Environment Agency
Asiantaeth yr Amgylchedd

Flood estimation guidelines

Operational instruction 197_08 **Issued 26/06/2012**

What's this document about?

Offers advice to help analysts make the most of the material in the Flood Estimation Handbook (FEH), other recent publications and older methods of flood estimation, when they're still applicable. It aims to ensure a consistent, robust approach, repeatable results and systematic recording of decisions made.

It complements the FEH and other publications. It is not an alternative short guide.

Document details

Who does this apply to?

All staff carrying out flood estimation in the Environment Agency.

Staff supervising studies or reviewing those carried out externally.

Managers of flood estimation studies, who should read at least the executive summary.

Consultants carrying out work for us or carrying out work requiring our approval.

Related documents

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Executive summary

Why we've included this summary

This executive summary gives a brief overview, intended mainly for managers of flood estimation studies.

If you think it's easy – you're not looking deeply enough

Although you can apply many of the FEH methods using straightforward software, flood estimation is a complex process with many aspects. Practitioners need many skills, including statistics, mathematical modelling, fluvial hydraulics and meteorology, and hydrology. An enquiring mind is essential and a determination to challenge assumptions and seek out facts. Analysts need to think, at all stages, about the problem they are solving.

So it's essential to ensure that those carrying out studies have the right knowledge, skills and experience and that they are allowing enough time for the task. Half a day may be just adequate for a preliminary assessment. But thorough flood estimation studies can take many days or weeks - the FEH suggests allowing between five and 50 days.

Table 2, on page 12, shows indicative levels of staff competence and timescales for different types of flood estimation studies. You must take a risk-based approach when considering the required competence and the time needed to carry out a study.

What to expect and not expect

We've designed these guidelines to complement the FEH and other publications. They're not an alternative short guide. Analysts still need to consult the FEH. We encourage all users to read at least Volume 1, which has only 61 pages, including a thought-provoking and frank interlude.

In line with the philosophy of the FEH, the guidelines offer few prescriptive instructions.
Example: In many situations, there's a choice of FEH methods and alternatives, sometimes giving a wide variety of results. These guidelines don't tell users which method to choose. But they do offer a framework for choosing a method and they give advice on:

- the ranges of applicability of each method;
- how to write a method statement;
- factors to consider when choosing a method;
- how to reconcile results from different methods;
- which methods to prefer for various unusual types of catchment;
- How to record and justify the choice of method.

The guidelines are intended mainly for river management and reservoir safety applications. They cover estimation of design floods over a range of annual exceedence probabilities up to the probable maximum flood.

How do I make sense of this hydrology report?

Much of our involvement with flood estimation comes from reviewing studies carried out by consultants. Before we revised these guidelines in 2006-2008, we consulted a sample of Environment Agency staff. They mentioned 18 typical shortcomings in flood hydrology reports. The most common were lack of information on assumptions, limitations of the methods and poor justification for the choice of method.

The guidelines now address these and other comments by including sections on assumptions and limitations (see Chapter 5, starting on page 70), a new flood estimation calculation record (SD01) and a Checklist for reviewing flood estimates (SD03).

The flood estimation record is for use on all Environment Agency studies, whether carried out internally or by our consultants. As well as assisting reviewers and project managers, it is also designed to help analysts ensure that they have thought through the choice of approach and applied the methods correctly. Analysts have a responsibility to establish this audit trail. Project managers are responsible for defining the purpose of the flood estimates they need and ensuring that they are used appropriately.

One minute overview of flood estimation methods

There are two principal techniques available:

1. the FEH statistical method;
2. the Revitalised Flood Hydrograph (ReFH) method.
   This has replaced the FEH rainfall-runoff method for most applications.

You can apply these on any UK catchment with an area larger than 0.5 km^2.

Difference between the two

The statistical method gives just a peak flow.

The rainfall-runoff techniques (ReFH or FEH) produce hydrographs.

Because it is more direct and based on a larger dataset, users often prefer the statistical method.

Using a hybrid method

If a hydrograph is needed, you can use a hybrid method to fit a hydrograph shape to the peak flow from the statistical method.

Other older approaches

On smaller catchments (see Small catchments and greenfield runoff, on page 87) or extremely heavily urbanised areas (see Development control and urban catchments, on page 91), older approaches are sometimes applied, such as the Institute of Hydrology Report 124 method for small catchments or the ADAS Report 345 method for greenfield runoff estimation. These guidelines recommend that FEH methods should now be used in preference.

The FEH also provides rainfall frequency estimates, which are most often used to provide input to rainfall-runoff models for flood estimation.

Catchment descriptors are a last resort

The FEH software enables rapid estimation of design floods from catchment descriptors. However, these are rarely likely to be the best estimates.

The first of the FEH’s six maxims states that flood frequency is best estimated from gauged data. For this reason, the guidelines offer advice on how to obtain flow data (the principal source is the HiFlows-UK dataset) and how to review data quality, in particular the accuracy of rating equations. The availability and quality of flow data can be the greatest influences on the accuracy of the resulting flood estimate.

On ungauged catchments, users can often apply data transfers by seeking nearby hydrologically similar catchments for which flow data are available. Selecting donor catchments is a subjective process. So the guidelines offer advice drawn from the FEH, more recent research and the accumulated experience of many users.

Quite, quite sure?

Even the 50 days of work the FEH suggests won't produce a definitive statement on the magnitude of a 1% flood or the rarity of an observed event. By its very nature, flood estimation is an uncertain business and the uncertainty is probably greater than many hydrologists realise.

These guidelines offer advice on identifying sources of uncertainty. Confidence limits for flood estimates are difficult to calculate and remain a subject for research. But the FEH offers advice on the uncertainty of some parts of the process and analysts should quote this information.

It's important to realise that a wide confidence interval doesn't necessarily mean that the best estimate is wrong. Analysts should aim for the best estimate at each stage in the flood estimation process. This is better then making successive decisions that are biased on the conservative side that could result in a final answer that lies a long way above the best estimate. If required, they can add a factor of safety to the outcome of the design process, such as a freeboard allowance that raises the design height of a flood defence.

A degree of pragmatism can be important in flood estimation. Since the answer is always uncertain, the analyst must be able to judge when they've found sufficient information and explored enough options to give a result suitable for the purpose of the study.

1. Introduction

Overview

In this chapter This chapter covers the following topics:

Development of the Flood Estimation Guidelines

Revisions The table below describes the publishing history of the Flood Estimation Guidelines.

Version	Authors, content and changes
1	Written by Bullen Consultants, with input from the Environment Agency and the Rivers Agency. Issued in August 2000.
2	Produced by the Environment Agency with the help of JBA Consulting. Based on version 1 with extensive revision and updates. Included new material, such as advice on non-FEH methods, reservoir safety methods, guidance on uncertainty and a checklist for reviewing calculations. Merged the two parts of version 1 into a single volume, with Part 1 (Overview) condensed into an executive summary. Issued in 2008.
3	Produced by the Environment Agency with the help of JBA Consulting. Includes research, software and datasets released between 2007 and 2009. Issued in 2009.
4	Produced by the Environment Agency with the help of JBA Consulting. Includes research and datasets released in 2010-12 and feedback from users. Issued in 2012.

About these guidelines

Purpose These guidelines offer advice to help analysts make the most of the material in the FEH and later publications, as well as older methods of flood estimation where they are still applicable. Their aim is to ensure a consistent and robust approach, repeatable results and systematic recording of the decisions made. They provide a framework in the form of:

- a Flood estimation calculation record (SD01, SD02) to enable robust recording and quality assurance of the results;
- and a Checklist for reviewing flood estimates (SD03).

Other aspects the guidelines address include levels of competence and supervision.

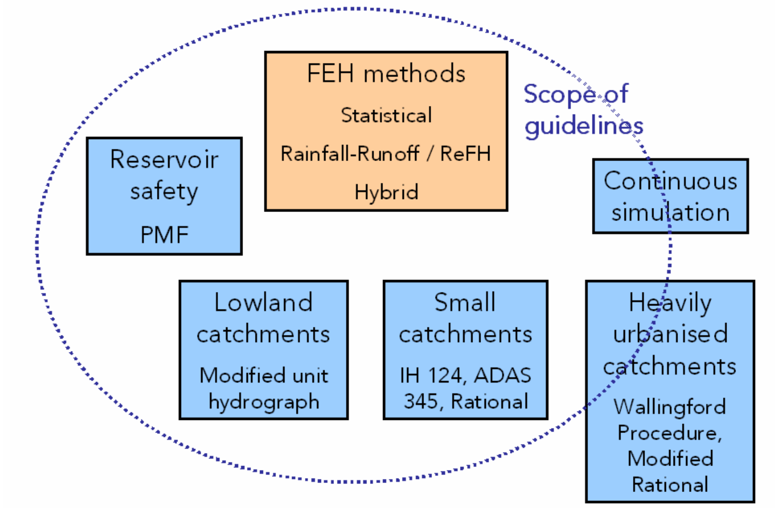
Scope

As Figure 1 below shows, these guidelines concentrate mainly on methods used for flood estimation for river management and reservoir safety, that is, the FEH procedures and the more recent ReFH method.

These guidelines also review alternative methods for unusual catchments, such as small ones or lowland areas with pumped drainage. They only briefly mention sewer design methods and alternative approaches to flood estimation, such as continuous simulation.

Figure 1

This diagram shows applications and methods covered by the guidelines.



Relationship to FEH

These guidelines complement the FEH and other publications. They are not an alternative short guide.

Analysts: you must read and consult the FEH and other relevant publications.

References to the FEH follow conventions used in the FEH.
Example: The reference **1** 2.2 in these guidelines refers to Volume 1, Section 2.2 in the FEH.

In line with the approach adopted by the FEH, these guidelines do not offer prescriptive methods.

Precedence

Analysts or project managers: you may sometimes need to depart from these guidelines. When you do, the Project Brief and the Proposal must make this clear.

The Project Brief and the Proposal then takes precedence over these guidelines. But, in all cases of apparent difference, consultants and Environment Agency analysts must first seek clarification from the Environment Agency's Project Manager.

Revisions

The original version of these guidelines was published in August 2000. Since then, use of the FEH has become widespread and users have accumulated a great deal more experience. There have been developments in research (for example, the ReFH method and improvements to the statistical method) and data management (such as HiFlows-UK) that have changed the way we use the FEH. There is also an increasing emphasis on catchment-scale flood estimation.

For these reasons, we comprehensively revised the guidelines in 2006-7. We broadened the scope to include non-FEH methods when these are still applicable, particularly for very small catchments. We updated the guidelines again in 2009 and 2010-12.

There will be future revisions following any major changes in methodology or at least every four years.

If you think you've found a mistake

Report any suspected mistakes in these guidelines to the Mapping and Modelling Team by e-mail at glenda.tudor-ward@environment-agency.gov.uk.

Presenting return periods

These guidelines quote the frequency of a flood in terms of a return period.

Definition

The **return period** of a flood is the average interval between floods of that magnitude or greater. We use return periods to remain compatible with the previous version of the guidelines and with the FEH. See also Note on the definition, immediately below.

Alternative expression

Alternatively, we can express flood frequency in terms of an annual exceedence probability (AEP). This is the inverse of the return period. **Example:** A 1% AEP flood has a 1% chance of being exceeded in any year.

Presenting results to non-specialists

Use the alternative expression. Non-specialists may associate the concept of return period with a regular occurrence rather than an average recurrence interval. Table 1, below, provides a quick conversion between return periods and AEPs.

Note on the definition

Strictly speaking, this is the return period on the peaks-over-threshold scale. There is an alternative definition, based on annual maximum floods, which the FEH uses more widely (**1** Appendix A). The difference is only important at short return periods, under 20 years. The AEP is the inverse of the annual maximum return period.

Table 1

The table below provides conversions between return periods and AEPs.

Return period (in years)	2	5	10	25	50	75	100	200	1000
AEP (in percentages)	50	20	10	4	2	1.33	1	0.5	0.1

Using the FEH and these guidelines

Finding information and sharing experience

The Environment Agency's focal point for discussion and review of technical aspects of flood estimation is the Mapping and Modelling team. Send any suspected mistakes in these guidelines by e-mail to glenda.tudor-ward@environment-agency.gov.uk.

Consult the FEH page on the Easinet for information relating to FEH technical and software support. It also includes information on our policies, these guidelines and details of training courses.

Inconsistencies in flood data are sometimes identified when carrying out flood studies. FEH analysts should provide feedback to the hydrometric section of the relevant gauging authority for these to be investigated. They should submit any errors or suggestions relating to the HiFlows-UK dataset, using the feedback form on the HiFlows-UK website.

FEH web pages

Information about the FEH is provided on the FEH website and the CEH Wallingford website. They include news on updates, frequently asked questions and information on training courses.

Select this link for a list of FEH errata/corrigenda on the CEH Wallingford website. **Analysts**: it is recommended that you make hard-copy corrections to your copy of the FEH.

Software

Currently, the latest releases of the FEH software packages are:

- FEH CD-ROM version 3.0 (released in September 2009);
- WINFAP-FEH version 3.0.003 (released in November 2009);
- ReFH spreadsheet version 1.4;
- ReFH Design Flood Modelling Software (released in July 2007).
- A number of hydraulic models have the facility to implement the FEH rainfall-runoff method.

Notes:

1. Report any installation errors to the Corporate Information Services (CIS) help desk (tel. 8080).

Competencies and training

Range of skills

Flood estimation is complex. There are many aspects to the process. Practitioners need many skills including statistics, mathematical modelling, fluvial hydraulics and meteorology, and hydrology. An enquiring mind is essential and a dogged determination to challenge underlying assumptions in datasets and seek out facts.

It is essential, therefore, to ensure that:

- the people carrying out studies have the correct knowledge, skills and experience;
- and that sufficient time is allowed for the task.

See Table 2, on page 12, for more details.

Competency framework

A disciplined framework for carrying out studies ensures good quality flood estimates. It is essential that those who work on, supervise and approve flood studies have suitable training, professional qualifications and experience. Table 2, below, provides an indicative hierarchy of flood estimation studies and the time required for different types of studies. It aims to help:

- managers and analysts to discuss the levels of effort and competence required;
- and team leaders to allocate staff to studies.

Table 2 The table below provides indicative levels of competence and supervision for flood estimation staff.

Notes

1. The values in all columns are **indicative**.
2. FM: flood mapping; CFMP: Catchment Flood Management Plan.
3. Interpret the competence criteria as minimum levels.
4. An analyst who has not carried out or supervised the study must give approval.
5. Level 1: hydrologist with minimum approved experience in flood estimation.
6. Level 2: senior hydrologist.
7. Level 3: senior hydrologist with extensive experience of flood estimation.

Complexity of the flood estimation study	Example of a study	Value of flood defence works or damages	Indicative timescale for flood estimation	Competence criteria	
				Analyst	Supervision and approval
Simple	Preliminary assessment; culvert capacity check	-	<1 day	Level 1	Level 2
Routine	Low-risk development application	<£50,000	1 - 2 days	Level 1	Level 2
Moderate	Small FM study or medium-risk development application	<£250,000	2 - 10 days	Level 2	Level 3
Difficult	Medium FM study or CFMP or pre-feasibility	<£1 million	2 - 4 weeks	Level 2	Level 3
Very difficult	Major scheme design or large FM study/ CFMP	>£1 million	>1 month	Level 3	Level 3

Training courses

All Environment Agency users of the FEH must attend an approved training course in flood estimation methods. We offer two FEH courses:

1. FEH Awareness, a 1-day course for project managers and others needing an overview;
2. FEH Users, a 2-day course for those who will be using FEH methods.

The users' course introduces all the basic techniques and software. It should enable most analysts to reach Level 1 in Table 2, on page 12. This is a minimum requirement.

For complex studies, analysts may require more detailed training in one or more of the FEH techniques or have gained experience under the supervision of senior colleagues.

You can find further information on these courses on the FEH page on the Easinet.

Neither course covers flood estimation for reservoir safety. More advanced training courses are available from various consultants and academic institutions. Information on other internal hydrological courses can be found in the Learning and Development course directory

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Getting experience

There is no substitute for experience to develop familiarity with the challenges of flood estimation.

Analysts: you will find that time spent on the worked examples in the FEH is repaid by additional insight into many facets of the FEH methods.

Supervision

Supervision, by a more experienced colleague, can provide support and create the opportunity to learn. It enables problems to be shared. This, in turn, may provide reassurance when handling the more knotty aspects of a difficult study. Supervision also provides a quality control mechanism on a day-to-day basis.

Project Managers and team leaders: you are responsible for ensuring that staff experienced in flood estimation are adequately supervising all flood studies.

Managing studies

Project Managers: When commissioning a study, you must discuss your requirements with the hydrologists (within the Environment Agency or consultants) who will be carrying out and supervising the study. These discussions enable both parties to identify the options available for the study and agree a specification. You can record this specification, usually as the Project Brief and in a Proposal.

You can use the Environment Agency's SFRM Model Report Performance Scope as a starting point.

Completing the calculation record establishes an audit trail for every flood estimation study. But there is still a need to monitor the execution of studies to ensure that they are technically correct and meet your needs.

Signing off responsibility

Supervisors: you must sign off completed studies to certify their technical basis and validity.

Analysts: you must sign off the results of the flood estimation to confirm that they are fit for the purposes of the study.

Consultants

Consultants must be able to demonstrate that staff who carry out flood estimation have appropriate qualifications, training, experience and supervision to meet the aims described above in this chapter.

2. Hydrometric data and catchment descriptors

Overview

In this chapter

This chapter covers the following topics:

Selecting and examining flood peak data

Rationale

The availability and quality of flow data can be the greatest influences on the quality of the resulting flood estimate. A review of hydrometric data is, therefore, vital at the outset of most studies.

The most useful type of data in flood estimation is normally a peak flow series. However, other sorts of data can also be valuable, including records from stations that measure only water levels.

Available data

The FEH provided flood peak data for 1000 gauging stations when it was first published. This dataset ended at about 1995.

In 2005, the HiFlows-UK dataset version 1 was released. It was an updated version of the FEH dataset. It contained approximately 1000 sites. Some of the original FEH stations were removed and others were added.

HiFlows-UK has since been updated in 2008, 2009 and 2011. The current version is 3.1.2 (released in December 2011) which contains annual maximum and POT data up to the end of water year 2008-09 (plus the November 2009 floods at some stations).

All FEH users: you must use the HiFlows-UK dataset as your primary source for flood peak data. You can download the latest version from the HiFlows-UK page on our website. You should overwrite the dataset provided with WINFAP-FEH.

Description of HiFlows-UK

HiFlows-UK builds on the dataset assembled for the FEH research. It includes suitable flow sites from all the UK gauging authorities. The website provides peak flows, levels, rating histories, photographs and information on each gauging station. It provides:

- guidance on the quality of data;
- and a statement indicating whether each station is considered suitable for:
  - estimating QMED;
    That is, moderate floods.
  - and/or pooling.
    That is, extreme floods.

This suitability considers only data quality, not record length or the nature of the catchment.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	There are two main uses for the HiFlows-UK dataset: 1. You can use stations suitable for pooling to create pooling groups, by downloading the dataset and saving it to a directory used by WINFAP-FEH. Most users find it convenient to ensure that WINFAP-FEH only uses the subset of stations that are classed as suitable for pooling when it constructs pooling groups. You can do this by browsing to the appropriate directory under the Load Options tab in the General options menu in WINFAP-FEH. 2. You can consider stations suitable for QMED as potential donor sites. You can locate these using the search facility on the website.
2	For most lower risk studies, you can use the HiFlows-UK dataset without any need for further review or searching for data.
3	If you are using the data in more detailed studies, there are limitations in the dataset to address: ▪ there are other sources of flow data not in the HiFlows-UK dataset; **Examples:** Recently installed stations, temporary flow loggers and stations that were not judged to be of suitable quality at the time of compiling the dataset. You should investigate all gauging stations at or near the reach of interest because even if their high flow data is inaccurate or uncertain, it may still result in better estimates of QMED than those made solely from catchment descriptors. Even level gauges can be useful sources of evidence for flow magnitudes, for example if you are able to derive an approximate rating equation using spot gaugings or a hydraulic model. ▪ the dataset will typically lag a year or two behind the present, so there will often be scope to update flood peak series; ▪ some stations have flows in HiFlows-UK that currently differ from the data held on the Environment Agency's Wiski database; ▪ the data quality classification is 'indicative'. More detailed rating reviews are often worthwhile and can result

	in changes to the classification of stations.
4	In some studies, it is worth updating the flood peak records for stations on the study reach and at donor sites. This is more worthwhile at times when Hiflows-UK is less up to date or when there has been a recent major widespread flood.
5	Temporary flow loggers such as portable ultrasonic meters are worth installing for some studies, particularly if they can be installed at least two years in advance. This provides a long enough flood peak record to give an estimate of QMED that is more reliable than that obtainable from catchment descriptors (**3** 2.2). On 95% of typical catchments, you can expect catchment descriptors to give an estimate of QMED within about a factor of 2.0 of the real value. With just 2 years of flow data available, this uncertainty reduces to within about a factor of 1.7 of the real value (**3** 13.8.2. With 5 years of data, the factor drops to 1.4. So installing a temporary flow monitor could make a large difference to the outcome of a study, such as the number of people thought to be at risk of flooding or the level to which a flood defence should be constructed. On unusual catchments such as highly permeable or urban ones, an even shorter period of flow data may provide a more reliable estimate of flood frequency than catchment descriptors, due to the influence of local hydrological features that are not well represented, for example in the UK-average regression formula for QMED. In some unusual catchments you will have to accept a huge uncertainty in design flood estimates unless you obtain some flow data. **Example:** Within a month of its installation in 2010, a temporary flow logger installed on a small Magnesian limestone catchment near Doncaster recorded a flood peak that was more than twice the catchment-descriptor estimate of QMED. Although the flow record was too short to draw any statistically significant conclusions, the data cast serious doubt on the FEH estimates and supported the use of an alternative method (continuous simulation).
6	Visual examination of flood peak data is always worthwhile, see Figure 2, on page 18. Plotting a time series of flood peaks can reveal features such as: ▪ outliers; These are a typical feature of flood peak data but you should investigate them if additional information is available (**1** Interlude, p. 33-35). ▪ apparent upper bounds on the magnitude of flood peaks; These may be genuine features due to storage in the catchment or an artefact due, for example, to bypassing the gauging station. ▪ trends or fluctuations; These may be due to climate or land use. Investigation (**3** 21.4) may reveal no obvious cause for non-stationarity. But when you find a cause, data adjustment or curtailment may be relevant (**3** 21.1.3). One of the main findings to emerge from an analysis of trends in the original FEH dataset is that national trends in flood peaks, associated with land use change or climate change, cannot be easily identified or readily dismissed (**3** 21.5.4). ▪ step changes; These may indicate a sudden change in the catchment (such as the construction of a reservoir or flood storage area) or a change

	in the station or rating which has altered the apparent flows. ▪ unusually small annual maximum flows. This can occur, for example, on a highly permeable catchment that has not experienced a flood in a particular water year. These catchments require special treatment (**3** 11.2). Small flows may otherwise be due to missing data. You should investigate years with missing data to see if the annual maximum may have occurred in the missing data period and the year excluded or included accordingly. Investigation methods include comparison of flows with another station(s) on the same or neighbouring river, or comparison with rainfall data.
7	Correlation plots between flood peaks at upstream and downstream gauging stations, or those on adjacent tributaries, are another useful tool for examining data. They can help identify patterns or inconsistencies in hydrological behaviour (see Figure 3, on page 19).
8	The recommended methods for growth curve estimation, in **3** Table 8.3, assume that the flood record at the subject site is of average quality. You should informally reduce the record length in the table if the gauged record is considered unusually poor or increase it if the record is particularly good (**3** 8.2).

Figure 2: Example flood peak time series

The graph below illustrates a flood peak time series on the River Stour at Langham, Essex/Suffolk.

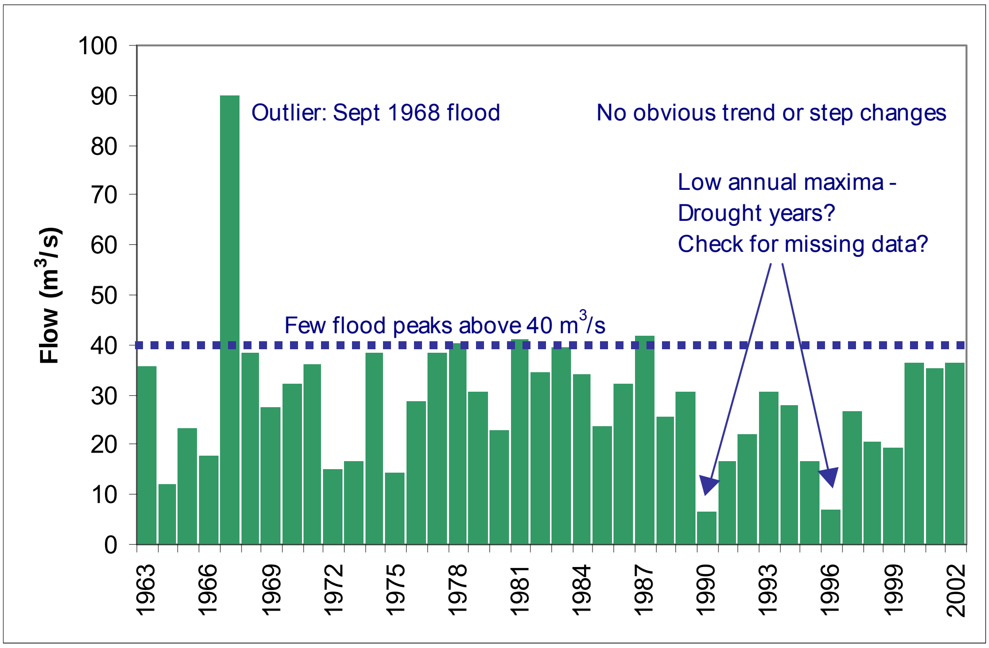
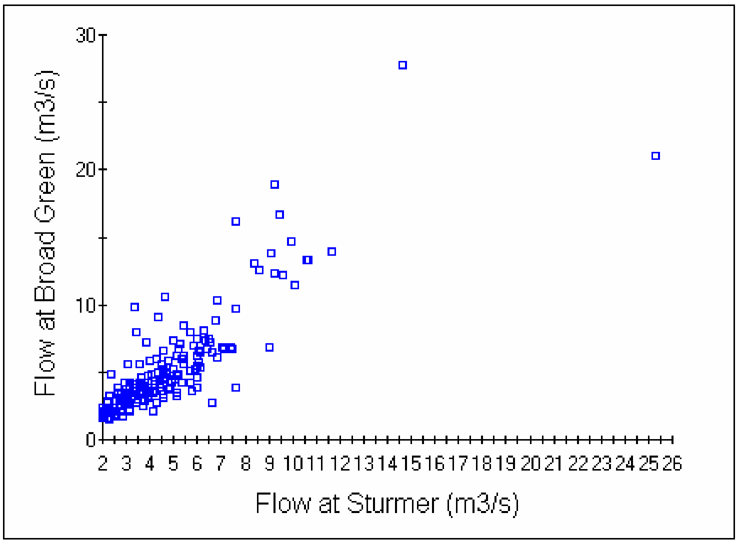


Figure 3: Example flood peak correlation plot

The graph below shows a flood peak correlation plot, using flood peaks (from POT data) on adjacent tributaries of the River Stour in Essex/Suffolk.



The catchments are similar in size, soils and geology. But the Stour Brook at Sturmer is affected by urbanisation and a major flood storage scheme. The correlation coefficient is 0.84, indicating close correlation. Flood peaks at Broad Green are generally higher than those at Sturmer, although the 1968 event (pre-scheme) is an exception. One possible explanation is that the scheme is reducing flood peaks to less than those expected from a rural catchment.

