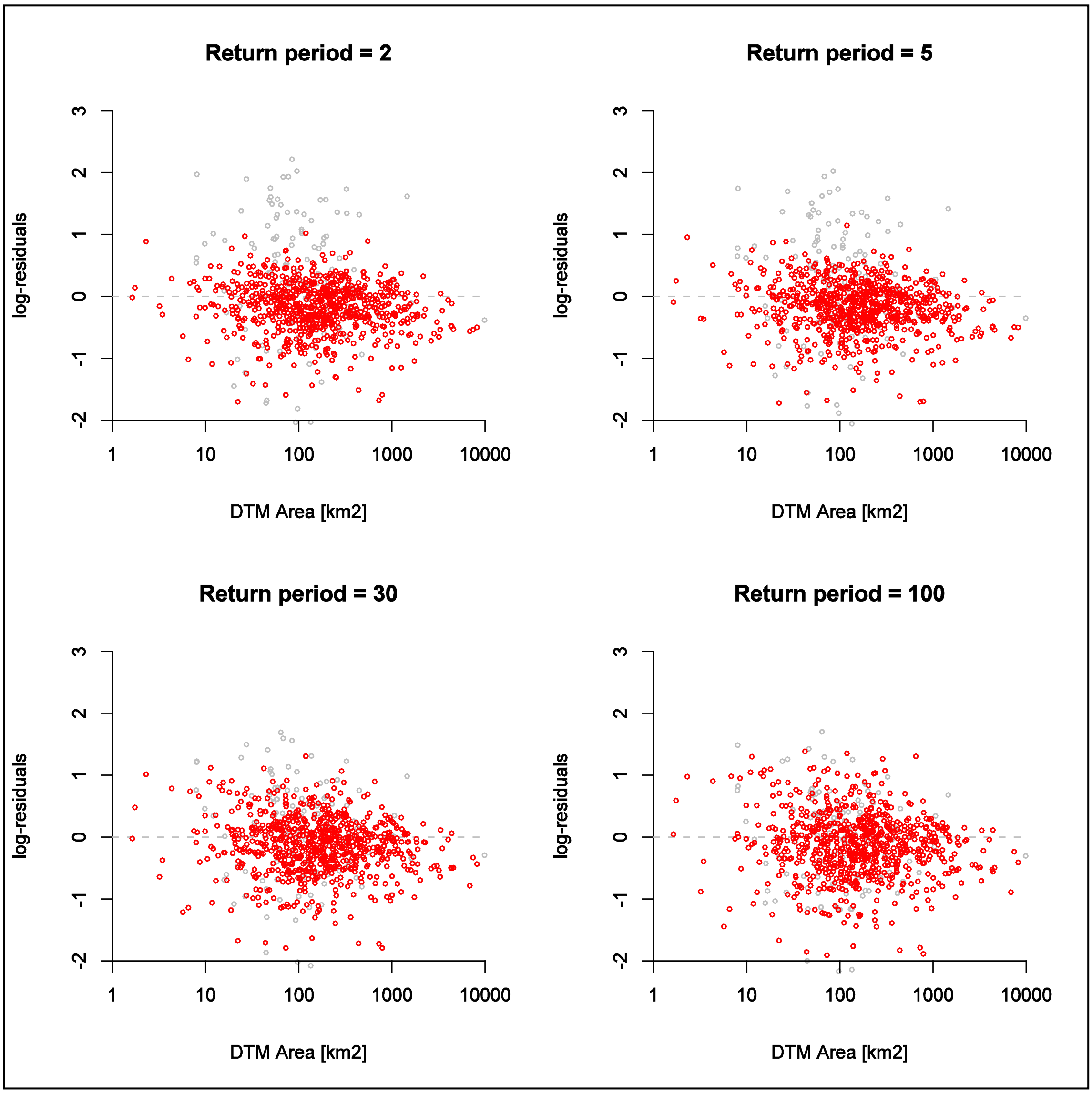


Figure 6.13 Comparison of log-residuals for return periods of 2, 5, 30 and 100 years for the ReFH method (grey dots represent catchments where BFIHOST is greater than 0.65)

For the same subset of small catchments, the log-residuals were derived based on application of the ReFH model. The resulting plots are shown in Figure 6.14. Again assuming the residuals to be normally distributed, t-tests indicate that the mean values of residuals within each bin are not statistically significant from zero.

