RIVER MEDWAY (FLOOD RELIEF) ACT 1976

Proof of evidence of Ben Gibson: **Appendix 2**

Flood Estimation Guidelines

Technical guidance **197_08** Issued: **June 2020**

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 aims to complement rather than replace the FEH and other publications, and is not intended as training material for readers who are new to the FEH methods.

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.

Contact for queries and feedback

- National Flood Hydrology team FloodHydrology@environment-agency.gov.uk
- Anonymous feedback for this document can be given here

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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 deep 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 and a determination to challenge assumptions and seek out facts is essential. 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. However, thorough flood estimation studies can take many days or weeks - the FEH suggests allowing between five and 50 days.

Table 2 indicates the various 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. Since the publication of the FEH in 1999, research has continued and most of the original methods have now been replaced or updated. However, the core principles remain unchanged and analysts still need to consult the FEH, along with other research reports and guidance documents. These are signposted in the guidelines.

We encourage all who will be carrying out or checking flood estimation to read at least Volume 1 of the FEH, including its thought-provoking and frank interlude.

In line with the philosophy of the FEH, the guidelines offer few prescriptive instructions. For instance, 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 favour 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 exceedance probabilities up to the probable maximum flood.

How do I make sense of this

Much of our involvement with flood estimation comes from reviewing studies carried out by consultants. Before we revised these guidelines in 2006-

hydrology report?

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 address these and other comments by including sections on assumptions and limitations (see Chapter 5), a flood estimation calculation record (SD01) and a Checklist for reviewing flood estimates (SD02).

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 considered 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:

- the FEH statistical method;
- the Revitalised Flood Hydrograph (ReFH/ReFH2) method.
  This has replaced the FEH rainfall-runoff method for most applications. ReFH2 uses a similar rainfall-runoff model as ReFH1 but with improved procedures for estimating model parameters and defining the design storm.

You can apply these techniques to any UK catchment or plot of land.

The FEH also provides rainfall frequency estimates, which are most often used to provide input to rainfall-runoff models for flood estimation. The FEH 2013 rainfall frequency statistics are currently used.

Difference between the two techniques

The statistical method gives just a peak flow.

The rainfall-runoff techniques (ReFH2, ReFH or FEH) produce hydrographs using a design flood event.

Because it is more direct, based on a larger dataset and can more easily assimilate local data, hydrologists 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.

Alternatives

Alternatives to FEH methods include:

- Continuous simulation - This is a rainfall-runoff method that simulates a long series of rainfall and flow, rather than simulating a single design flood of an assumed probability. It avoids some of the assumptions of other methods and is worth considering on catchments where there are complex combinations of factors that affect flood levels.
- Direct rainfall - This involves a 2D hydraulic model which typically assumes that all runoff occurs as overland flow. This is not a good assumption in most rural areas, and so the direct rainfall approach needs to be used with great caution.

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 both obtain flow data and review data quality, in particular the accuracy of rating equations. The availability and the 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 is available. Selecting donor catchments is a subjective process. Therefore, 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 suggested by the FEH won't produce a definitive statement on the magnitude of a 1% probability flood or the rarity of an observed event. By its very nature, flood estimation is an uncertain business and this 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. However, 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 than 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 is often required in flood estimation. Since the answer is always uncertain, the analyst must be able to judge when they've found a sufficient amount of information and explored enough options to give a result suitable for the purpose of the study.

1 Introduction

1.1 Purpose and scope

Purpose of these guidelines

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 report (SD01) to enable robust recording and quality assurance of the results;
- and a Checklist for reviewing flood estimates (SD02). This has now been incorporated in the Hydrology Review Template.

Other aspects which are addressed in the guidelines include levels of competence and supervision.

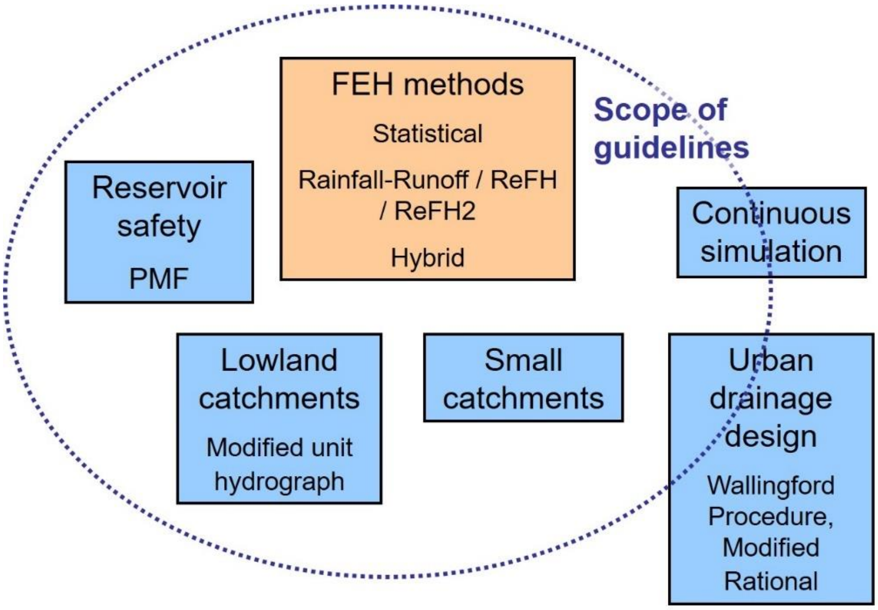
Scope

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 their successors.

The guidelines only briefly mention sewer design methods and alternative approaches to flood estimation, such as continuous simulation.

Figure 1: Scope of these guidelines

This diagram shows applications and methods covered by the guidelines.



Relationship to FEH and subsequent publications

These guidelines complement the FEH and other publications rather than attempting to reproduce all of their content. Since the publication of the FEH in 1999, research has continued and most of the original methods have now been replaced or updated. However, the core principles remain unchanged and many aspects of the FEH procedures are still applicable.

Analysts: you must read and consult the FEH and other relevant publications. Attending training courses should provide some basic knowledge and competence, but it cannot fully equip you for undertaking complex or high-risk flood studies. There is no substitute for self-learning and experience. Similar comments apply to those whose role is to review flood hydrology.

As a minimum, the following are recommended reading, in addition to the FEH:

- FEH Supplementary Report No. 1: The revitalised FSR/FEH rainfall-runoff method (2007)
- Science Report SC050050: Improving the FEH statistical procedures for flood frequency estimation (2008). Read the summary in Chapter 8 as a minimum.
- The Revitalised Flood Hydrograph Model ReFH2.3: Technical Guide (2019) – or any successors to this guidance.
- Technical Guidance 12_17: Using local data to reduce uncertainty in flood frequency estimation (2017).
- Science Report SC090031/R0: Estimating flood peaks and hydrographs for small catchments (Phase 2) (2019). A summary of an important research project, giving recommendations for practitioners.

These and many other relevant publications are signposted in the guidelines.

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. Instead they aim to inform and educate, helping to equip readers to make sound decisions.

Precedence

Analysts or project managers: you may sometimes need to depart from these guidelines. When you do, the project scope or the proposal must make this clear.

In all cases of apparent difference between the guidelines and project scopes, consultants and Environment Agency analysts must first seek clarification from the Environment Agency's Project Manager.

Presenting return periods

These guidelines quote the frequency of a flood mainly in terms of a return period, to remain compatible with the previous version of the guidelines and with the FEH.

Definition

The FEH mainly uses a return period based on analysis of annual maximum (AMAX) floods (**1** Appendix A). The return period of a flood on the AMAX scale is the average interval between AMAX floods of that magnitude or greater.

Alternative expression: AEP

Alternatively, we can express flood frequency in terms of an Annual Exceedance Probability (AEP). This is the inverse of the AMAX return period. For example, a 1% AEP flood has a 1% chance of being exceeded in any year. Its return period on the AMAX scale is 100 years (see Table 1).

Presenting results to non-specialists

When presenting results to non-specialists, use the alternative expression (AEP). Non-specialists may associate the concept of return period with a regularity of occurrence rather than an average recurrence interval. Table 1 (below) provides a quick conversion between return periods and AEPs.

POT scale

Return period can also be measured on the peaks-over-threshold (POT) scale. The return period of a flood on the POT scale is the average interval between floods of that magnitude or greater.

The difference between AMAX and POT return periods is only important for short return periods (under 20 years).

Table 1

Return period on AMAX scale (years)	1.6	2	5	10	25	50	75	100	200	1000
AEP (%)	63	50	20	10	4	2	1.33	1	0.5	0.1
Return period on POT scale (years)	1	1.5	4.5	9.5	25	50	75	100	200	1000

1.2 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 (in April 2019) the Flood Hydrology team within Incident Management and Recovery. Send any suggestions to improve these guidelines by e-mail to FloodHydrology@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.

If you identify any errors or inconsistencies in hydrometric data, provide feedback to the hydrometric section of the relevant gauging authority for these to be investigated. Submit any errors or suggestions relating to the NRFA peak flows dataset to nrfa@ceh.ac.uk.

FEH webpages

Information about the FEH is provided on the CEH website.

The website has a link for a list of FEH errata/corrigenda on the CEH Wallingford website. Analysts: make hard-copy corrections to your copy of the FEH.

Software

At the time of writing (September 2019), the latest releases of the FEH software packages are:

- FEH Web Service;
- WINFAP 4 (released in 2016);

- ReFH2.3 (released in 2019);
- ReFH2 calibration utility (released in 2016).
- A number of hydraulic modelling software packages have the facility to implement the FSR/FEH rainfall-runoff methods.

For updates to the FEH software, refer to the Wallingford HydroSolutions website: https://www.hydrosolutions.co.uk/software/.

For some applications, older versions of the FEH software are adequate and may be preferable in some cases.

1.3 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 and a dogged determination to challenge underlying assumptions in datasets and seek out facts is essential.

It is essential, therefore, to ensure that the people carrying out studies have the correct knowledge, skills and experience, and that enough time is allowed for the task.

See Table 2 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;
- team leaders to allocate staff to studies.

The complexity of the study may also be influenced by the type of catchment, the quality of the data available and the consequences of errors and uncertainties in the results on the overall project.

Table 2

The table provides indicative levels of competence and supervision.

Notes

- Interpret the competence criteria as minimum levels.
- An analyst who has not carried out or supervised the study must give approval.
- Level 1: hydrologist with minimum approved experience in flood estimation.
- Level 2: senior hydrologist.
- Level 3: senior hydrologist with extensive experience of flood estimation.

	Example of a study			Competence criteria

Complexity of the flood estimation study		Value of flood defence works or damages	Indicative timescale for flood estimation	Analyst	Super-vision and approval
Simple	Preliminary assessment; culvert capacity check	-	<1 day	Level 1	Level 2
Routine	Low-risk development application	<£50k	1 - 2 days	Level 1	Level 2
Moderate	Small flood mapping study or medium-risk development application	<£250k	2 - 10 days	Level 2	Level 3
Difficult	Medium flood mapping study or outline business case	<£2 million	2 - 4 weeks	Level 2	Level 3
Very difficult	Major scheme design or other high-risk project	>£2 million	>1 month	Level 3	Level 3

Training courses

All Environment Agency staff who carry out or review flood estimation must attend an approved training course in flood estimation methods. We offer two such courses:

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

The users' course introduces all the basic techniques and software, including research and guidance released since the FEH was published. It should enable most analysts to reach Level 1 in Table 2. This is a minimum requirement.