Feedback and errors

We strongly encourage users to feed back any further information and any errors they find to HiFlows-UK. You can do this on the HiFlows-UK enquiries and feedback page on our website.

It is often worth informing the gauging authority directly as well, for example through the Project Manager if the Environment Agency runs the gauge.

Rating reviews

Rationale

At most, flow gauging stations, rating curves are used to transform water level into flow.

Accurately calculating flood flows is problematic but of great importance.

Description

Flood rating curves, particularly those that represent out-of-bank conditions, are often based on a small number of measurements or on extrapolation from the highest flow gauging.

There are comments on ratings at most stations in the HiFlows-UK dataset. These are an important source of information. They should act as a prompt for users to enquire further, if appropriate.

Analysts: you must take into account any more recent rating reviews or high flow gaugings, which may not yet have been incorporated into HiFlows-UK. If there has not been a review and there are questions over the rating, it is often worth carrying out a review.

Requirements

Most flood estimation studies will require a review of rating equations at each gauging station used in the study (whether within the study reach or as a donor site), unless a recent review is available from another study.

Our Hydrometry and Telemetry teams, with input from hydrologists in other teams, carry out full reviews and revisions of ratings, which are complex procedures.

This section gives guidance on what you might expect in a typical rating review, carried out as part of a flood estimation study.
References: For further guidance on rating reviews, see the Operational Instruction on flow derivation methods (OI 188_07). For guidance on extending ratings, see Ramsbottom, D.M. and Whitlow, C.D. (2003) listed in Related documents.

Guidelines

The guidelines and advice in the table below are included to help users. Select references that are linked to see details in Related documents.

Item	Guideline or advice

1	The person carrying out the rating review needs:
	▪ a knowledge of:
	  ▪ hydrometry;
	  Example: See Herschy, R.D. (1998).
	  ▪ and hydraulics.
	▪ an understanding of the value of flood data.

2	Rather than being purely a statistical exercise, the review should take into account the nature of the gauging station. Current information about existing stations is available from the measurement authority (within the Environment Agency, from the Hydrometry and Telemetry and/or Hydrology teams) and any review should always involve staff from these teams.
3	A site visit often provides valuable insight into the way the station might perform during flood flows.
4	For detailed studies, it can be useful to obtain details of closed stations or information about the history of existing stations. You can find this in various sources, such as: ▪ the teams mentioned above; ▪ the station files held at CEH Wallingford; ▪ reports on earlier flood studies; ▪ and reports on previous hydrometric improvements.
5	The information to seek from all the sources listed in Item 4 above includes: ▪ investigating the history of the station, such as its original purpose and any changes in the channel, structure or rating equations; ▪ checking whether the rating is solely theoretical, checked by current meter gaugings or based solely on gaugings (empirical); ▪ establishing whether the rating is theoretical, by finding out how it was derived; **Example**: By hydraulic theory or physical model tests.

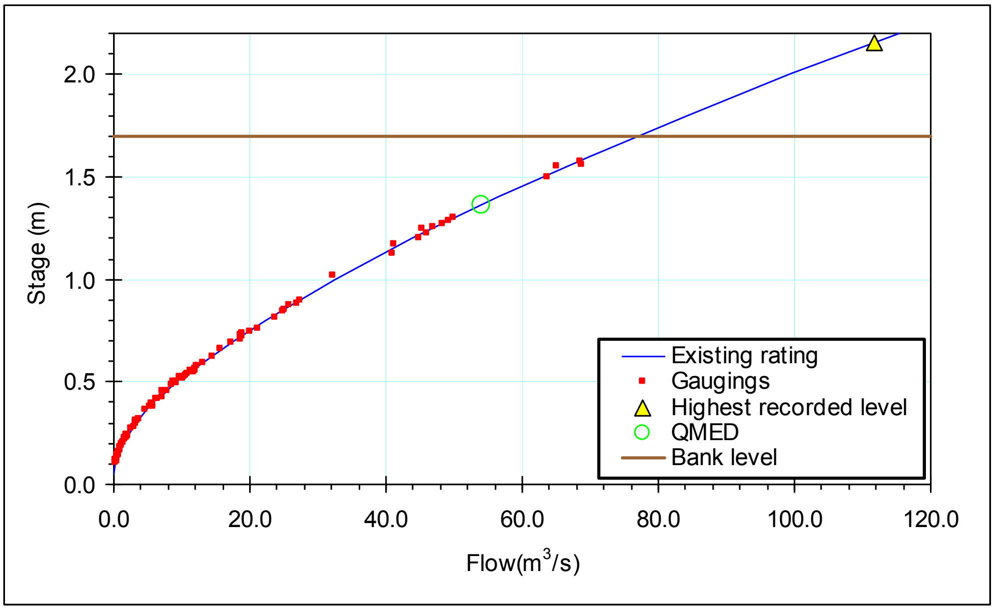
	▪ establishing whether the rating is empirical, by finding out how it has been extrapolated for measuring flows above the calibrated range;
	Note: Straight line extrapolation on a log scale is the normal method used but there are better techniques. For example, extrapolating the velocity rather than flow and using measured channel cross-sections is a better method but this is only the simplest of the possibilities. See Ramsbottom, D.M. and Whitlow, C.D. (2003).
	▪ finding:
	  ▪ how flow measurements are taken;
	  Example: By current meter (wading or cableway) or by an ADVP device that can be towed across the river.
	  ▪ and whether the measurements include flow through parallel channels or the floodplain;
	▪ comparing the valid range of the rating curve relative to the physical characteristics of the site, such as the bank levels and the levels recorded in flood conditions;
	▪ finding whether there have been any additional gaugings (or measurements, such as float runs or using portable ultrasonic flow meters) which current databases may not list;
	▪ assessing the potential for bypassing during flood flows;
	▪ checking for non-modular flow due to backwater effects;
	▪ checking for susceptibility to hysteresis (looped ratings due to storing flood water);
	▪ finding how the station is classified, according to the Gauging Station Data Quality system.
	Note: This assesses whether measurements for flows around half of QMED are reliable, based on site and station factors, and checks gaugings. See JBA Consulting (2003).

6	You can summarise some of the information, listed in Item 5 above, on a plot showing the rating curve against flow gaugings. A plot like Figure 4, on page 22, shows: ▪ the scatter in the gaugings (a measure of uncertainty); ▪ and how much the rating has been extrapolated for measuring the highest flow on record and for QMED. Adding the bank level can help to explain any changes to the slope of the rating curve, which often occur at bankfull flow. It can also be worthwhile plotting the channel cross section on a second x-axis.
7	You can statistically assess the accuracy of the rating if needed, but do this with caution. **Example:** Goodness-of-fit statistics such as R^2 tend to be dominated by the large number of low flow gaugings and may not reflect the quality of the rating for high flows.
8	It is also worth plotting a time series of the deviations between predicted and measured flows and showing the cumulative deviation. This can reveal any drift in the gaugings, which might suggest that the rating needs to be recalculated. Further investigations, if required (for example, if the gaugings are

	very scattered) could include separating the gaugings by: ▪ season, to investigate vegetation growth; ▪ or rising/falling stage, to investigate any hysteresis.

Figure 4

The graph below shows a rating curve plotted against flow gaugings on the River Kent at Bowston, Cumbria



Result of the review

The review should result in a conclusion about the suitability of the rating for high flow measurement and possibly recommendations for further work.

In some cases, it is appropriate to develop a new rating, if there have been additional recent high flow gaugings. Always carry this out in consultation with the Hydrometry and Telemetry team and ensure any revisions to the rating are fed back into the Environment Agency's WISKI archive.

In reaching the conclusion, it is important to realise that high flow measurement is uncertain at nearly all gauging stations. Before rejecting a station, consider what the alternatives are, bearing in mind their uncertainty. This is particularly the case if the alternative is to base a flood estimate solely on catchment descriptors, which the FEH describes as a last resort.

When to revisit the review

You will sometimes need to revisit the rating review later if the study goes on to develop a hydraulic model of the reach that includes the gauging station.

This may reveal the influence of downstream water levels on the high flow rating.
Examples: Constrictions at structures or inflows from downstream tributaries.

It may also show the effects of hysteresis, which is often due to storage of water on the floodplain.

Flood event data

Rationale

Similar to flood peak data, visually examining flood event data can reveal much about the hydrological behaviour of a watercourse.

It is also vital for checking the quality of data.
Example: Spotting spurious peaks or periods of missing data.

It can be useful to plot rainfall and flow together, as this may identify problems which may cause an event to be rejected (**4** A.4).

Description

Model parameters for the ReFH method (and the FEH rainfall-runoff method) are best estimated from flood event data, which is normally recorded at a time step of 15 minutes.

The ReFH method requires flow and rainfall data. It does not include the provision to use river level data for deriving time to peak, as in the FEH rainfall-runoff method. However, given the wider availability of river level recorders, there are likely to be some situations where analysts judge that level data are helpful in guiding the selection of parameters for the ReFH method.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	Flood event analysis needs to be based on catchment-average rainfall data. On smaller catchments with a nearby recording raingauge, it is often acceptable to treat the data from that gauge as the catchment average. On larger catchments, you should average data over several recording gauges. If these are not available, it is possible to use daily raingauges to improve the averaging.
2	Radar-derived rainfall data can provide a valuable additional source of information, when used with measurements from at least one raingauge (**4** A.4.1).
3	The ReFH method can also use potential evaporation data. These are required for setting the initial soil moisture when estimating model parameters from observed data or simulating observed events. One option is to use an annual sinusoidal series, which only needs the annual mean daily potential evaporation. Another option is to enter a potential evaporation time series, which can be obtained from the Met Office's MORECS or MOSES systems. For more guidance on how to obtain this data, see 414_07 Accessing Hydrological Data and Information, on Easinet.

Flood history

Rationale

You can often make flood estimates at longer return periods much more reliable by carrying out a historical review and incorporating floods before the period of gauged records.
Reference: Bayliss and Reed (2001).

Most studies need an estimate of the 100-year flood, which is not that likely to have occurred during most gauged records (see The risk equation below).

Historical reviews, similar to pooled analysis, can supply a wider perspective (**1** C). Uncovering forgotten information can also add credibility to the analysis and contribute to public understanding of flood risk (**1** C.2).

The risk equation

The probability p that a T-year return period flood (or larger) will occur at least once in an N year period is given by the risk equation:

$$p = 1 - (1 - 1/T)^N$$

A typical record length for flood peak data is 40 years. The risk equation gives the probability of a 100-year flood occurring during this period as 33%. In other words, there is a one in three chance that the 40-year record will include the 100-year flood.

Description

Historical reviews are often required in flood estimation studies. In many studies, they are too often left out or only given lip service. Perhaps they are seen to need more effort and thought than a pooled analysis that can be carried out using the FEH software.

However, historical reviews can be rewarding as well as valuable and they can have a large influence on the design flows. For example, a study (Black and Fadipe, 2009) found that 100-year flood flows at three out of four sites increased by more than 50% as a result of incorporating reliable historical information.

There is a great deal of historical flood information available. Archer (1999) suggests that you may obtain useful information for a period of at least 150 years in virtually every flood-prone catchment in England. MacDonald (2009) describes how relatively good records of flooding are available for large catchments since 1500, and very good records since 1750.

MacDonald and Black (2010) present a reassessment of flood risk at York using documentary records dating back to 1263AD. The study showed that the FEH estimates of 100-year flow (whether from single-site or pooled analysis) were implausibly high as the estimated flow rates had not been reached in the entire 737-year historic series. The preferred estimate of 100-year flow was nearly 20% smaller than the FEH pooled estimate.

Going even further back, historical reviews can extend into palaeoflood investigations which use evidence such as sediment deposits, tree rings and pollen to develop very long-term records of major floods. You can find an example in Brown (2009) who developed a 1500 year record of flood flows on the River Trent using geomorphological and geoarchaeological data.

Palaeoflood techniques have particular potential in making assessments of the very largest floods that a landscape has experienced. You should consider using palaeoflood methods for high-risk studies such as those involving the safety of dams or facilities handling catastrophically dangerous materials (Bayliss and Reed, 2001).

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	**Project Managers and analysts:** you must agree at the start of a study whether to include a historical review. For all except simple or routine studies, see Table 2 on page 12, you should normally include a historical review or an update of a previous review, if it will supplement an existing gauged flow record. While the scale of the study should dictate the effort employed, experience suggests that a thorough review of historical sources may take no more than two to eight days.
2	For information, you can refer to: ▪ the FEH (**1** C) and Bayliss and Reed, 2001 for advice on carrying out a historical review; ▪ the BHS Chronology of British Hydrological Events, although rather qualitative, is a very useful resource for information up to 1935; ▪ other websites can add information, usually on more recent events; ▪ numerous other sources, including local newspapers, local history books, the British Rainfall publication series and flood marks on buildings. It can be important to go back to the original sources of historical data and to critically assess their quality (see Bayliss and Reed, 2001) They can provide source information for studies on neighbouring catchments (for example, dates of flooding) and should be added to the BHS Chronology website, to enable wider access.
3	In some cases, historic information can be used to guide the choice between a single-site and a pooled growth curve, without any need for quantitative data. One way to approach this is to rank historic events, or classify them as major, moderate or minor floods. You can then compare the results with the size of the highest floods within the gauged record, to see whether the single-site growth curve is consistent with the longer-term history. The FEH recommends an informal method (**1** C.3.3) for incorporating historical flood data into estimation of the flood frequency curve. Archer (1999) outlines an example of using practical informal methods. More detail appears in Bayliss and Reed (2001), which reviews various methods for incorporating historical data in a flood frequency analysis and advocates using simple methods. Take care if there have been substantial changes to the catchment that would affect its flood behaviour. You may also need to consider the effects of climatic fluctuations, although MacDonald and Black (2010) point out that, once long periods are considered (over 250 years), climatic variability becomes inescapable, and that inclusion of

	flood rich and flood poor periods leads to more robust flood frequency estimates.
4	Bayliss and Reed (2001) recommend particular care in cases when the historical flood data suggest that the preferred frequency curve is too high, because of the scope to overlook floods. The FEH suggests giving greater respect to historical flood data when they suggest that the preferred frequency curve may be too low. You should adjust the fitted distribution to acknowledge the historical data (**1** C.3.3).

Catchment descriptors

Information available

The FEH CD-ROM version 1 offered 20 catchment descriptors for sites within the resolution of the underlying digital terrain model, IHDTM.

Version 2 of the CD-ROM provided three additional catchment descriptors based on an improved and more recent land cover map, in particular $URBEXT_{2000}$. $URBEXT_{2000}$ is defined differently from $URBEXT_{1990}$ and typically has a higher value for the same degree of urbanisation **Reference**: See Bayliss, A.C., Black, K.B., Fava-Verde, A., Kjeldsen, T.R. (2007) listed in Related documents.

It is based on three land cover types: urban, suburban and inland bare ground (which in urban areas corresponds to gravel car parks, railway sidings, derelict areas and so on). Therefore, do not use $URBEXT_{2000}$ in the original FEH equations for urban adjustments. Only use it in equations developed specifically for $URBEXT_{2000}$.

Version 3 of the CD-ROM adds another three catchment descriptors. **Reference**: Kjeldsen, T.R., Jones, D. A. and Bayliss, A.C. (2008) listed in Related documents):

1. FPEXT: floodplain extent, the fraction of the catchment inundated by a 100-year flood, used when selecting pooling groups;
2. FPLOC: floodplain location relative to the catchment outlet;
3. FPDBAR: mean depth of water on floodplains in a 100-year event.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	Ten descriptors are used in flood estimation procedures. The others provide extra information for the analyst to use when comparing catchments for data transfer and selecting pooling groups.
2	Do not use catchment descriptors, obtained from the FEH CD-ROM, without, at least, a rudimentary check. In particular, confirm **catchment boundaries**, based on the IHDTM, and therefore area (AREA), urban extent (URBEXT) and the effect of reservoirs and lakes (FARL). Use information such as OS maps, digital elevation models (DEMs) and local knowledge. **Analysts:** you may find that a site of interest will not be found within the resolution of the FEH CD-ROM data. Version 2 of the CD-ROM corrected some of the more major errors, but you will find places

	where the catchment boundaries are still in error. Checking is particularly important for small catchments, see Figure 5, on page 28.
3	It's particularly worthwhile to verify catchment boundaries: ▪ in fenland areas; ▪ or when there are artificial influences; **Examples:** Reservoir catchwaters, diversion channels or embankments. ▪ or groundwater interactions. You should also investigate any other local anomalies that might affect hydrological response.
4	The best way to check a catchment boundary is usually with GIS. But, due to data licensing restrictions, it is not possible to import boundaries from the FEH CD-ROM to a GIS package. CEH Wallingford can provide digital boundaries on request for a fee. Or you can visually compare boundaries from the CD-ROM with those derived in a GIS from information such as the Nextmap DEM or contours on an OS map. You can print a map at a user-defined scale and you can import shape files and add them to the map display.
5	As well as catchment boundaries, you should normally check **soil characteristics** from the HOST classification. This is particularly important on small catchments, where the use of SPRHOST may be inappropriate due to the 1 km resolution of the summary HOST data (**5** 5.4). You can check soil characteristics against soil and geology maps. **Note:** The Soil Survey of England and Wales (now the National Soil Resources Institute) published a 1:250,000 Soil Map of England and Wales in 1983 and have larger-scale maps of some areas, see the Landis website. For an online summary of the 1:250,000 map see this Soilscapes page. For important studies on smaller catchments, a site survey of soil properties may be worthwhile. Appendix C of FEH Volume 4 lists the HOST classes allocated to each soil association shown on the soil maps. You can derive SPRHOST and BFIHOST from the HOST classes, using **5** Table 5.1. You should always view low values of SPRHOST in what appear to be relatively impermeable areas with suspicion. **Example:** Some Pennine catchments where soil associations on the Soil Survey map indicate slow-draining soils having SPRHOST below 20%, whereas 30-50% would be expected.
6	It is worth carrying out a quick check of the **FARL** value. For most catchments, this will be close to 1.0, indicating no significant attenuation from lakes or reservoirs. Many flood storage reservoirs are not included in the dataset on which FARL is based and there are some errors in the CD-ROM where outflows from water bodies are in the wrong location. You can correct these omissions or errors by manually calculating FARL (**5** 4.3); see Item 7.
7	When you find any FEH CD-ROM catchment boundaries are

incorrect, you will need to manually adjust the descriptor values (**5** 7.2.1).

You can adjust many of the catchment descriptors using a simple area weighting method (**5** 7.2.2). However, this is not applicable to all descriptors.

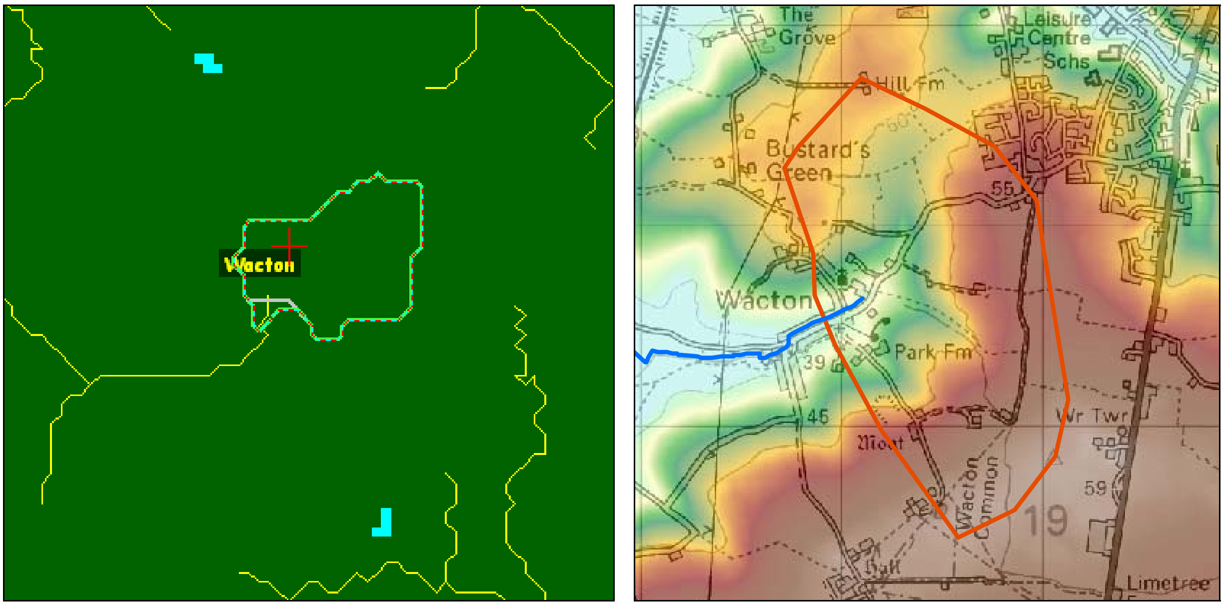
You cannot adjust FARL by area weighting.

You can estimate DPLBAR approximately by regression on the catchment area.

You must apply adjustment procedures with care.

Analysts: you should take account of the derivation and purpose of the descriptor and record the adjustment fully.

Figure 5 **Example:** The maps below show a catchment boundary error around Wacton Stream, Norfolk.



FEH CD-ROM: catchment area is 0.55 km^2.

Catchment boundary from Nextmap DEM: area is 2.01 km^2.

Notifying errors

Notify any errors in catchment boundaries or descriptors to CEH Wallingford, by e-mail, to fehsofthelp@ceh.ac.uk.

3. Choice of methods

Overview

Basic methods available

The basic methods available are:

- the FEH statistical method;
- the ReFH method;
- the FEH rainfall-runoff method, sometimes known as the FSR rainfall-runoff method because the FEH made few changes.
  Superseded by ReFH in most cases but versions of the method are still applicable for reservoir safety work and on pumped catchments.
- various older methods used on very small catchments or for greenfield runoff estimation.

Six maxims

The FEH offers six maxims (***1*** *2.2*), summarised below. These should guide the choice of method.

1. Flood frequency is best estimated from gauged data.
2. While flood data at the subject site are of greatest value, data transfers from a nearby site, or a similar catchment, are also useful.
3. Estimation of key variables from catchment descriptors alone should be a method of last resort. Some kind of data transfer is usually feasible and preferable.
4. The most appropriate choice of method is a matter of experience and may be influenced by the requirements of the study and the nature of the catchment. Most importantly, it will be influenced by the available data.
5. In some cases, a hybrid method, combining estimates by statistical and rainfall-runoff approaches, is appropriate.
6. There is always more information. An estimate based on readily available data may be shown to be suspect by a more enquiring analyst.

Analysts: approach to choosing a method

The six maxims stress the need for you to think, at all stages, about the problem you are solving and not to simply feed data into software packages.

These guidelines further promote this philosophy. You have to make decisions and you may have to improvise. You have to rely on judgement based on experience, the nature of the problem and, not least, the available data and time.

When necessary, you should seek assistance from a senior colleague.

Prescriptive rules on choice of method are neither feasible nor desirable. The FEH says that choice of method is 'both complex and subjective'. It acknowledges that 'different users will obtain different results, by bringing different data and experience to bear' (1 5.1).

In this chapter

This chapter gives guidance on the basic choice between approaches. For many studies, this means deciding between a statistical and a rainfall-runoff approach. It includes a suggested framework for decision-making and emphasises the importance of starting with a method statement.

For information on the limitations of various methods, see Chapter 5, on page 70.

For guidelines on choosing a method for unusual catchments, see Chapter 6, on page 77.

A framework for choosing a method

Summary

The diagram in Figure 6, on page 31, illustrates a framework for decision-making.

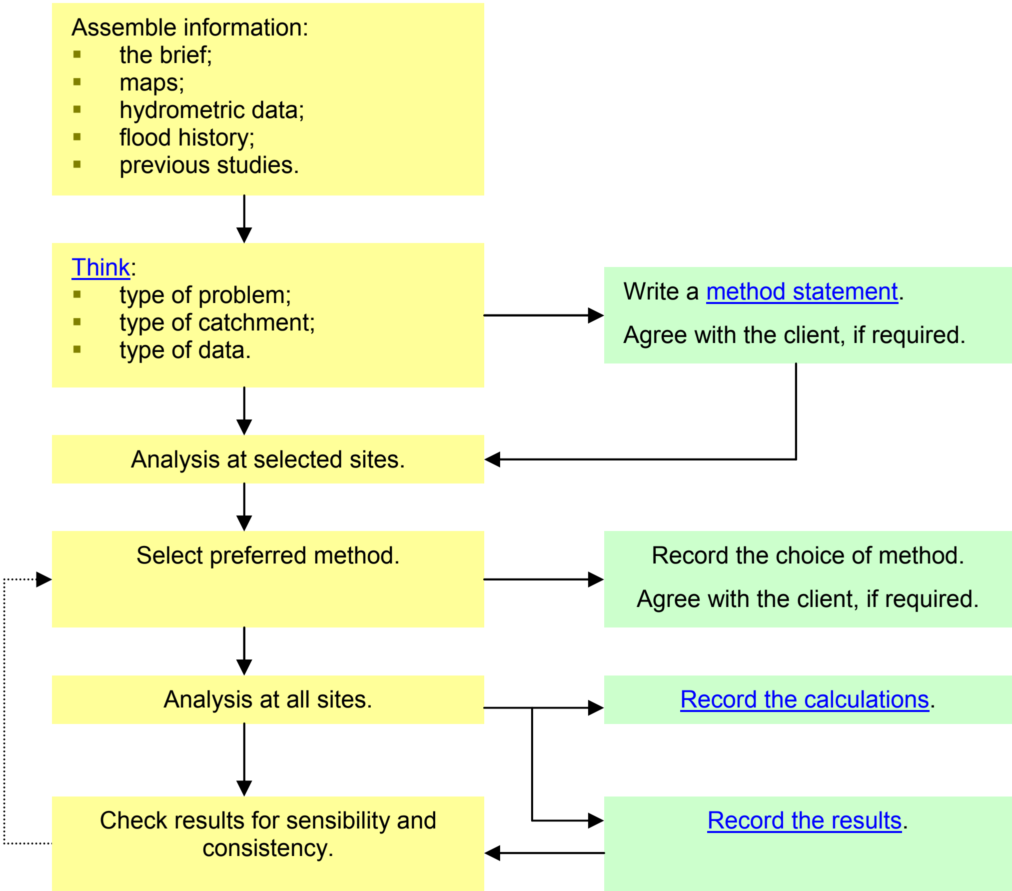
Choosing the method occurs at several stages:

- the analyst makes an initial choice, which often involves a number of possible approaches, during preparation of the method statement;
- they then derive initial flood estimates, using the selected methods, often just at example locations, such as gauging stations or important confluences or flood risk areas;
- by comparing results, they select the preferred method (or methods) and apply this at all locations;
- finally, they check the results and, if necessary, they revisit the calculations.

If analysts follow this framework, there is no need to carry out calculations at numerous sites several times over. This takes a lot of time and tends to result in multiple tables of results, with the potential for misinterpretation.

Figure 6 The diagram below illustrates a framework for decision-making that is intended to guide analysts through the thought processes that are required. It shows the main stages they should follow in flood estimation for a typical study, involving multiple flow estimation points (such as a flood mapping study or CFMP). They can apply a simpler version to smaller-scale studies.

The right-hand column of the diagram, in light green, shows the outputs that they should produce. Select links in the diagram to move to sections in this document providing more details.



The need to think

Three factors to think about

Choice of method is important and rarely straightforward. The many factors to consider can be grouped into three categories. Select the links to read more details in Chapter 6 on specific issues.

1. type of problem;
   Examples: Is a hydrograph needed? How will the flows be applied to any hydraulic model? Is the flood estimate for a reservoir spillway assessment? What return period is required?
2. type of catchment;
   Examples: Is it large? Permeable? Urban? Pumped? Are there disparate subcatchments? (**4** 9.2) Is there a reservoir? (**4** 8) Are there extensive floodplains? (**1** 3.1.2)
3. type of data.
   Examples: Is there a flood peak record? How good are the high flow measurements? Are flood event data available? What about flood history?