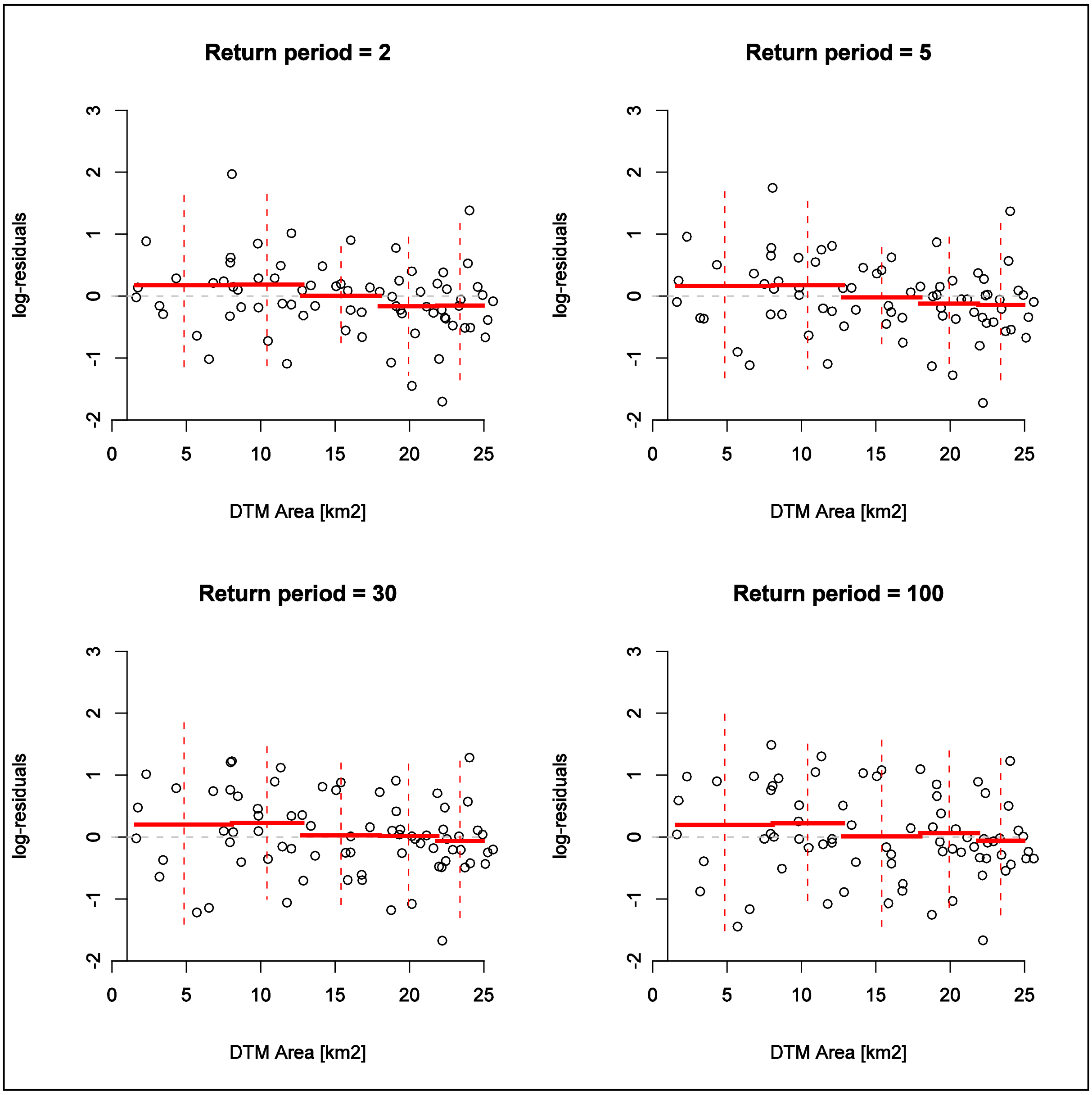


Figure 6.14 Log-residuals of design peak flow estimates. Red lines indicate average residual value within bin plus the 95% confidence interval (dashed red lines)

6.3.4 Discussion

The results presented in this section provide a useful assessment of the accuracy and uncertainty of the FEH methods when applied to ungauged catchments. Critically, the results show that the accuracy of the methods is not scale dependent, and that the FEH can be applied with the same level of confidence across all catchment sizes represented within the HiFlows-UK dataset. However, it is recommended that further flood peak data from small catchments should be analysed for both rural and urban catchments. The implications of these findings for Phase 2 of the study are further discussed in Section 7, also taking into account the requirements of the user community. It should be noted that additional data from the NRFA are available, but the resources and scope of this study did not allow for the quality-checking of these data, which would be required for a comparison with the high quality dataset currently available within HiFlows-UK.

7 Conclusions and recommendations

7.1 Introduction

This section summarises the conclusions drawn from the review of methods of flood estimation that are currently applied to small catchments in the UK (Section 5) and the analysis of the performance of some of those methods (Section 6), and makes recommendations for further analysis and the development of practical methodologies.

7.2 Summary of Phase 1

7.2.1 Task 1: Identification of the types of catchment to be included in the study

This task has established that small catchments can generally be considered to be less than about 25 km^2 in area, although many flood studies are carried out on smaller plots of land which form only part of a catchment and may not contain a watercourse. Flood risk assessments are often required for new developments, which in turn requires estimation of both pre- and post-development flow rates. The scoping study has considered the applicability of currently available flood estimation methods to small rural and urban catchments, and to plot-scale areas.

7.2.2 Task 2: Review of current datasets, techniques and knowledge on small catchments

Review of existing datasets

The review of existing datasets has concluded that small catchments are only sparsely represented in the flow records that have been used to develop the FEH methods. There is some scope for including further small- and medium-sized catchments from sources such as the National River Flow Archive, the use of which would reduce uncertainty in flood estimates. There is a general lack of small urban catchments within HiFlows-UK, but it is thought that some flow records may exist already that would potentially be of use within the Phase 2 analysis. These may include water level gauges if a suitable rating equation can be established.

Review of current methods in small catchments and plots

It is clear from Section 5 of this report that a wide variety of methods, some of which were developed more than 35 years ago, are still applied to the estimation of flood peaks and hydrographs in small catchments. The methods based on the most extensive research are those derived from the FSR (NERC 1975) and the FEH (Institute of Hydrology 1999) and subsequent updates. In both cases, while the methods presented were not developed primarily with small catchments in mind, they are based on wide-ranging analyses of flood peak data from a large number of UK catchments. However, the FSR has now been superseded by the FEH which makes use of up-to-date flood peak datasets and digital catchment descriptors.

Guidance to use the IH 124 (based on the FSR analysis) or ADAS 345 methods for catchment areas less than about 2 km^2 appears to be related more to the ease with which the methods can be applied than the appropriateness of the methodologies themselves (though some users are concerned that the FEH statistical method does not take explicit account of catchment slope or channel length). In addition, the fact that application of the methods does not require access to the FEH digital datasets available on the FEH CD-ROM is seen as an advantage by some practitioners. The continued use of IH 124 cannot be justified for a number of reasons, including the fact that many of the catchments used in the IH 124 analysis were upland, impermeable catchments, and thus are rather different in nature to the types of site to which the method is often applied. Moreover, most of the IH 124 catchments were subsequently included in the FEH analysis. Finally, the FEH requirement to access catchment descriptors will shortly be made simpler for infrequent users of the methods through the establishment of an enquiry service at CEH.

The results presented in Section 6 suggest that the FEH statistical method and the ReFH event-based method both perform well on a range of catchment sizes, although the results of the former may be more uncertain on small catchments. Comparisons of QMED estimation using the FEH methods and the IH 124 and ADAS 345 methods have shown that the FEH statistical method gives the best performance. The ReFH method tends to underestimate QMED on average, although its performance is improved by the exclusion of permeable catchments (for which its use is not generally recommended). These results mostly support the findings of previous and ongoing research at the CEH into national procedures for flood frequency estimation and the continuing development of FEH methods. Both the FEH statistical method and the ReFH method were specifically developed to be applicable to a range of catchment sizes and types, and to be representative of the catchments typically encountered in practical UK flood hydrology. This reaffirmation that the FEH suite of methods performs well across such catchment sizes should bring comfort to the user community. However, the need exists to include more small catchments in the basic dataset used to calibrate the methods. Moreover, there is a growing focus on very small catchments (under about 2 km^2), for which there is little readily available data to test the methods, let alone develop improvements.

In considering runoff estimation for small plots, it is sometimes argued that FEH methods, developed using flow data from catchments containing watercourses, should not be applied at the scale of development sites. However, this argument applies equally to the LR 565, ADAS 345 and IH 124 methods, which have all been widely used for greenfield runoff estimation. In LR 565 (and its derivative ADAS 345) the smallest catchment used was 2.8 km^2. In IH 124, only the two smallest catchments, of 0.9 and 1.0 km^2, were smaller than the smallest in the FEH QMED dataset, 1.1 km^2, though the smallest in the improved QMED dataset was 1.6 km^2. If methods based on data from watercourses cannot be used, what methods can? As discussed in Appendix B, it is valid to suggest that greenfield runoff rates can be estimated at the small catchment scale rather than the plot scale, but research is needed to test this further.