Before reviewing and approving flood studies, you should gain experience carrying out such work yourself. There is no substitute for experience to develop familiarity with the challenges of flood estimation and to equip you to spot pitfalls.

For complex studies, analysts may require more advanced training or to have gained experience under the supervision of senior colleagues.

Supervision

Supervision by a more experienced colleague can provide support and create the opportunity to learn. It enables problems to be shared, which may provide reassurance when handling the knottier 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 in the project scope.

For all but simple or routine projects, establish a break-point in which the method statement is reviewed by the Environment Agency before work continues. This creates a valuable opportunity to agree on the intended approach and address any difficulties with availability of data or information from previous studies. Reviewers not fully involved with the project should be provided with all the relevant background information and any particular concerns. Where possible, encourage third parties such as developers who commission flood studies to follow this process too.

Completing the calculation record establishes an audit trail for every flood estimation study. However, 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 the appropriate qualifications, training, experience and supervision to meet the aims described above in this chapter.

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2 Hydrometric data and catchment descriptors

2.1 Hydrometric data

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. Examining such data also provides a valuable opportunity to learn about the hydrology of the catchment, in particular, its flow response in flood conditions.

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.

NRFA Peak Flows dataset

A peak flow dataset is hosted by the National River Flow Archive (NRFA). It is updated approximately on an annual basis.

Use the NRFA Peak Flow dataset as your primary source for flood peak data. You can download the latest version from the link above. You should overwrite the dataset provided with WINFAP and make sure that WINFAP is set up to read in the correct dataset when creating pooling groups.

The NRFA includes suitable flow measurement stations from all of the UK gauging authorities. Its website provides peak flows, levels, rating histories, photographs and information on each gauging station. It provides:

- annual maximum (AMAX) flow data;
- peaks-over-threshold (POT) data (for most gauges);
- guidance on the quality of data;
- a statement indicating whether each station is considered suitable for:
  - estimating QMED (stations that can measure moderate floods) and/or
  - inclusion in pooling groups (stations that can measure extreme floods)

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

Guidelines on using peak flow data

Item	Guideline or advice
1	There are two main uses for the NRFA Peak Flows dataset: • You can use stations suitable for pooling to create pooling groups by downloading the dataset and saving it to a directory used by WINFAP. • You can consider stations suitable for QMED as potential donor sites. You can locate these using the search facility on the website or within WINFAP.

2	For some lower risk studies, you can use the NRFA dataset without any need for further review or searching for data.
3	If you are using the NFRA data in more detailed studies, there are limitations of the dataset you need to address: • there are other sources of flow data not in the NRFA Peak Flows dataset such as 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 the opportunity to update flood peak series; • some stations have flow data in the NRFA 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 NRFA 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 in comparison to catchment descriptors. This may be due to the influence of local hydrological features that are not well represented in generalised methods. In some unusual catchments you may have to accept a huge uncertainty in design flood estimates unless you obtain some flow data.
6	Visual examination of flood peak data is always worthwhile (see Figure 2). 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 changes in land use or climate, whether fluctuations or progressive change, for example, the changes associated with global warming. Refer to the section on non-stationarity. • 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. • occasional 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 period where data is missing and the year excluded or included accordingly. Investigation methods include comparing the flows with those recorded at 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).
8	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, for example by plotting an annual hydrograph.

Figure 2: Example flood peak time series

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

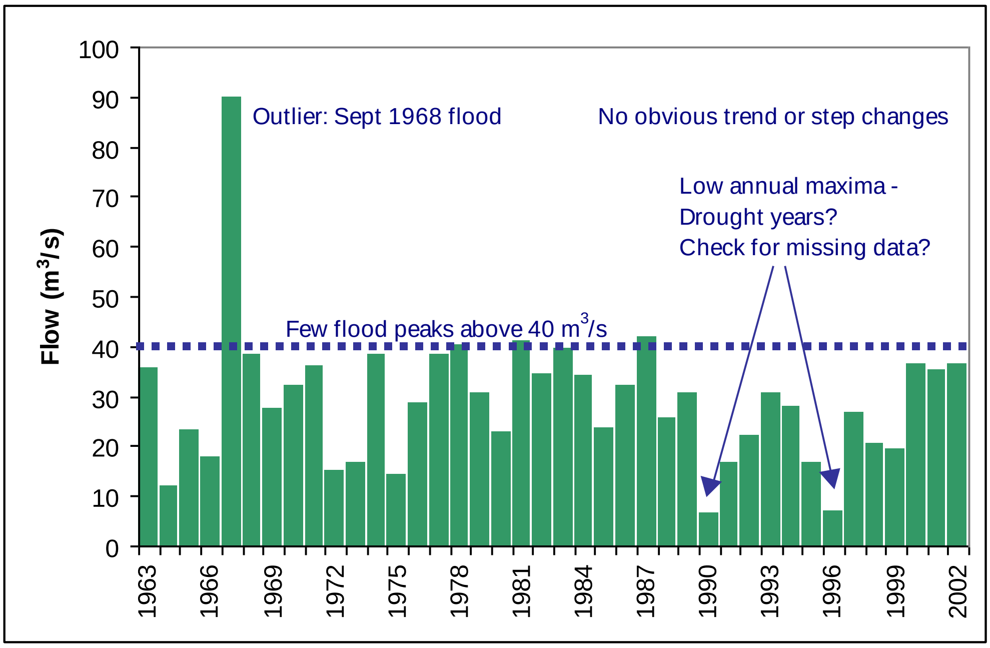
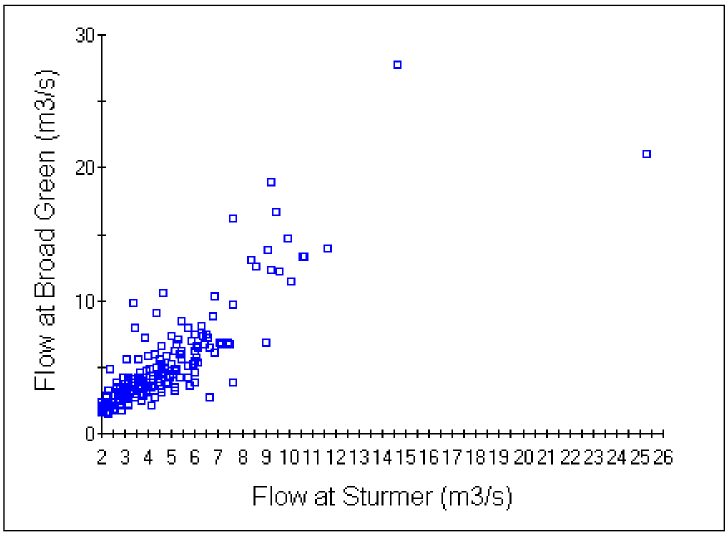


Figure 3: Example flood peak correlation plot

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. However, the Stour Brook at Sturmer is affected by urbanisation and a major flood storage scheme. The correlation coefficient is 0.84, indicating a 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.

Rating reviews and improvements

Rationale

At most flow gauging stations, water level is measured and transformed into flow using a rating curve. Accurately calculating flood flows is problematic but of great importance.

Description

Flood rating curves, particularly those that represent out-of-bank conditions, are sometimes based on a small number of measurements or on extrapolation from the highest flow gauging without any consideration of the channel and floodplain hydraulics.

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

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

Requirements

Many 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.

Some studies also call for improvements to rating equations, such as revising them to include recent gaugings or extending the rating using a hydraulic model.

This section gives guidance on what you might expect in a typical rating review carried out as part of a flood estimation study.
For guidance on extending ratings, see Ramsbottom and Whitlow (2003), listed in Related documents, and Technical Guidance on High flow rating curve development using hydraulic models (466_15).

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.

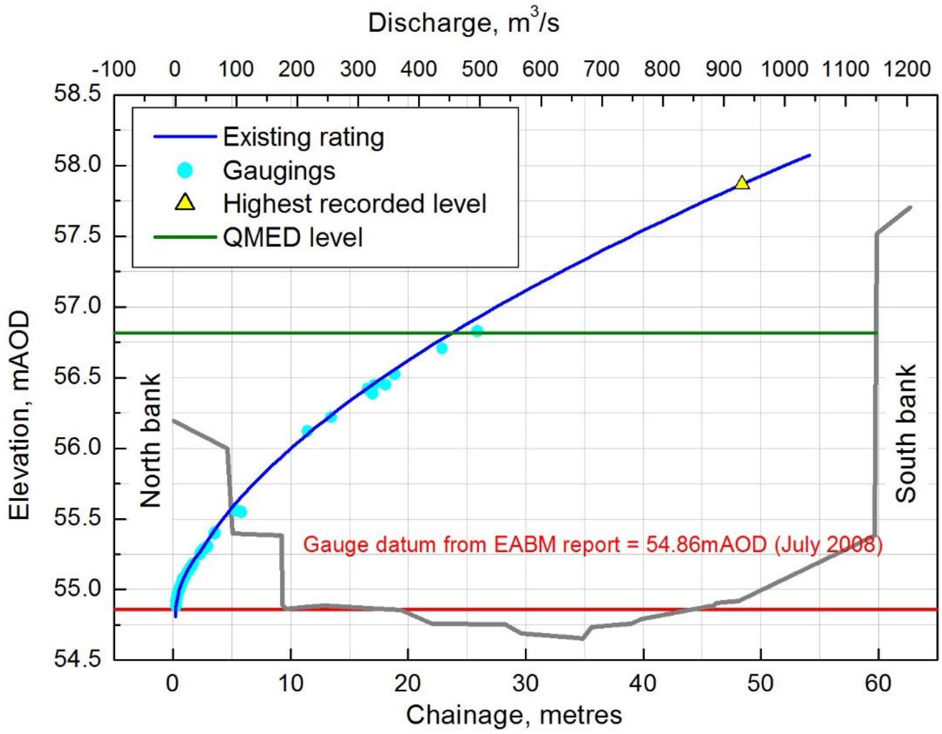
Item	Guideline or advice
1	The person carrying out the rating review needs to have a knowledge of hydrometry and hydraulics. As well as understanding the limitations of flow data, they should also appreciate its value in flood estimation.
2	Rather than being purely a statistical exercise, the review 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. It should be a standard part of any rating review.
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; • 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 spot gaugings or based solely on gaugings (empirical); • if the rating is theoretical, finding out how it was derived; • if the rating is empirical, 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 and Whitlow (2003). • finding how spot gaugings are taken and whether the measurements include flow through parallel channels or the floodplain; • finding when the gaugings were taken, and whether there has been any change to the hydraulic control since that time; • 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; • 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; • 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 that in Figure 4 shows: • the scatter in the gaugings (a measure of uncertainty); • 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 necessary, but this should be done with caution. 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; • rising/falling stage, to investigate any hysteresis.