Show how factors have influenced choice

It is often helpful to include a section in a hydrological report dealing with each of the above three factors. It aids the thinking process and it demonstrates that you have considered all the factors that might influence the choice of method.

Preparing method statements

Time needed

Preparing a method statement helps analysts to plan their studies carefully. While half a day may be adequate for a preliminary assessment, thorough flood estimation studies can take many days, even weeks. The FEH suggests allowing five to 50 days (**1** Interlude, p 37).

Major flood studies need planning in advance, with time to review and update data. There are many factors to consider when choosing the approach to adopt.

Analysts: you should agree the level of detail required with the Project Manager at the start of a study. It will depend on the application and its importance, and on available data.

Description

The method statement represents an opportunity to develop a conceptual understanding of the catchment.

It may help to visualise what conditions are likely to lead to flooding of the areas of interest (sometimes referred to as the 'design condition'). See Examples of conditions, on the next page.

Examples of conditions

Consider these examples:

- is flooding likely to be dominated by the magnitude of peak flows or are flood volumes or tide levels also likely to have an effect?
- will it be a joint probability problem, for example due to the presence of tributaries with different hydrological characteristics, or a combination of high flows and high groundwater levels?
- is there a possibility that the most severe floods could arise from runoff generated on only part of the catchment?
  Examples: An area downstream of a reservoir or an impermeable portion of a geologically mixed catchment.
- is the catchment likely to be vulnerable to snowmelt floods?
- is there an additional risk posed by landslides, bridge collapses or flood debris creating temporary dams that could collapse?
  Example: See the report on the 2004 Boscastle flood, listed in Related documents.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	If river flow or level data are available, it is worth carrying out some initial analysis. **Example:** Plotting time series and looking at hydrograph shapes. If there are several gauging stations, then it can be worthwhile looking at travel times and correlations between peak flows, and the relative seasonality of flood peaks at different stations (as floods that occur in different seasons tend to arise from different processes). On permeable catchments, you can investigate the importance of baseflow. **Example:** By plotting daily mean flow data.
2	Review: ▪ the quality of data; See Selecting and examining flood peak data, on page 15. ▪ and the availability and quality of historical data. See Flood history, on page 24.
3	For lengthy or high-risk studies (for example, those in the bottom two rows of Table 2, on page 12), it is advisable to agree the method statement with the Project Manager before going any further. **Example:** You could sketch a conceptual model of the system and present it to Area staff who are familiar with the catchment.

Choosing between the FEH methods

Background

For the first six years after the FEH was released, the most difficult choice was often between the FEH statistical and rainfall-runoff methods because they can give such different results.

The ReFH method has now superseded the FEH rainfall-runoff method for most applications. It tends to give results that are more consistent with the statistical method. However, the choice of method can still have a major influence on the results.

Factors favouring the statistical method

The **statistical method** is likely to be preferred in many cases, particularly when any of these apply:

- there are more than two or three years of flood peak data on the watercourse (even if not at the sites of interest), from a gauging station suitable for high flow measurement;
- the catchment is larger than 1000 km^2;
  Rainfall-runoff approaches assume a catchment-wide design storm, which is less realistic for large catchments.
- the catchment is highly permeable (approximately BFIHOST>0.65).
  Neither ReFH nor the FEH rainfall-runoff method work well on permeable catchments. See Permeable catchments, on page 99, for more details.

Factors favouring the ReFH method

Examples of factors that might favour a rainfall-runoff approach (in most cases, the **ReFH method** but you may consider **FEH rainfall-runoff** in some situations) include:

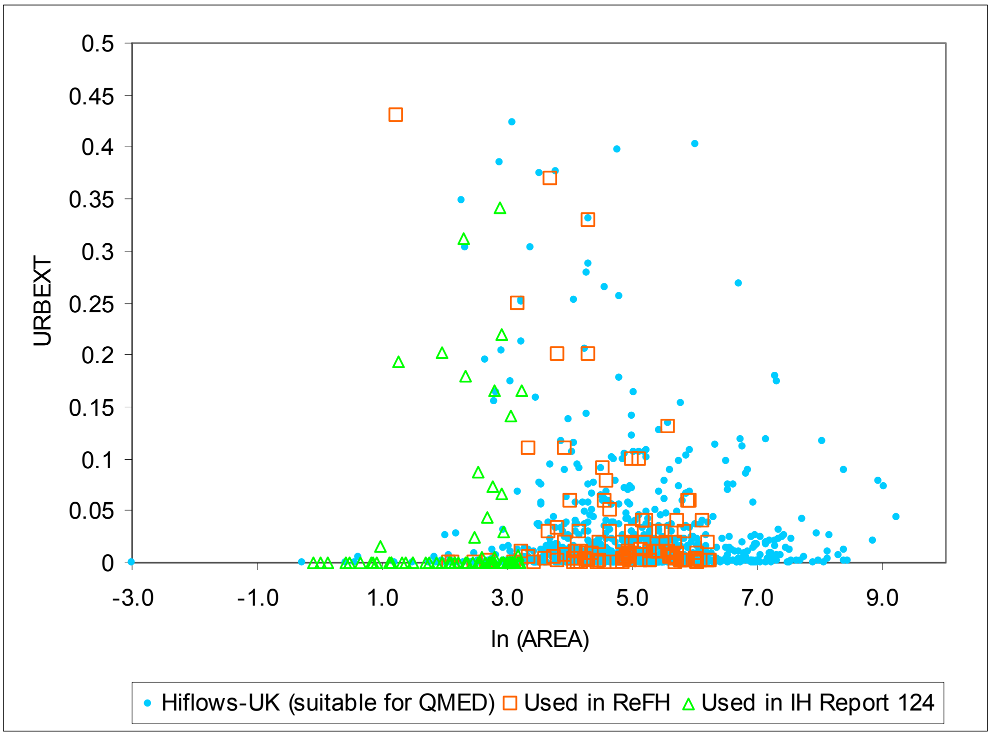
- there is no continuous flow record, but rainfall and flow data are available for five or more flood events;
- the problem involves flood storage and/or routing (for example, reservoirs or an unusually extensive floodplain) and there is no flood peak data that implicitly account for the effects of the storage;
- the return period is long, for example 1000 years;
  Estimating long return flood periods, on page 107, discusses the applicability of ReFH for long return periods. ReFH will not always be the best choice in this case and it is important to compare with the results of the statistical method.
- the study involves designing works to counter the effects of a new urban development and/or storm sewer design;
- the catchment includes subcatchments with widely differing flood responses;
- the catchment is low-lying, with pumped drainage.
  See Pumped catchments, on page 81.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	Because the statistical method is based on a much larger dataset of flood events, and has been more directly calibrated to reproduce flood frequency on UK catchments, you should often prefer it to any rainfall-runoff approach (**1** 5.6). However, the choice is not always clear cut. Sometimes you will choose both approaches for different reasons, such as those listed in Factors favouring the statistical method and Factors favouring the ReFH method, on page 34. It will often be worth deriving results at example sites using several methods. In doing so, additional information may emerge which can help the final decision. The FEH suggests that sometimes an intermediate estimate can be adopted (**1** 5.6).
2	Like the FEH rainfall-runoff method, the ReFH method's design procedure was calibrated with a dataset much smaller than that available for the statistical method: 100 catchments compared with around 960 in the HiFlows-UK dataset that the statistical method can draw on for flood frequency estimation. **Note:** Although several catchments were added to the flood event archive during the ReFH research, many were found to have insufficient event data for large floods. Figure 7, on page 36, illustrates this. It shows, in particular, the lack of small, large or urban catchments available for calibrating ReFH. A similar range of catchments was used in calibrating design events in the FEH rainfall-runoff method.
3	It's important to understand that the quality of flood frequency estimates, from design event methods such as ReFH or FEH rainfall-runoff, is influenced by the appropriateness of the 'design package', (that is, the combination of storm depth, duration, profile and soil moisture) to the catchment. It is not just influenced by the quality of the rainfall-runoff model parameter estimates (**1** 12.2). The ReFH method, on page 64, gives more information on when you should, and should not, use ReFH.
4	The FEH discourages users from choosing a method because: ▪ it gives the highest or lowest flow (**3** Box 7.1); ▪ or it gives results that match those from a previous study (**1** 5.8).
5	**Analysts:** there will be times when the FEH methods are inappropriate and you may need to consider an alternative method (see Small catchments and greenfield runoff, on page 87).

Figure 7 The graph below shows a range of catchment types that the FEH statistical, ReFH and IH Report 124 methods draw on.



Hybrid methods

Description

When you need a design hydrograph, the preferred approach will sometimes be a hybrid method.

A hybrid method combines a hydrograph shape with an estimate of peak flow by the statistical method (**1** 5.6, 3 10 and **4** 7.3). Hybrid methods are used commonly in hydrodynamic modelling studies.

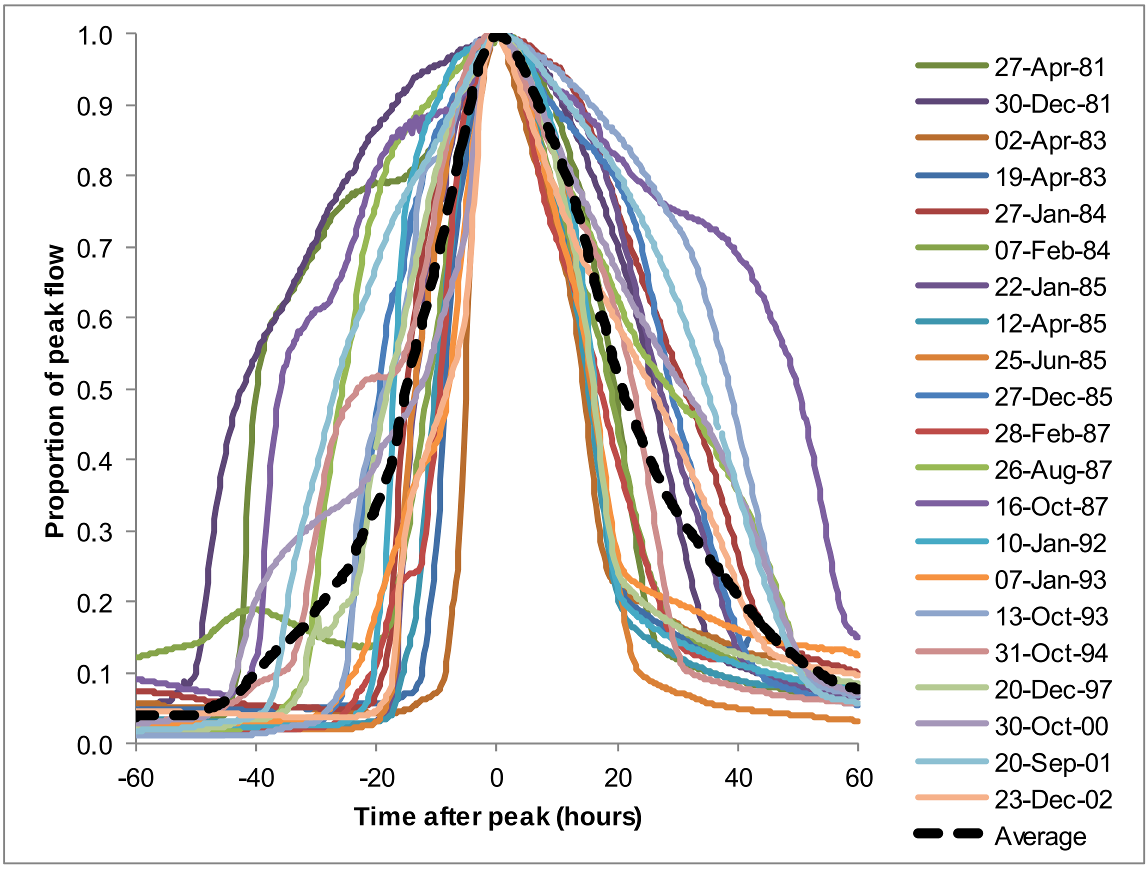
Possible methods

The FEH suggests three hybrid methods, listed below. Others, such as (d) below, are used occasionally.

Possible options	Description and guidelines
(a) Generating the hydrograph from the ReFH method, then scaling it to match the statistical estimate.	This is the quickest method and often the best. You can apply it to gauged or ungauged catchments. The disadvantage is that it is rather a 'brutal' application of the ReFH method, losing the information on runoff volume. It is not well suited to large catchments or those dominated by storage, where hydrograph shapes are less likely to resemble the simple ReFH hydrograph. However, it can sometimes be applied in these catchments by splitting them up into subcatchments and routing the resulting hydrographs.
(b) Adjusting the parameters of the ReFH model until the simulated peak flows match the preferred values (**3** 10.2).	This might appear more elegant than option (a) but you should use it with caution. It is only valid if the parameters have not already been estimated from local flood event data. It assumes that the reason for the ReFH method giving a poor answer is that the model parameters have been poorly estimated, which is not

	always the case. It may prove difficult to match the statistical results over a range of return periods, because the ReFH method may give a different growth curve.
(c) Using a simplified model of the hydrograph shape (**3** 10.4).	This constructs a symmetrical hydrograph, using a parameter defining the width of the hydrograph at half the peak flow. You can estimate this from recorded events or from Tp(0). This approach is rarely used.
(d) Basing the hydrograph shape on gauged flow data.	You can derive a shape by averaging the hydrographs of major events, standardised by their peaks. You can do this by: ▪ simple averaging of the hydrograph ordinates (see Figure 8 below); ▪ or using a more sophisticated procedure, such as deriving the duration of Exceedence of selected percentiles of peak flow. **Reference**: Archer, D., Foster, M., Faulkner, D. and Mawsdley, J. (2000) listed in Related documents. The above paper recommends using observed events on catchments with significant storage (in aquifers, lakes or floodplains), unless the storage is to be modelled explicitly as part of the study. A simpler alternative is to use the shape of the largest flood on record, particularly attractive if the peak is thought to have a return period similar to that of the required design event. This approach is only possible at a gauging station or shortly up or down river.

Figure 8 The graph below shows the average flood hydrograph shape on the River Ore at Beversham.



Checking results

Questions to ask

It is vital to check that flood estimates are sensible. This can sometimes help in choosing between results from alternative methods. Some questions to ask are listed in the table below. Select the links in the table to read more detail in Chapter 6.

If there are multiple flow estimation points, some of the questions are best answered graphically.
Examples: Plotting long sections of specific discharge against location or maps of growth factors.

Item	Question
1	Are the results spatially consistent between upstream and downstream points and at confluences?
2	Are the growth factors sensible? In the FSR regional growth curves, the ratio of the 100-year to the 2-year flow varies from 2.1 to 4.0. You should investigate 100-year growth factors that fall significantly outside this range. You can sometimes justify much higher growth factors on highly permeable, clay or urban catchments (or catchments containing mixtures of these characteristics), where they are consistent with the flood history.
3	What specific discharge (that is, flow in litres/second/hectare) do the results equate to? Can you explain the variations in specific discharges between different locations across the catchment?
4	What return period do the results imply for major events during the gauged record? This can help in the choice between single site and pooled curves.
5	Are the results consistent with the longer-term flood history?
6	Are flows generated by a hydrodynamic or routing model, consistent with those estimated from a lumped catchment FEH estimate, at locations within the model reach? If not, the inconsistency needs to be explained and you will need to make a decision about the preferred method for flood estimation.

Using the checklist

You can use the Checklist for reviewing flood estimates (SD03) which includes the questions above and others. This checklist can be used by:

- analysts checking their own work;
- supervisors carrying out internal reviews;
- and project managers reviewing calculations.

Conclusion

Use the six maxims as a guide

Use the six maxims, on page 29, to guide all aspects of the choice of method.

As the sixth one says, 'there is always more information'. Some pragmatism is needed in deciding when a flood estimate is good enough for the needs of the study.

No prescriptive set of rules

The reconciliation of estimates by different methods is a skilled task. It is not possible to give a prescriptive set of rules.

Part of the skill is in knowing when - having explored the possibility – to accept or reject a particular adjustment.

Adopting unusual approaches

Sometimes the best flood estimates are derived from approaches, which do something out of the ordinary.
Examples: Incorporating historical data or accounting for unusual flood-generating processes.

If you are adopting an approach that deviates from normal practice, it is all the more essential to justify the decisions made and check that the answers are sensible by following the advice given in this chapter. Too often, an unusual approach results in flood estimates that are difficult to defend and no better (or even worse) than could be obtained using more conventional methods.

Incorporating information from hydraulic models

Sometimes the only indication that the design flows need altering comes once they have been applied to a hydraulic model. Water levels or flood extents are easier to visualise than flow rates. If the model results are not consistent with local knowledge or flood history, then this can act as a prompt to revise the design flows, as long as there is enough confidence in the hydraulic model structure and parameter values. This last point is important because sometimes it is the model or the modeller's assumptions that need to be altered. Flow rates inferred using an uncalibrated hydraulic model should not be treated with the same level of confidence as those derived from a rating curve at a gauging station.

4. Advice and cautions on FEH and ReFH methods

Overview

Reminders, guidance and latest research

There are many opportunities for choice when applying the FEH methods, including somewhere the unwary might miss a subtle variation in the options facing them. The sections in this chapter aim to help less experienced analysts use the FEH and act as a reminder to more frequent users. They concentrate mainly on areas that FEH users tend to find difficult, or areas that tend to have the largest effects on the results.

The sections also highlight findings from more recent research, giving advice on when and how it to put into practice.

Analysts: general advice

You should establish what previous flood studies have been carried out for the subject site or within its catchment. These are often worth examining. They may provide information on data sources and accuracy, catchment conditions and flood history.

You should note results for comparison and investigate unexpected discrepancies, except where you consider, and record, that this is unnecessary.

In this chapter

This chapter includes the following topics:

Design rainfall

Description of the DDF model

The depth-duration-frequency (DDF) model provided on the FEH CD-ROM enables the estimation of design rainfalls for any location in the UK or the return period of an observed rainfall.

The DDF model is fitted to rainfalls with durations from one hour to eight days (**2** 12.1).

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	You can rely on the results for durations as short as 30 minutes. For shorter durations, you must revert to the Flood Studies Report (FSR) rainfall statistics, listed in Related documents.
2	Rather than using the FSR statistics directly, we suggest that you use them to factor down to shorter durations from the 1-hour FEH rainfall depth. **Example:** You require a 15-minute depth. Calculate the ratio of the 15-minute and 1-hour depths from FSR statistics. Then multiply it by the 1-hour depth from FEH.
3	Design rainfalls produced by the DDF model are for sliding durations, which are durations that start at any time (**2** 2.5). There is an option to adjust rainfall depths to convert between fixed (duration starts at discrete times only) and sliding durations. You will normally only need this if you are estimating the return period of a storm that has been measured only at daily raingauges.
4	Flood estimates from rainfall-runoff approaches need a catchment-average rainfall. You can estimate catchment rainfall automatically using the DDF model provided on the rainfall model part of the FEH CD-ROM. The areal reduction factor formula is in **2** 3.4.
5	**Definition:** The index variable, **RMED**, is the median of annual maximum rainfalls (for a given duration) at a site. Digital maps of RMED on a 1 km grid were developed for combination with rainfall growth curves. Catchment average values of RMED, on the catchment descriptor part of the FEH CD-ROM, are not for use in rainfall frequency estimation (**2** 7.1). **Analysts:** you should always use the rainfall DDF model rather than the RMED values given with catchment descriptors.
6	The FEH recommends that, generally you should not use local data for refining design rainfall estimates, even where rainfall records are long (**2** 12.2). However, given that 17 years has elapsed since the FEH rainfall data was collected, you may find sites where you can calculate a more reliable estimate of RMED than the FEH value, particularly for durations shorter than 1 day.

Revised rainfall frequency statistics have been developed as part of a research project at CEH Wallingford; see Stewart, Lisa and others (2010). They are expected to be available in a future release of the FEH CD-ROM. The main focus of the project was improving estimates for extreme return periods (see Flood estimation for reservoir safety, on page 104) but design rainfalls for return periods of 100 years or less will also change.

Statistical method – general

Data and software

Flood estimates from the statistical method depend on the quality and extent of available gauged data:

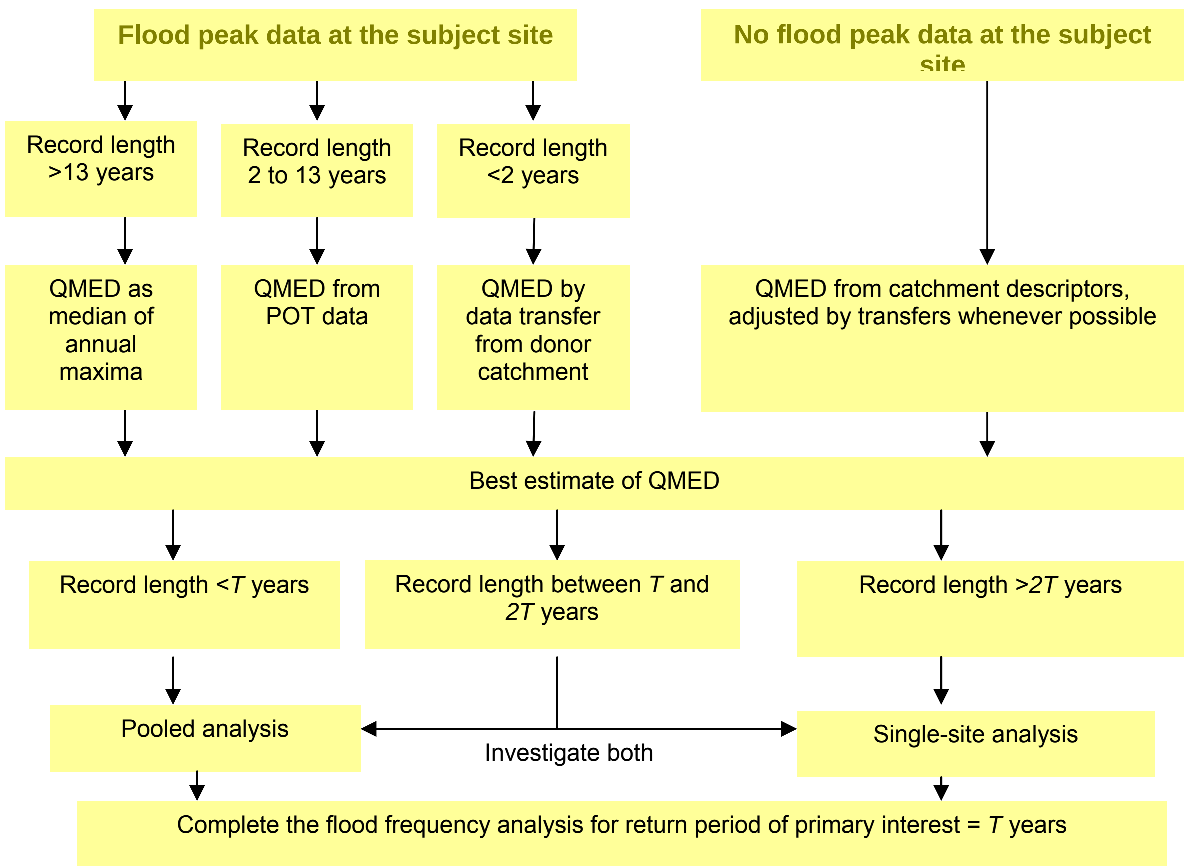
- at subject sites or donor sites to estimate QMED (**1** 5.3);
- and at pooled gauging stations to construct the pooled growth curve.

The statistical method is usually applied using WINFAP-FEH. The current version of the software is v3, released in September 2009.

WINFAP-FEH is not a straightforward package to use. Some analysts find it convenient to record their calculations in a spreadsheet, which they can also use to calculate QMED and design flows given the growth curve parameters produced by WINFAP-FEH.

Figure 9

The diagram below illustrates the main options available to analysts. There are no short cuts to choosing the most suitable method and analysts need to consult the FEH (**1** 5 and all of Volume 3).



Statistical method – index flood, QMED

Topics in this section

This section includes the following topics:

General information

Guidelines

The guidelines and advice listed in the table below are for all users.

Item	Guideline or advice
1	When you estimate QMED from flood peak data, the gauged record at the subject or donor sites should be of sufficient length and quality (**1** 5 and **3** 2.2, 12).
2	You should consider the possibility of trends in flood peaks (**3** 21.3.3, 21.5.4). If a trend is identified, there may be a case to sacrifice length of record for realism (**3** 2.2, 21).
3	Climatic variability can result in flood-rich or flood-poor periods. In QMED estimation, it is important to watch out in case such a period distorts the estimate from gauged data. The FEH recommends that QMED is adjusted for climate variation if the station's record is shorter than 14 years (**3** 2.2, 20).
4	The presence of tied values (identical annual maxima) in a flood series can compromise the estimate of QMED (**3** 2.3). You can identify these by examining the ranked flood peak data.
5	The FEH includes two additional approaches to estimate QMED that are rarely used: **1.** continuous simulation modelling, see page 69; **2.** channel dimensions (**3** 5.2). The second method can form the basis for a second opinion on QMED. QMED is estimated from the bankfull channel width. The method is only applicable on natural reaches with a bankfull width not much less than 5 m. Someone with geomorphological knowledge will need to visit the site to ensure that the conditions in FEH **3** 5.2 are met.

From catchment descriptors

The revised QMED equation

The original QMED equation provided in the FEH was superseded in 2008 by the revised equation in Science Report SC050050, listed in Related documents. It was developed using the longer and higher quality flood peak records available from the Hiflows-UK dataset and more advanced regression techniques.

This revised QMED equation is:

$$QMED = 8.3062 \ AREA^{0.8510} \, 0.1536^{\frac{1000}{SAAR}} \ FARL^{3.4451} \ 0.0460^{BFIHOST^2}$$

This equation performs significantly better than the original FEH equation. It gives lower QMED estimates at most sites in East Anglia and the English Midlands (where SAAR is low), and higher estimates in most other locations, apart from where SAAR is very high. This revised equation was developed from data on 602 rural catchments, with catchment descriptors covering the following ranges:

- AREA: 1.6 - 4590 km^2;
- SAAR: 560 - 2850 mm;
- FARL: 0.645 - 1.000;
- BFIHOST: 0.20 - 0.97.

Using the revised QMED equation

You should use the revised equation for all new studies. It is included in v3 of WINFAP-FEH.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	You should only consider estimating QMED from catchment descriptors as a last resort.
2	You should not: ▪ extrapolate the formula beyond its calibration range; ▪ or rely on it when FARL<0.9 due to reservoirs (**3** 3.3, 13).
3	The model for QMED cannot account for all catchment features. **Example:** You should not use it on karst catchments and generally avoid it on artificially drained fenland catchments.
4	The FEH includes suggestions on using locally derived values for some of the variables in the catchment descriptor equation for QMED, for example SPR or BFI (**3** 13.7.3). The suggestions on using SPR are no longer relevant because the revised QMED equation excludes SPRHOST. It would be possible to substitute a gauged estimate of BFI for BFIHOST in the above equation, for example at a gauging station, which provides reasonable data for average flows but poor flood peak data. However, there is no specific recommendation available on the value of this adjustment.

Urban adjustment

The issues

Urbanisation modifies the natural flood response. In the absence of flood peak data for the site of interest, both QMED and the growth curve need to be adjusted for urbanisation (**3** 9). The guidance below explains some important issues with the adjustment of QMED within WINFAP-FEH.

Although the FEH only mentions performing the urban adjustment for urban catchments, it makes sense to apply it on all catchments to avoid a discontinuity when $URBEXT_{2000}$ exceeds the threshold value of 0.030.