Assessment of uncertainties associated with data and methods

The results presented in this report have highlighted the broader issue of the uncertainty involved in flood frequency estimation in ungauged catchments. These uncertainties will arise from a number of sources, which can conveniently be classified as:

- *Data uncertainty*

  This typically originates from difficulties in accurate measurement of peak flow values under high flow conditions in the river, as well as uncertainties associated with extrapolation from rating curves.

- *Sampling uncertainty*

  The paucity in time and space of observed peak flow values.

- *Model uncertainty*

  The inability of hydrological models to represent the complex flood hydrology of real catchment systems. This includes the inadequacy of existing catchment descriptors in explaining flood data (e.g. soils and watercourse extent information), the use of descriptors in inappropriate forms (note the new transformations of SAAR and BFIHOST used in the improved FEH QMED equation), and problems in model fitting (e.g. fitting criteria, error distributions etc.).

There are a number of ways to address these sources of uncertainty. Firstly, reducing the uncertainty in underlying datasets would require additional effort in quality-checking the available flow data for small rural and urban catchments and improving the rating equations. Secondly, sampling uncertainty could be reduced by extending the Environment Agency gauging network, or including hitherto unused stations in the HiFlows-UK archive – especially for small catchments. Of course, this might, in turn, raise additional issues of data uncertainty regarding stations deliberately omitted from HiFlows-UK. The third source of uncertainty is related to the hydrological models, and improving modelling systems is probably the least costly strategy for reducing prediction uncertainty in small ungauged catchments. However, developing successive revisions to regression equations may cause confusion, and may not be considered appropriate if the improvements are minor.

7.3 Interim guidance on flood estimation for small catchments and plots

This scoping study has identified a number of areas of further research needed to improve flood estimation in small catchments and plots in the UK. However, the following recommendations are made to practitioners in the interim period.

> Based on the results of the analysis in Section 6, it is recommended that flood estimates on small catchments should be derived from FEH methods in preference to other existing methods. The current versions of the FEH statistical approach or the ReFH rainfall-runoff model should be used except on highly permeable catchments (BFIHOST>0.65), where ReFH should be avoided, and possibly on urban catchments ($URBEXT_{2000}$>0.15), where the results of the ReFH model can be less reliable. Checks should be carried out to ensure that the flood estimates are within expected ranges based on what is known about the history of flooding and the capacity of the channel (including evidence from previous flood marks).
>
> For catchments smaller than 0.5 km^2 and small plots of land, runoff estimates should be derived from FEH methods applied to the nearest suitable catchment above 0.5 km^2 for which descriptors can be derived from the FEH CD-ROM and scaled down by the ratio of catchment areas. The decision to translate FEH estimates from catchment scale to plot scale should be accompanied by an assessment of whether the study site is representative of the surrounding catchment area.

7.4 Suggested improvements to FEH models

A particular aspect of the FEH methods which would potentially yield the largest benefit, especially for small catchments, is a revision of the underlying catchment descriptor dataset. The FEH catchment descriptors were developed in the mid to late 1990s and are largely based on pre-existing national datasets. In particular, the IHDTM, the topographical dataset on which the FEH catchment descriptors are based, was available at a spatial resolution of 50 m; this led to the lower limit of catchment area of 0.5 km^2 being adopted. Most of the other datasets used to develop the FEH are based on even larger spatial resolutions, for example HOST soil type (1 km^2) and PROPWET (40 km^2). With the release of the Environment Agency's Detailed River Network (DRN) and the planned release of a more detailed 5-m national digital terrain model (DTM) by the Ordnance Survey, CEH is currently undertaking research into the feasibility of developing a high-resolution version of the FEH CD-ROM. In addition to the topographical data, efforts are planned to investigate the feasibility of incorporating high-resolution soils data and revising several other descriptors.

In some cases, current practice in small catchment hydrology relies on growth curves published in the FSR and derived in the early 1970s. Knowing the uncertainty associated with the estimation of growth curves, the additional 40 years of data combined with developments in statistical and numerical methods in hydrology suggest that these methods are outdated. To provide the user community interested in small catchments with easy-to-use tools that do not require the formation of pooling-groups, further work should investigate the relationship between L-moment ratios (L-CV and L-SKEW) and available catchment descriptors within a hydrological regression framework. It is envisaged that this work would make use of the regression modelling framework developed for the QMED equation by Kjeldsen and Jones (2010). The outcome of this work would be two new regression models which could predict the L-moment ratios, thus defining the growth curve on small catchments using the FEH catchment descriptor data.

A particular problem in flood hydrology is to assess the impact of environmental change on the flood frequency relationship. Recently research at CEH has considered the effects of urbanisation on flood frequency relationships derived from the FEH statistical method (Kjeldsen *et al.* 2008, Kjeldsen 2010). In addition, Kjeldsen (2009) makes a suggestion for extending the ReFH rainfall-runoff model to better represent the hydrological cycle in catchments with significant amounts of urban land cover. A case study showed that including explicit consideration of runoff from impervious areas could potentially result in a more accurate description of the flood runoff process. It is recommended that further testing of this methodology should be undertaken.

7.5 Recommendations for Phase 2

The following conclusions are drawn from the results of this scoping study:

- The existing FEH methods (improved statistical and ReFH methods) have been shown not to be particularly scale dependent and thus can be applied across all catchment sizes represented in their development.
- It is recommended that further flood peak data from small catchments should be analysed for both rural and urban catchments.
- Despite lack of bias, uncertainty in flood estimation remains high, and there is a need to develop and test improved catchment descriptors, especially of soils and watercourse extent.
- There is a requirement for improved hydrological methods to support fluvial flood risk assessment in very small catchments and also to support drainage design.
- Estimates are required of both flood peaks and hydrographs to give flood volumes.

It is recommended that Phase 2 of the project should address the main issues identified above to provide further guidance on flood estimation in small catchments. In particular, it is proposed that this work should include a limited expansion of the available flood peak data for small catchments, especially in urban areas. Further analyses should be undertaken to investigate the availability of improved catchment descriptor information for small catchments, to develop new or modified methods appropriate to small catchment and plot-scale runoff estimation, and to provide guidance on the use of local data. A pilot study of high intensity, short duration rainfall is also proposed to improve hydrological design in small, especially urban, catchments. Following on from Phase 2, it is expected that a new software tool will be developed as part of the FEH suite.