Figure 4: Example rating curve

The graph below shows a rating curve plotted against flow gaugings on the South Tyne at Haydon Bridge. The plot also shows, in grey, the channel cross-section at the gauge site, on the same vertical scale as the rating.



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 or if there are other sources of evidence to consider such as:

- a hydraulic model that represents out-of-bank flow conditions;
- a flood forecasting model that allows comparison with flows recorded at other gauges on the river, and with rainfall.

Always develop new ratings 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. 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 exploring 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.

It can be useful to plot rainfall and flow together, as this may identify problems which may cause an event to be rejected from analysis.

Model parameters for the ReFH and FSR/FEH rainfall-runoff models are best estimated from flood event data. To estimate the time to peak parameter, data from raingauges and river level recorders is adequate, with no need for a rating equation.

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 the data obtained from several recording gauges, for example using Thiessen polygons or Voronoi interpolation. Data from daily raingauges can also help improve the averaging.
2	Radar-derived rainfall data can provide a valuable additional source of information. It may show cells of intense rainfall that were missed by raingauges. HYRAD provides catchment-average rainfall accumulations. It also displays the “best rainfall observation” which merges point rainfall intensity measurements with radar images.
3	The ReFH model uses potential evaporation data 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.

2.2 Flood history and palaeoflood data

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.

In a similar way to pooled analysis, historical reviews 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).

Historical reviews are often required in flood estimation studies. In too many studies, they are either left out or carried out half-heartedly so that they have no opportunity to influence the results.

However, historical reviews can be rewarding as well as valuable and they can have a large influence on the design flows. For example, one 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.

Description

For detailed guidance on the value of historical reviews and the methods for acquiring and using historical data, refer to Technical Guidance 12_17 (FEH Local) and Bayliss and Reed (2001). A summary of the relevant part of 12_17 is given below.

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 and Sangster (2017) describe how many flood records are available in Britain from 1750. In contrast, most gauged records of peak river flows start between 1950 and 1980. There are only eight UK river gauges with flood peak data before 1930.

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.

When to include a historical or palaeoflood review

Project Managers and analysts: you must agree at the start of a study whether or not to include a historical review.

For all except simple or routine studies (see Table 2), 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 about three to eight days.

If you are carrying out a project where there is a serious risk to life or critical infrastructure you should consider including palaeoflood analysis. This is particularly important where other sources of information such as gauged flow records, augmented by pooled analysis or flood history, are insufficient to adequately estimate design floods. Examples of this type of project include estimation of design floods for the spillways of Category A or B reservoirs, or for nuclear installations. These typically require estimation of either the 10,000-year return period flood or the probable maximum flood, using rainfall-runoff methods. The uncertainty in the result will be very large, and a palaeoflood review could uncover evidence of past extreme floods that challenge the initial estimates of design flow. Refer to Technical Guidance 12_17 for information and examples of how to incorporate palaeoflood data.

How to find and evaluate historical flood data

Step	Action
1	**Search for the data** The main types of sources are: • **Previous flood studies** or **journal papers** that have already compiled a flood history or descriptions of specific events. There are many flood chronologies in reports on flood mapping studies, catchment flood management plans and reports on scheme design. • **The Chronology of British Hydrological Events** - a useful website that you can search by place name, river basin or date. There is also an interactive map search option, although many entries have not yet been georeferenced. • **Chronologies of flash floods** in northern and south-west England, developed for the SINATRA project (Susceptibility of catchments to INTense RAinfall and flooding). This rich resource includes 3,700 entries describing flash floods and the impacts of hail and lightning, covering the period from 1700 to 2013. Refer to Archer and others (2019). • **Information** on previous events and flood studies held by hydrometric, flood management and modelling teams in the gauging authorities. • **Post-flood reports** produced by gauging authorities or other interested parties, or in journals such as Weather or the Quarterly Journal of the Royal Meteorological Society. • **Instrumental records** such as long river flow or level series (on the catchment of interest or nearby catchments) or long rainfall series, which you can use to identify potential dates of floods. Some daily rainfall records date back to the 19th century. There are summaries of extreme rainfall totals for each year between 1860 and 1968 in the **British Rainfall** publication, available from the Met Office website. There is a digitised version of this archive available from the Centre for Environmental Data Archival. • **Weather diaries** such as this British Isles Weather Diary, with daily entries since 1999. • **Local newspapers**, many of which are available online through the British Newspaper Archive. • **Local history** books, journals and websites. • **Other sources of local history** such as diaries, chronicles and records compiled by churches and estates. • **Physical marks** on bridges, buildings etc., known as epigraphic data (Figure 5). **Figure 5: Flood marks on the River Tay at Perth**

<table>
<tr><td></td><td>

People: both local residents and gauging authority staff may have knowledge of past flooding.
Social media for photographs and news of floods in the last few years.

There is detailed guidance on most of these sources in Bayliss and Reed (2001).
It is possible to access some of this information easily and quickly. Flood chronologies have already been compiled for many catchments. Elsewhere, it will take some determination, persistence and detective skills to compile a chronology, but it is usually well worth the effort. </td></tr>
<tr><td>2</td><td> Evaluate the historical information
Follow the guidance in Chapter 3 of Bayliss and Reed (2001), which is reproduced in brief here. Consider the format and authenticity of the information.
In evaluating written information, investigate whether the author had a reason to exaggerate or fabricate the information on the event. Was the account written by someone who witnessed the event first-hand, or who had access to first-hand oral or written reports, or is it derived from other accounts of the event (in which case it is more likely to be prone to transcription errors)?
For all types of historical information, ask:

how closely the information relates to the site of interest;
whether or not there is enough information to be reasonably certain when the event occurred;
what information there is on the peak flow, level or rank of the flood.

It is not necessarily essential to determine the exact date the flood occurred, although this will assist in the search for historical information. Establishing the year of occurrence may be sufficient. </td></tr>
<tr><td>3</td><td> Define the period of time (h) represented by the historical data
It is usually appropriate to take the start of the time period as being some time before the date of the first flood that has been identified, rather than equal to the date of the flood (which introduces a bias).
Where the earliest historical event is supported by contemporary reporting, try searching the supporting source (such as a local newspaper), and any predecessor source, for reports of earlier floods. If you do not find one, you might use the start-date of the supporting source as the time-origin of the historical flood series.
Where this procedure is not possible, statistical reasoning would lead to an estimate of the total period of time (h) equal to twice the mean of the periods of time between </td></tr>
</table>

	each historical flood and the start of the systematic record. Further guidance is available in report SC130009/R and in Section 4.4.3 of Bayliss and Reed (2001).
4	**Understand impacts of changes in the catchment, river channel or climate** When the catchment has changed during the period of historical record in a way that is expected to have a significant effect on its flood response, information on historical flood events may be less valuable. However, many catchment changes, such as in agricultural land management, are not likely to have significant effects on large floods. Changes in the conveyance of the river channel or floodplain may mean that the stage-discharge characteristics have changed since historical floods. Before attempting to convert historical levels to flows, or ranking historical events on the basis of their levels, check what is known about changes in conveyance. These can occur due to bed scour during floods, gravel extraction from river beds, channel widening, alterations to weirs, the replacement of bridges, the building of raised flood defences or the raising of land on the floodplain. You should not use the fact that the catchment or channel has changed as an excuse for dismissing the relevance of flood history. Another important consideration is to ask whether the period for which gauged or historical data is available is representative of present-day or future conditions. Consider the period of time over which your flood frequency estimate needs to be valid. For example, are the design flows needed for a flood risk map representing present-day hazard, or for design of infrastructure which may still be present in 100 years' time? In deciding how to account for longer-term flood history you may need to make a trade-off between the advantages of stationarity on the one hand and increased sample size on the other.
5	**Estimate peak discharges from information on historical events where possible** If peak water levels have been recorded and can be related to present-day datum levels or features, it may be possible to convert them into estimated peak discharges. You can do this using hydraulic models, rating curves at gauging stations or simple hydraulic calculations such as the slope-area method. Hydraulic methods unavoidably introduce extra sources of uncertainty as it is usually necessary to assume or estimate channel slope, cross-section geometry and hydraulic roughness. Nevertheless, even historical data affected by such errors are often valuable for flood frequency analysis. Besides, even extreme flows measured at gauging stations tend to suffer from considerable uncertainty. Try to quantify the uncertainty associated with the flow estimate, for example, by carrying out sensitivity tests in which you try a range of realistic values for the water level and hydraulic parameters such as roughness.
6	**Incorporate the historical flood data in the flood frequency analysis** Refer to the later section on estimating flood growth curves.

2.3 Catchment descriptors

Source of descriptors

The FEH web service replaced the FEH CD-ROM in 2015. Most catchment descriptors have not been updated from the FEH CD-ROM v3. The main differences (currently) between the two data sources are:

- FEH 2013 rainfall statistics are available from the web service;

- An improved soils descriptor, BFIHOST19, is available from the web service. This is the outcome of a comprehensive revision of the BFIHOST calculation process, which provided a set of revised BFIHOST coefficients for each of the 29 HOST classes (Griffin and others, 2019). Some coefficients are very different from those in the original HOST classification. This revision opens up an opportunity to re-estimate the regression equations used by FEH methods. However, even without an update to the QMED regression, the BFIHOST19 descriptor has been found to improve the estimation of QMED. BFIHOST19 is also recommended for use in the ReFH 2.3 method, because it provides improved predictions of model parameters, particularly on some clay and peat catchments.

If you are assessing earlier studies you may find reference to the FEH CD-ROM. There were three versions:

- v1 was the original FEH CD-ROM;
- v2 improved catchment boundaries in some areas and added the URBEXT2000 descriptor;
- v3 added the floodplain descriptors FPEXT, FPLOC and FPDBAR. They are defined in Kjeldsen and others (2008) listed in Related documents.

Guidelines

Item	Guideline or advice
1	Ten descriptors are used in flood estimation procedures. The numerical distribution of values for 943 gauged catchments is given for many descriptors in Volume 5. This provides an indication of what the normal range of values might be. The others provide extra information for the analyst to use when comparing catchments.
2	Do not use catchment descriptors obtained from the FEH web service without, at least, a rudimentary check. In particular, confirm catchment boundaries, which are calculated from the Integrated Hydrological Digital Terrain Model (IHDTM). With a grid resolution of 50m, this is much coarser than newer terrain datasets such as LIDAR. Analysts: you may find that a site of interest will not be found within the resolution of the FEH web service data. Some of the more major errors have been corrected, but you will find places where the catchment boundaries are still wrong. Checking is particularly important for small catchments; see Figure 5.
3	It's particularly worthwhile to verify catchment boundaries: • in fenland areas; • when there are artificial influences such as reservoir catchwaters, diversion channels, canals, embankments, mines; • where there may be groundwater interactions (consult geological and hydrogeological maps and memoirs). You should also investigate any other local anomalies that might affect hydrological response, for example, unusual land cover or land use.
4	The best way to check a catchment boundary is usually with GIS.