For more general advice on urban catchments, refer to Development control and urban catchments.

Using WINFAP-FEH to adjust QMED for urbanisation

To adjust QMED for urbanisation, multiply the rural estimate of QMED (from catchment descriptors) by an urban adjustment factor, UAF.

The UAF used in v3.0.003 of WINFAP-FEH is calculated from a pair of formulae that have not been published together. Despite the message given within WINFAP-FEH, the adjustment method is not quite the same as that published by Kjeldsen (the reference is given as 2009 but the paper actually came out in 2010; it is listed in Related documents).

UAF is calculated by WINFAP-FEH using Equation 8 from Kjeldsen (2010):

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

where PRUAF is the percentage runoff urban adjustment factor, which quantifies the effect of urbanisation on percentage runoff.

In Kjeldsen (2010) PRUAF is calculated from a formula based on BFIHOST (Equation 6 in the paper). However, when WINFAP-FEH v3 was developed it used an earlier version of the formula from Bayliss *et al.*, 2007 in which PRUAF was calculated from SPRHOST:

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

It is noted that the BFIHOST formula can give near-infinite values for PRUAF as BFIHOST approaches 1.

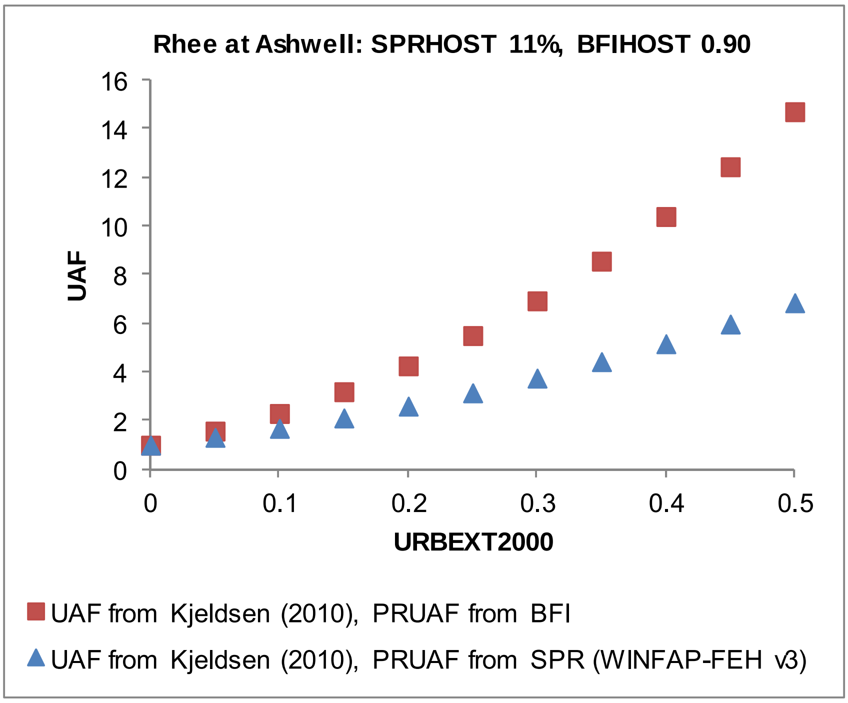
There are plans that in the next release of WINFAP-FEH the full Kjeldsen (2010) method will be implemented with a modification, as proposed by CEH, to avoid the discontinuity in catchments with a BFIHOST value of 1.

Although there is some concern that the UAF formula applied in WINFAP-FEH was developed using values of PRUAF that were defined differently to their implementation in WINFAP-FEH, in fact the alternative formulae for PRUAF result in similar values of UAF on average for most catchments. The exceptions to this are permeable catchments.

Urban adjustment on highly permeable catchments

The two methods start to diverge for highly permeable catchments. Figure 10 shows an example of the difference between urban adjustment factors for a chalk catchment with BFIHOST = 0.90. The actual urban extent for this catchment is 0.15, for which the urban adjustment factor calculated from BFIHOST is 1.5 times that calculated from SPRHOST.

Figure 10 Comparison of urban adjustment factors derived from BFIHOST and SPRHOST



Urban adjustment of QMED on highly permeable catchments

If you are dealing with an urbanised catchment for which BFIHOST > 0.8, you need to be aware UAF calculated using the two PRUAF methods may be very different, and the UAF calculated in WINFAP-FEH is likely to be an underestimate.

Note that WINFAP-FEH v3 does not offer the option to calculate UAF from an alternative method. The option to select versions 1 to 3 for urban adjustment applies only to the growth curve, not to QMED.

You should not revert to the Bayliss *et al.*, 2007 method for adjusting QMED because it was based on the original FEH regression formula for QMED.

It is important to understand that urban, highly permeable catchments are outside the range of the vast majority of catchments from which FEH methods have been developed. There is very little data on the effects of urbanisation on highly permeable catchments and so it is difficult to know which method is more appropriate. On such catchments the only reliable flood estimates are likely to be derived from local flow data.

Additional notes on adjusting QMED

When using alternative software such as a spreadsheet to calculate QMED, you should record and justify what method you use for the urban adjustment with the above issues in mind.

Adjustment of growth curves

Recent research (Kjeldsen, 2010) has led to a revision of the urban adjustment procedures. The research recommends that the UAF is used only for the adjustment of QMED. Unlike in earlier methods, growth curves are to be adjusted using a new method that does not include UAF. You should use this new method for adjusting growth curves (see Pooled growth curves).

Data transfer

The issues

The main area where difficulty or disagreement can arise in QMED estimation is the selection of donor catchments, which are intended to improve the estimate of QMED.

The FEH provided some guidance on selecting donor and analogue catchments (for example, **1** 3.3 and **3** 4), and further ideas emerged through the experience of FEH users.

Science Report SC050050, see the FSR listed in Related documents, presents a revised method for applying donor catchments. This gives a more structured way of selecting donors, but data transfer is still a subjective process with no universally applicable rules. There is scope for disagreement even between experienced hydrologists.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	It is important to take heed of the latest research. The original FEH data transfer method, at least as interpreted by some analysts, has been shown to give estimates of QMED that are worse than those obtained from catchment descriptors in many cases. **Note:** The performance of various data transfer approaches was tested by applying them at the sites of gauging stations and then comparing the resulting adjusted QMED estimates with the best estimates, that is, those obtained directly from flood peak data. To perform well, a data transfer approach needs to give an adjusted QMED value that is closer (than the initial catchment descriptor estimate) to the best estimate of QMED.
2	The data transfer method presented in Science Report SC050050 stops using the term analogue catchment and uses a single local donor. This is selected purely on the basis of distance between catchment centroids. There is no requirement for the donor to be on the same watercourse as the subject site, although in practice this is said to be likely if the catchment centroids are close. The adjustment ratio is not applied in full. Instead it is moderated by a power term, *a*, so that the adjusted QMED at the site of interest is given by: $QMED_{s,adj} = QMED_{s,cds}\left(\frac{QMED_{g,obs}}{QMED_{g,cds}}\right)^{a}$ where: ▪ $QMED_{s,adj}$: adjusted QMED at the site of interest; ▪ $QMED_{s,cds}$: initial estimate from catchment descriptors at the site of interest; ▪ $QMED_{g,obs}$: estimate from observed data at the gauging station (donor site); ▪ $QMED_{g,cds}$: estimate from catchment descriptors at the gauging station (donor site).

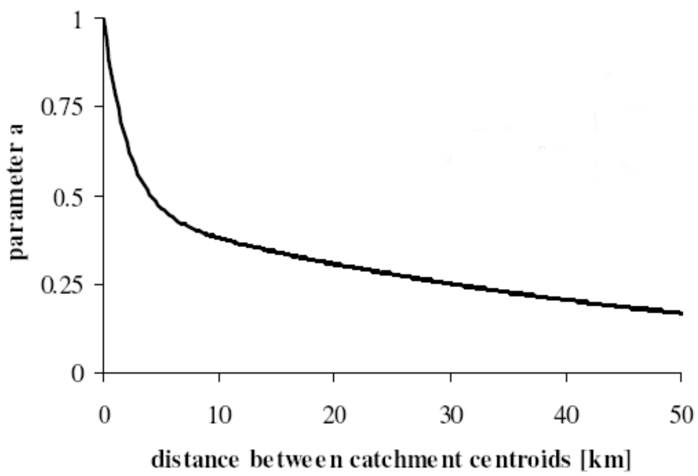
3	The FEH procedure for data transfer used the same equation, apart from the power term *a*. This reduces with distance between the catchment centroids. The adjustment has its full effect when the subject site is at a gauging station. The effect declines to quite small once the centroids are more than 10 km apart; see Figure 11, on page 49.
4	The research underlying the revised data transfer method involved comparing the performance of alternative techniques for selection of donor or analogue catchments. It found that identification of potential donor catchments should be based on geographical closeness rather than on hydrological similarity as defined by catchment descriptors. It did not examine the option of considering both distance and similarity, partly because it was considered difficult to automate the subjective process that analysts might adopt in selecting donors in order to test the process on a national scale. However, when considering an individual application it makes hydrological sense to consider the physical similarity of catchments as well as their proximity. See Figure 12, on page 50, for an example from a real study.
5	As in the FEH data transfer method, particular caution is required when proposing a transfer to or from a catchment affected by urbanisation, reservoir development, opencast mining, forest drainage or other major artificial influence (**3** 4.6). You should also be careful if flow is known to be out-of-bank below QMED in either the subject or donor catchments, resulting in attenuation of QMED. One way to estimate the potential for significant attenuation is to check the value of FPEXT.
6	A donor site should have good quality flood data, which will generally mean it is classed as suitable for QMED by HiFlows-UK. However, a review of the rating is worthwhile for high risk studies. Donor sites with longer records are preferable to those with short records, especially if the short records are thought to cover an atypical period in terms of flood frequency.
7	In some cases, there will be several suitable donors at similar distances from the subject catchment. **Analysts:** You should calculate adjustment factors for two or three potential donors in this case, rather than automatically selecting the one that happens to be nearest by what could be a small margin. If the various donor sites give similar adjustment factors, then this should strengthen confidence in the resulting estimate of QMED. If there is a wide variation in adjustment factors, then it is worth carrying out a more detailed review of the suitability of the potential donor catchments, in terms of both data quality and relevance to the subject site, before making a final choice.
8	There is no current definitive guidance on how to calculate an adjustment factor based on more than one gauge. Science Report SC050050 mentioned it as a possible topic for future research. The FEH suggests using a weighted average (**3** 4.4), where the weights reflect the suitability of the donor and the quality of the QMED estimate. It also recommends using a geometric mean rather than an arithmetic mean, which is not appropriate for the averaging of ratios.

	It would be possible to apply such an approach with the revised adjustment procedure. **Example:** Calculate a value for $\left(\frac{QMED_{g,obs}}{QMED_{g,cds}}\right)^{a}$ at several donor sites. Then derive a weighted average of the individual factors.
9	You should check adjusted estimates of QMED to ensure they are consistent with observations at upstream or downstream gauging stations. Consistency is not guaranteed when using the data transfer method in SC050050. In some situations applying the power term, *a*, from the revised transfer procedure can lead to inconsistent results with upstream and/or downstream sites. In these cases you are advised to ignore the moderation term and use a more appropriate adjustment factor. See Figure 13, on page 51, for an example.

Figure 11

The graph below shows the relationship between moderation term, a, and the distance between centriods, *dij*.

$a = 0.4598*\exp(-0.020*d_{ij}) + (1-0.4598)*\exp(-0.4785*d_{ij})$



Graph provided in personal communication from Thomas Kjeldsen at CEH Wallingford.

Figure 12: example from a real study

Description of the site

The Morton Beck near Keighley in West Yorkshire has a catchment area of 10 km^2. The gauged catchment with its centroid closest to that of the Morton Beck is the River Aire at Lemonroyd Weir with an area of 865 km^2. The centroids of the catchments are just 1.8 km apart, yet the catchments are clearly very different (one is nearly 100 times the size of the other).

Decision

In reality, Lemonroyd Weir would not be suitable as a donor because it is urbanised. But even if it had been rural, it would have been difficult to believe that it could be relied on as a valid donor site for the Morton Beck catchment.

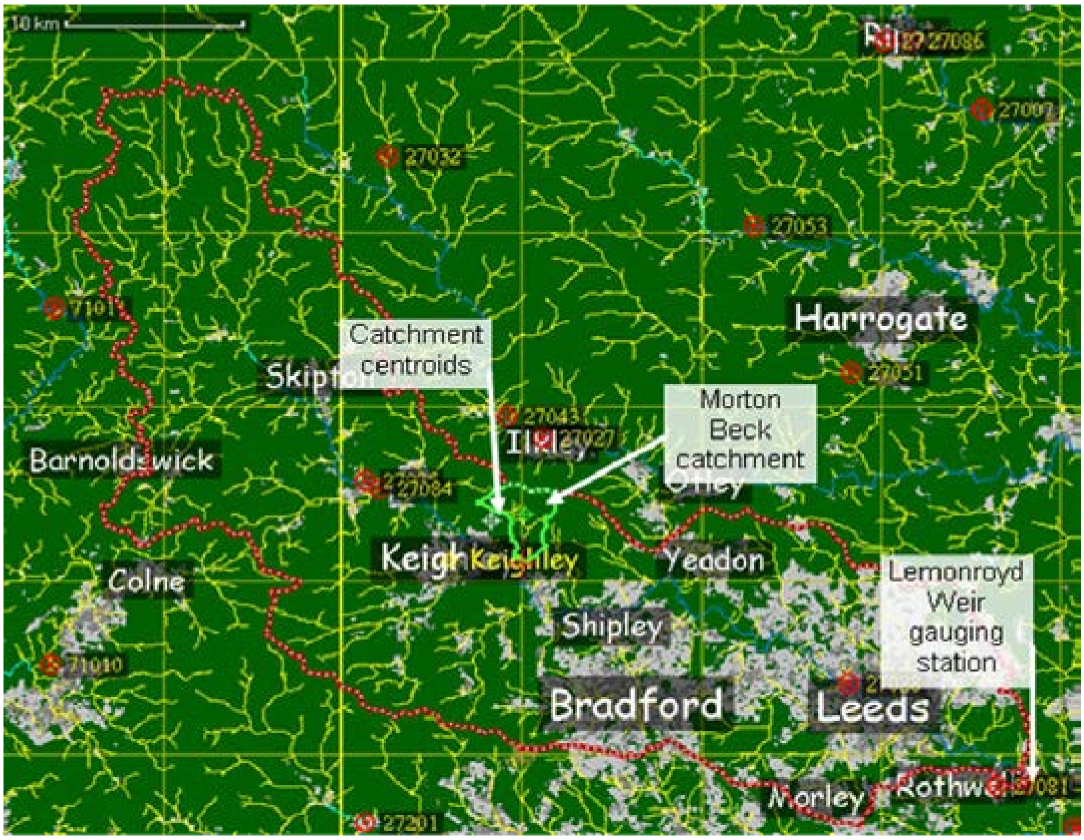


Figure 13: an example

Description of the site

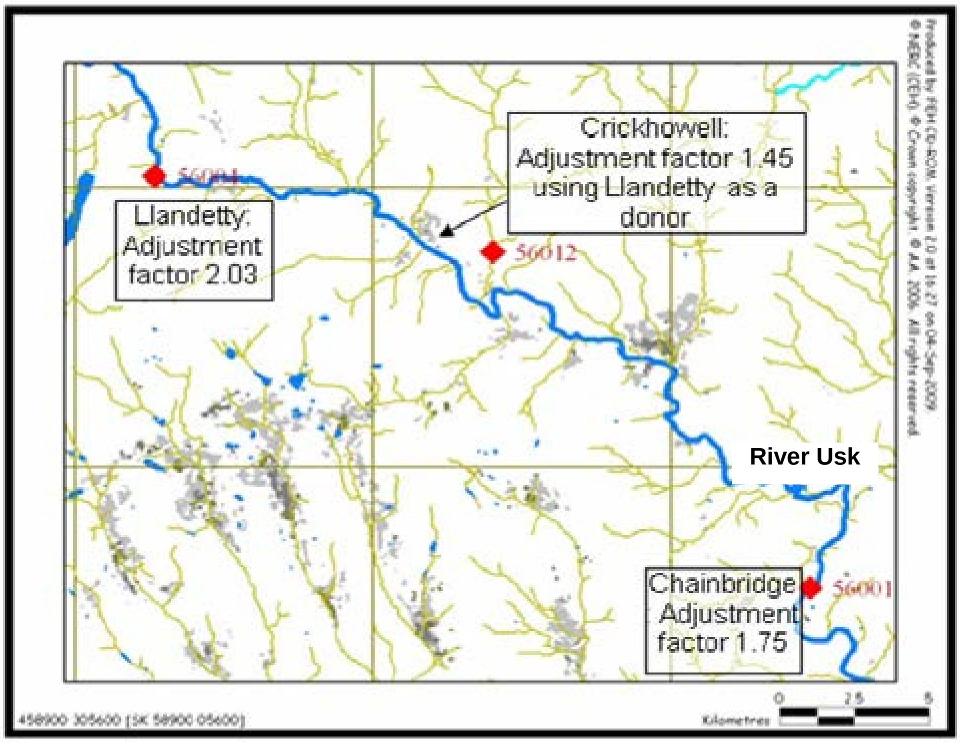
The site of interest is Crickhowell. The most appropriate donor appears to be Llandetty. It is shortly upstream on the same river and the catchment centroids are just 3.6 km apart. However, this short distance is enough to reduce the adjustment factor from 2.03 at Llandetty to 1.45 at Crickhowell, when applying the revised data transfer method.

Applying the adjustment factor

When the adjustment factor of 1.45 is applied to Crickhowell, the resulting estimate of QMED is less than the QMED at Llandetty, despite being 10 km downstream. This reduction in QMED is unlikely in practice and is merely a product of the new geographically weighted method.

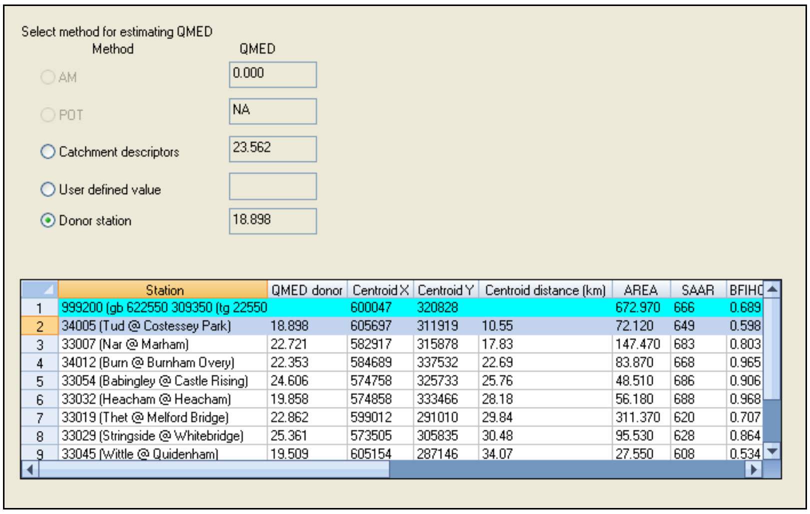
The analyst's decision

The analyst decided (wisely) to override the recommended use of the moderation term (*a*) and assume an adjustment factor of 2.03 at Crickhowell. An alternative, particularly if flood estimates had been required at multiple locations within the reach, would be to calculate a weighted average of the adjustment factors at the upstream and downstream gauging stations, perhaps basing the weights on distance along the river and again ignoring the moderation term.



Using the software

Version 3 of WINFAP-FEH enables you to automatically identify the nearest donor and calculate the moderated adjustment factor. You can also select another donor if preferred, from a list ranked by distance between the catchment centroids, see the screen below.



The list includes information on the catchment descriptors of the potential donor sites and links to pages on the HiFlows-UK website. Use these facilities as an encouragement to explore the information provided rather than automatically picking the closest donor site.

Important note: If you set up the load options in WINFAP-FEH to read in only stations classed as suitable for pooling, the list of potential donor sites will miss some stations that are classed as suitable for QMED for not pooling. You should look at other sources of information on available donors such as the display of station locations on the FEH CD-ROM or the HiFlows-UK website.

Summary of advice on data transfer

You should carry out data transfer in all cases where QMED is estimated at an ungauged site, apart from very low risk studies.

Donor sites should be:

- close to the subject site;
- classed as suitable for QMED in HiFlows-UK or shown to be suitable in a more recent review of data quality;
- rural in most circumstances ($URBEXT_{2000}$<0.030), even if the subject catchment is urbanised (**3** 4.6.1);
- not strikingly different from the subject site in terms of the key catchment descriptors: size, soils, wetness and reservoir/lake influence.

In most cases, the chosen donor should be the closest to the subject site. If there is more than one potential donor at similar distances, you should consider them and compare their adjustment factors. If necessary, you could calculate a weighted average.

You should moderate the adjustment using the power term calculated from the distance between catchment centroids as described above.

You should check the adjusted QMED for consistency with QMED estimated from flood peak data at any upstream or downstream gauging stations.

Since data transfer can be a subjective process, it will often be worthwhile seeking a second opinion from a more experienced colleague. It is also particularly important to record the process of decision-making.

Statistical method – growth curves

Topics in this section

This section includes the following topics:

Pooling groups

The issue

Pooling data from hydrologically similar sites provides more data and enables more reliable estimates of the growth curve for rarer floods (**3** 6.1 and 16.1).

Pooled analysis is essential for an ungauged catchment and necessary in most other cases, except when the record length is more than twice the target return period (**3** 6, 11.5 and 16).

Guidelines The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	Aspects to consider are: ▪ catchments within a pooling group should be essentially rural (**3** 6.1); ▪ the subject site should be excluded from its own pooling group when the subject catchment is urbanised.
2	Science Report SC050050 (listed in Related documents) changed the way pooling groups are formed. You should implement these changes using versions 3 of the FEH CD-ROM and WINFAP-FEH. BFIHOST is no longer used in the revised method. Instead you can measure catchment similarity by AREA, SAAR, FARL and a new catchment descriptor that measures the extent of floodplains (FPEXT).
3	Another aspect of the revised method is to fix the size of pooling groups to 500 station-years of data, irrespective of the return period of interest.
4	You should review pooling groups (**3** 6.3, 6.6, 16.3 and 16.6). The extent of the review and any modifications depends on the purpose of the study and your experience. In most cases, modifications to the pooling group tend to have a relatively minor effect on the final design flow (compared with, for example, selection of donor sites for QMED). In particular, sites that are least similar to the subject site (that is, placed near the bottom of the pooling group) list have little influence on the pooled growth curve because of the low weights allocated to them.
5	One trigger for a review of the pooling group can be the presence of a discordant site or a high value of heterogeneity. However, the FEH advises experienced hydrologists to take a precautionary approach, reviewing the pooling group before using the statistical tests for discordancy or heterogeneity. It is vital to remember that you should not remove sites from the pooling group just because they are discordant or they reduce the heterogeneity (**3** 16, 6.5). In many cases, discordancy is due to the presence of extreme floods in the annual maximum series. In this case, you should normally leave the discordant site in the group. However, you should exclude all records shorter than eight years (**3** 16.2.3).
6	The review should assess physical and hydrological differences between subject and pooled catchments such as: ▪ topography, geology, reservoirs, lakes and floodplains; ▪ local climate; ▪ urbanisation and other anthropogenic activity (**3** 9, 21); ▪ station locations and periods of record; ▪ flood seasonality; ▪ quality of high flow data (refer to the station information in HiFlows-UK).

Pooled growth curves

The issue

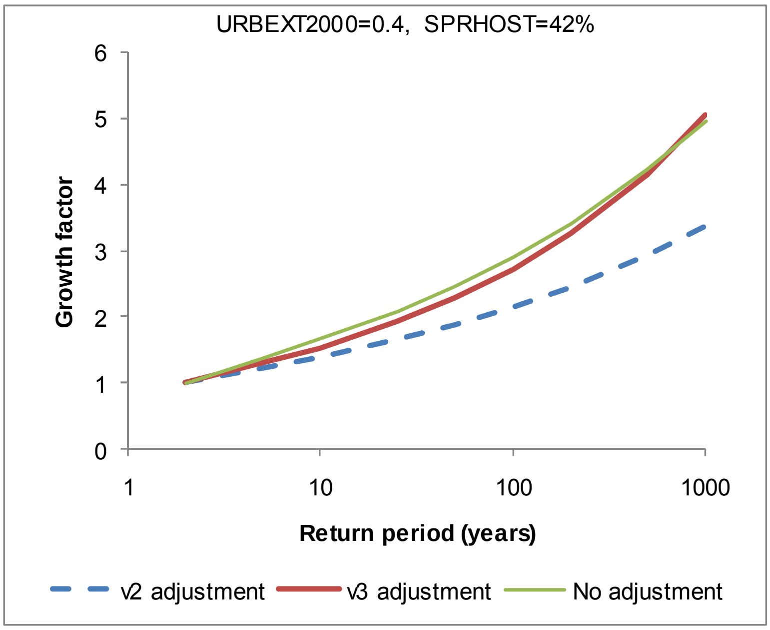
There is no way of knowing which distribution is the correct choice for fitting to the pooled growth curve, because the underlying 'parent' distribution is unknown.

On average, the GL distribution is considered to perform better than the GEV for pooled growth curve derivation (**3** 7.3, 15.3 and 17.3.2). For some pooling groups, other distributions are found to fit better than the GL.

Analysts: you should usually select the distribution that gives the best fit.

Guidelines The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	For catchment-wide studies, it is acceptable to select different distributions for different locations, although imposing a single distribution may help to ensure that design flows are spatially consistent. The choice between distributions often has a fairly minor effect on the resulting design flow for return periods within the recommended range of the statistical method (2-200 years).
2	The method of weighting the L-moments from each catchment in the pooling group was changed in Science Report SC050050. Weights are calculated from record length (as in the original FEH method) and the distance in catchment descriptor space from the target site, rather than from the rank within the pooling group. So moving catchments up or down the ranking order does not alter the weights. Another change is that separate weights are calculated for L-CV and L-skew. These improvements are in v3 of WINFAP-FEH.
3	You will need to adjust the growth curve for urbanisation if the subject site is urbanised. As for QMED, it's sensible to carry out the adjustment even for catchments with $URBEXT_{2000}$ below the threshold of 0.030. There have been three versions of the urban adjustment: v1 in the FEH; v2 described in Morris (2003) and Bayliss *et al.* (2007) (2007); and v3 published by Kjeldsen (2010). The references are listed in Related documents. Version 3 of WINFAP-FEH allows you to use either v2 or v3 of the urban adjustment. You should normally use v3. Unlike earlier versions, which adjusted the growth factors, v3 adjusts the L-moments. The v3 adjustment to growth curves is based solely on the value of $URBEXT_{2000}$, another change from earlier versions which used the same urban adjustment factor as is used for QMED (calculated from URBEXT and also SPRHOST). The v3 formulae for adjusting the L-moments are: $L\text{-}CV_{urban} = L\text{-}CV_{rural} \times 0.5547^{URBEXT2000}$ $L\text{-}skew_{urban} = ((L\text{-}skew_{rural}+1) \times 1.1545^{URBEXT2000}) -1$ The interpretation is that L-CV decreases on urban catchments and L-skew increases. These changes tend to reduce the gradient of the growth curve at lower return periods and increase the gradient at higher return periods as shown in Figure 14 for an example site. The effect of the v3 urban adjustment is minor at this site in comparison with the v2 adjustment. However, results elsewhere will differ depending on the values of the L-moments as well as on $URBEXT_{2000}$.