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Glossary

ADAS 345	MAFF Agricultural Development and Advisory Services Reference Book 345 (ADAS 1982)
AMAX	Annual maximum
AREA	Catchment drainage area (km^2)
BFIHOST	Baseflow index derived using the HOST classification
BL	Baseflow lag-time
BR	Baseflow recharge
CEH	Centre for Ecology & Hydrology
C_{max}	Maximum soil capacity
D	Rainfall duration
DPLBAR	Index describing catchment size and drainage path configuration (km)
DPSBAR	Index of catchment steepness (m/km)
DRN	Detailed River Network
DTM	Digital terrain model
FARL	Index of flood attenuation due to reservoirs and lakes
FEH	*Flood Estimation Handbook*
FPEXT	Floodplain extent
fse	Factorial standard error
FSR	*Flood Studies Report*
FSSR	Flood Studies Supplementary Report
GL	Generalised Logistic distribution
GSDQ	Gauging station data quality
HOST	Hydrology Of Soil Types classification
IH 124	Institute of Hydrology report 124 (Marshall and Bayliss 1994)
L	Catchment length
NRFA	National River Flow Archive
P	Rainfall depth (mm)
PDM	Probability distributed model
POT	Peaks-over-threshold
PPS25	Planning Policy Statement 25
PR	Percentage runoff
PROPWET	Index of proportion of time that soils are wet

Q	Flow
QBAR	Mean annual maximum flood
QMED	Median annual maximum flood
Q_T	Flood peak with a return of T years
RC	Routing factor depending on D and T_p
ReFH	Revitalised Flood Hydrograph model
RMSE	Root mean square error
S	Catchment slope
SAAR	Standard average annual rainfall
SOIL	Index of winter rainfall acceptance potential
SUDS	Sustainable urban drainage systems
T	Return period in years
TAN15	Technical Advice Note 15: Development and flood risk
T_c	Notional time of concentration in hours
T_p	Time to peak
$URBEXT_{1990}$	FEH index of fractional urban extent for 1990
$URBEXT_{2000}$	FEH index of fractional urban extent for 2000
WASSP	Wallingford Storm Sewer Package

Appendix A

Quick estimates of T-year flood peaks using FSR/FEH methods

Sometimes a quick estimate of T-year flood peak is needed when full application of the FSR/FEH statistical procedures, including obtaining all the catchment descriptors, is not possible or considered appropriate (e.g. for small catchments). For such cases the various equations can be used to give a simple table of flood rates per unit area (l/s/ha) against soil type (with factors to adjust for climate etc. if necessary). T-year values can then be found using the FSR growth curves in FSSR14 (Institute of Hydrology 1983). There is little data from small areas to validate these values, but they do indicate likely contributions towards larger catchments downstream. Values for the older methods are not recommended directly, but do give some indication of how consistently the approach behaves.

QBAR, Mean Annual Flood (l/s/ha) by FSSR6 (Institute of Hydrology 1978) and Institute of Hydrology Report 124 (IH124) (Marshall and Bayliss 1994) methods for AREA 1 km^2 and SAAR 800 mm give:

SOIL	**FSSR6**	**IH124**	**SOIL**	**FSSR6**	**IH124**	**SOIL**	**FSSR6**	**IH124**
1	0.5	.4	3	3.7	3.7	5	5.7	6.0
2	2.1	2.0	4	4.7	4.8			

where SOIL type was mapped over the UK – see FSR Vol. 5 (among other places).

Factors to adjust for other values of AREA and SAAR (if considered necessary) are:

FSSR6:	AREA=10, F_A=0.83	SAAR=600, F_S=0.70	SAAR=1500, F_S=2.15
	AREA=100, F_A=0.69	SAAR=1000, F_S=1.31	SAAR=2000, F_S=3.06
IH 124:	AREA=10, F_A=0.77	SAAR=600, F_S=0.71	SAAR=1500, F_S=2.09
	AREA=100, F_A=0.60	SAAR=1000, F_S=1.30	SAAR=2000, F_S=2.92

QBAR may be scaled to T-year values for the FSR regions using the FSSR14 growth factors:

Region	T=2	T=5	T=10	T=25	T=50	T=100	T=500
1	0.90	1.20	1.45	1.81	2.12	2.48	3.25
2	0.91	1.11	1.42	1.81	2.17	2.63	3.45
3	0.94	1.25	1.45	1.70	1.90	2.08	2.73
4	0.89	1.23	1.49	1.87	2.20	2.57	3.62
5	0.89	1.29	1.65	2.25	2.83	3.56	5.02
6,7	0.88	1.28	1.62	2.14	2.62	3.19	4.49
8	0.88	1.23	1.49	1.84	2.12	2.42	3.41
9	0.93	1.21	1.42	1.71	1.94	2.18	2.86
10	0.93	1.19	1.38	1.64	1.85	2.08	2.73

Newer FEH methods replaced the five SOIL types with 29 HOST classes. Values of QMED (l/s/ha) by the FEH equation (AREA 1 km^2, SAAR 800 mm, FARL=1), and $QMED_i$ by Kjeldsen *et al.*'s (2008) improved equation (AREA 10 km^2, SAAR 800 mm, FARL=1) are:

HOST	QMED	$QMED_i$	HOST	QMED	$QMED_i$	HOST	QMED	$QMED_i$	HOST	QMED	$QMED_i$
1,2	0.1	0.3	**9**	1.2	1.1	**16**	1.0	0.9	**23**	4.3	4.9
3	0.5	0.5	**10**	2.7	2.5	**17**	1.9	1.8	**24**	5.0	4.2
4	0.1	0.8	**11**	0.1	0.4	**18**	1.9	2.5	**25**	7.0	5.2
5	0.5	0.5	**12**	5.2	5.2	**19**	1.6	2.9	**26**	4.0	4.7
6	1.5	1.6	**13**	0.1	0.3	**20**	1.3	2.4	**27**	3.6	4.6
7	0.7	0.8	**14**	4.7	3.6	**21**	3.8	4.0	**28**	1.0	2.0
8	1.7	2.2	**15**	3.1	3.6	**22**	2.9	4.2	**29**	4.1	4.8

Unfortunately, HOST fractions are currently only available averaged on a 1-km grid, and have not been widely distributed (they are not on the FEH CD-ROM). A description of each HOST class' attributes is given by Boorman *et al.* (1995).

Factors to adjust for other AREA, SAAR and FARL (if considered necessary) are:

FEH QMED	AREA=10.0, F_A=0.90 AREA=100.0, F_A=0.70	SAAR=600, F_S=0.64 SAAR=1000, F_S=1.42 SAAR=1500, F_S=2.66	FARL=0.9, F_F=0.76 FARL=0.8, F_F=0.55
Kjeldsen *et al*. $QMED_i$	AREA=1.0, F_A=1.41 AREA=100.0, F_A=0.71	SAAR=600, F_S=0.46 SAAR=1000, F_S=1.60 SAAR=1500, F_S=2.98	FARL=0.9, F_F=0.70 FARL=0.8, F_F=0.46

Note that Kjeldsen *et al.*'s (2008) $QMED_i$ shows greater dependence on AREA, SAAR and FARL. It was evaluated for AREA=10 km^2 to fall better within the range of the data and to yield more consistent values.