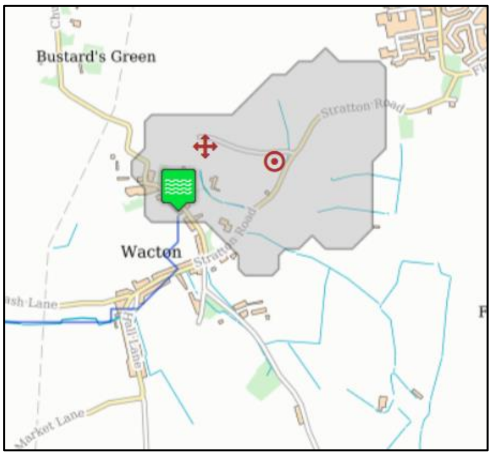
	Download the boundary as a shapefile from the FEH web service and then use information such as Ordnance Survey maps, higher-resolution digital elevation models (DEMs), and local knowledge. If amendments need to be made to the catchment boundary, you will need to manually adjust it using a GIS package and the boundary downloaded from the FEH web service. It is most important to ensure that the AREA value is correct. However, before making any adjustments, think about the size of the alteration compared to the catchment area draining to the point of interest. If the proportional change is very small, it may not be worth making any amendments as they will have little effect on the results.
5	If you do make significant changes to the catchment boundary then it is also worth recalculating DPLBAR, FARL and URBEXT. The other descriptors are more spatially consistent and are less likely to need amending unless a catchment boundary error results in a large area being added or removed from the catchment (**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: • To adjust FARL you can use area weighting in the logarithmic domain. Alternatively, calculate FARL using the FEH procedure (**5** 4). • You can estimate DPLBAR approximately by regression on the catchment area. Refer to the section on distributed application of rainfall-runoff methods for important advice on adjusting descriptors for intervening areas. Analysts: you should take account of the derivation and purpose of the descriptor and record the adjustment fully.
6	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 descriptors based on HOST 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 high-risk studies on smaller catchments, search for more detailed soil maps, for example, at 1:63,360, 1:50,000 or 1:25,000 scale. A soil survey may be worthwhile for problematic cases. 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. To derive BFIHOST19, refer to the coefficients in Griffin and others (2019). In general, use BFIHOST19 in preference to BFIHOST. You should avoid using BFIHOST on clay catchments in south-east England, which are associated with HOST classes 23 or 25.

	In the original HOST model, the BFIHOST values for these classes are 0.218 and 0.170 respectively. These coefficients are now thought to be too low; Griffin and others (2019) provide the equivalent coefficients for BFIHOST19, which are 0.302 and 0.209 respectively.
7	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 (including those which are normally dry) are not included in the dataset on which FARL is based and there are some errors in the FEH web service where outflows from water bodies are in the wrong location. There are also large water bodies, such as Roadford Reservoir, which are not included in the dataset. You should carefully check mapping to identify if there are any omissions or errors in the dataset. It can help to compare FARL values for points upstream and downstream of lakes to ensure that the lake has been picked up. You can correct omissions or errors by manually calculating FARL (**5** 4.3).
8	Check the urban area defined by the FEH against current mapping. The FEH web service provides a layer which shows the urban areas defined by $URBEXT_{1990}$ and $URBEXT_{2000}$. This is often reasonable and all that is required is to update the value to the current year using the UK average models of urban growth. These are included in WINFAP but you would need to apply them manually if using other software such as ReFH2. Occasionally you may find that there has been substantial urban development within a catchment since the URBEXT values were derived. In this case, estimate the value of the Flood Studies Report characteristic, URBAN. It is the fraction of the catchment area shown as urbanised on an OS 1:50,000 map. The equations that link URBAN and URBEXT are: • URBEXT1990 = URBAN / 2.05 • URBEXT2000 = 0.629 URBAN The equations are taken from FEH **5** 6.5.5 and Bayliss and others (2007). URBEXT2000 is defined differently from URBEXT1990 and typically has a higher value for the same degree of urbanisation. It is based on three land cover types: urban, suburban and inland bare ground. Therefore, do not use URBEXT2000 in the original FEH equations for urban adjustments or in ReFH1. Only use it in equations developed specifically for URBEXT2000. See Bayliss and others (2007) listed in Related documents.
9	**Important!** Catchment descriptors do not give a complete picture of the physical characteristics of a catchment and there is no substitute for visiting the catchment. A field visit should always be included when carrying out a small catchment flood study of moderate complexity or above. This is the only way you are likely to obtain some types of information, such as evidence of spillage from neighbouring catchments. For reservoir safety studies, a field visit is essential.

Figure 6: Catchment boundary error

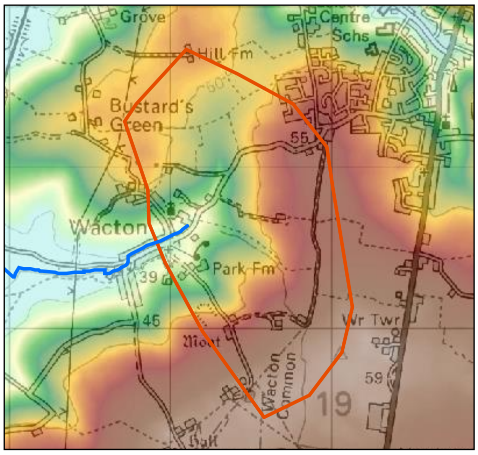
The maps below show a catchment boundary error around Wacton Stream, Norfolk.

FEH web service: catchment area is 0.55 km^2.



Contains OS data © Crown copyright and database right (2019).

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



© Crown Copyright. All rights reserved. Environment Agency, 100026380, (2009).

3 Choice of methods

3.1 Overview

Basic methods available

There are two principal techniques for flood estimation available:

- the FEH statistical method;
- a design flood method using a rainfall-runoff model, the Revitalised Flood Hydrograph (ReFH) model, with two versions:
  - ReFH1,
  - ReFH2.

ReFH2 uses a similar rainfall-runoff model as ReFH1 (at least on rural catchments), but with improved procedures for estimating model parameters and defining the design storm. In these guidelines, the model that underlies both ReFH1 and ReFH2 is referred to as the ReFH model.

Other methods include:

- the FSR/FEH rainfall-runoff method. This is superseded for most applications but is still used for reservoir safety work;
- a precautionary method of estimating greenfield runoff using freely available data;
- continuous simulation;
- direct rainfall modelling.

Six maxims

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

- Flood frequency is best estimated from gauged data.
- While flood data recorded at the subject site are of greatest value, data transfers from a nearby site, or a similar catchment, are also useful.
- Estimation of key variables from catchment descriptors alone should be a method of last resort. Data transfer of some kind is usually feasible and preferable.
- 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.
- In some cases, a hybrid method, combining estimates derived from statistical and rainfall-runoff approaches, is appropriate.
- 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 must make decisions and you may have to improvise. You must rely on judgement based on experience, the nature of the problem, and, not least, the available data and time.

Seek assistance from more experienced or skilled colleagues where needed.

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 how to choose between the basic 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.

For guidelines on choosing a method for particular applications, see Chapter 6.

For guidelines on choosing a method for unusual catchments, see Chapter 7.

3.2 A framework for choosing a method in larger projects

Summary

Figure 7 illustrates a framework for decision-making.

Choosing the method occurs at several stages:

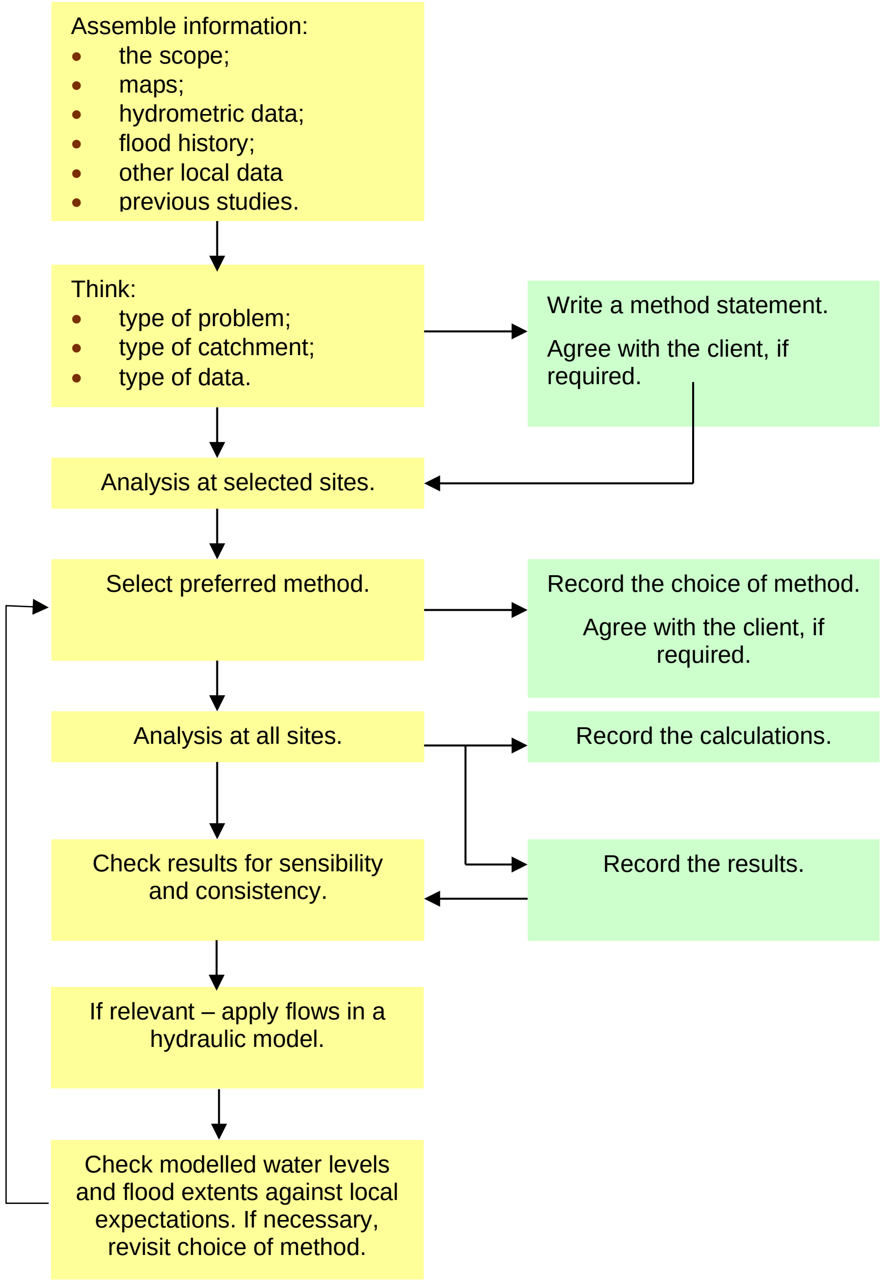
- the analyst makes an initial choice, which often involves a number of possible approaches, during preparation of the method statement;
- they then derive initial flood estimates, using the selected methods, often just at example locations;
- by comparing results, they select the preferred method (or 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 should be little need to carry out calculations at numerous sites several times over. This takes time and tends to result in multiple tables of results, with the potential for misinterpretation.