Figure 14 **Comparison of urban adjustment for growth curves**	
	On some urban catchments you may find that design flows for longer return periods increase substantially over those from previous studies as a result of the new adjustment method for growth curves. You should discuss the implications of these changes with experienced colleagues before deciding to adopt the revised design flows.
Bug in WINFAP-FEH	WINFAP-FEH V3 lets you supply a user-defined value of URBEXT2000. This is correctly applied in adjusting QMED for urbanisation, but WINFAP-FEH ignores the user-supplied value when adjusting the growth curve. The difference in the results is likely to be minor in most cases.
4	You should not normally apply an urban adjustment to a growth curve derived from enhanced single-site analysis (see below) because enhanced single-site analysis is not suitable for urban catchments. If carrying out calculations outside WINFAP-FEH (for example, using a spreadsheet), take care not to apply an urban adjustment to a single site growth curve.

Growth curves for sites with flood peak data

The issues

In deriving flood growth curves at a flow gauging station, the choice between single site and pooled curves can have a large impact on the results.

Originally, the FEH's basic recommendation was to rely on the pooled growth curve unless there is a flood peak record at the site of interest, twice as long as the return period required (*T*). However, you can give some weight to the single site curve if the record length is between *T* and 2*T*.

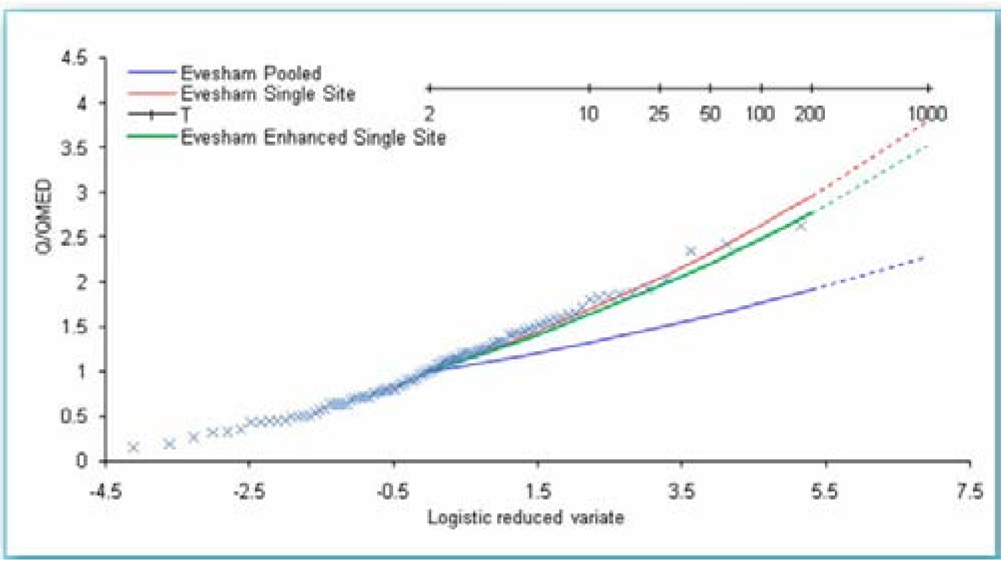
As usual in the FEH, there is some flexibility about this. Other factors to bear in mind are:

- the quality of flood peak data;
- the longer-term flood history;
- and any unusual characteristics of the catchment compared with others in its pooling group.

For rural sites, the choice between single-site and pooled curves is now simpler due to the introduction of enhanced single-site analysis in v3 of WINFAP-FEH. If the subject site is gauged, it is given a lot more weight than the rest of the sites in the pooling group. This helps to remove some of the very large differences that have been observed between pooled and single site growth curves. You can find the details of the enhanced single-site method in Science Report SC050050.

Figure 15

The graph compares a pooled curve in which the subject site is treated as ungauged with one derived from an enhanced single-site analysis. The latter is much close to the single site curve because a large weight is given to the subject site due to the long length of its annual maximum series.



Guidelines

The guidelines and advice listed in the table below are for all users.

Item	Guideline or advice
1	You should normally carry out an enhanced single-site analysis when deriving a pooled growth curve for a site draining a rural

	catchment with at least 8 years of good-quality flood peak data. You should compare the resulting growth curve with a plot showing the annual maximum flows and a standard single-site growth curve. Be aware that WINFAP-FEH will default to enhanced single-site analysis when you create a pooling group for a gauging station's catchment descriptor (.cd3) file taken from HiFlows-UK, when the gauge is classed as suitable for pooling and the catchment is rural. If you create a .cd3 file by extracting the catchment descriptors from the FEH CD-ROM at the site of a gauge, the site will be treated as "ungauged" by WINFAP-FEH and a conventional pooled analysis will be carried out. Data from the gauging station will be included in the analysis, but without the extra weight used for enhanced single-site analysis. WINFAP-FEH does not report the relative weights used in enhanced single-site analysis. When your subject site is urban ($URBEXT_{2000}$>0.030) you should normally avoid enhanced single-site analysis because the pooling group would contain a mixture of urban and rural sites, and it would then not be possible to apply a valid urban adjustment to the growth curve. In that case you should fit a standard pooled curve (adjusting the pooled L-moments for urbanisation) and a single-site curve and compare them. If necessary, you could use joint analysis (**3** 8.2) to produce a compromise growth curve, giving increased weight to the pooled L-moments at longer return periods.
2	It is important to realise how fickle a single site analysis can be. When extrapolated to the typical return periods used in fluvial flood studies, single-site growth curves can be very vulnerable to: ▪ the period of record that the gauging station happens to cover; ▪ and to the quality of high flow data. It is all too easy to derive a single-site flood frequency curve that appears to fit the annual maximum data, but is a long way from the true underlying distribution (which we can never fully know). See the illustration in Figure 16, on page 60. So just because you prefer the look of the single-site growth curve it does not mean that you should use that curve if you cannot justify it based on statistical arguments and an understanding of the catchment's hydrology.
3	The two basic approaches to improving on extrapolation of single-site data are: 1. search for historic data; 2. add data from other sites by pooling. You should attempt both approaches in many hydrological studies. There is a paper comparing different approaches to extrapolating flood growth curves; see Gaume (2006).
4	In some cases, the difference between the single-site and pooled curves is so wide that it is clear something is wrong. **Example:** The pooled curve might lie so far below the single-site data that the top few flood peaks all appear to have return periods longer than 10,000 years according to the pooled curve. In such cases, it is particularly important to check that the rating can be relied on for the highest flows on record. If it can, then it is very likely that the pooled curve is too flat.
5	If you have several flow estimation points, some of which are at

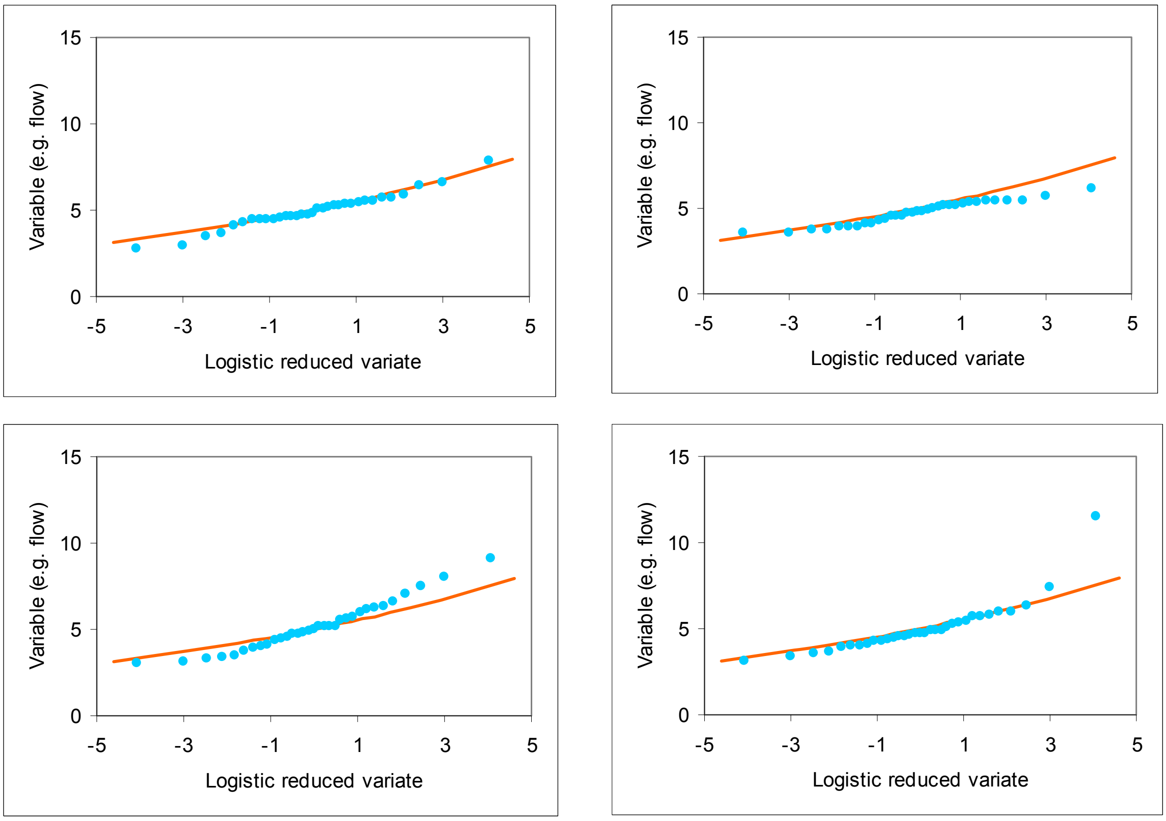
	gauging stations, you may find large changes in growth curves over short distances if you apply single-site or enhanced single-site analysis only at the gauges. You should ensure a smooth variation in growth curve, choosing and applying the preferred growth curve(s) manually to all flow estimation points.

Figure 16: an example

This example illustrates how easy it can be to derive a single-site flood frequency curve that appears to fit the annual maximum data, but is a long way from the true underlying distribution (which we can never fully know).

The graphs below show four plots of annual maximum values of a variable (for example, river flow). Each plot has 33 years of data, the mean record length in the Hiflows-UK dataset. Each plot includes a curve plotted for return periods up to 100 years. In some cases, the curve fits the data well and in others, the fit is rather poor, especially for long return periods.

It may be tempting to try to redraw some of the curves so that they fit the data better. However, in this case it would not be right to alter the curves. Here, the underlying distribution is known and the points on the plots are not real observed data. They are all random samples from a Generalised Logistic distribution: location: 5, scale: 0.5, shape: -0.1. This distribution is shown by the curve plotted on each graph. Some of the samples, like the first, are quite well representative of the underlying distribution, but others have rather more or rather fewer high values than would be expected in a typical period of 33 years.



Applying the illustration

To apply the illustration above to a typical FEH problem, imagine that one of the lower two plots shows a pooled growth curve along with single-site flood peak data. One interpretation would be that the pooled curve is underestimating the correct distribution. But this example shows that it is quite possible for the sample flood peak data to plot some distance away from their underlying distribution, due, for example, to the gauged record covering an unusually flood-rich period. So it is quite possible that the pooled growth curve would be a correct representation of the underlying distribution.

This is why the FEH recommends only relying on a growth curve fitted to single-site data for return periods up to half the record length.

Rainfall-runoff approaches

Topics in this section

This section covers the FEH rainfall-runoff method and the ReFH method, released in early 2006. ReFH has superseded the FEH method for most applications (the main exceptions being reservoir safety and pumped catchments).

Analysts: you can refer to FEH Supplementary Report No. 1 for details of the ReFH method. For information on the research, see Kjeldsen and others. (2005). Both are listed in Related documents.

This section includes the following topics:

General information

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	Both the FEH rainfall-runoff and ReFH methods use the FEH rainfall frequency statistics to create design rainfall events, which form the input to the rainfall-runoff model. Storm profiles were not investigated in the FEH rainfall frequency research. The FEH rainfall-runoff and ReFH methods continue to use the profiles given in the FSR. The two profiles recommended for use in the rainfall-runoff method are: **1.** the 75% winter profile, for rural catchments; **2.** the 50% summer profile, for urban catchments. These profiles are recommended for durations of 'up to several days' (**2** 4.2). There is no guarantee that a rainfall profile of a shape other than the recommended one will produce a design flood of the required return period (**2** 4.3).
2	Alternative rainfall-runoff methods are occasionally used for UK flood estimation, such as the NAM model in MIKE-11 or FRQSIM (used

	mainly in Greater London). FEH rainfall statistics could be used to provide an input to such models, with any storm profile, as long as the catchment model was calibrated so that the combination of inputs results in a flood of the required return period (**2** 4.1). The onus is on the analyst to demonstrate that this is so, if using an alternative rainfall-runoff model. **Important note:** You must consider the FEH and ReFH rainfall-runoff methods as a complete package. They were both calibrated so that the recommended design inputs gave rise to an output hydrograph with a peak of the required return period.

Lumped or distributed approach?

The issue

A fundamental decision regarding any rainfall-runoff technique is whether to apply it:

- in a lumped fashion to the entire catchment upstream of the site of interest;
- or in a distributed approach, splitting up the catchment and routing the design flows from each subcatchment.

In practice, this decision is often dictated by the nature of the study. **Example:** Catchment-wide hydrodynamic modelling studies tend to follow a distributed approach.

Storm durations for lumped and distributed models

Lumped
When modelling a **lumped** (individual) catchment, the storm duration should be set to the recommended value given by the equation based on time to peak and SAAR. This equation tends not to give the critical duration (particularly when using the ReFH model), but it matches the duration that was used in the calibration of the ReFH model's design event.

Distributed
In a **distributed** rainfall-runoff application, it is vital to apply an identical design storm (in terms of duration and areal reduction factor) to each subcatchment. Using an individual design storm for each subcatchment, with a duration set to the critical duration of the subcatchment, is physically unrealistic and will overestimate the combined flood peak.

You should try a realistic range of durations for the design storm, to find the critical duration at the subject site by trial and error. This optimisation can be carried automatically in ISIS. The critical duration is the one that gives the highest flow (or water level or storage pond volume, for some studies) at the site of interest. At an early point in the study, you should select, agree and record the location of that site.

When there is significant variability in rainfall patterns over a large area, you can derive the rainfall depth separately for each subcatchment, as long as a common return period is used. When the design storm duration is set to a value much longer than the critical duration for a subcatchment, beware that the ReFH method can overestimate the flow (see The ReFH method).

Guidelines

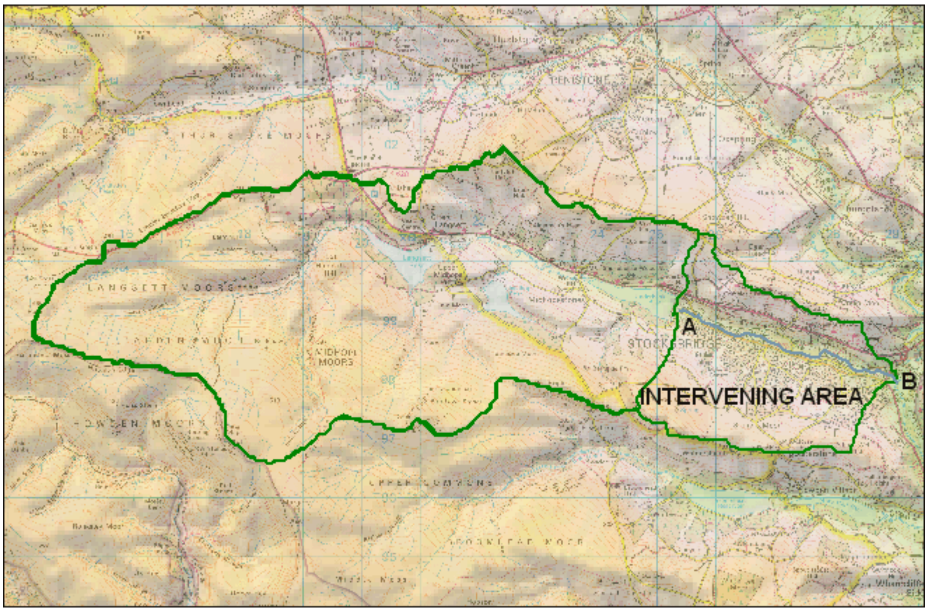
The guidelines and advice in the table below are included to help users.

Item	Guideline or advice

1	**Analysts:** there is a choice: a distributed approach is the natural choice for large or varied catchments and for those with floodplain or reservoir storage. But it can introduce great complexity and force you to make uncomfortable assumptions.
2	In a distributed application, it is important to avoid excessive detail in subdividing catchments. Observed flood hydrographs can help to identify multiple peaked events, which may indicate differing responses from subcatchments. All subcatchments should result in a significant change in catchment area when added to the upstream area.
3	Areas draining directly to the modelled watercourse, or containing numerous small subcatchments, are usually treated as 'intervening areas', see Figure 17, on page 64.
4	You can estimate catchment descriptors for intervening areas by area weighting, using the upstream and downstream lumped catchments (at points A and B in Figure 15), or based on the descriptors of a significant watercourse within the intervening area. Take care over some descriptors, particularly DPLBAR. You can calculate it for an intervening area from DPLBAR, LDP and AREA for the upstream and downstream catchments. It is unwise to rely on the regression equation for DPLBAR in **5** 7.2.4, which is designed for real catchments, not intervening areas.
5	Estimate hydrographs for intervening areas by applying FEH methods to the derived catchment descriptors, as for any other subcatchment. However, intervening areas are not real catchments, so the FEH methods are not strictly applicable to them. For this reason, intervening areas are best kept to a minimum.
6	An alternative approach to estimating hydrographs for intervening areas, which avoids having to define catchment descriptors, is to estimate hydrographs for the lumped catchment upstream of (excluding) the intervening area and downstream of (including) the area. The upstream hydrograph is subtracted from the downstream one to give the hydrograph for the intervening area. You should check the resulting hydrograph to ensure that its shape is physically realistic.
7	One important use of intervening areas comes in examining flood risk for locations downstream of a reservoir (or other storage). If the site of interest is some distance downstream of the reservoir, it's important to check whether the reservoir can attenuate flood flows to such an extent that the site is more sensitive to heavy rainfall (over a shorter duration) concentrated on the intervening area downstream of the reservoir than it is to an event over the whole catchment.
8	**Analysts:** you may be interested to know about a recent research study (SC060088) investigating spatial coherence of flood risk. The report on the research will include a discussion of the implications of modelling spatially distributed flood flows without taking into account the statistical dependencies between the flood frequency curves at different places. The approach taken in the FEH and ReFH methods makes an assumption of complete dependence between rainfall in different parts of the catchment.

Figure 17: an example

The map below shows an example of an intervening area at Little Don at Stocksbridge, South Yorkshire. The intervening area is the catchment at B minus the catchment at A.

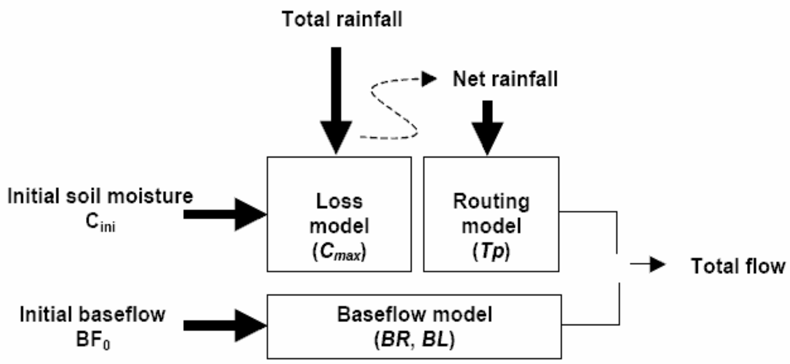


The ReFH method

Summary of the method

The ReFH method was developed to address several problems in the FEH rainfall-runoff method, which was largely unchanged from the earlier Flood Studies Report method. Figure 18, below, summarises the ReFH method.

Figure 18



Reproduced from Kjeldsen and others (2005) with the permission of CEH Wallingford.

Four parameters

The four model parameters shown inside the boxes in Figure 15 are:

1. C_{max}, the maximum of the range of soil moisture capacities across the catchment;
2. Tp, the time to peak of the unit hydrograph;
3. BR, the baseflow recharge (ratio of runoff to recharge);
4. BL, the baseflow lag (rate of exponential decay of baseflow).

All four parameters are best estimated from hydrometric data, where available, using the ReFH design flood modelling software. The baseflow parameters are calculated by fitting recession curves to flow data. C_{max} and Tp are calculated jointly by an optimisation method that requires observed rainfall, flow and evaporation data.

In the absence of data or for low risk applications (for example, where ReFH is being used to determine a hydrograph shape that will be fitted to a peak flow from the Statistical method), parameters can be estimated from FEH catchment descriptors. Note that the FEH supplementary report gives parameters calculated from flow data at 101 gauging stations and you can use this to replace the catchment-descriptor values in the spreadsheet.

Differences

The table below lists some differences between application of the FEH rainfall-runoff and ReFH methods

Item	Difference
1	The time to peak for ReFH is not quite the same as that used in the FEH rainfall-runoff method. It is estimated differently, whether from data or from catchment descriptors.
2	ReFH does not include the provision to use river level data for deriving time to peak, as in the FEH rainfall-runoff method. However, given the wider availability of river level recorders, there are likely to be some situations where analysts judge that level data are helpful in guiding the selection of parameters for the ReFH method. This could be done, for example, by assuming that the time to peak in ReFH can be adjusted using a factor derived from comparing the catchment-descriptor estimate of the FEH rainfall-runoff time to peak with that derived from lag analysis.
3	The ReFH research did not examine the value of data transfer for refining parameters. The report, therefore, gives no recommendations on use of donor sites. Faulkner, D.S. and Barber, S. (2009), listed in Related documents, have published more recent research showing that using the closest available gauge from the ReFH calibration dataset as a donor site appears to offer no benefit on average, in comparison with estimating parameters from catchment descriptors. However, it seems highly likely that many subject sites, with a donor site nearby on the same watercourse, will benefit from data transfer. **Analysts:** you should consider data transfer when there is a flow gauging station nearby on the same watercourse as the subject site. This involves estimation of each of the four model parameters at the gauging station from flow and rainfall data using the ReFH design flood modelling software and also from catchment descriptors. For each parameter, the ratio of the two estimates at the gauging station is used to adjust the catchment-descriptor estimate at the site of

	interest. Do not use the moderation factor (power term) developed for data transfer of QMED for adjusting ReFH parameters.
4	ReFH allows for more seasonal variation in the design event. As well as the choice of winter or summer rainfall profiles (as in the FEH), it also adjusts the rainfall depth and the initial soil moisture for the season. The ReFH Technical Report recommends using the summer design event on heavily urbanised catchments ($URBEXT_{1990}$>0.125). However, current guidance is that ReFH is not used for such catchments (see When to apply ReFH with caution below).
5	ReFH uses equal return periods for the input rainfall and output flow hydrograph.
6	ReFH was calibrated for return periods up to 150 years. This is considerably longer than the 10-year return period limit of calibration for the FEH rainfall-runoff method, which has been widely used for estimation of design flows for extreme return periods. For guidance on estimation of extreme events, refer to Estimating long return period floods (150-1000 years), on page 107.

When to apply ReFH with caution

One of the most significant aspects of ReFH is that the design event was calibrated to match, on average, flood frequency curves derived from pooled analysis at 100 gauging stations (using the HiFlows-UK dataset). For this reason, ReFH tends to give peak flows that are much more consistent with those from the FEH statistical method. However, due to limitations of the calibration, there are some catchment types where ReFH should be applied with caution, if at all. Links are to other sections with more details.

1. Only seven of the calibration catchments were heavily urbanised and so the report states that applicability of ReFH to urban catchments ($URBEXT_{1990}$>0.125) is 'unclear without further research'. On many urban catchments, the results of ReFH appear suspect because the winter season event tends to give higher flows than the summer event, contrary to expectations.
   ! Important Don't use ReFH in its original form to estimate peak flows on heavily urbanised catchments. However, recent research (Kjeldsen, 2009) has led to a modified version of ReFH that accounts for increased runoff volumes on urban catchments. Refer to Development control and urban catchments for more information on this.
2. As with other rainfall-runoff methods, ReFH struggles on permeable catchments (approximately BFIHOST>0.65). The calibration procedure gave unrealistically large values of C_{max} to reproduce the losses on permeable catchments. The flood event archive was deficient in events on permeable catchments. On permeable catchments, ReFH has been found to underestimate QMED by a long way and to give unrealistic return periods (>10,000 years) for the July 2007 floods (Faulkner, D and others).
   ! Important You should not use ReFH to estimate peak flows on permeable catchments. The statistical method is normally a better choice.
3. The largest catchment used for calibrating the ReFH design event was 511 km^2. The method was validated for catchments up to 750 km^2. The FEH Supplementary Report recommends applying ReFH **for areas up to 1000 km^2**. Rainfall-runoff approaches are less valid on large catchments because they rely on a characteristic distribution of rainfall across the catchment. This limitation applies equally when a large catchment is split into subcatchments.
4. ReFH has been found to overestimate design flows when it is run with a storm duration **much longer than the critical or recommended**

durations for the catchment. On impermeable and wet catchments (BFIHOST<0.4 and PROPWET >0.45), it can even give a flow volume that is greater than the volume of the input rainfall. This needs further investigation, but in the meantime check that the effective percentage runoff is realistic and use an alternative method if necessary.

When hydrographs are required for catchments unsuitable for ReFH, you may use the method to derive a hydrograph shape which could then be fitted to a peak derived by a more suitable method.

Available data and software

You can apply the ReFH method using a spreadsheet available free from CEH Wallingford. This can be downloaded from the Centre for Ecology and Hydrology website, or Environment Agency staff should obtain it via the Service Desk.

The spreadsheet does not allow calculation of model parameters from observed data, which is computationally complex. Instead, it calculates parameters from catchment descriptors. However, the FEH supplementary report gives parameters calculated from flow data at 101 gauging stations and the spreadsheet allows users to modify parameters.

The spreadsheet is only intended for design rather than simulation of flood events, that is, it cannot be run using observed rainfall.

Wallingford HydroSolutions Ltd. released a more comprehensive ReFH software package in 2007. The ReFH design flood modelling software includes:

- a database for storing flood and rainfall event data;
- software for fitting model parameters to observed data;
- software for running the ReFH model with both design and observed events
- reservoir routing.

There is also a ReFH unit within version 2.5 of ISIS.

Users and project managers: When you use ReFH to estimate peak flows or flood volumes at or near a flow gauging station, you should normally estimate the parameters from observed data using the ReFH design flood modelling software, or the published values if the station is listed in the FEH supplementary report. As with other FEH methods, parameters estimated from local data are likely to give significantly more accurate results. If the study is simple or routine, see Table 2 on page 12, it may be acceptable to base the parameters on catchment descriptors.

Project managers: You should be aware that applications of ReFH that involve estimation of parameters from observed data will take much more time than those that rely on catchment descriptors.

The ReFH method has not yet been updated to use $URBEXT_{2000}$, so you should base all ReFH calculations on $URBEXT_{1990}$ (updated to current levels of urbanisation).

FEH rainfall-runoff method

The issues

ReFH has superseded the FEH rainfall-runoff method for the majority of river management applications. However, there are some situations where the earlier method is still applicable and others where there will be interest in comparing results. The main examples are on pumped catchments and for reservoir safety. Select the links to read more details in later sections.

You can also consider application on some heavily urbanised catchments, given the unsuitability of ReFH for such catchments.