To avoid the pooling-group analysis, QMED (T=2) could scaled to other T-year values by using again the FSSR14 regional growth factors (re-standardised by the values at T=2)

Region	T=5	T=10	T=25	T=50	T=100	T=500
1	1.33	1.61	2.01	2.36	2.76	3.61
2	1.22	1.56	1.99	2.38	2.89	3.79
3	1.33	1.54	1.81	2.02	2.21	2.90
4	1.38	1.67	2.10	2.47	2.89	4.07
5	1.45	1.85	2.53	3.18	4.00	5.64
6,7	1.45	1.84	2.43	2.98	3.63	5.10
8	1.40	1.69	2.09	2.41	2.75	3.88
9	1.30	1.53	1.84	2.09	2.34	3.08
10	1.28	1.48	1.76	1.99	2.24	2.94

Appendix B

Translation of flows from catchment scale to plot scale

B.1.1 Why plot-scale runoff estimates are needed

The reason for estimating greenfield runoff is often to set a limit on the peak discharge from a site which is to be developed.

Runoff volumes from developed sites (e.g. roofs, car parks) are required to design water management measures, typically involving storage of water within the development site. There are several criteria for the design of storage (Kellagher 2004); in order of typical return period they are:

i. River water quality protection.

ii. River regime protection (ensuring that runoff does not exceed the greenfield rate for common events, typically with a 1-year return period).

iii. Site level of service protection (typically to a 30-year return period standard).

iv. River and site flood protection (typically to a 100-year return period standard).

The primary motivation for limiting discharges from development sites is usually to avoid an increase in flood risk at some location further down the catchment, at which point there may well be a watercourse (i.e. the flooding is fluvial). Cawley and Cunnane (2003) point out that the need to reduce the impact of urbanisation is generally at the local drainage area scale rather than at the individual site scale.

However, another consideration may be to avoid any increase in surface water flooding, that is before the runoff reaches a watercourse, and this type of flooding may be more local to the development site.

The distinction is significant because it influences the selection of a suitable method for flood estimation. Many flood estimation methods are developed from streamflow data and are therefore primarily valid for catchments containing watercourses. They may not necessarily be valid for estimating runoff at the plot scale. Even a method such as ADAS 345, which is recommended in some guidance documents for application at small scales (areas under 0.4 km^2), was developed from a predecessor which was based on streamflow data rather than plot-scale runoff data (Young and Prudhoe 1973).

If the main consideration is to avoid an increase in fluvial flooding further downstream, then there is a need to relate flows at two different spatial scales. Transferring information from one spatial scale to another has been described as one of the most daunting scientific challenges in hydrology, particularly hydrological modelling where disparities of scale exist in nearly every phase of model development and application (Wigmosta and Prasad 2005). In this case it would seem valid to use methods that have been developed for the catchment scale to estimate runoff at the plot scale. The quantity of interest is not so much the runoff hydrograph at the outlet of the plot as the contribution of the plot to the river flow hydrograph at the downstream site. One question that arises is how to scale down flow estimates from catchment to plot. This is discussed in the following section.

If plot-scale runoff estimates are required for purposes other than avoidance of downstream fluvial flooding, such as assessment of surface water flood risk local to the development site, then methods developed from river flow data will not necessarily be appropriate. In such cases it will be particularly important to account for local soil and land cover characteristics. Each small plot is likely to contain unique features that may influence the production of runoff and may not be well represented in national maps of soils and land cover.

B.1.2 Applying catchment-scale flows at the plot scale

It is possible to estimate design flows for extremely small areas using any of the FEH methods, by simply adjusting the value of the catchment descriptor AREA. However, this involves applying the methods outside the range for which they have been developed. This is generally unwise, both for empirical models (FEH statistical) and conceptual models (ReFH).

Another approach for transposing a design flow down to the plot scale is to scale it by area. This is advocated in Defra/EA (2004) for areas smaller than 0.5 km^2. It makes the simplifying assumption that peak flow varies linearly with catchment area and ignores heterogeneity in the catchment properties. This is equivalent to the long-established practice of applying greenfield runoff rates in litres per second per hectare as rules of thumb. In practice this may be a sensible and pragmatic approach, but it is worth exploring the assumptions in some more detail.

For medium to large catchments, peak flows do not generally vary linearly with catchment area. For example, in the FEH statistical method regression equation for QMED (Kjeldsen *et al.* 2008), QMED varies with $AREA^{0.85}$. In IH 124, QBAR varies with $AREA^{0.89}$. A catastrophe curve based on maximum peak discharges observed in a range of UK catchments (Acreman 1989) shows that specific discharge increases markedly as the catchment area reduces from 10,000 km^2 to 10 km^2.

This non-linearity might be ascribed to various effects: the areal reduction effect in rainfall (e.g. quoted in Institute of Hydrology 1999, Volume 3), increase in the critical storm duration for larger catchments (hence reduction in the rainfall intensity) and attenuation of peak flows due to channel and floodplain storage. However, ascribing physical significance to regression coefficients is risky: they include the effect of associations between the various independent variables. For example, the AREA exponent in the FSR QBAR equation increased from 0.73 to 0.95 as additional independent variables were added to the equation.

There are some reasons to expect that the relationship between peak flow and area may become more linear for smaller catchments. Flood-producing rainfall is more likely to span the entire catchment. In a small catchment there will be a shorter stream length and smaller area of floodplain and so one might expect less of an opportunity for attenuation of peak flows. Wigmosta and Prasad (2005) state that even for most medium size catchments (up to hundreds of km^2) the timing and magnitude of the runoff hydrograph is dominated by hillslope processes rather than the channel network. Pattison *et al.* (2008) found that attenuation, translation and tributary timing effects became less significant for smaller catchments in a study of the River Eden. The peak specific discharges plotted by Acreman (1989) show less convincing signs of increasing once the area drops below 10 km^2.

Such effects may explain the feature that was incorporated into the FEH regression equation for QMED (Institute of Hydrology 1999), in which the exponent for AREA increased to 1 as AREA dropped to 0.5 km^2, thus imposing a linear relationship between QMED and AREA for the smallest catchments. In contrast, more recent research (Kjeldsen *et al.* 2008) found no non-linearity in the way that QMED residuals vary with catchment size and hence no need to vary the exponent for AREA for smaller catchments.

The hypothesis of linearity between peak flow and area on small catchments is borne out by the limited experimental data available from nested pairs of small catchments. For three nested pairs of homogeneous small catchments at Plynlimon, Wales, it was found that the ratio of QMED is similar to the ratio of catchment area. When QMED at the smaller catchment in each pair was estimated from scaling down QMED at the larger one by area, the results were found to differ from the observed QMED by 1%, 10% and 12%, respectively, for the three pairs (Table B.1).