Figure 7: Framework for choice of method

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 you should follow in flood estimation for a typical study involving multiple flow estimation points. You can apply a simpler version to smaller-scale studies.

The right-hand column of the diagram, in light green, shows the outputs that you should produce.



3.3 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. You will find more details in Chapter 6 on specific issues.

- 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?
- type of catchment;
  Examples: Is it large? Permeable? Urban? Pumped? Are there disparate sub-catchments? (**4** 9.2) Is there a reservoir? (**4** 8) Are there extensive floodplains? (**1** 3.1.2)
- 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.

3.4 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).

Much of this time can be taken up with developing the method statement. Major flood studies need planning in advance, with time to review and update data and gain familiarity with previous studies. There are many factors to consider when choosing the approach to adopt.

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 make a note of the results for comparison and investigate unexpected discrepancies. Note that the most recent flood study may not be the most comprehensive or important.

Analysts: you should agree the level of detail required in the method statement with the Project Manager at the start of a study.

Catchment understanding

The method statement represents an opportunity to develop a conceptual understanding of the catchment. Use information from Ordnance Survey maps, satellite images, maps of geology, hydrogeology and soils, the FEH web service, field visits and previous reports to get to know the catchment and the areas where flood risk is being considered.

Visualise what conditions are likely to lead to flooding of the areas of interest (sometimes referred to as the 'design condition'). For example:

- 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 such as 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?

Review and interpretation of hydrometric data

Include in the method statement plots and interpretation of peak flow data and flood hydrographs, along with any other relevant exploration of local hydrometric data. Refer to Chapter 2.

3.5 Choosing between the FEH methods

Factors favouring the statistical method

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 design event (rainfall-runoff) approach (**1** 5.6).

The statistical method is particularly preferable in the circumstances listed below, but in many other situations too:

- If there are more than two or three years of peak flow data on the watercourse (even if not at the sites of interest) from a gauging station suitable for high flow measurement;
- If the catchment is larger than 1000 km^2. Rainfall-runoff approaches assume a catchment-wide design storm, which is less realistic for large catchments. ReFH2 tends to overestimate flows on large catchments, particularly where there are extensive floodplains (high FPEXT descriptor);
- If there are lakes or other water bodies in the catchment and you are not planning to use flood routing to represent them. Their influence will be represented in a general way via the FARL descriptor, which is used in the statistical method but not in design event methods.

Factors favouring a design event approach

Examples of factors that might favour a design event approach using a rainfall-runoff model include:

- there are reasons to think that the flood hazard is influenced by factors other than peak flow, such as the volume or timing of the flood hydrograph. For example:
    - the site of interest is downstream of a reservoir or an unusually extensive floodplain and there is no peak flow data that implicitly account for the effects of the storage;
    - the catchment is low-lying, perhaps with pumped drainage;

    - the watercourse is tidally influenced or flood-locked.
- the study involves designing works to counter the effects of a new urban development and/or storm sewer design;
- there is no continuous flow record, but rainfall and flow or river level data are available for five or more flood events;
- the catchment includes sub-catchments with widely differing flood responses, and there is no peak flow record downstream of their confluence;
- there is a need to estimate extreme floods, for instance in reservoir safety work.

Factors favouring continuous simulation

Continuous simulation can be worth considering when all three of these apply:

- there are multiple influences affecting the flood hazard, such as complex interactions of peak flow and flood volume or contributions from different tributaries;
- there is enough data to allow calibration of a continuous rainfall-runoff model and a stochastic rainfall model;
- there is enough time, budget and expertise.

More guidelines on choice of flood estimation approach

Item	Guideline or advice
1	The choice between methods is not always clear cut. Sometimes there will be factors that favour both statistical and rainfall-runoff approaches. The FEH suggests that sometimes an intermediate estimate can be adopted (**1** 5.6). 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. Sometimes, it is not until the initial flow estimates have been tested in a hydraulic model that it becomes evident that one set of results is unrealistic. For example, it may predict that the estimated 100-year flood causes no inundation of an area that is known to have flooded several times in recent years. In this sort of situation, it is important to assess the evidence systematically, bearing in mind that there will be uncertainties associated with the hydraulic calculations, and that flood levels may be influenced by other factors as well as peak flow. This last point is important because sometimes it is the model or the modeller's assumptions that need to be altered. Do not treat flow rates inferred using an uncalibrated hydraulic model with the same level of confidence as those derived from a rating curve at a gauging station. For a step-by-step guide, refer to the section on **How to use information on the impacts of recent floods in flood frequency estimation** in Technical Guidance 12_17, 'Using local data to reduce uncertainty in flood frequency estimation'.
2	It's important to understand that the quality of flood frequency estimates from design event methods is not just influenced by the accuracy of the rainfall-runoff model. Another important factor is the appropriateness of the 'design package' (that is, the combination of storm depth, duration, profile and soil moisture). Having well-calibrated parameters for a rainfall-runoff model should mean that the model can simulate observed floods

	faithfully, but this does not guarantee that design floods will be well estimated.
3	Seek out local data to help guide the selection of an appropriate method. This might include longer-term flood history, channel width measurements, information gleaned from field visits, palaeoflood data, data from river level gauges or temporary flow gauges, or groundwater level data. Refer to Technical Guidance 12_17 for ideas on how to find and exploit such data.
4	The FEH discourages users from choosing a method based on reasons such as: • 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).

Choosing between ReFH versions

Differences between ReFH1 and ReFH2.3

The ReFH2 method was first released in 2015. It was updated in 2016 to use the latest rainfall frequency statistics for the UK, FEH 2013 and improved in 2019 when a closure of the water balance was introduced, along with other changes.

The version at the time of writing is ReFH2.3. Refer to Wallingford Hydrosolutions (2019a,b,c).

ReFH2 uses the same rainfall-runoff model as the original ReFH method (ReFH1) to represent rural catchments. ReFH2 also includes the facility to represent the different runoff characteristics of urban areas. This aspect is based on papers published in 2009 and 2013 which were subsequently widely implemented in ReFH1.

The main other differences between ReFH2.3 and ReFH1 methods are:

- Revised equations for estimating model parameters from catchment descriptors.
- Ability to construct the design storm using the FEH 2013 rainfalls.
- Revised equations for estimating initial soil moisture, Cini, during a design flood. These were calibrated against QMED estimated from peak flow data across the whole NRFA dataset, a much larger dataset used than for ReFH1. In ReFH2.3, a separate summer Cini equation was reinstated.
- Removal of the α scaling factor for Cini (as long as the FEH 2013 rainfall depths are used). This means that flood growth curves estimated using ReFH2 are independent of those estimated using the FEH statistical method.
- Alternative parameter estimation equations which allow application of the method at the plot scale for estimating pre-development runoff rates.
- Option to close the water balance over the event that is being modelled (ReFH2.3).
- Revised guidance on default parameters to represent urban runoff (ReFH2.3).

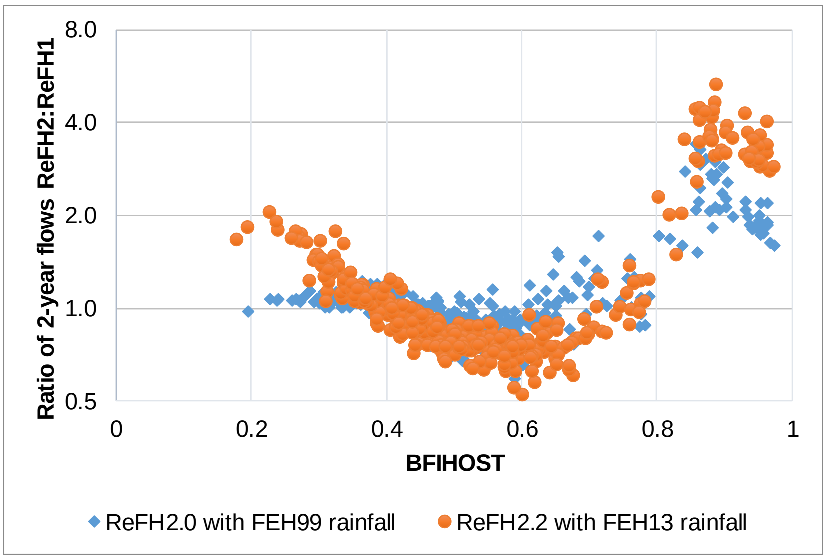
Differences in the performance of the ReFH1 and ReFH2 methods can be summarised as:

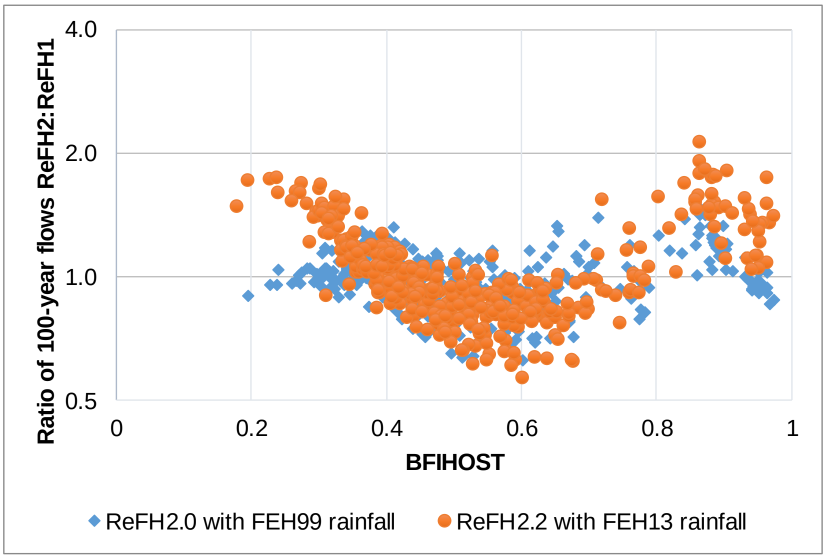
- Reduced bias and factorial standard error when estimating QMED from ReFH2 compared with ReFH1. There is a very large improvement in performance on permeable catchments.

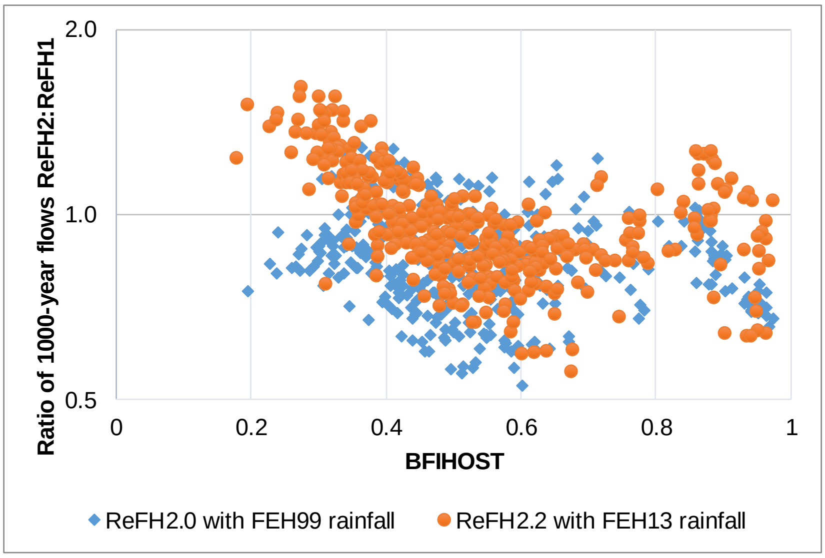
- An increase in peak flows for most low-BFIHOST and high-BFIHOST catchments and a decrease or little change in peak flows for BFIHOST of about 0.4 (Figure 8).