The main decisions in applying the rainfall-runoff method are about how to estimate the model parameters, with preference given to local data as is usual for FEH methods.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	You can use donor catchments to estimate the parameters when there is no data at the site of interest.
	In selecting donors, use the following guidelines: ▪ you can identify donors using similar criteria to those for selecting QMED donors; See From catchment descriptors, on page 44. ▪ Tp(0) depends only on the timing of flood peaks, so there's no need for high quality flow data; You can estimate it by lag analysis at any flow or level gauging station as long as there is a recording raingauge close enough to the catchment. ▪ the requirements for SPR donors are rather less strict than those for Tp(0) donors: it is sufficient that catchments are similar in terms of soils, land use and topography.
3	Most studies estimate Tp(0) from a lag analysis and SPR through the baseflow index (which is readily available at most gauging stations from the Hydrometric Register and Statistics publications by CEH Wallingford). The FEH describes this as 'indirect analysis of gauged data', which comes second to a full flood event analysis, that is, deriving a unit hydrograph. However, there is no commercial software widely available for flood event analysis and so it is not widely done. Analysis of five flood events is the minimum required for confidence in the results (**4** 2.1.2).
3	Appendix A of FEH Volume 4 contains results from the UK Flood Event Archive, giving values of Tp(0), SPR and baseflow for several hundred gauging stations. It is worth checking there for model parameters before deciding to estimate them from flood event data. You should check flood peaks from the events in Volume 4 against those in Hiflows-UK for any changes in rating equations.

Continuous simulation - an alternative rainfall-runoff approach

Description

Continuous simulation of flows offers an attractive alternative to design event methods such as FEH and ReFH. The idea of this is to produce long series of simulated rainfall data (for example over 1000 years) and run them through rainfall-runoff models to produce a long flow series.

You can then rank the peaks of the flow series and analyse them to obtain design flows of the required return period. This removes many of the assumptions and restrictions of the design event approach.

The method allows you to incorporate complex dependencies within the catchment (for example, flood control structures) and also deals with problems of spatial dependence if it is driven by a suitable spatial rainfall model.

Recent research

A research project has developed methods of estimating continuous rainfall-runoff model parameters from catchment properties or by transfer from similar gauged catchments; see Calver, A. and others (2005), listed in Related documents.

Research and testing of continuous simulation is continuing, but it has already been applied to flood estimation on some catchments judged to be too complex for FEH methods, such as the Don in South Yorkshire where flood flows are controlled by regulators and washlands. See Faulkner, D.S. and Wass, P. (2005), listed in Related documents.

5. Assumptions, limitations and uncertainty

Overview – a common criticism

Two common criticisms

Two of the commonest criticisms of project reports on flood estimation are that they:

1. fail to acknowledge the assumptions and limitations of the methods used;
2. do not discuss the uncertainty of the results.
   See Pappenberger, F. and Beven, K. J. (2006), listed in Related documents.

Possible reasons

One possible reason for the lack of discussion of uncertainty is that, to most hydrologists, it is all too obvious that flood estimation is uncertain. They don't see much value in talking about it, when the point of the exercise is to obtain the best estimate.

Some analysts worry that project managers or decision makers could misuse statements about uncertainty, seeing them as carte blanche to choose an answer that suits their prejudices or their pockets.

A more practical limitation is that there is no standard accessible method for quantifying the uncertainty in a design flow.

Similar reasons probably explain why assumptions tend not to be acknowledged. They tend to be similar for many studies (so what is the point of listing them?) and many analysts would probably have difficulty identifying and describing all the assumptions that they implicitly rely on.

In this chapter

This chapter includes the following topics:

Why bother with uncertainty?

Does uncertainty matter?

While it is obvious to most hydrologists that their flood estimates are uncertain, there are probably many who don't have a good idea of how large that uncertainty can be. There's also still a tendency among non-specialists to treat results of complicated procedures as the final truth, particularly if they are quoted to several decimal places. But does this matter?

Result of uncertainty on decisions

Uncertainty in flood estimates is often important to the subsequent process of making decisions.
Example: A method that gave more certain answers would tend to be preferred over a less certain alternative.

Sensitivity analysis can be used to test the effects of uncertainty on the subsequent modelled water levels (or whatever quantity is of interest). If this shows that the results are too uncertain, then it might be an incentive to improve the flood estimate. However, often the only way to give a substantial improvement is to install a flow logger and wait until it has recorded enough data. These tests often show that modelled water levels are more sensitive to uncertainty in the design flows than in hydraulic model parameters, indicating that it's worthwhile spending time and effort on improving the design flows.

In development control, uncertainty in a flood estimate may lead to a decision not to allow a proposed development (that is, a hazard), because there's not enough information on its consequences.

How uncertainty affects perception

Acknowledging uncertainty can affect how results are presented and perceived.

Although it may have apparent disadvantages, such as project managers taking the results less seriously or ignoring the best estimate, it can help avoid a crisis when one study appears to contradict a previous one.
Example: A flood alleviation scheme was designed with a return period of 30 years. But the standard of protection was later reassessed at 50 years. If the latter result had been presented as 'between 30 and 70 years', the difference might not have seemed so great.

Importance of uncertainty

The Flood and Coastal Risk Management Modelling Strategy 2010–2015 (see Related documents) states that

“We will understand and communicate uncertainty in modelling outputs to assist decision-making by ourselves, our partners and our customers. We will reduce any uncertainty that prevents us from making sound decisions.”

An aspiration of the strategy is to use uncertainty in a positive way to gain a fuller understanding of the risks we are modelling. An example of this might be combining uncertainty estimates in design flows with defence failure probabilities and flood damage measures to obtain overall measures of flood risk.

Why we should acknowledge uncertainty

One of the main reasons for acknowledging assumptions and limitations is that it forces the analyst to think through their work and identify and address any weaknesses.

It also provides useful information for anyone reviewing the calculations.

For this reason, we require a section describing limitations in hydrological studies and hydraulic models as part of reports produced under our SFRM Model Report Performance Scope.

Typical assumptions

General assumptions not that useful

Many flood studies rely on some general assumptions, such as:

- the flow data are recorded accurately;
- the catchment descriptor equation for QMED is applicable to all sites in the study area;
- the growth curve at the subject site is identical to that derived from the pooling group.

Listing assumptions like these isn't very helpful because they are rather obvious, they are often very hard to test and they are not specific enough.

To take things to an absurd extreme, you could simply state a single assumption: 'The flood estimates are assumed to be correct', which would be completely obvious and of no use.

Identifying the most useful assumptions

The most useful assumptions to identify are ones that:

- are specific to the study;
- or can be tested;
- or have a large effect on the results.

Some examples (which are not necessarily recommended in any particular case) are listed in the table below.

It may help to list assumptions grouped under similar headings to those used below.

Assumption	Examples
Assumptions about data	▪ the rating curve at Station X can be extended up to QMED (this could be tested by carrying out some high flow gaugings this winter); ▪ all large floods since 1800 have been identified during the historic review.
Assumptions about hydrological processes	▪ flood flows arise mainly from runoff generated from the impermeable parts of the catchment; ▪ the catchment and watercourse have been largely unchanged since the historic data recorded in the early 20th century; ▪ the pumping stations operate at full capacity during major floods.
Assumptions about the methods used	▪ a single adjustment factor for QMED can be applied all the way along the study reach (this could be tested by installing a temporary flow logger at the upstream limit); ▪ the ReFH method will give improved answers if Tp(0) is adjusted using donor sites, even though the gauges are level-only and the Tp(0) has therefore been derived from lag analysis rather than the recommended optimisation method; ▪ the 1000-year growth factors are best estimated from a rainfall-runoff approach, given the greater confidence in rainfall growth curves for longer return periods.

Typical limitations

Most common limitations

The most common limitations are due to applying methods outside the range (of catchment size or type or return period) for which they have been developed or calibrated. It's important to acknowledge when this has happened.

Table 3

The table below summarises the validity ranges for selected methods, based on information in the FEH (mostly from **1** 3.1) and other publications. These are ranges over which the methods are 'principally intended to be used' or ranges covered by the data used to develop the methods.

Method	Return period limits	Catchment area limits	Urbanisation limits	Other limits
FEH statistical	2 – 200 years (but has been applied up to 1000 years)	Over 0.5 km^2 but can be applied for smaller areas	$URBEXT_{1990}$ up to 0.5	Each method has various types of catchment for which it is not ideal – Choosing between the FEH methods
FEH rainfall-runoff (largely superseded by ReFH)	2 – 2000 years	0.5 to 1000 km^2 but can be applied for smaller areas	$URBEXT_{1990}$ up to 0.5	
ReFH	Up to 150 years – but see Note 1	0.5 to 1000 km^2 but can be applied for smaller areas	Only reliable for $URBEXT_{1990}$ <0.125 – but see Note 2	
FEH rainfall frequency	2 – 2000 years	n/a	n/a	Durations 1 hour to 8 days

Notes to Table 3

1. See Estimating long return period floods (150-1000 years), on page 107.
2. See Development control and urban catchments for advice on applying a modified version of ReFH to more heavily urbanised catchments.

Guidelines

The information in Table 3, above, is not intended to say that you should never use the methods outside the ranges given.

Item	Guideline or advice
1	**! Important** You should choose methods by following the guidance in Chapter 3, on page 29, rather than by elimination using Table 3.
2	It is inevitable that on unusual catchments or for extreme return periods, there are few ideal methods. Standard methods are likely to be least applicable to very small and very large catchments, complex urban catchments, permeable catchments and extreme events. However, design flows are still needed in such cases and so it is often necessary to use a method outside the range for which it was calibrated or for which it is principally recommended.

Assessing uncertainty

The issues

Flood frequency estimates are inherently uncertain because they cannot be measured or formally validated against observed data.
We often break uncertainty down into different components:

- natural uncertainty, from the inherent variability of the climate;
  This tends to be the largest source of uncertainty in flood estimates for long return periods such as 100 years, because they are derived (however indirectly) from flood data series that rarely exceed 50 years in length.
- data uncertainty, from the measurement of flood flows;
- model structure uncertainty, from the choice of model, such the selection of a growth curve distribution;
- model parameter uncertainty, from selection of parameters for a growth curve or a rainfall-runoff model.

Qualitative assessment

One way of presenting information on uncertainty for a particular flood estimate is a qualitative assessment of the relative contributions from the various sources of uncertainty.

Example: You can class the contributions as high, medium or low.

Sources of uncertainty might include rating equations, length of a flood peak record, choice of pooling group, choice of distribution or ReFH model parameters.

Quantitative assessment

Quantitative assessment of uncertainty often uses confidence intervals. The 95% confidence interval is the range within which we are 95% confident that the true answer lies.

There are no widely available straightforward techniques for assessing confidence intervals for flood estimates (**1** 5.6). The FEH provides confidence intervals for some components of flood estimates, but does not suggest any techniques for combining them together and accounting for the other sources of uncertainty.

See the examples on the FEH statistical method and rainfall-runoff techniques on page 75.

Examples in FEH statistical method

Examples of quantitative assessment in the FEH statistical method include:

1. You can derive confidence intervals using the resampling routine in WINFAP-FEH for single-site growth curves, but not for the much more widely used pooled growth curves, although this is theoretically possible and could be done if suitable software was developed.
2. You can obtain confidence intervals for QMED when QMED is derived from flood peak data (**3** 12.5) or catchment descriptors. In the latter case, you should replace the confidence intervals given in **3** 13.8.1 using the factorial standard error associated with the revised QMED equation, which is 1.43. The revised 68% confidence interval for QMED is (0.70QMED, 1.43QMED) and the revised 95% interval is (0.49QMED, 2.04QMED).
3. The overall uncertainty is a combination of:
   - the variability of QMED;
   - the variability of the growth curve;
   - and the covariance between QMED and the growth curve.
     At long return periods, the uncertainty of the growth curve may be the dominant factor. See Kjeldsen, T.R. and Jones, D.A. (2004), listed in Related documents.

Examples with rainfall-runoff techniques

Examples of quantitative assessment in rainfall-runoff techniques include:

1. You can produce confidence intervals for rainfall growth curves by resampling. These measure the uncertainty in rainfall growth rates due to limitations in the sample size (but not due to other sources of error). The FEH describes how to evaluate these confidence intervals, but has not evaluated them at all sites because it was not computationally feasible.
2. An important factor is the uncertainty in estimating the index rainfall. You can estimate this approximately from maps in Volume 2.
3. As for flood growth curves (see above), you would need to combine the various components of uncertainty to give an indication of the overall uncertainty in rainfall frequency estimates. You would then need to combine this with the uncertainty due to the estimation of rainfall-runoff model parameters and the (large) uncertainty introduced by the composition of the design event package.

Analysts: what you need to do

It is clear that uncertainty is an uncertain business.

Assessing uncertainty for flood estimates remains a matter for researchers.

But you should still quote what information you can about the uncertainty of their results, rather than simply copying general text about uncertainty from a previous report.

See also the example in Figure 19 on page 76.

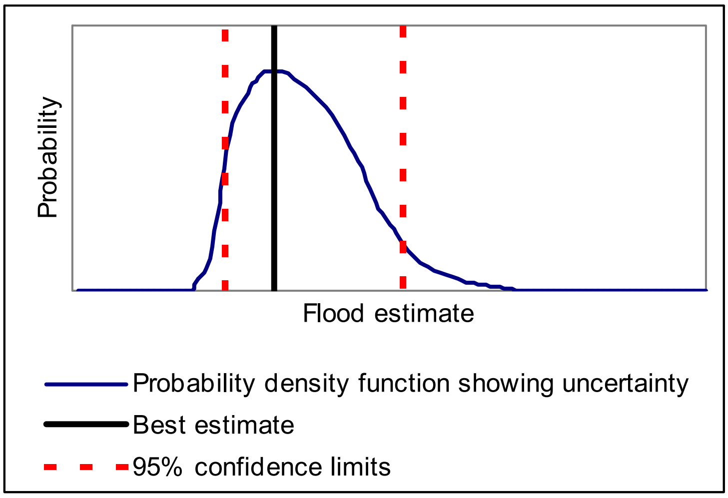
Figure 19: an example of uncertainty

A design flow of Q, based on a QMED estimated from catchment descriptors, has a 95% confidence limit of **at least** 0.49Q, 2.04Q. In other words, the true value may be less than half or more than twice the best estimate. Results for longer return periods are considerably less certain.

This degree of uncertainty may be surprising and worrying for many people. It is important to realise that a wide confidence interval does not necessarily mean that the best estimate is wrong. It is much more likely to be correct than are the values at the upper and lower confidence limits, as illustrated in the diagram below.

The result shows that the typical allowances made for the possible effects of climate change (an increase of 20 or 30% on peak flows) are much less than the uncertainty in many flood estimates.

The sketch below gives the probability density function illustrating uncertainty in a flood estimate for a given return period.



Based on a sketch graph in: Committee on Risk-Based Analysis for Flood Damage Reduction, Water Science and Technology Board, National Research Council (USA) (2000). Risk Analysis and Uncertainty in Flood Damage Reduction Studies.

6. Application-specific guidance

Overview

In this chapter

This chapter provides a brief overview of issues that an analyst should consider when assessing how to approach flood estimation in a specific application. In many cases, converting flood peak flows and hydrographs, derived using the FEH, into water levels may be all that is required. In others, FEH results will feed into detailed hydraulic modelling or other studies. This chapter also discusses flood estimation on unusual catchments.

Analysts: in all cases, you will need to carefully consider the specific requirements of the study when developing a method statement.

Flood mapping and hydrodynamic models

Steady and unsteady hydraulic models

Flood mapping indicates areas at risk from a flood event of a certain frequency. When floodplain storage is not significant, you can identify the extent of flooding from a steady-state hydraulic model.

An unsteady hydraulic model is appropriate when:

- floodplain storage is significant;
- or you require a more accurate assessment of complex floodplains;
- or you require the model for other applications, such as flood warning or forecasting.

An unsteady model requires the derivation of inflow hydrographs, using either a rainfall-runoff method or a hybrid approach (see Hybrid methods, on page 36). These are then routed through hydraulic models to identify the extent of flooding.

The issue: striking a balance

Unsteady hydraulic models or flow routing models can help in understanding how flood peaks propagate down the catchment and their relative timing at confluences. This knowledge can inform the process of flood estimation.

However, these models tend to rely on a rainfall-runoff approach to provide inflows. It is important to remember that it may not provide the best estimates, particularly when there are flood peak data at sites within the model reach. Also, the need to derive a hydrograph volume and shape introduces another element of uncertainty.

There are many ways of deriving inflows for unsteady models. It is often necessary to strike a balance between two extremes.

Two extremes

Excessive reliance on the hydraulic model	↔	Imposing the design flows on the model
Example: Ignoring flood peak data at sites within the study reaches.		That is, adjusting model inflows so that it reproduces the preferred FEH estimates at all points in the system.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	If a hybrid method is used to generate design flows, there is no guarantee that hydrographs scaled to match peak flows from the statistical method at model inflows will result in statistical peak flows being reproduced further downstream within the model. At each point of interest in the model, it is necessary to decide how to strike the balance described above.
2	There can be a risk of double-counting floodplain attenuation in unsteady modelling. This could happen if a downstream donor site (at which flows are affected by attenuation) is used to estimate or adjust design flows for an inflow to a model, which then routes the flood hydrograph, allowing for the same attenuation processes again.

	You can avoid this by ensuring that the flow within the model gives a close match to design flows estimated at the site of the gauging station.
3	There is no catchment-wide design flood. The severity of any real flood event will be greater at some locations than elsewhere in the catchment (**1** 9.3). Therefore, if you have used a rainfall-runoff approach for flood mapping, you need to estimate the design flood separately at each site of interest, using a design storm appropriate for the catchment draining to that site (**1** 9.4). If you are applying a distributed rainfall-runoff approach (see Lumped or Distributed approach? on page 62) you will also need to ensure that, for each site of interest, you apply a uniform storm duration and areal reduction factor across all subcatchments. The above advice can be confusing at first sight. Imagine you have a hydraulic model with four inflows from subcatchments. There are three key sites within your model reach where you need design flows. Site 1: use uniform storm duration D_1 for all four subcatchments and an areal reduction factor calculated for area A_1 Site 2: use uniform storm duration D_2 for all four subcatchments and an areal reduction factor calculated for area A_2 Site 3: use uniform storm duration D_3 for all four subcatchments and an areal reduction factor calculated for area A_3 See also Issues with catchment models, below.

Issues with catchment models

Some studies have used catchment models to help to derive parameters for the FEH rainfall-runoff model. Parameters for various inflow catchments are adjusted by trial and error to give a match between observed and predicted flows or levels further down the model. This approach is not mentioned in the FEH, but it can be valuable.

However, it can also be very misleading. In many cases, the studies refer to the catchment model as 'calibrated', implying that it can then be used with confidence for synthesising design events. This has led to over-reliance on the FEH rainfall-runoff method in some studies, which can give very poor design flows, even when the model parameters are well estimated (see Choosing between the FEH methods, on page 34).

Analysts: we strongly recommend that you stick to the language used by the FEH. Refer to 'estimating the model parameters' rather than 'calibration'. Lumped or distributed approach? on page 62, gives further guidance on distributed application of rainfall-runoff methods.

Catchment-wide studies

The issue

Catchment-wide studies, whether broad scale, like CFMPs, or more detailed, such as flood risk or strategy studies, make extensive use of FEH methods. FEH methods are intended for application at particular (subject) sites. This is not surprising. They are calibrated against flood data at particular (gauged) sites.

Additional factor: spatial consistency

There are some additional factors to consider in larger scale studies. The most important is spatial consistency. The CEH report on automation of the statistical method addressed this in detail, see Morris, D.G. (2003), listed in Related documents. It suggests some rules for spatial consistency:

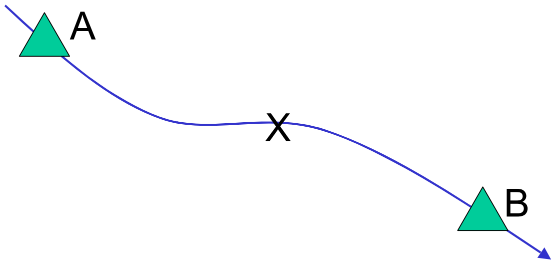
- sudden increases in flood estimates should only occur at confluences;
- flood estimates should not decrease in the downstream direction unless there are clearly defined physical causes (such as floodplain attenuation);
- the flood estimate immediately downstream of a confluence must be consistent with those immediately upstream;
  That is, it should not be greater than the sum of the upstream ones or smaller than the larger of them. It will normally be smaller than the sum of the upstream estimates because the two watercourses will not usually peak at the same time.
- flood estimates at, and close to, gauging sites should be consistent with the gauged record unless there are valid reasons to the contrary.

The FEH methods are not guaranteed to meet these rules. Additional inconsistency can be introduced by applying donor sites. See Figure 20.

Figure 20: an example

In the map below, if donor A is used to adjust QMED for all points upstream of X and donor B used downstream of X, there could be a sudden jump in QMED at X.

Weighted averaging of adjustment factors can help avoid this. For similar reasons, and to save time, it is usually advisable to apply the same pooling group at several sites on the same watercourse.



Post-event analysis

Guidelines

Post-event analysis may be required to assess the severity of a specific flood. The guidelines and advice in the table are included to help users.

Item	Guideline or advice
1	Take care not to quote hasty assessments for rainfall and flood rarity. Ensure that the message is clear, simple and user friendly but still technically accurate. Refer to our Understanding and Communicating Flood Risk policy, listed in Related documents. Simple factual statements about the ranking of the event provides an immediate perspective alongside reassurance that a thorough review has been initiated.
2	If flow data for the event are available, you will need to interpret them with care, bearing in mind the quality of the rating curve for high flows.

3	Another aspect to consider is the bias inherent in estimating the flood frequency and return period, particularly using a single site analysis (**3** Add. Note 11.2). **Analysts:** you should seek expert advice when there is a need to make an adjustment.
4	The ReFH method can assist in event analysis when there is no recorded flow data. The data required to simulate an observed event in ReFH is: ▪ catchment-average event rainfall (for example, at a time step of 1 hour or 15 minutes) from tipping bucket raingauge(s) or radar data; ▪ catchment-average daily rainfall from the start of the year preceding the flood; ▪ potential evaporation, either a daily series or a mean daily value.
5	Input the data specified in Item 4 into the ReFH Design Flood Modelling software. It calculates the initial soil moisture from the daily rainfall and evaporation data and then runs the ReFH model to simulate the flood hydrograph from the event rainfall data. You can assess the return period of the peak flow, using the most appropriate FEH method. In most cases, it is sensible to use ReFH for deriving the flood frequency curve as well as for simulating the flood. Any errors in model parameters can be expected to cancel out to some extent as described in the FEH (**4** 5.4.2).

Reassessing estimates and recalibrating models

Large and rare floods provide invaluable data with which to reassess flood estimates and recalibrate hydraulic models. This should lead to improved estimation of:

- downstream water levels;
- hydrograph shape;
- travel time;
- flood extents;
- flood return periods.

Modelling effects of land-use change on flooding

Description

CFMPs make use of FEH methods to examine the effects of various policies, such as changes in farming and forestry on flooding. This has been done by sensitivity testing, altering the values of Tp and SPR in the FEH rainfall-runoff method. See CFMP Processes and Procedures Guidance.

Guidelines

The guidelines and advice listed in the table below are for all users.

Item	Guideline or advice
1	The best approach is to compare observed flood impacts on paired catchments with different land uses. Then use data transfer

	techniques to apply the observed impacts to the study catchment. However, it is rare to find observed data from suitable analogue catchments. So most CFMP studies use a more generalised approach. **Example:** Increasing SPR by a factor of 1.15 to represent agricultural intensification.
2	Now that ReFH has superseded the FEH rainfall-runoff method, there is an opportunity for updating the guidance on modelling the effects of land-use change. However, in the meantime, you could use the FEH rainfall-runoff method to indicate the relative effects on flood peaks, even if the best estimates of peak flows are derived using a different method.

Pumped and other low-lying catchments

The issue

Catchments draining to pumping stations present an additional complexity. Research has shown that the response of pumped catchments is different to that from typical gravity catchments.

Catchment boundaries tend to be manmade rather than natural, the water table is lowered by drainage, watercourses are often artificial and flows are affected by pump operations. For these reasons, predicting design flows from catchment descriptors is unlikely to be successful.

Much of the guidance in this section is also applicable to low-lying catchments drained by gravity, for example through sluices that open at low tide.

Guidelines

The guidelines and advice in the table below are included to help users.

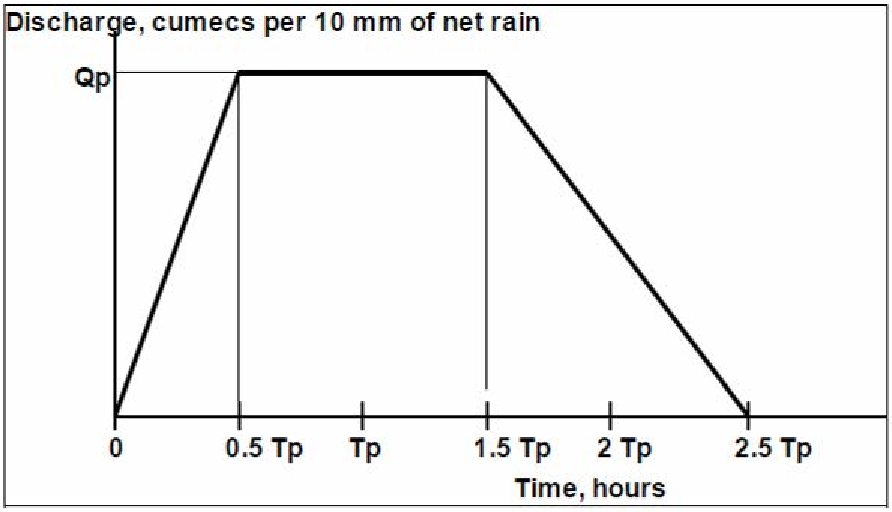
Item	Guideline or advice
1	There are few flow gauging stations on lowland catchments, partly because of the historical necessity to use weirs for flow measurement. The FEH did not include pumped catchments in the derivation of the empirical equation for QMED. Given the factors listed in The issue, above, there should be no expectation that any FEH procedures are applicable to lowland pumped catchments (**3** 13.7.4).
2	The FEH makes little reference to pumped catchments. Most studies continue to use a variation of the FSR rainfall-runoff method first published in 1987. See Samuels (1993) and IWEM (1987) Part 1 – both listed in Related documents. A recent Environment Agency science project, SC090006 (Flikweert and Worth, 2012) has updated the earlier guidance but the basic method is unchanged. In summary, the tailored version of the FSR rainfall-runoff method involves: ▪ estimating time to peak preferably from local data or else (as a last resort) setting it to 24 hours, rather than using catchment descriptors; ▪ using a trapezoidal unit hydrograph shape, which reaches the peak flow at 0.5 Tp and remains at that flow until 1.5 Tp; See Figure 21, on page 85. The peak flow is 1.59/Tp m^3/s per 10 mm of rainfall per unit area, compared with 2.20/Tp using the conventional triangular unit hydrograph or 1.80/Tp using the ReFH unit hydrograph; **Note:** The magnitude of the unit hydrograph peak is not clear in the R&D report on ReFH. This value comes from the FEH Supplementary Report on ReFH. ▪ estimating SPR by back-calculation from rainfall and pumping station data in preference to using soil mapping. Pumped catchments are particularly sensitive to volumes of runoff so it is important to estimate SPR as accurately as possible. An alternative, not mentioned in SC090006, would be to use the ReFH model to calculate the volume of runoff. Since ReFH has superseded the FSR rainfall-runoff method for most applications,

	there is no particular reason not to use it for pumped catchments. If you decide to use ReFH, ensure that the unit hydrograph shape is modified as explained above. ▪ calculating a critical rainfall duration by iteration as explained in FEH **4** 9.2.2. ▪ being careful with the design rainfall profile if the critical duration is longer than 48 hours. The recommended procedure is to distribute the design rainfall depth in time using the temporal profile of one or more notable long-duration rainfall events that were experienced locally or regionally. ▪ accounting separately for runoff for upland or urban areas. You should refer to SC090096 for more detailed information and guidance when studying pumped catchments. SC090096 also recommends that you use pumping station records to investigate the performance of the drainage system, estimating a flow hydrograph for past events and comparing the rainfall duration and profile with those of the design storm event.
3	You need to apply careful judgement before using the above technique to generate inflows into lowland drains for subsequent hydraulic modelling of the drains and pumping station. The trapezoidal (flat-topped) form of the unit hydrograph partly reflects the influence of storage in the drain system and its role in attenuating the flood discharge. As a result, using the trapezoidal unit hydrograph combined with a hydraulic model that also explicitly includes this channel storage could cause underestimation of flood levels through over-representation of the attenuation. Therefore you should not use the trapezoidal unit hydrograph as a model boundary condition at the point of entry to the main-drain system. However, it may not be appropriate to use the standard FEH or ReFH unit hydrograph either, since peak flows may be impeded for quite some distance upstream of pumping stations due to the shallow gradients. When deciding how to represent inflows to models of lowland drains you should take into account the length of the model reach and the degree of influence of the pumping station at the upstream model boundaries. SC090006 suggests a trial and error approach to this problem, adjusting model inflows (for example the time to peak or the shape of the unit hydrograph) until the hydrograph simulated by the model at the pumping station matches that estimated using the trapezoidal unit hydrograph.
4	An alternative method of flood estimation on pumped catchments is flood frequency analysis of annual maximum pumped volumes; see Part 1 of IWEM (1987). You should use this in preference when long records are available for the pumping station (which in practice seems to be rarely). Another alternative, not mentioned in published guidance, is to represent the entire pumped area using a 2D or linked 1D-2D hydraulic model with rainfall applied directly to the 2D model domain. This avoids the need for a unit hydrograph, but the resulting flow estimates will be heavily influenced by the assumptions made in the hydraulic model development. This has been applied on a small number of projects to date. Science project SC090006 recommends a tiered approach when selecting a method for flood estimation on pumped catchments.