Table B.1 Scaling of QMED and AREA on nested pairs of small catchments

<table>
<tr><th></th><th>Reference</th><th>Name</th><th>Area (km²)</th><th>QMED (m³/s)</th><th>Ratio of AREA</th><th>Ratio of QMED</th></tr>
<tr><td>Upstream gauge</td><td>54091</td><td>Severn @ Hafren Flume</td><td>3.5</td><td>5.9</td><td rowspan="2">2.51</td><td rowspan="2">2.54</td></tr>
<tr><td>Downstream gauge</td><td>54022</td><td>Severn @ Plynlimon Flume</td><td>8.7</td><td>15.0</td></tr>
<tr><td colspan="7">If QMED at the smaller catchment was estimated from scaling down the larger one by area, it would be 1% higher than the measured value</td></tr>
<tr><td>Upstream gauge</td><td>54097</td><td>Hore @ Upper Hore Flume</td><td>1.6</td><td>3.5</td><td rowspan="2">2.00</td><td rowspan="2">1.80</td></tr>
<tr><td>Downstream gauge</td><td>54092</td><td>Hore @ Hore Flume</td><td>3.2</td><td>6.3</td></tr>
<tr><td colspan="7">If QMED at the smaller catchment was estimated from scaling down the larger one by area, it would be 10% lower than the measured value</td></tr>
<tr><td>Upstream gauge</td><td>55034</td><td>Cyff @ Cyff Flume</td><td>3.1</td><td>5.7</td><td rowspan="2">3.39</td><td rowspan="2">2.98</td></tr>
<tr><td>Downstream gauge</td><td>55008</td><td>Wye @ Cefn Brywn</td><td>10.5</td><td>17.0</td></tr>
<tr><td colspan="7">If QMED at the smaller catchment was estimated from scaling down the larger one by area, it would be 12% lower than the measured value</td></tr>
</table>

The above arguments apply to small catchments, but there is little evidence as to how flood statistics vary with area on very small plots that do not contain watercourses. Few plot-scale runoff measurement experiments have records that are continuous or long enough to enable estimation of statistics such as QMED. However, some insight can be gained by examining individual flood events.

Figure B.1 shows flow recorded on a pair of nested catchments at Pontbren, Wales (Marshall *et al.* 2009). One is a small hillslope which drains via a field drain with a contributing area of 0.36 ha and via overland flow from an area of 0.44 ha. Both drain flow and overland flow are monitored, the latter by means of a gutter inserted into the ground. Further down the catchment, stream flow is collected at a gauging station with a catchment of 3.17 km^2. Data from Pontbren has been provided by Imperial College, who carried out the research as part of a multi-disciplinary programme undertaken by the Flood Risk Management Research Consortium.

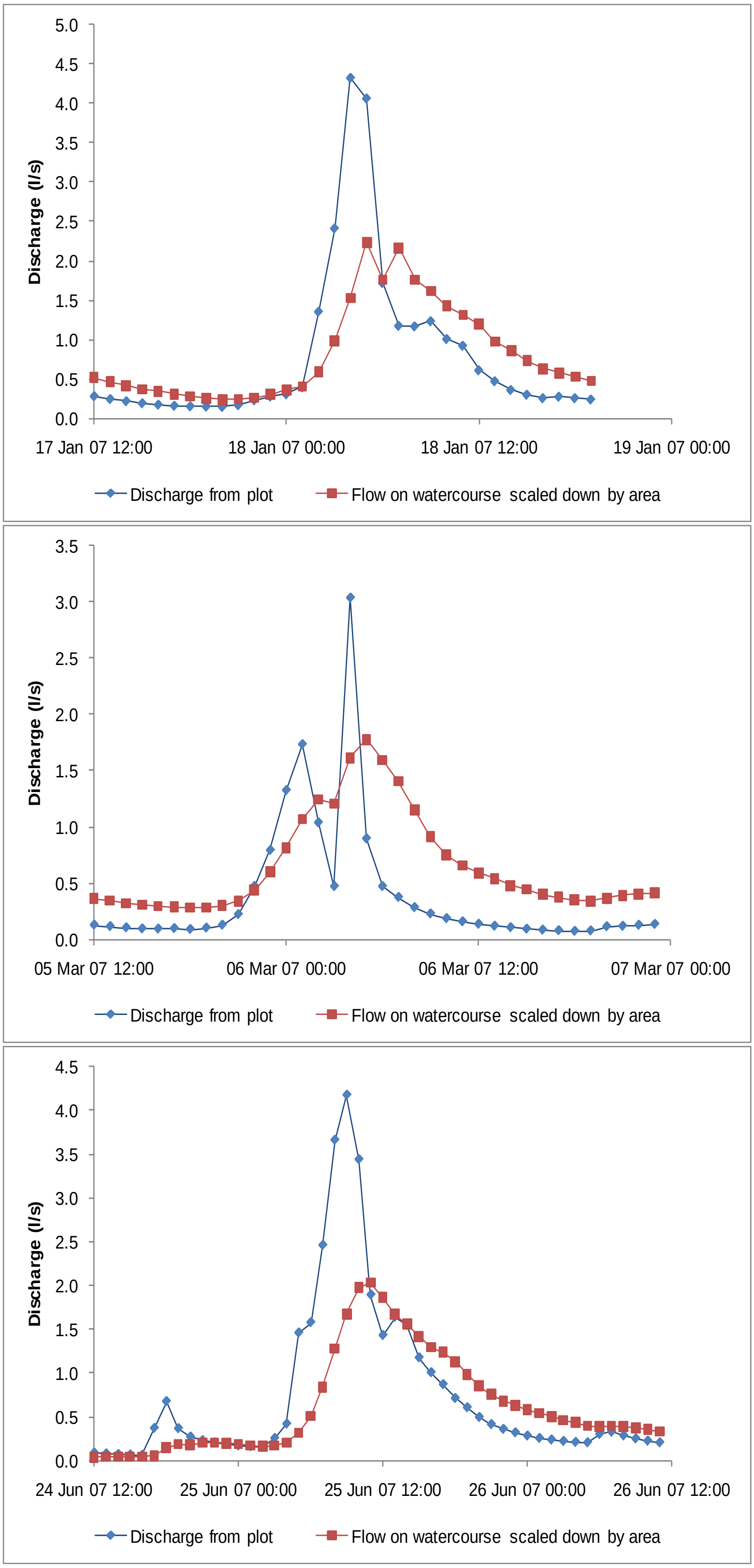

Figure B.1 Comparison of discharge measured at a plot and flow scaled down from a catchment for three events at Pontbren

On Figure B.1, the flow from the stream gauge has been scaled down by the ratio of the plot area to the catchment area, a factor of 792. It can be seen that, while the volume of runoff is comparable, the runoff recorded from the plot is considerably more peaky than the scaled-down flow from the stream gauge. This could be due to attenuation of peak flows, but another possible explanation is the heterogeneity in catchment properties and hence runoff processes. For example, the gradient of the hillslope is more than twice as steep as that of the catchment as a whole.

There is not nearly enough data currently available to form any conclusions on the relationship between flood flows at the plot and catchment scales. Additional plot-scale datasets are expected to be provided soon, and it is recommended that further analysis is carried out during Phase 2 of this study.