Figure 8: Comparing ReFH2 and ReFH1

Comparison of ReFH2 and ReFH1 for catchments across England and Wales as a function of BFIHOST, for return periods 2, 100 and 1000 years.







Choosing between ReFH1 and ReFH2

In most situations, apply the current version of ReFH2 in preference to ReFH1. Unlike ReFH1, ReFH2 is suitable for estimating design flood hydrographs on permeable catchments (BFIHOST > 0.65). It can also be applied at the plot scale.

In some situations, ReFH1 may still be appropriate. These might include:

- When a rainfall-runoff method is being applied only to create the shape of the flood hydrograph, with peak flows estimated using another method.
- When access to software creates difficulties with applying ReFH2, for instance if creating inflows for a hydraulic model. Although ReFH2 is implemented in some hydraulic modelling packages, there are currently some limitations and inflexibility with its implementation in some of these models. An alternative option is to copy hydrographs from ReFH2 into a flow-time boundary unit in a hydraulic model. This is feasible although vulnerable to errors and can create difficulties with testing critical storm durations.

Choosing water balance option in ReFH2.3

ReFH2.3 includes an option to close the water balance, i.e. to ensure that the volume of flow generated by the model matches the volume of input rainfall, allowing for any change in storage. This option is the default for modelling design floods, and the only way available in the software for modelling real floods. The option is not available for permeable catchments (BFIHOST>0.65) because of the difficulties of accounting for recharge to aquifers with long residence times.

ReFH2.3 closes the water balance by making two changes to the rural model:

- The baseflow recharge (BR) changes from a model parameter to a state variable, the value of which is set automatically to ensure that volume is conserved.
- The model run is divided into segments, with the initial soil moisture (Cini) recalculated at the start of each segment to allow for drainage. The length of each segment is the recommended storm duration for the catchment.

In the urban model, the concept of depression storage is introduced to improve the way that the volume of runoff from impervious surfaces is handled to ensure mass is conserved within the urban model. In the same vein, the green spaces within the urban model also generate baseflow.

You can find out more in Wallingford HydroSolutions (2019a,b).

This feature of ReFH2.3 was new at the time these guidelines were updated in 2019 and so had not been applied in practice.   However, in general it seems worth selecting the option to close the water balance.

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

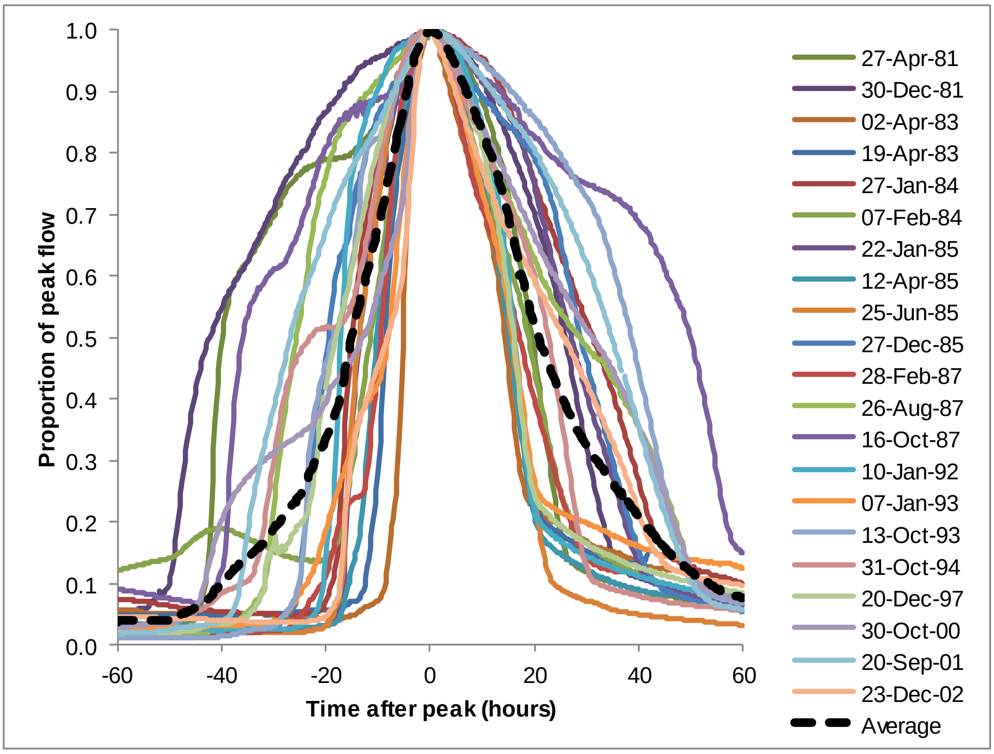
The FEH suggests three hybrid methods, listed as (a) to (c) below. Others, such as (d) below, are used occasionally.

Possible options	Description and guidelines
(a) Generating the hydrograph from a design event 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 / ReFH2 method, losing the information on runoff volume. It is not well suited to large catchments or those dominated by storage. However, it can sometimes be applied in these catchments by splitting them up into sub-catchments 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 / ReFH2 method giving a poor answer is that the model parameters have been poorly estimated, which is not always the case. A more logical approach is to adjust the initial soil moisture, Cini, since this is not a model parameter. It may prove difficult to match the statistical results over a range of return periods.
(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.	This approach is only possible if there is a gauging station near enough to be representative of the site of interest. 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 9 below); • or using a more sophisticated procedure, such as deriving the duration of exceedance of selected percentiles of peak flow. Reference: Archer, D., Foster, M., Faulkner, D. and Mawdsley, 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. It is worth checking for any tendency for larger floods to have a different shape, for example due to more floodplain attenuation or faster overland runoff processes. 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.

Figure 9: Flood hydrograph shapes on the River Ore at Beversham

The graph shows hydrograph shapes for 21 different floods, normalised by their peak flow and aligned so that the peak occurs at the same time. The dashed line shows the average, calculated as the arithmetic mean of the proportional flow rate at each time step.



3.6 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, for example by 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? There are no defined limits within which growth factors should fall, apart from not falling below 1. In the Flood Studies Report's regional growth curves (no longer used, but can be a useful yardstick on plots), the ratio of the 100-year to the 2-year flow varied from 2.1 to 4.0. It would be sensible to investigate 100-year growth factors that fall significantly outside this range.

	You can sometimes justify much higher growth factors on catchments containing areas of high permeability, where they are consistent with the flood history.
3	What specific discharge (that is, flow in litres/second/hectare) do the results equate to? Again, there are no agreed limits, but 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 (SD02) which includes the questions above and other possible questions. This checklist can be used by:

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

3.7 Conclusion

Use the six maxims as a guide

Use the six maxims 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, such as 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. Sometimes 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.

4 Advice and cautions on flood estimation methods

4.1 Overview

Reminders, guidance and latest research

There are many opportunities for choice when applying the FEH methods, including some where the unwary might miss a subtle variation in the options facing them. The sections in this chapter aim to both 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.

4.2 Design rainfall

Source of rainfall frequency statistics

The depth-duration-frequency (DDF) model provided with the FEH (1999) was replaced in 2015 with the FEH 2013 rainfall model. See Stewart and others (2013) in Related documents.

Both the FEH99 and FEH 2013 rainfall statistics are available via the FEH web service. They enable the estimation of design rainfalls for any location in the UK or the return period of an observed rainfall.

Use the FEH 2013 rainfall statistics in preference to FEH99 for all applications unless you have evidence that FEH99 should be preferred in a particular location.

Guidelines

Item	Guideline or advice
1	The DDF model covers a range of rainfall durations from 1 hour to 8 days. You can rely on the results for durations as short as about 30 minutes.
2	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.
3	Flood estimates from rainfall-runoff models need a catchment-average rainfall. This is provided by the FEH web service, which applies an areal reduction factor. The areal reduction factor formula is in **2** 3.4. Use point rainfalls for other applications such as drainage design, investigation of surface water flooding or estimating the return period of a rain gauge measurement.

4.3 Statistical method

Fundamental assumption: stationarity

Trend and non-stationarity

The FEH methods assume that in a data series, each value, for example, each annual maximum flow, is independent and has the same probability distribution as all the other values. This means that the exceedance probability of any flow rate is constant throughout the period of record, that is, the data represent a stationary process.

If the flood frequency behaviour of a catchment is not constant over time (non-stationary), the peak flows are not identically distributed and so this assumption is violated. For example, the probability of exceeding a particular flow rate might increase as a result of urban growth in the catchment or climate change.

There are alternative methods of flood frequency analysis that allow for non-stationarity in annual maximum flows. The items in the boxes below suggest some of the approaches to dealing with non-stationarity.

The current guidance on application of non-stationary methods is:

- For Cumbria and North Lancashire non-stationarity flood frequency estimation can be (but does not have to be) applied to Flood Alleviation Schemes, and local guidance has been issued on how this should be done. Non-stationary methods should not be applied to other studies (e.g. floodplain mapping) in Cumbria and North Lancashire.
- Elsewhere in England, non-stationary methods should not be applied to any studies.

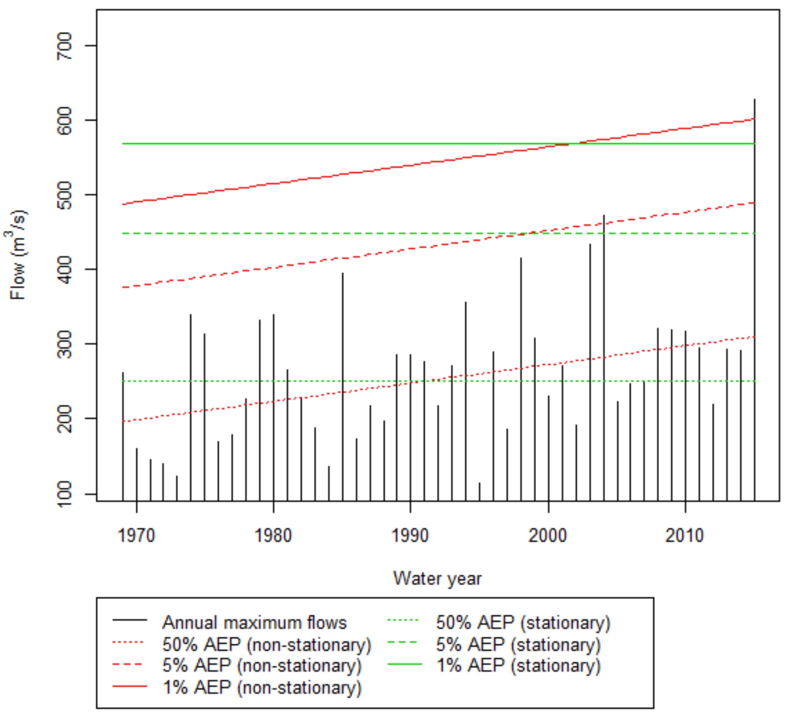
National guidance and tools on applying non-stationary methods are due for release in 2020.