	More advanced methods are needed when the analysis needs to provide more detailed answers and there is enough reliable data to justify the application of advanced methods.
5	Water balance calculations can be helpful on pumped catchments, either over a long period or for individual floods (whether observed or design events). SC090006 gives some guidance on this.
6	If estimating design flows for locations downstream of pumping stations, you should limit the outflow hydrographs from pumped catchments to the pump capacities. They can either be taken as constant flows or, if the volume is thought to be limited, routed through a notional reservoir that has an upper limit set on its outflow.

Figure 21

The diagram below shows a trapezoidal unit hydrograph for pumped catchments, from Science Report SC090096.



Water level management plans and short return period estimates

Description

Water level management plans establish a regime to protect and enhance the conservation status of areas where habitats rely upon water levels in harmony with their flora and fauna. These areas, which are likely to experience regular inundation, are most vulnerable to change in the pattern of frequent events rather than to infrequent extreme floods.

The FEH methods are likely to be at their most robust for frequent events and can supply valuable estimates of inundation frequency using statistical methods.

Two types of return period

For estimation of frequent flood events, it's important to understand the difference between:

- the annual maximum return period, used in the FEH;
- and the POT return period, sometimes known as the average recurrence interval.

The two types of return period are related using Langbein's formula, included in Appendix A of FEH Volume 1.

Return periods of 1 year or less are meaningless on the annual maximum scale. So, if you require a design flood for a return period of 0.5 years, you must convert this POT-scale value to the corresponding annual maximum-scale return period, which is 1.16 years. You can calculate the design flow for this return period using an appropriate FEH method.

An alternative way of estimating short return period floods, particularly where short flood peak records are available, is to analyse POT data using the method described in the Flood Studies Report (Volume 1, section 2.7.5).

Note: Both methods described here have attracted criticism for ignoring dependence between successive flood peaks, which has been found to result in slight overestimation of design flows. See Archer, D. R. (1981), 'A catchment approach to flood estimation', listed in Related documents.

Seasonal flood estimation

Although the FEH provides information on mean date of flooding and variability, it does not specifically address the problem of seasonal flood estimation.

Example: Assessing the flow of a given return period for a specified period of the year.

This may be important in the winter, for maintaining high conservation levels, or in the summer, for impact on crop growth.

However, the peaks over a threshold database provides information from which such information can be assessed. Archer's 'The seasonality of flooding and the assessment of seasonal flood risk' (1981) provides a practical method of such an assessment. See Related documents.

Comparing estimates and simulations

When frequency and extent of flood inundations are critical, you will require estimates of flood hydrographs using the ReFH method.

But, when good records are available, simulation with measured flows may be preferable and more readily understood by lay stakeholders.

Small catchments and greenfield runoff

The issues

By their very nature, there are many more small catchments than large ones. So many flood estimates are carried out on small catchments. This is particularly true in development control, where additionally greenfield runoff estimates are needed for development sites, which generally do not form complete catchments. FEH methods were not originally intended for catchments smaller than 0.5 km^2, unless flow data are available (**1** 3.1.2). Older methods have often been used instead, but recent research has shown that FEH methods should be preferred.

Reasons for uncertainty on small catchments

More generally, flood estimates are particularly uncertain on small catchments (say, below 25 km^2) because:

- there is a shortage of such catchments in the FEH dataset used to derive the regression equations for ungauged sites and the HiFlows-UK dataset used to select pooling groups and donor catchments (see Figure 7, on page 36);
- digital catchment descriptors are more difficult to derive for small catchments, which is why the FEH CD-ROM imposes a minimum area of 0.5 km^2;
- flood peaks on small catchments are more susceptible to being influenced by local features, such as flow diversions, field drainage or storage of flood water behind culverts, bridges or embankments.

Guidelines

The guidelines and advice listed in the table below are for all users.

Item	Guideline or advice
1	For small catchments, checking catchment descriptors becomes more important. There is more scope for the DTM or the thematic datasets to be wrong for such small areas. It may be worth doing a soil survey or at least checking HOST values against soil maps.
2	Guidance on choice of method for flood estimation on small catchments has been developed in Science Project SC090031: Estimating flood peaks and hydrographs for small catchments. The report on Phase 1 (Faulkner *et al.*, 2012) gives interim recommendations as follows: "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." The next phase of project SC090031 is due to lead to development of new simple methods for flood estimation in small catchments and guidance on how to incorporate additional local information.
3	You are likely to come across studies that continue to use older methods. These are reviewed in the following sections: Rational method, starting below ADAS Report 345, starting on page 89 Institute of Hydrology Report 124, starting on page 90

Rational method

Description

In the rational formula, peak flow is estimated with the equation:

$Q = 0.278\ KIA$, where:

- K is the runoff coefficient;
- I the rainfall intensity over the time of concentration;
- A the catchment area (km^2).

The two key choices are the time of concentration and the runoff coefficient.

The Bransby-Williams formula has often been used to estimate the time of concentration from the length, slope and area of the catchment.

FEH recommendation

The FEH doesn't recommend the rational method using this formula (**4** 3.4.2) as it gives peak flows typically twice as large as those from the FEH rainfall-runoff method for small lowland catchments. See Institute of Hydrology (1978).

Modified rational method

There is a modified rational method, from the National Water Council (1981), listed in Related documents. It is used for sewer design and includes formulae to aid estimation of the two key parameters:

1. time of concentration is divided into time of entry and time of flow though the pipe system;
2. the runoff coefficient is related to the percentage runoff used in the Wallingford Hydrograph Method and moderated by a routing coefficient that allows for the typical shapes of time-area diagrams and rainfall profiles.

The method is not suitable for greenfield runoff estimation as it is designed for sewered urban areas.

ADAS Report 345

Reference

HMSO (1982) ADAS Reference Book 345. The design of field drainage pipe systems.

Description

This was developed as a way of designing field drainage systems to protect crops from flood damage. It is only suitable for small rural catchments with no formal drainage system.

Flow is estimated from land use, soil type and rainfall, using a graphical solution to an equation ultimately based on the rational method.
Note: ADAS Book 345 gives no information about how the method was derived. Find that in: Bailey, A.D. and others (1980), listed in Related documents.

The relationship between flow and return period is based on rainfall intensities derived by Bilham in 1962, which are clearly rather dated.

Alternative approach

An alternative approach is to derive the 2-year flow and then use a growth curve from FSR or FEH to obtain results for other return periods (from personal communications from Steve Rose and Rob Arrowsmith, both formerly of ADAS).

For the 2-year flow, see the line labelled as 'Grass' on the graph in ADAS 345 Appendix 6. The label should actually say 'Intensive grass and cereals', for consistency with MAFF Report 5 (see Related documents) which states that the 2-year return period corresponds to intensive grass and cereals. It can be seen that the Grass line in ADAS 345 corresponds to the 2-year return period line in MAFF Report 5 Figure 4.

Estimate of soil type factor

The soil type factor in ADAS 345 is estimated from characteristics such as permeability and soil texture. MAFF Report 5 presents a way of calculating the soil type factor from the FSR WRAP maps, which is more straightforward for most analysts.

Results of tests

Science Project SC090031 found that ADAS 345 tends to underestimate QMED and has a mean error that is much higher than any other method tested. The research report also pointed out that ADAS 345 is based on a very small dataset of limited length.

Therefore, we advise users to avoid ADAS 345 for flood or greenfield runoff estimation on small catchments.

Institute of Hydrology Report 124

Reference

Marshall, D.C.W. and Bayliss, A.C. (1994) Flood estimation for small catchments. IH Report 124. Institute of Hydrology, Wallingford. Download from the CEH website.

Description

The study derived equations for Tp(0) and QBAR, using data from 71 small rural catchments in lowland England. Many of these catchments were upland, relatively wet and impermeable. Only two of the catchments were smaller than the smallest in the data set used to derive the latest FEH equation for QMED. The flood peak records used for the research do not include the most recent 20 years of data.

Guidelines

The guidelines and advice in the table below are included to help users. Select references that are linked to see details in Related documents.

Item	Guideline or advice
1	The QBAR equation in IH 124 has been recommended for greenfield runoff estimation in a wide range of guidance documents including the Interim Code of Practice for SUDS and the SUDS Manual. The recommendation was based on a guide by HR Wallingford first published in 2004. The most recent version is Kellagher (2012). The guide 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. Although the recommendation to use IH 124 is maintained in Kellagher (2012) (albeit alongside FEH methods), it has now been superseded by Science Project SC090031: see item 4 below.
2	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.
3	A disadvantage of the statistical method in IH Report 124, is that it relies on the FSR regional flood growth curves, which is a step backwards from the flexible pooling system introduced in the FEH. However, it is possible to combine an estimate of QBAR from IH 124 with a pooled growth curve from FEH, as long as the calculation accounts for the different return periods of QBAR and QMED.
4	Science Project SC090031 found that IH 124 tends to underestimate QMED and has a mean error that is higher than the FEH Statistical method. Therefore, we advise users to avoid IH 124 for flood or greenfield runoff estimation on small catchments.

Development control and urban catchments

The issues

Development control is one of the most difficult application areas (**1** 12.6).

Urbanisation has a widespread and significant effect on flood frequency.

Some development control applications will be beyond the scope of the FEH methods.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	The FEH has much to say on development control and urban catchments (**1** 8, **3** 9, **3** 18, **4** 9.3, **5** 6). Urbanisation can have a major influence on the flood frequency curve. The type of influence is affected not just by the amount of urban area in the catchment but also by factors such as the pre-urban runoff rate (i.e. the soil type), the type of development, the way in which it is drained (including the extent of any SUDS measures), the location and the spatial concentration of the urbanisation. Because of this wide variety of factors, you cannot expect to get a very reliable estimate of the flood frequency curve using generalised methods, i.e. those derived using data from other catchments. There is no substitute for obtaining local data. With a little advance planning, you can sometimes achieve this without incurring large delays or expense. Even two years worth of flood peak data recorded, for example, using a temporary ultrasonic flow meter, can be expected to give a more certain estimate of QMED than the FEH equation based on catchment descriptors. If timescale, budget or practical considerations mean that it is not possible to obtain local data, you will have to accept a large amount of uncertainty on design flows for small urban catchments.
2	On heavily urbanised catchments you should obtain information on the urban drainage network: locations of combined sewer overflows and storm sewer outlets, and the extent of the sewer network draining to these locations. You may find that the boundary of the urban drainage catchment is significantly different from the topographic catchment boundary. Sewers may take water out of the topographic catchment or bring water into the catchment from neighbouring areas. A complicating factor is that urban drainage systems have a limited capacity. Modern systems are designed for a return period of 30 years, but older systems may have a capacity of 5-20 year return period. In more extreme storms, the excess water will flow overland, following the contours of the ground. So the catchment boundary can vary according to the intensity of the rainfall. See Beskeen and others (2011). If this is the case then you should use a rainfall-runoff method in preference to the Statistical method, separating the catchment into different zones (for example, rural areas, urban areas drained by combined or surface water sewers, areas where sewers drain out of the topographic catchment, areas where sewers drain into the catchment from other topographic catchments, and so on). See below for guidance on choice of rainfall-runoff method and an

	example of how to divide up the catchment. If any flow or water level data is available you should examine it, along with rainfall data to check for evidence of a multi-peaked response to rainfall which might be expected if urban and rural areas both contribute significant amounts of runoff. The approach to flood estimation needs particularly careful thought when there is a mixture of urban and rural areas in the catchment. This needs to be considered when developing the conceptual model, see Preparing method statements, on page 32.
3	Although the FEH advances the merits of SUDS (**1** 12.6), it cautions that the effect of runoff control techniques are usually only examined at the local scale. A more holistic approach is required to ensure that they do not have adverse effects elsewhere within the catchment (**1** Interlude).
4	When a floodplain is threatened by development, flow hydrographs will assist examination of the options to mitigate the loss of floodplain storage. In other cases, a simple steady-state model may be sufficient to demonstrate that the proposed development does not impede flood flows. In all cases, it is important to check for consequential and detrimental effects elsewhere in the catchment.
5	The degree of urbanisation of a catchment is measured using URBEXT2000 (used in the Statistical method) or URBEXT1990 (used in the ReFH and Rainfall-Runoff methods). For information on the differences between $URBEXT_{1990}$ and $URBEXT_{2000}$, refer to the R&D Report by CEH Wallingford, see Bayliss, A.C. and others (2007), listed in Related documents.

Up to moderately urbanised catchments

Recommended methods

For catchments up to moderately urbanised ($URBEXT_{1990}$<0.125 or $URBEXT_{2000}$<0.150):

You can consider any of the usual rural catchment methods, applying an urban adjustment if you choose the Statistical method. The ReFH method treats catchments up to moderately urbanised as essentially rural.

Heavily or very heavily urbanised catchments

Option 1: Statistical method

For heavily or very heavily urbanised catchments ($0.125 \leq URBEXT_{1990} < 0.500$ or $0.150 \leq URBEXT_{2000} < 0.600$):

You should put careful thought into the choice of method for such catchments, first developing an understanding of the urban drainage network (see above).

If there is little difference between the boundaries of the topographic and sewer catchments, or if you are interested in extreme events for which sewer flows can be neglected, you can use the Statistical method, with an urban adjustment applied. The revised urban adjustment (Kjeldsen, 2010) was developed using data from 206 urban catchments. The Statistical method benefits from an up-to-date flood peak dataset, unlike earlier methods which are all dated to some extent. The method also has the advantage of avoiding the need to make assumptions about factors such as the nature of the design flood, the rainfall duration, the time of concentration etc.

You should not use the Statistical method to predict the future effect of urbanisation (**3** 9.1).

Option 2: Revised version of ReFH method

An alternative method, which can also be applied when the topographic and sewer catchments differ, is the revised version of ReFH published by Kjeldsen (2009). You should not use the original version of ReFH because its summer design event was calibrated on only seven urban catchments.

The revised ReFH method for urban catchments alters the percentage runoff to account for the presence of paved areas. It uses the full ReFH model in rural areas and within the green portion of urban areas (gardens, parks etc.). In the portion of urban areas covered in hard surfaces, the ReFH losses model is not used; instead the percentage runoff is set to a fixed value (70% is suggested in the paper, which is the figure used in the FSR rainfall-runoff method; see **4** 2.3.1). This avoids the need to depend on aspects of ReFH that are poorly calibrated for urban catchments:

- the regression equation for CMAX, which does not represent the increase in runoff volume with urban extent;
- the way in which the initial soil moisture, Cini, is calculated for design events based on an equation calibrated from only 7 catchments and which gives a physically unrealistic increase in Cmax as PROPWET decreases;
- the α factor used to scale Cini to ensure that the resulting flood frequency curve is consistent with the results of the FEH statistical method - again, this factor was derived from analysis of only 7 catchments.

Kjeldsen (2009) describes calibration of the revised ReFH method by comparison of modelled and observed hydrographs on two catchments. Although the applications described in the paper are simulation of observed flood events, not estimation of design events, the revised method has recently been applied to estimate design flows on several complex urban catchments and appears to give sensible answers. See below for an example of its application.

Alternative rainfall-runoff methods

In the past, and still in some studies, other rainfall-runoff approaches (including the Rational, Modified Rational and FSR/FEH rainfall-runoff methods) have been widely applied on small urban catchments. Rainfall-runoff approaches are conceptually appealing because of the clearer link between rainfall and runoff in urban areas, where soils, and soil moisture, are less influential. However, all these methods have their disadvantages, including:

- The rational method assumes that the peak flow is proportional to the rainfall intensity. It is necessary to estimate the time of concentration, over which time the rainfall intensity is calculated. It is also necessary to guess a value for the runoff coefficient. Refer to the earlier section on small catchments.
- The modified rational method is used for sewer design within the Wallingford Procedure. It includes formulae to aid estimation of the two key parameters. Time of concentration is divided into time of entry and time of flow though the pipe system. The formula for time of entry, based on length and slope, is appropriate for small events only (return periods of weeks to months). For a return period of 5 years, the Wallingford Procedure recommends using 3-6 minutes for the time of entry. There is no guidance on what to use for longer return periods. This method may be a good choice for estimation of low return period floods on small catchments (up to 20 hectares) that are completely developed and drained by sewers. However, it is difficult to justify using it on larger catchments with a stream network.
- The FEH rainfall-runoff method tends to overestimate flows in many areas (sometimes by a factor of five or more) and has been superseded by the ReFH method.

You are recommended to consider the revised ReFH method as a first choice, but there is no ideal method for heavily urbanised catchments and in some situations it is possible that the alternatives listed above are more appropriate than ReFH. Another alternative is FRQSIM, a rainfall-runoff model developed for Greater London; see the information below.

Extremely heavily urbanised catchments

Recommended methods

For extremely heavily urbanised catchments ($URBEXT_{1990}$>0.5 or $URBEXT_{2000}$>0.6):

You should not routinely apply the FEH flood frequency methods to these catchments (**5** 6.5.5). However, alternative methods have drawbacks too, as discussed above.

For deriving flows from urban sewered areas it may be more appropriate to use sewer design methods, such as the modified rational (for peak flows) or the Wallingford hydrograph method, a version of the FSR rainfall-runoff method which is used in sewer network modelling software. You can find an example of its application for estimation of fluvial flood flows in Beskeen and others (2011).

An alternative is FRQSIM, a rainfall-runoff model developed for Greater London; see the information below.

Flood FReQuency SIMulation (FRQSIM)

Description

FRQSIM stands for flood FReQuency SIMulation. It was initially developed in the 1970s by the Greater London Council to provide design flows for flood alleviation schemes in the highly urbanised catchments of the Thames tributaries in London. However, use of the model is not restricted to these areas and it has been applied to other urban areas such as Manchester.

You can find information on the model in the user guide, FRQSIM Hydrological Model, listed in Related documents. Recent versions of ISIS include a FRQSIM unit.

Method

The catchment to be modelled is separated into 'node areas', which are equivalent to sub-catchments used in FEH methods. These are based not only on topographic information, but also on drainage networks.

Each node area is then divided further into 'sub-areas', defined as either paved or open.

The model differs from the FEH rainfall method because it uses a time-area method to produce synthetic unit hydrographs (SUH). A separate SUH is produced for paved and open areas. A third SUH is produced to represent gardens and verges within urban areas. Time of travel estimates are needed for each sub-area. FRQSIM does not allow for situations where the topographic catchment is different from the sewer catchment: see Beskeen and others (2011).

Other features of FRQSIM

FRQSIM includes a loss model, which determines the effective rainfall for open areas.

One other useful feature is the recognition of the finite capacity in the surface water drainage network. FRQSIM assumes that capacity of the network is the 5-year storm and that any rainfall above this will be stored in the model and released over subsequent time steps until all of the runoff has gone through the network.

Design rainfall and storm profiles

Other notable differences from the FEH rainfall runoff method include the shape of the design storm profiles used.

Ten storm profiles are available, based on 250 flood producing storms observed across the London area.

The design procedure used in FRQSIM has been criticised in the past for being rather obscure. For example, it is not clear why the 250 storms should represent 100 years of flood-producing rainfall, which is a fundamental assumption of the procedure.

Beran (1987) (see Related documents) recommended that the storms should be regarded as representing 250 years of data.

FRQSIM has been developed over the years, with a recent change being to obtain storm depths from the FEH rainfall frequency statistics. However, in any event-based method for estimating design flows, it is necessary to ensure that the composition of the design event (rainfall depth, duration, profile and catchment wetness) gives rise to a peak flow of the required return period. It is not clear that FRQSIM achieves this (Onof *et al.*, 1996).

Differences between design flows

FRQSIM has been seen to give design flows much higher than those from FEH methods (for example, on the Cobbins and Salmons Brooks and the Lower Lee).

The large differences between design flows from FRQSIM and FEH statistical methods, particularly at locations where the latter are based on local flood peak data, should act as a prompt to review some of the assumptions made in the FRQSIM design procedure. However, you should recognise that FEH methods do not perform at their best in heavily urbanised catchments. Both FEH and FRQSIM have pros and cons.

Example application of revised ReFH method

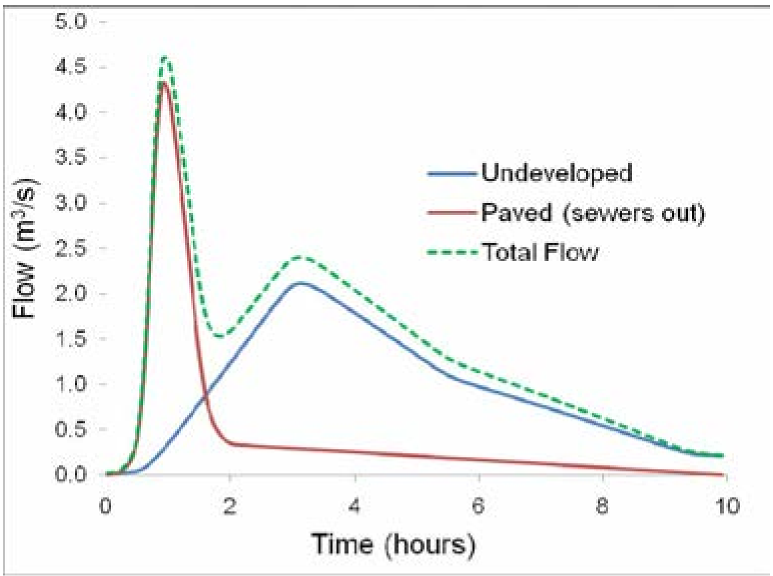
Example of revised ReFH method

The revised version of ReFH described above was used to estimate design flows for a flood mapping study on a heavily urbanised watercourse in Cheshire. The table below lists the steps involved in applying the method. The steps are intricate and much more time-consuming than conventional application of FEH methods to a lumped catchment. However, in the absence of any flood peak data for the watercourse, flood estimation on heavily urbanised catchments often needs this type of detailed analysis.

Project managers and team leaders: you should ensure that flood studies on heavily urbanised catchments allow enough time and budget for detailed hydrological calculations, and that staff working on such studies are given extra guidance and supervision until they are experienced in urban hydrology.

Step	Action
1	Division of catchment The catchment was divided into three categories of sub-catchment, based on sewer maps and LIDAR data. The three categories, shown on the map below, were: ▪ undeveloped sub-catchments; ▪ urban sub-catchments where the topography drains towards the

Step	Action
	watercourse but the sewers drain out of the catchment; ▪ urban sub-catchments where both the topography and the sewers drain towards the watercourse. Some catchments will have a fourth category, areas where sewers drain into the watercourse from outside the topographic catchment.  The sewer catchments consist of both combined and surface water sewers. The analyst assumed that the sewers would be at capacity for a 10-year return period rainfall event. This means that any rainfall over that of the 10-year event will end up contributing to flow on the watercourse even in areas where the sewers drain out of the catchment. A more accurate sewer capacity could be obtained from hydraulic modelling of the urban drainage network. The descriptors AREA, DPLBAR and $URBEXT_{1990}$ were altered to suit each sub-catchment.
2	Calculation of flows for undeveloped areas These flows were estimated using the standard ReFH model, applied separately to each rural sub-catchment and also to 60% of the area of each urban sub-catchment. The analyst assumed that 60% of urban areas are unpaved (i.e. water can infiltrate as it would on the rural catchments). Kjeldsen (2009) suggests 70%, but 60% was thought to be more appropriate on the study catchment as parts are heavily urbanised, with supermarkets, car parks and industrial buildings. The method assumes that the unpaved portion of urban areas behaves as the rural areas, unaffected by sewer systems.$URBEXT_{1990}$ values were altered to 0, resulting in the longer time to peak that would be expected in rural areas.
3	Calculation of flows for the paved portion of urban areas where the topography drains towards the watercourse but the sewers drain away For return periods up to 10 years the analyst assumed that all storm water leaves the catchment via the urban drainage system. For longer return periods, the 10-year rainfall intensity was subtracted from the design rainfall hyetograph, to give the excess water that

Step	Action
	was assumed unable to enter the sewer system. In practice the analyst applied this approximately by altering the rainfall return period entered to the ReFH spreadsheet. In order to represent the generation of runoff over an urban area, the percentage runoff (PR) was set to 70%, as suggested by Kjeldsen (2009).PR from the ReFH model can be calculated by dividing direct runoff by design rainfall. The ReFH spreadsheet was altered to produce a hydrograph where PR was approximately 70%, reducing the Cmax parameter by trial and error. URBEXT1990 was set to 0.5 (a higher value may have been more appropriate) to represent faster routing of water through the urban catchment, resulting in a shorter time to peak than seen on the rural catchments.
4	Calculation of flows for the paved portion of urban areas where both the topography and the sewers drain towards the watercourse The method was similar to that at step 3, but with no need to reduce the rainfall intensity to allow for the sewer capacity, as all water falling on the catchment will reach the watercourse, regardless of whether this is via sewer or topographic routes. Again the URBEXT1990 value was set to 0.5, and the model was adjusted to produce a PR value of 70%.The method assumes similar routing of flows whether within sewers or overland.
5	Hydrograph addition The previous steps produced two or three hydrographs for each sub-catchment, representing undeveloped and paved areas. The hydrographs were added together to produce inflows for use in a hydraulic model. Many of the combined hydrographs had double peaks, because of the differing flow routing times between the undeveloped and paved portions of the sub-catchment (see the graph below). Within each run of the hydraulic model, a common storm duration was used for all ReFH modelling. A range of storm durations was investigated to identify the critical duration.  Addition of hydrographs for undeveloped and paved areas in a sub-catchment

Permeable catchments

Why to avoid design event methods

Design event methods such as the FSR/FEH rainfall-runoff method or ReFH are generally not recommended for highly permeable catchments. Floods in catchments underlain by fissured aquifers, such as the Chalk, are influenced by hydrogeological factors that are not adequately represented in techniques developed for quick response catchments where surface features are the main control. See Bradford and Faulkner (1997).

Webster (1999) found that the relationship between the return periods of storms and floods became increasingly scattered for more permeable catchments, and concluded that permeable catchments are not really suitable for design flood analysis using an event-based method.