A more significant assumption made in transposing design flows to the plot scale may be the neglect of heterogeneity. There is a large body of literature showing substantial variations in soil properties and runoff processes even over very small scales. Features such as macropores can have a large influence on the production of runoff and are difficult to account for without intensive field study, which is unlikely to be practical for most flood studies. Such considerations led Cawley and Cunnane (2003) to conclude that 'The implementation of stormwater management based on a site by site evaluation of greenfield runoff would be fraught with difficulty given the high variability of runoff characteristics at such scales*'.*

However, without some consideration of site-specific characteristics there would be a risk that a greenfield runoff rate applied as an average across a small catchment may be too high or too low for a particular development site whose soils or land use are not typical of the catchment average. Overestimation of a greenfield runoff rate would result in the limiting discharge from a development being set higher than the actual greenfield rate, and hence an increase in downstream flood flows.

It is therefore suggested that the decision to translate flood estimates from catchment scale to plot scale should be accompanied by an assessment of whether the study site is representative of the surrounding catchment area. With knowledge of the characteristics of a site, it should be possible to assess whether runoff rates at the plot scale are likely to be greater or less than the average rate for the surrounding small catchment. The approach has the disadvantage of relying on judgement and therefore an element of subjectivity, but it allows for a site-specific understanding of uncertainty in the flow assessment, and is in keeping with the analytical approaches now accepted for river flow estimation.

Another approach to downscaling would be to translate not flow rates but rainfall-runoff model parameters. For example, the ReFH model could be applied at a plot scale using parameters based on those estimated at a catchment scale. For some applications it would be very beneficial to be able to apply a rainfall-runoff model such as a version of ReFH that could represent the effects of small-scale changes in land use such as those encountered during the development of sports pitches or quarries. However, before this is carried out it would be important to ask whether the structure and parameters of the ReFH model are suitable for application at the plot scale. Dominant hydrological processes can vary greatly between hillslope or plot scale and catchment scale. It is rarely appropriate to scale down or extrapolate models without reformulation to include previously neglected processes (Wigmosta and Prasad 2005). Further investigation of this could be an important component of Phase 2.

B.1.3 Concluding remarks

It is sometimes argued that plot-scale runoff estimates, whether for greenfield or developed sites, should be based on simple approaches such as the rational method.

This has several disadvantages, including the need to define values for the runoff coefficient and the time of concentration. In addition, the rational method, and hence relationships derived from it, make the assumption that peak runoff scales linearly with area, and if this assumption is to be accepted then it would seem reasonable to support scaling down of flood estimates obtained from more contemporary FEH-style methods applied at a catchment scale.

There are several reasons, both theoretical and empirical, to support the suggestion that greenfield runoff rates can be estimated at the small catchment scale rather than the plot scale. As well as allowing the use of well-founded models that draw on large and contemporary flow datasets and avoid the need to subjectively define coefficients, this approach has the benefit of focusing attention on the scale at which the impacts of any increased runoff are likely to be noticed.

However, even if the main focus is to be on the catchment scale there is a need to consider site-specific characteristics in order to account at least partially for heterogeneity. It is thus recommended that Phase 2 includes further comparisons of plot-scale and catchment-scale runoff datasets to aid in the development of new methods or guidance on the applicability of existing methods.

In the case of post-development runoff rates there is an argument for focusing more on the plot scale because of the frequent need to calculate the volume of runoff needing storage in various SUDS features. Currently post-construction runoff rates at the plot scale are often estimated using urban drainage design methods. However, as for greenfield runoff, this runs the risk of losing the focus on the main purpose of the flood storage, which is to alleviate downstream flooding. An alternative approach would be to estimate both pre- and post-development runoff at the catchment scale, which has the added benefit of a greater prospect of consistency between the methods used for the two calculations.

At the catchment scale, the impact of urbanisation has often been investigated using the FEH rainfall-runoff method, increasing the urban extent. Statistical methods are less appropriate for assessing the incremental effect of urban development, because the urban adjustment in the statistical method represents only the net effect of urbanisation on catchments that have had a typical degree of flood alleviation works (Institute of Hydrology 1999). Arguably, a similar point could be made about aspects of the FEH rainfall-runoff method, for example the regression equation for time to peak which is also calibrated using flood event data from catchments that will have been subject to flood alleviation works.

Appendix C

Gauging stations used for comparison of methods

The table below lists the gauging stations that were used for the tests described in Section 6.2.

Station number	Watercourse	Station	Source of flood peak data or QMED estimate	Area (km^2)	BFIHOST	SAAR (mm)	FARL	URBEXT 2000
18016	Kelty Water	Clashmore	Hydrometric Register (2009)	2.62	0.51	2147	1.00	0.00
18017	Monachyle Burn	Blaquhidder	Hydrometric Register (2009)	7.24	0.37	2417	1.00	0.00
18018	Kirkton Burn	Blaquhidder	Hydrometric Register (2009)	6.96	0.49	2150	0.98	0.00
19009	Bog Burn	Cobbinshaw	Hydrometric Register (2009)	8.65	0.35	992	0.61	0.00
19010	Braid Burn	Liberton	HiFlows-UK v3.1	15.39	0.51	770	0.95	0.16
22003	Usway Burn	Shillmoor	HiFlows-UK v3.1	21.87	0.03	1056	1.00	0.01
23018	Ouse Burn	Woolsington	HiFlows-UK v3.1	10.48	0.31	669	0.98	0.10
25019	Leven	Easby	HiFlows-UK v3.1	15.07	0.53	830	1.00	0.00
25808	Un-named tributary of Tees	Burnt Weir at Moorhouse	HiFlows-UK v3.1	0.0482	0.23	1922	1.00	0.00
25809	Un-named tributary of Tees	Bog Weir at Moorhouse	HiFlows-UK v3.1	0.0546	0.23	1837	1.00	0.00
25810	Un-named tributary of Tees	Syke Weir at Moorhouse	HiFlows-UK v3.1	0.0381	0.23	1813	1.00	0.00
26802	Gypsey Race	Kirby Grindalythe	HiFlows-UK v3.1	15.85	0.96	757	1.00	0.00
27010	Hodge Beck	Bransdale	HiFlows-UK v3.1	18.84	0.34	987	1.00	0.00
27038	Costa Beck	Gatehouses	HiFlows-UK v3.1	7.98	0.77	722	0.99	0.02
27051	Crimple	Burn Bridge near Pannal	HiFlows-UK v3.1	8.13	0.31	855	1.00	0.01
28030	Black Brook	Onebarrow	Hydrometric Register (2009)	8.15	0.35	733	0.99	0.00