The comments above about not applying non-stationary methods do not replace the need for normal hydrological judgement. For example, if an analyst considers that the early part of a record is unreliable it would be normal practice for the calculations to ignore it, or to apply a sensitivity analysis.

Item	Guideline or advice
1	When analysing flood peak data, always plot a time series and check for trends. While a visual check is a good starting point, in many cases it will be worthwhile applying a statistical test. The Mann-Kendall test is commonly used in hydrology to assess the statistical significance of trends. It assesses whether or not there is a monotonic upward or downward trend in a variable over time. The test is not dependent on the magnitude of the data but is based on the proportion of increases and decreases between pairs of values. In trend testing, the usual null hypothesis is that the data represents a stationary process. The tests output a probability value, and if this is less than a chosen significance level, often 5%, then the null hypothesis is rejected. The provisional conclusion is then usually that a statistically significant trend exists. Note that the test does not directly measure the magnitude of the trend. For a long dataset it could be possible to detect

	a trend that is statistically significant but too small to be of practical consequence.
2	If you detect a trend, do what you can, within the scope of the study, to identify its cause, or at least eliminate potential causes. For example, might the trend be spurious due to changes in hydrometric practice during the period of record (for example, application of different rating curves, some of which are more valid at high than others)? Has there been urban development or other changes in land use in the catchment? Has the river channel been altered over the period of record, for instance by construction of embankments or dredging? Have peak flows reduced as a result of the introduction of flood storage? If you can rule out other causes, you could provisionally infer that the trend is due to climatic factors. What is more difficult is to distinguish between progressive and cyclical changes in climate. Many UK river gauges were installed in the 1960s. The following few decades, until the end of the 1990s, were relatively flood-poor in comparison with the longer-term flood history of the UK. More recently, large floods have become more common in many parts of the UK. This may be a natural fluctuation, or it may be exacerbated by the warming climate. For further information on attribution of trends, refer to Merz and others (2012) or Hall and others (2014).
3	If the trend is statistically significant, large enough to concern you and not, as far as you can tell, spurious, then consider the implications for flood frequency estimation. These will depend on whether you are planning to use the flood peak data for estimating QMED only, or for including in a flood frequency analysis. Methods of flood frequency analysis are available that can account for non-stationarity. The aim is to estimate a flood frequency curve that is representative of present-day conditions. Extrapolating the trend into the future is not recommended. One approach is to attempt to remove the trend from the data before the analysis. This tends to rely on an assumption that the trend affects only the mean or median. If the trend appears to be due to a sudden change such as the creation of a flood storage area or reservoir, it may be better to discard the portion of the dataset that pre-dates the change. Some of the NRFA peak flows series already mark such data as rejected. A more robust approach for flood frequency analysis of annual maximum data is to fit a flood frequency distribution where one or more parameters are allowed to vary with time, or with another covariate. Methods of non-stationary flood frequency analysis cannot be applied using the standard FEH software. They are straightforward to apply using statistical programming languages such as R. Non-stationary methods of flood frequency analysis have drawbacks, the main one being an increase in uncertainty due to the larger number of parameters that need to be fitted. There are numerous examples of non-stationary flood frequency analysis in the literature. Suggested reading includes Faulkner and others (2019) and Prosdocimi and others (2014).

Figure 10: Example of non-stationary flood frequency analysis



This analysis is for the River Lune at Killington. The graph shows stationary and non-stationary estimates of flow for three probabilities. The non-stationary estimates increase over the period of record.

Overview of FEH statistical method

Data: Annual maxima or POT?

The FEH statistical method is largely based on annual maximum (AMAX) flow data. There are various reasons for this, including a more widespread availability of annual maxima as opposed to POT data. POT cannot be defined on some baseflow-dominated catchments. There are missing portions in some POT records.

One drawback of analysing only annual maxima is that some information is discarded. Frequency analysis of POT data, for instance fitting a Generalised Pareto distribution, can sometimes give very different results, even for short return periods. This can occur due to the presence of peak flows in the POT dataset that are not annual maxima but are larger than the lowest AMAX observation in the dataset.

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

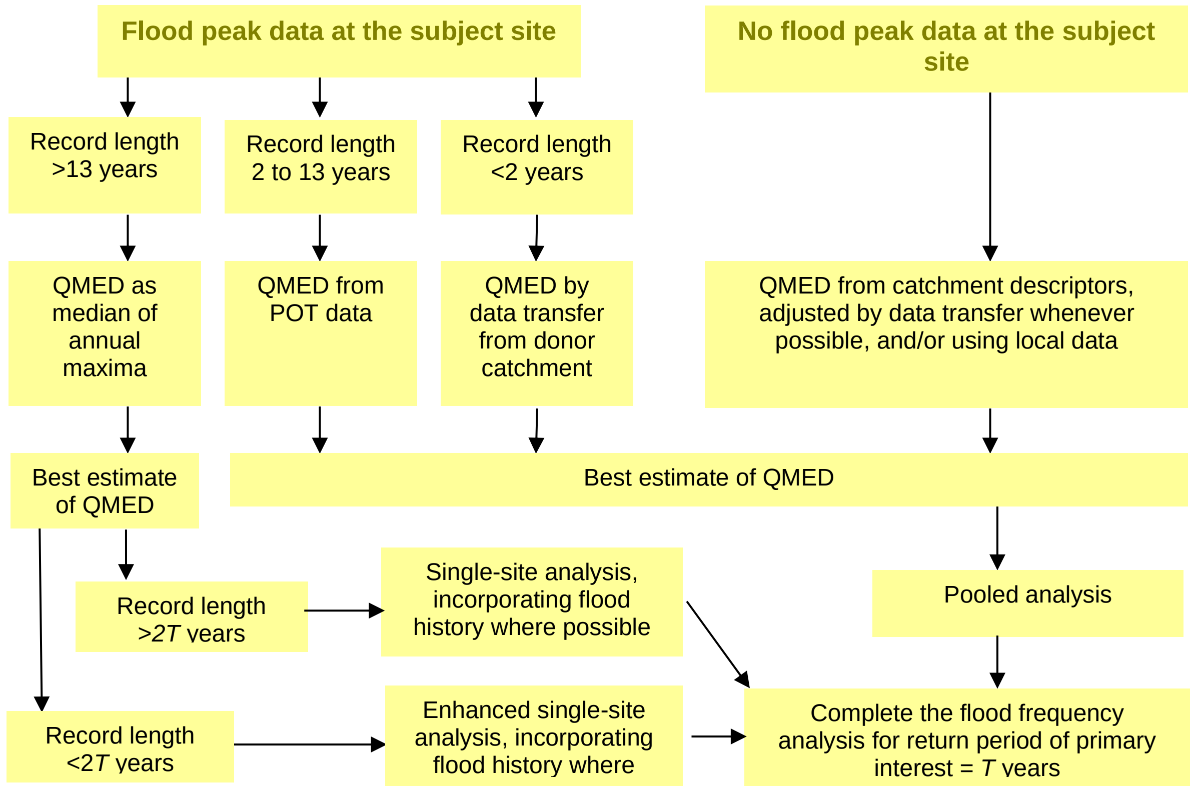
- at subject sites or donor sites to estimate QMED;
- and at pooled gauging stations to construct the pooled growth curve.

Software

The statistical method is usually applied using WINFAP. The current version of the software is v4, released in 2016. The core methods are similar to those in v3 (known as WINFAP-FEH), but v4 has some additional options, including a revised urban adjustment procedure, the ability to apply the enhanced single site analysis within urbanised catchments and to apply multiple donor adjustment procedures to QMED.

Some analysts find it convenient to record their calculations in a spreadsheet, which they can also use to calculate QMED and design flows with the aid of the growth curve parameters produced by WINFAP.

Figure 11: Flow chart The diagram illustrates the main options available to analysts. There are other options that will be preferable in some cases.



Index flood, QMED

Guidance on estimating QMED from peak flow data

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	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).
3	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.

QMED from catchment descriptors

The QMED equation

The QMED regression equation provided in the FEH was superseded in 2008 by the revised equation in Science Report SC050050, listed in [Related documents](#).

This QMED equation is still current and is represented as:

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

It 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.

The factorial standard error (FSE) for this regression equation is 1.431. Refer to section 5.4 for guidance on calculating confidence intervals from the FSE.

Guidelines

Item	Guideline or advice
1	You should only consider estimating QMED from catchment descriptors as a last resort. Use a data transfer to reduce uncertainty.
2	You should not rely on the QMED equation when FARL<0.9 due to reservoirs (**3** 3.3, 13). Refer to the section on catchments containing reservoirs.
3	The model for QMED cannot account for all catchment features. Avoid using it on artificially drained fenland catchments.
4	There are alternative methods of estimating QMED which are worth considering in cases where FEH methods are difficult to apply convincingly (for example, if the catchment extent is unclear) or give answers that appear unrealistic. Alternatives, which are explained later, include: • Estimating QMED from bankfull channel width; • Estimating QMED from flow duration curve percentiles.

Urban adjustment for QMED

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.

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 URBEXT2000 exceeds the threshold value of 0.030.

For more general advice, refer to Urban catchments.

Adjusting QMED for urbanisation

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

You can do the urban adjustment in WINFAP or alternative software such as a spreadsheet. WINFAP 4 uses a revised adjustment method which overcomes a problem with the implementation of the urban adjustment in v3. It also provides more flexibility in that it relates the adjustment more directly to the physical characteristics of urban areas. Use this revised adjustment in all cases.

The adjustment is described in Wallingford HydroSolutions (2016a), listed in Related documents.

Use the pair of equations below to calculate UAF.

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

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

where:

- IF is the impervious factor, i.e. the fraction of urban areas covered with impermeable surfaces. This is set to 0.3 by default.
- PR_{IMP} is the percentage runoff for impermeable surfaces, 70% by default.
- URBAN is the fraction of the catchment shown as urban on OS 1:50,000 mapping. This is a characteristic that was used in the Flood Studies Report and can be estimated from the FEH descriptor URBEXT2000 using:

  $$URBAN = 1.567\ URBEXT_{2000}$$

- PRUAF is the percentage runoff UAF, calculated from the second equation.

The same parameters are used to represent the effect of urbanisation in the ReFH2 rainfall-runoff method, although different default values are recommended in ReFH2.3. These parameters could be potentially altered to represent the differing drainage characteristics of particular urban areas, for instance, attempting to represent the effect of sustainable drainage systems (SuDS).

If you alter any of the default parameters, state what value you have used and why.