These comments also apply to the ReFH method, although its improved baseflow model may offer some advantages over the FEH rainfall-runoff method. The ReFH report states that caution is needed when applying the method in baseflow-dominated catchments, as the regression equations may underestimate the model parameter that represents maximum soil moisture storage. These guidelines recommend that ReFH is not used for estimating peak flows on permeable catchments.

The FEH Statistical method is normally the most appropriate choice on highly permeable catchments. However, it is important to be aware of two issues:

Issue 1: Large uncertainty in QMED

There is anecdotal evidence that the current regression equation for QMED (from Science Report SC050050) can under or over-estimate by a long way on some permeable catchments. Examples include:

- Extreme over-estimation on the South Winterbourne at Winterbourne Steepleton, a small chalk catchment in Dorset, where QMED estimated from catchment descriptors is 5.5 times larger than that estimated from annual maxima.
- Over-estimation on the Pang at Pangbourne, another chalk catchment, where QMED from catchment descriptors is 4 times larger than from annual maxima.
- Extreme under-estimation on the Rhee at Ashwell, a part-urbanised chalk catchment, where QMED from catchment descriptors is 5 times smaller than from annual maxima.

Underestimation on some catchments may be associated with the fact that the BFIHOST term is squared in the regression equation – although the non-linear term was found necessary in order to avoid overestimation of QMED on gauged catchments with high BFIHOST (see Figure 4.3 in Science Report SC050050).

It is possible that the confidence limits for QMED estimation are much wider on permeable catchments than the UK-average limits derived from the factorial standard error of the regression equation. So you should be aware that flood estimates on ungauged permeable catchments are likely to be extremely uncertain. If you need a more confident result, consider installing a temporary flow logger. Even a few month's worth of data may enable you to estimate design flows with more confidence than relying on catchment descriptors for a highly permeable catchment, for example if it enables calibration of a rainfall-runoff model for use in continuous simulation (see later).

Issue 2: Pooling groups	In the original FEH method, pooling groups for permeable catchments were generally composed of gauged permeable catchments. This is no longer the case using the method presented in Science Report SC050050 which does not use BIFHOST to select pooling groups. BFIHOST was excluded because it was found to have very little influence on the sample values of L-moments calculated from a large number of individual annual maximum series. For L-CV, the report states that a minimum of ten other variables were selected in a multiple regression before BFIHOST was included. So the data are saying that BFIHOST has no effect on the L-moments, and hence on the growth curves. When a similar method was used in the original FEH research, it found that BFIHOST was very influential. The change may be due to the addition of FARL and FPEXT as variables for selecting pooling group, because all three of these catchment descriptors represent catchment storage effects to some extent. Table 6.3 in SC050050 indicates the relative performance of different pooling group methods. The FEH method (i.e. v1 or v2 of WINFAP-FEH) performs slightly worse than a pooling group selected purely by geographical proximity. Out of the seven methods listed in the table, the FEH method gives the second highest uncertainty. The implication is that it would be unwise to revert to v2 of WINFAP-FEH for constructing pooling groups even if you were concerned about the exclusion of BFIHOST in the v3 method. Earlier research, including the FEH and Flood Studies Supplementary Report 4 (1977) has consistently reported differences in flood growth curves on permeable and nearby impermeable catchments: generally less year-to-year variation on the permeable catchments and hence flatter growth curves. Looking at flood history on permeable catchments, we should perhaps expect high skewness of annual maximum flows owing to occasional extreme floods – as mentioned in FSSR 4. But there don't seem to be many of these evident in the gauged period of record and so there is little effect on the sample L-moments.
So do permeable catchments need special pooling groups?	In light of the above considerations and bearing in mind the physical processes that lead to flooding, many hydrologists would consider it quite reasonable to expect BFIHOST to influence the growth curve, despite the findings of Science Report SC050050 It is worth bearing in mind that the results in SC050050 are UK averages. It's possible that an investigation focused purely on permeable catchments might come up with different findings. **Analysts**: if you want to allow for permeability in the composition of the pooling group, do this by manual editing of the group rather than reverting to v2 of WINFAP-FEH, for the reason given above and also because you would lose out on the other benefits of the v3 pooling procedure such as the revised weighting method and the option to carry out an enhanced single-site analysis.
Urban permeable catchments	Permeable catchments that are also urbanised pose particular problems in flood estimation. Refer to the section on urban adjustment in the Statistical method.

Guidelines The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	An understanding of the catchment geology and hydrogeology can be valuable when estimating floods in permeable catchments. In particular, it is important to establish the possible processes that might lead to flooding. These could include intense rainfall on scarp

	slopes, prolonged winter rainfall, snowmelt, rain falling on frozen ground or runoff from impermeable or urban areas of the catchment. If there is a correlation between river flows and groundwater levels, it may be possible to use long-term groundwater level data in the flood frequency analysis. The groundwater catchment boundary may be very different from the topographic boundary. You can investigate the location of groundwater divides by looking at geological or hydrogeological maps. Consider consulting colleagues in hydrogeology teams as well.
2	Significant floods tend to be infrequent on permeable catchments, but they can be unexpectedly severe when they do occur. This means that you need to interpret relatively short gauged records with caution, for example when fitting a single-site growth curve. Another consequence is that longer-term flood history is particularly valuable. The HiFlows-UK website does not provide data in the form of .pt files (for use in WINFAP-FEH) where baseflow dominance is such that POT extraction would be unrealistic without detailed analysis. This affects many, but not all, permeable catchments. POT data for permeable catchments is, however, given in .csv files. These may require care in their use because data from different sources may have different flow thresholds.
3	For many permeable catchments, there are some years in which no floods occur and the annual maximum flow is due to baseflow alone. Including non-flood annual maxima in a frequency analysis can result in a fitted growth curve that is bounded above (that is, the growth factors reach an upper limit). When you are carrying out single-site analysis on a permeable catchment, or pooled analysis for a group consisting largely of permeable catchments, use the technique described in the FEH (**3** 19) for removing flood-free years by adjusting the L-moments. Permeable catchments are defined in the FEH Statistical method using an arbitrary threshold of SPRHOST<20%, which corresponds roughly to BFIHOST>0.75. The calculations for adjusting L-moments are not carried out by WINFAP-FEH. It is necessary to solve the equation for the shape parameter (**3** Equation 19.4) numerically, which can be done using the Solver function in Excel or a root-finding subroutine in Fortran (for example). The adjustment generally has a fairly small effect on growth curves.
4	Where full hydrographs are needed, you can implement a hybrid approach. However, the influence of baseflow on flood flows in permeable catchments means that estimating flows from catchment descriptors alone could provide misleading flow values and hydrograph shapes. In these situations, it is important to refine model parameters, where possible, from local data.
5	Prolonged floods can occur on permeable catchments due to high groundwater levels. The volume and duration of floods are, therefore, important factors to consider. Bradford, R.B. and Goodsell's study in 2000 (see Related documents) of flood volumes on permeable catchments

	recommended carrying out volume frequency analysis by fitting a Generalised Logistic distribution to a series of annual maximum flood volumes over a given duration. This involves extracting discharge volumes over a period of *d* consecutive days from daily mean flow data, where *d* is the duration of interest. The maximum volume is determined for each water year. The annual maximum series is standardised by its median and the distribution is fitted by L-moments as for flood peaks.
6	Flood estimation by continuous simulation is a particularly attractive prospect on permeable catchments, particularly where there is a shortage of flood peak data. The simulation is likely to be more convincing if the rainfall-runoff model can be calibrated jointly against river flow and groundwater level data, where it is available (Reed, 2002). An example of such a model, which has been applied on the Chalk River Lavant catchment is described by Moore and Bell (2002). A related approach to consider is to combine aspects of FEH methods and continuous simulation. An example of this might be using a short record of flow data to estimate QMED and deriving the growth curve from continuous simulation.

Summary

Our summary of recommendations for permeable catchments includes:

- develop an understanding of the hydrological and hydrogeological processes that might result in a flood;
- be aware that significant floods can happen in permeable catchments but they tend to be infrequent;
- carry out a review of historical floods;
- use the statistical method in preference to a rainfall-runoff technique; In particular, you should not use ReFH when BFIHOST>0.65.
- acquire local flow data (even a very short record) if possible rather than relying on catchment descriptors for estimation of design flows. Refer to the example under Selecting and examining flood peak data in which even a month of flow data on a limestone catchment was enough to cast serious doubt on the catchment-descriptor estimate of QMED.
- adjust single-site growth curves to account for non-flood years in the dataset when SPRHOST<20%.

Catchments containing reservoirs

In this section

This section is about reservoir routing as part of a wider study when the reservoir and its safety is not the subject of the study. See also Flood estimation for reservoir safety, on page 104.

Description

The FEH statistical method accounts for lakes and reservoirs in a general way, using the catchment descriptor FARL:

- to reduce QMED when there are water bodies present in the catchment;
- and using FARL (in v3 of WINFAP-FEH) to guide the selection of the pooling group.

You should not rely on the QMED equation when FARL is below around 0.9 due to impounding reservoirs, unless they are kept permanently full and thus act like natural lakes (**3** 8.3.2, 13.7.4).

If flood peak data are available downstream of the reservoir and close to the site of interest, you can use them to estimate QMED directly and thus implicitly account for the effects of the reservoir.

In the absence of suitable flood peak data, you should use the ReFH method on catchments with a significant reservoir influence, along with a flood routing calculation which determines the outflow from the reservoir (**4** 8).

Unless the subject site is directly downstream from a single reservoir, it will be necessary to incorporate this in a flow routing model to allow for inflows from the rest of the catchment.

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	The ReFH flood modelling software, along with many other modelling packages, can carry out reservoir routing calculations. There are several points to beware of: ▪ because reservoirs delay flood hydrographs, the critical storm duration needs to be extended (**4** 8.2, **1** Interlude) and some iteration is necessary to find the critical duration; ▪ if there are multiple reservoirs in the catchment, the calculation becomes quite complex; It is necessary to estimate the direct inflow to each reservoir as well as the routing of outflows from upper reservoirs (**4** 8.3.2). ▪ when the design storm duration is much longer than the critical duration for the catchment flowing into a reservoir, beware that the ReFH method can overestimate the flow (see The ReFH method, on page 64); ▪ if the site of interest is some distance downstream from a reservoir, it is important to check whether the critical design event might arise from a shorter-duration storm on the intervening area downstream of the dam. (See Lumped or distributed approach? on page 62.)
2	The design of operating rules for both on-line and off-line flood storage reservoirs requires the derivation of flood hydrographs and knowledge of the discharge characteristics of the inflow and outflow structures. Flood hydrographs must be routed through the reservoir to determine its performance. In the absence of gauged data to simulate actual events, or where a T-year event is required, you should use the ReFH or hybrid methods.

Flood estimation for reservoir safety

In this section

Estimating floods to design or assess reservoir spillways is a specialised subject. This section gives a brief overview of the methods available and the latest current guidance (at July 2009).

Analysts: you should ensure that you are familiar with the methods and up-to-date with the guidance. Find the latest research and guidance on the Defra website.

Description

Reservoir spillway capacities are usually assessed as part of a detailed inspection that is carried out by Panel Engineers under Section 12 of the Reservoirs Act 1975 every 10 years. The final water level of the reservoir during a design storm is assessed to ensure there is adequate freeboard in the reservoir. The final water level includes a wave assessment, which is not covered in these flood estimation guidelines. Design floods at reservoirs are also needed for the preparation of reservoir flood plans.

Guidelines

The guidelines and advice in the table below are included to help users. Select references that are linked to see more details.

Item	Guideline or advice
1	Flood estimates for reservoir safety require great care and should be carefully checked. You should check catchment descriptors manually. It is sometimes necessary to calculate the flow contributions from catchwater channels. We recommend site inspections to establish whether drainage paths are likely to change in an extreme event. Refer to Floods and reservoir safety.
2	The Reservoirs Act 1975 provides a safety regime for raised reservoirs with a capacity greater than 25,000m^3. Dams are divided into four categories, A to D, based on the consequences of a breach. This is described in Floods and reservoir safety. The design standard for the spillway depends on the category – see Table 4, on page 105. A Panel Engineer classifies the reservoir and the record of the classification is maintained in the Prescribed Form of Record. The design flood of the required return period is derived for the catchment flowing into the reservoir and then routed through the reservoir, allowing for the reservoir lag effect in the storm duration.
3	Estimating long return period floods (150-1000 years), on page 107 covers long return periods. But there are specific methods prescribed for reservoir safety calculations. In particular, the ReFH method has not yet been accepted for reservoir safety work. Instead, you should use the FEH rainfall-runoff method, on page 61, for estimating the 150-year flood (Category D dams).
4	For longer return periods, particularly 10,000 years, users should be aware that the FEH rainfall frequency statistics were not derived with

	such extreme events in mind. When extrapolated to a return period of 10,000 years, they give some contradictions with estimates of the probable maximum precipitation. See MacDonald, D.E. and Scott, C.W. (2000).
5	After reviews by Babtie Group and Sir David Cox, Defra commissioned a project starting in 2005 to investigate alternative methods of extreme rainfall estimation for return periods up to 10,000 years and, if appropriate, to amend the FEH methodology for extreme rainfall. This research is complete, see Stewart, Lisa and others (2010), but has not yet been published. So Defra's interim guidance for reservoir safety calculations (March 2004), is still current. It states that: ▪ 1000-year rainfalls are estimated from both FSR and FEH methods and the more extreme result should be used; ▪ 10,000-year rainfalls are derived from FSR rather than FEH methods; ▪ In both cases, the FEH rainfall-runoff method should be used to derive the flood hydrograph from the appropriate design storm; model parameters should be estimated from local data or catchment descriptors if data are not available. Refer to Floods and Reservoir Safety – Revised Guidance for Panel Engineers.
6	The FSR rainfall frequency method involves using tables (FSR Volume 2) and maps (FSR Volume 5).
7	The estimation of the PMF is set out in FEH **4** 4. It is a version of the rainfall-runoff method, with the following changes: ▪ the design rainfall event is the probable maximum precipitation, PMP; this is estimated from a rather involved procedure (**4** 4.3) based on information from maps and tables; ▪ you should apply both summer and winter PMPs, to see which gives the larger flood; ▪ the time to peak of the unit hydrograph is reduced by one third to account for the more rapid response of an exceptional flood; ▪ when applying the winter PMP, the standard percentage runoff is set to a minimum of 53% to account for frozen ground; ▪ when applying the winter PMP, you should consider snowmelt; You can add it to the event precipitation and the antecedent rainfall. Take the melt rate and snow depth from maps. ▪ the catchment wetness index is increased to allow for greater antecedent rainfall.
8	You can do the PMF calculations in ISIS, which can also optimise to find the critical storm duration. Some consultants continue to use the Micro-FSR software, which was developed by the Institute of Hydrology to support the FSR methods.

Table 4 The table below lists dam categories.

Dam category	Potential effect of a breach	Design flood inflow (when overtopping cannot be

		tolerated)
A	Endangering lives in a community	Probable Maximum Flood (PMF)
B	Endangering lives not in a community, or causing extensive damage	10,000-year flood
C	Negligible risk to life and limited damage	1000-year flood
D	Special cases where no loss of life can be foreseen and very limited additional flood damage would result from a breach (mainly ornamental lakes)	150-year flood

Summary

Our summary of guidance on flood estimation for reservoir safety includes the following. References are listed in Related documents.

Date	Document	Main aspects still current (July 2009)
1996	Floods and reservoir safety (3rd ed.)	Overview, legal requirements, engineering aspects, flood routing and wave calculations
1999	FEH Volume 4	Estimation of PMF and 150-year flood. Rainfall-runoff modelling for other return periods
2004	Floods and Reservoir Safety Revised Guidance for Panel Engineers	Choice of method for 1000-year and 10,000-year rainfall. Summary of other current guidance.

Estimating long return period floods (150-1000 years)

The issues

There has been an increasing demand for flood estimates at return periods longer than 100 years, particularly in flood mapping and flood-warning studies that now include the 1000-year flood. In Wales, TAN15 also requires developers to assess the 1000-year flood on their development.

Description

All flood estimates for extreme return periods rely, however indirectly, on extrapolation. For this reason, given the typical length of flood peak records, the FEH statistical method was originally recommended principally for return periods up to 200 years. In the past, most flood estimates for longer return periods have been derived from the FSR/FEH rainfall-runoff method.

Guidelines

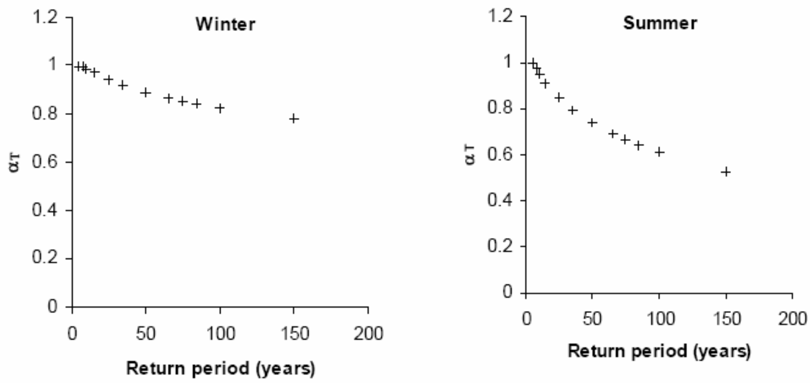
The guidelines and advice in the table below are included to help users. Select references that are linked to see details in Related documents.

Item	Guideline or advice
1	The main reason for preferring a rainfall-runoff approach is that you can define rainfall growth curves for long return periods with much more confidence than flood growth curves. This is particularly true for the FEH rainfall analysis, which drew on a much larger and longer dataset than is available for flood peak data. Furthermore, the spatial consistency of extreme rainfall allowed the rainfall growth curves to be extended to long return periods using a model of spatial dependence.
2	Before the ReFH method was developed, the FEH statistical method was widely used (outside its initial recommended range) to estimate 1000-year floods. This was partly due to concerns that the FEH rainfall-runoff method overestimated design flows in many locations. A significant application of the statistical method at long return periods was the automated estimation of flows by CEH, which were subsequently used in the mapping of the Environment Agency’s Extreme Flood Outline. See Morris, D.G. (2003).
4	The design event used in ReFH is calibrated up to return periods of 150 years. This is an improvement on the FEH rainfall-runoff model that was only calibrated up to 10 years, in a simulation exercise carried out for the FSR research in the early 1970s. However, there are concerns that some aspects of the ReFH design procedure have not been tested at return periods longer than the calibration limit of 150 years. The most obvious extrapolation is for the α_T calibration coefficient, see Figure 22. Another concern about using ReFH for long return periods is that the seasonal correction factors used for design rainfalls may not be applicable for extreme events (which may be caused by different rainfall processes). The ReFH research only derived correction factors for a return period of five 5 years, although it found no strong variation with the return period. More recent research has led to revised design rainfalls and seasonal correction factors. See Stewart, Lisa and others (2010).

	Eventually ReFH will be recalibrated to incorporate these changes.
5	Despite the concerns described in items above, the ReFH method is worth considering as an approach for estimating floods for return periods up to 1000 years, apart from catchment types where ReFH is not recommended. See When to apply ReFH with caution, on page 66. Its results should be treated with caution, and always compared with pooled growth curves from the statistical method.
6	If flood estimates are needed for a range of return periods up to 1000 years, it may often be the case that the statistical method is preferred for the shorter return periods. To avoid a discontinuity in the results if you choose ReFH for the longer return periods, one approach is to use ReFH to obtain the ratio of the 1000-year flow to the (say) 100-year flow. You can then multiply that ratio by the preferred estimate of the 100-year flow, which may be from the statistical method.
7	Historical flood data are particularly valuable as a guide in the estimation of extreme design events. If you can identify a flood chronology spanning several hundred years, this may lead to a statistical approach being preferred for estimation of 1000-year flows.

Figure 22

The graphs in the diagram below show the variation of the α_T coefficient in the ReFH design event. In the winter event, α_T varies only slightly with return period, with the graph starting to level off as the return period approaches 150 years. Extrapolation of this relationship is therefore unlikely to introduce significant errors.



Reproduced from Kjeldsen and others. (2005) with the permission of CEH Wallingford.

Summary

Our summary of recommendations for estimating long return period floods:

- No current method can be recommended unequivocally. Guidance is likely to keep developing as research continues.
- There are theoretical reasons for preferring rainfall-runoff approaches at long return periods.
- For long return periods, apply the ReFH rainfall-runoff method with caution **and always compare it with the FEH statistical method**.
- Where flood peak data are available, gather information on the longer-term flood history and use it to guide the derivation of the flood frequency curve.
- Consider the physical processes that might result in a 1000-year flood, and whether these might be different from processes that give rise to more moderate floods.

7. Audit trail

Overview

In this chapter

This chapter covers the following topics:

Flood estimation calculation record

Purpose

The Flood estimation calculation record (SD01) supports these guidelines and serves three important functions:

1. to help analysts ensure that they have thought through the choice of approach and applied the methods correctly;
2. to assist analysts, reviewers and project managers by setting out the calculations in a standard format;
3. to provide an audit trail of the study so that the work can be reproduced in the future if needed.

Using the record

The flood estimation calculation record is mainly intended to be an appendix to a report. The report usually includes supporting information, such as the background to the study, a description of the catchment, details of any rating reviews and a summary of the results.

You could use it as a stand-alone record of a minor study. In this case, you can expand it to include other items, such as a description and map of the catchment.

It is designed for studies that include multiple flow estimation points. You can add more rows to the tables, as required.

There is a shorter version. The Flood estimation calculation record for single sites (SD02) also supports these guidelines.

Requirement

Documenting calculations and the decisions made is mandatory for all Environment Agency staff and consultants working on Environment Agency projects. Using the flood estimation calculation record is the recommended way of doing this.

You may use other records with the agreement of the project manager.

Filling in the calculation record

Description

The calculation record consists of a series of tables for you to fill in. It does not attempt to record all the parameters used and decisions made during calculations. Instead, it provides enough information for a review and to enable future reproduction of the results.

The most important aspects to record are those that deviate from the default methods.

The table below describes the sections.

Section	Description
First section	This is a method statement (see Preparing method statements, on page 32). It covers the requirements of the study, a review of hydrometric data and an initial choice of method. You should record this at the start of the study. For lengthy or high-risk studies, you should agree it with the project manager before carrying out further work.
Second section	Deals with selecting subject sites and checking catchment descriptors. In the multi-site version of the record, each site is referred to by a site code, which saves having to type in the river and location name in every subsequent table. The site codes could be gauging station numbers, if all the sites are at gauges, or hydraulic model node labels if available. In many cases, however, analysts have to make up suitable site codes. To help reviewers, make codes follow a logical system, such as a four-letter code based on the river name plus a two-digit code starting at the downstream end of the study reach. **Example**: LAMB01 for a site at the downstream end of the River Lambourn. You can copy and paste the catchment descriptors into the Word document from a spreadsheet.
Next section	Covers the FEH statistical method. The first tables deal with estimation of QMED. All pooling groups used in the study are described after that, with the following table showing how the growth curve was derived at each subject site. This gives you the scope to apply a pooling group at several subject sites.
Subsequent sections	Describes flood estimation using the ReFH and FEH rainfall-runoff methods. You can remove any sections not needed.
Final section	Provides a comparison and discussion of the results. Records the final design flows and how they have been checked.

Other information

You should regard the calculation record as a minimum requirement. You can add other information when necessary.

The record does not include tables for recording aspects that are only carried out occasionally, to avoid it becoming excessively long and unwieldy. **Example:** Some studies include detailed reviews of ratings or historical reviews. You can add them to the calculation record or present them in an accompanying report.

The calculation record is not designed for recording the use of non-standard methods, such as continuous simulation. You will need to report them separately in detail. The calculation record is not intended for recording PMF calculations used in reservoir safety assessments. You can modify it, if required, for such situations.

Presenting results

Guidelines

The guidelines and advice in the table below are included to help users.

Item	Guideline or advice
1	**Analysts**: you should consider the needs of the study when presenting results. In some cases, these may need to be presented at public meetings or in press releases and should respect the knowledge of a lay audience.
2	**Analysts**: Do not just hand over the output produced by the FEH software. You have a responsibility when presenting results: ▪ to avoid implying false levels of accuracy or high confidence, especially when confidence intervals cannot be quoted; **Example:** Using too many significant figures, such as quoting the 100-year flood as 145.7m^3/s. ▪ to set down any qualifications or other limitations of the study clearly and ensure they are understood by the project manager; ▪ to discuss how the figures should be best used and presented as a result of the uncertainties, or what could be done to improve them.
3	In many cases, when reporting the return period of a notable flood it will be sufficient to indicate its severity. You should not quote the best estimate too precisely: 'larger than 100 years' or 'between 5 and 10 years'. Simply report the event as the second highest in 30 years of data to meet the needs for press releases and so on. Refer to the Environment Agency Policy on Communicating and Understanding Flood Risk. Section 6 gives more information on assumptions, limitations and uncertainty.
4	Estimating design flows rarely marks the end of a project. In many cases, the flows are used as input to a hydraulic model. **Analysts:** if you are not going to be doing the modelling, you should ensure that you provide enough information for the modeller. The final choice of peak flows should be clear. For an unsteady hydraulic model, you should provide inflow hydrographs (see Flood mapping and hydrodynamic models, on page 78, for further discussion on applying flows to unsteady models).

Recording the data used

Saving the data

We can only reproduce calculations if we can access the data that was used again.

If you have used the HiFlows-UK dataset without alteration, it is sufficient to record the version number of the dataset.

If you have made changes, for example updating the flood peak records at selected stations, we recommend that you keep a copy of the entire altered dataset, to ensure that the pooled growth curves can be reproduced.

8. List of acronyms

Acronyms

The table below lists acronyms that are related to flood estimation. To look up all terms and acronyms, you can use the Glossary on Easinet.

Acronym	Full expression
ADVP	Acoustic Doppler Velocity Profiler
AEP	Annual Exceedence Probability
AREA	Catchment area (km^2)
BFI	Base Flow Index
BFIHOST	Base Flow Index estimated from soil type
CFMP	Catchment Flood Management Plan
DDF	Depth Duration Frequency
DEM	Digital Elevation Model
DPLBAR	Index describing catchment size and drainage path configuration
DTM	Digital Terrain Model
FARL	FEH index of flood attenuation due to reservoirs and lakes
FCA(s)	Flood Consequence Assessment(s)
GEV	General Extreme Value (a statistical distribution)
GL	General Logistic (a statistical distribution)
HOST	Hydrology of Soil Types
MORECS	Meteorological Office Rainfall & Evaporation Calculation System
MOSES	Meteorological Office Surface Exchange Scheme
PMF	Probable Maximum Flood
POT	Peaks Over a Threshold
PROPWET	FEH index of proportion of time that soil is wet
QBAR	Mean annual maximum flood
QMED	Median annual maximum flood (with return period 2 years)

R&D	Research and Development
ReFH	Revitalised Flood Hydrograph method
RMED	Median annual maximum rainfall (mm)
SAAR	Standard Average Annual Rainfall (mm)
SPR	Standard Percentage Runoff
SPRHOST	Standard Percentage Runoff derived using the HOST classification
SUDS	Sustainable Urban Drainage Systems
Tp	Time to peak
Tp(0)	Time to peak of the instantaneous unit hydrograph
$URBEXT_{1990}$	Original FEH index of fractional urban extent
$URBEXT_{2000}$	Updated version of urban extent, defined differently from $URBEXT_{1990}$
WINFAP-FEH	Windows Frequency Analysis Package - FEH version
WRAP	Winter Rainfall Acceptance Profile

9. Related documents

Supporting documents

- 197_08_SD01 Flood estimation calculation record.
- 197_08_SD02 Flood estimation calculation record for single sites
- 197_08_SD03 Checklist for reviewing flood estimates

Chapter 2

414_07 Accessing Hydrological Data and Information

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