Station number	Watercourse	Station	Source of flood peak data or QMED estimate	Area (km^2)	BFIHOST	SAAR (mm)	FARL	URBEXT 2000
28033	Dove	Hollinsclough	HiFlows-UK v3.1	7.92	0.40	1346	1.00	0.00
28070	Burbage Brook	Burbage Moor	HiFlows-UK v3.1	8.46	0.43	1006	1.00	0.00
30013	Heighington Beck	Heighington	HiFlows-UK v3.1	24.04	0.95	605	0.96	0.08
30014	Pointon Lode	Pointon Little Wisbeach	HiFlows-UK v3.1	10.94	0.34	591	1.00	0.01
31023	West Glen	Easton Wood	HiFlows-UK v3.1	4.32	0.32	641	1.00	0.00
31025	Gwash	Manton	HiFlows-UK v3.1	23.94	0.31	663	1.00	0.01
31026	Egleton Brook	Egleton Gwash	HiFlows-UK v3.1	1.92	0.56	645	1.00	0.01
32029	Flore	Flore	HiFlows-UK v3.1	8.31	0.43	624	1.00	0.00
33040	Rhee	Ashwell	Environment Agency (2011)	0.75	0.91	567	1.00	0.15
37029	St Osyth Brook	Main Road Bridge	Hydrometric Register (2009)	7.76	0.40	544	0.97	0.00
37033	Eastwood Brook	Eastwood	Environment Agency (2011)	9.71	0.34	555	1.00	0.41
38007	Canons Brook	Harlow (Elizabeth Way)	HiFlows-UK v3.1	20.73	0.35	601	0.99	0.25
39017	Ray	Grendon Underwood	HiFlows-UK v3.1	21.15	0.24	622	0.98	0.00
39055	Yeading Brook West	North Hillingdon	HiFlows-UK v3.1	16.82	0.17	657	1.00	0.54
39061	Letcombe Brook	Letcombe Bassett	Environment Agency (2011)	3.99	0.96	733	1.00	0.01
39082	Graveney	Longley Road	Environment Agency (2011)	21.00	0.36	639	1.00	0.79
39113	Manor Farm Brook	Letcombe Regis	Environment Agency	1.38	0.97	723	1.00	0.00
39116	Sulham Brook	Sulham	Hydrometric Register (2009)	3.03	0.41	657	1.00	0.00
39134	Ravensborne East	Bromley (Bromley S)	HiFlows-UK v3.1	9.79	0.69	680	0.99	0.49
39145	Yeading Brook East	Western Avenue A40	Environment Agency (2011)	8.95	0.18	644	1.00	0.53
41021	Clayhill Stream	Old Ship	HiFlows-UK v3.1	7.10	0.25	805	1.00	0.00
41033	Costers Brook	Cocking	Hydrometric Register (2009)	2.74	0.89	965	1.00	0.02
42017	Hermitage Stream	Havant	HiFlows-UK v3.1	17.33	0.25	785	0.99	0.24
44009	Wey	Broadwey	HiFlows-UK v3.1	7.90	0.79	895	1.00	0.02
45816	Haddeo	Upton	HiFlows-UK v3.1	6.81	0.59	1210	1.00	0.01
45817	Rhb Trib	Upton (Trib)	HiFlows-UK v3.1	1.74	0.60	1207	1.00	0.00
45818	Withiel Florey Stream	Bessom Bridge	HiFlows-UK v3.1	9.93	0.58	1270	1.00	0.00
47804	Hennard Stream	Moors Mill	HiFlows-UK v3.02	7.17	0.40	1150	1.00	0.00
50801	Yeo	Parkham	HiFlows-UK v3.02	7.51	0.47	1238	1.00	0.00

Station number	Watercourse	Station	Source of flood peak data or QMED estimate	Area (km^2)	BFIHOST	SAAR (mm)	FARL	URBEXT 2000
52026	Alham	Higher Alham	Hydrometric Register (2009)	4.90	0.61	1006	1.00	0.00
54087	Allford Brook	Childs Ercall	Environment Agency	2.92	0.86	663	1.00	0.00
54090	Tanllwyth	Tanllwyth Flume	Hydrometric Register (2009)	1.10	0.33	2462	1.00	0.00
54091	Severn	Hafren Flume	HiFlows-UK v3.1	3.46	0.30	2513	1.00	0.00
54092	Hore	Hore Flume	HiFlows-UK v3.1	3.22	0.33	2533	1.00	0.00
55033	Wye	Gwy Flume	HiFlows-UK v3.1	3.84	0.33	2575	1.00	0.00
55034	Cyff	Cyff Flume	HiFlows-UK v3.1	3.10	0.40	2415	1.00	0.00
55035	Iago	Iago Flume	HiFlows-UK v3.1	1.01	0.34	2461	1.00	0.00
68014	Sandersons Brook	Sandbach	POT data provided with the FEH	3.77	0.39	742	0.99	0.02
69034	Musbury Brook	Helmshore	POT data provided with the FEH	3.03	0.35	1454	1.00	0.00
69042	Ding Brook	Naden Reservoir	Hydrometric Register (2009)	2.18	0.40	1488	1.00	0.00
76011	Coal Burn	Coalburn	HiFlows-UK v3.1	1.59	0.20	1096	1.00	0.00
80003	White Laggan Burn	Loch Dee	HiFlows-UK v3.02	5.70	0.39	2469	1.00	0.00
80004	Green Burn	Loch Dee	Hydrometric Register (2009)	2.62	0.37	2383	1.00	0.00
80005	Dargall Lane	Loch Dee	Hydrometric Register (2009)	2.07	0.36	2435	1.00	0.00
89008	Eas Daimh	Eas Daimh	Hydrometric Register (2009)	4.79	0.38	3131	1.00	0.00
89009	Eas a' Ghaill	Succoth	Hydrometric Register (2009)	9.80	0.38	3054	1.00	0.00
91802	Allt Leachdach	Intake	HiFlows-UK v3.1	6.52	0.40	2555	0.99	0.00
203038	Rocky	Rocky Mountain	Hydrometric Register (2009)	6.80	0.33	1610	1.00	0.00
203046	Rathmore	Rathmore Bridge	HiFlows-UK v3.1	22.51	0.43	1043	1.00	0.00
205101	Blackstaff	Eason's	HiFlows-UK v3.1	14.15	0.41	990	1.00	0.42
206007	Tullybranigan	Bonnys	Rivers Agency (2011)	3.60	0.45	1455	1.00	0.00
206015	Burren	Castlewellan	Rivers Agency (2011)	8.60	0.66	1248	0.95	0.00
205108	Knock	Rosepark	Rivers Agency (2011)	1.98	0.50	936	1.00	0.11
205031	Woodburn	Woodburn West	Rivers Agency (2011)	0.23	0.39	1145	1.00	0.00
205032	Woodburn	Woodburn Central	Rivers Agency (2011)	0.32	0.39	1145	1.00	0.00
205033	Woodburn	Woodburn East	Rivers Agency (2011)	0.5	0.39	1145	1.00	0.00
n/a	Nant Pontbren	Gauge 6	Imperial College (2010)	3.17	0.28	1265	1.00	0.00

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