When using WINFAP4, care must be taken when conducting Enhanced Single Site Analysis for an urban catchment. Normally, the ‘Deurbanise at-site L-moments?’ check box should be selected if you consider the influence of urbanisation at the site to be significant. The flow results provided are then the “as rural” estimate of QMED (de-urbanising the observed QMED) and the rural growth curve (with the at-site L-moments deurbanised). If the ‘Show urbanised Flood Frequency results’ check box is selected, the flow results provided are then the observed (i.e. urban) QMED and the urban adjusted growth curve. If the ‘Deurbanise at-site L-moments?’ check box is not selected, then the at-site QMED and L-moments are treated as rural.

The issues

Important! 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 guidelines below contain some important information.

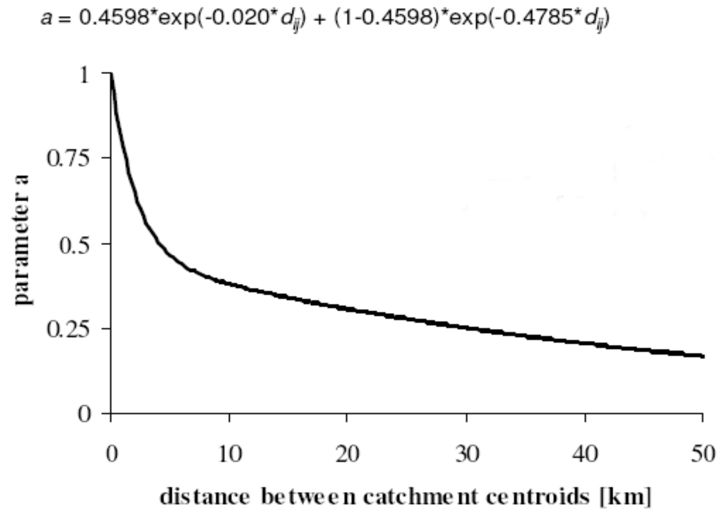
Science Report SC050050 (see Related documents) presented a revised method for applying donor catchments. This gives a more structured way of selecting donors, but many practitioners have continued to apply judgement and to implement elements of the original FEH guidance.

Subsequent research has found that QMED estimation can be improved by selecting multiple donors and that screening donor catchments by their physical characteristics can lead to a poorer estimate. See the guidelines below.

Data transfer remains a process with no universally agreed rules. There is scope for disagreement even between experienced hydrologists.

Guidelines

Item	Guideline or advice
1	The data transfer method presented in Science Report SC050050 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).
2	The power term, a, reduces with distance between the catchment centroids. The adjustment has its full effect when the subject site is at a gauging station. The effect becomes quite small once the centroids are more than 10 km apart; see **Figure 12.** **Figure 12: Relationship between moderation term, a, and the distance between centroids, d_{ij}**

	 Graph provided in personal communication from Thomas Kjeldsen at CEH.
3	The research underlying the revised data transfer method (SC050050) involved comparing the performance of alternative techniques for the 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. This is 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. More recent research on small catchments (SC090031, see Related documents) has supported the findings of SC050050, again recommending that donors are selected purely on the basis of proximity. For many hydrologists, this finding is counterintuitive. In common practice, there is a reluctance to use large catchments as donors when the subject catchment is small. Such analysts may expect that the balance of physical processes differs between small and large catchments, for example, with floodplain storage being more important on larger watercourses. To counter this argument, SC090031 makes the point that descriptors such as AREA are included in the regression equation for QMED, so that the donor adjustment process accounts for the differences in size between the donor and subject catchments. Indeed, the research found no correlation between error in QMED prediction and the area of the donor catchment. SC090031 also explains that the overarching pattern of QMED model residuals across the UK follows a smooth spatial pattern, hence the recommendation to choose donors by proximity. The recommendations on data transfer in SC090031 conclude as follows: "…although there are some advantages to filtering potential donors for small catchments by AREA and SAAR, they are outweighed by disadvantages, particularly if the estimate of QMED given before donor transfer is poor (which will not be known if the catchment of interest is ungauged)." These issues reflect a broader conflict between expert judgement and algorithms. Unsurprisingly, experts pride themselves in understanding what they regard as the unique local circumstances

	of cases and tend to consider complex combinations of features when making their predictions. However, numerous studies have shown that algorithms make better predictions than experts in uncertain and unpredictable cases, in fields ranging from medicine to social sciences and finance. For more insights into this topic, refer to Kahneman (2011).
5	Despite the above, there will be some circumstances in which you can expect expert judgement and local knowledge to trump a dispassionate algorithmic approach to adjustment of QMED. For instance: • Give preference to donor sites on the same watercourse as the subject site. • Exercise caution when transferring QMED to or from a catchment affected by urbanisation, reservoirs, opencast mining, forest drainage or other major artificial influence (**3** 4.6). The FEH recommends avoiding urbanised donors, even for an urbanised subject catchment. However, WINFAP 4 allows urban donors, applying the UAF in reverse in an attempt to remove the urban influence. This is likely to be a wise choice in some circumstances, for instance, if the donor and subject sites are on the same watercourse and so have the same urban area in their catchments. • 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. 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, perhaps at similar distances from the subject catchment. WINFAP 4 allows you to use multiple donors and will identify a mathematically optimal number of donors. The procedure is based on a publication by Kjeldsen and others (2014). The authors found that six or more is an optimum number of donors to minimise the error in the estimate of QMED. Weights for the donors are calculated as a function of the distance between the centroid of the subject catchment and that of each donor catchment. Some practitioners believe using six donors is a step too far towards automation. As an alternative to the automated process of averaging adjustment factors from multiple donors, they carry out a more detailed review of the suitability of potential donor catchments, in terms of <u>both</u> data quality and relevance to the subject site, before making a final choice. This may be particularly worthwhile if there is a wide variation in adjustment factors between the candidate donors. The section below, Using the software, gives details of selecting donors using WINFAP 4. If you prefer a less automated approach, you can carry out data transfer using two donors outside WINFAP v4. Use the equations

	below to calculate the weights α$_1$ and α$_1$. They are taken from Kjeldsen (2019). $$QMED_{s,adj} = QMED_{s,cd}\left(\frac{QMED_{1,obs}}{QMED_{1,cd}}\right)^{\alpha_1}\left(\frac{QMED_{2,obs}}{QMED_{2,cd}}\right)^{\alpha_2}$$ where the subscripts s, 1 and 2 refer to the subject site and donor sites 1 and 2. $$\alpha_1 = \frac{\rho_{s1} - \rho_{12}\rho_{s2}}{1 - \rho_{12}^2}$$ $$\alpha_2 = \frac{\rho_{s2} - \rho_{12}\rho_{s1}}{1 - \rho_{12}^2}$$ where ρ_{ij} is a measure of the spatial correlation of errors in the QMED prediction model. It is a function of the distance d_{ij} between the centroids of catchments i and j: $$\rho_{ij} = 0.4598exp(-0.020d_{ij}) + (1 - 0.4598)exp(-0.4785d_{ij})$$
8	The reduction in uncertainty as a result of applying data transfer is modest, with the 68% confidence interval for QMED on a rural catchment narrowing from: • 0.69-1.45 times the estimate with no donor to • 0.70-1.42 times with one donor and • 0.71-1.40 times with six donors. These figures are taken from Technical Guidance 12_17. Despite this relatively small effect on the degree of confidence, the estimate of QMED can change markedly as the result of some data transfers.
9	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 for an example.

Figure 13: Consistency of QMED adjustment factors

Description of the site

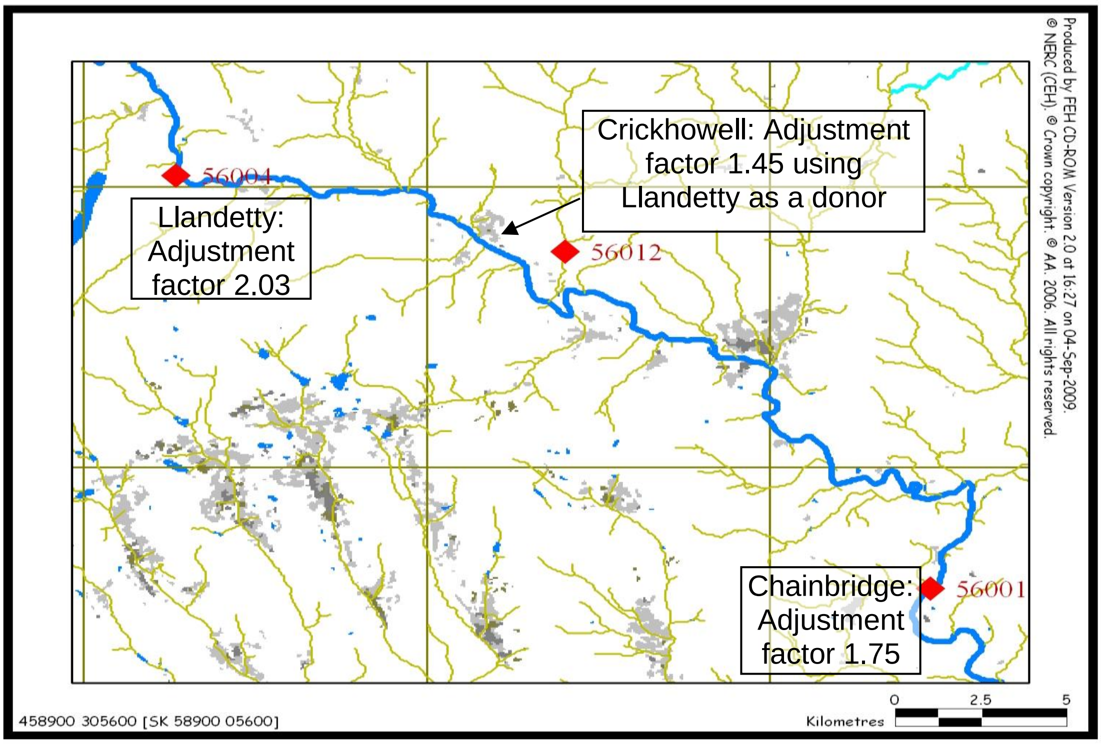
The site of interest is Crickhowell. The most appropriate donor appears to be Llandetty. It is shortly upstream on the same river and the catchment centroids are just 3.6 km apart. However, this short distance is enough to reduce the adjustment factor from 2.03 at Llandetty to 1.45 at Crickhowell, when applying the data transfer method from SC050050, due to the moderation term (a).

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 moderation of the adjustment factor by distance.

The analyst's decision

The analyst decided (wisely) to override the recommended use of the moderation term 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

WINFAP 4 enables you to automatically identify the nearest donors and calculate the moderated adjustment factor. You can also select another donor if preferred, from a list ranked by distance between the catchment centroids. The list includes information on the catchment descriptors of the potential donor sites and links to pages on the NRFA website.

For an ungauged site, WINFAP 4 shows the QMED value from the rural regression equation on catchment descriptors. To use donor catchments, the user can “Edit QMED Method”, in which case WINFAP 4 selects six donors using the procedure in a publication by Kjeldsen and others (2014).

Weights for the donors are calculated as a function of the distance between the centroid of the subject catchment and that of each donor catchment. The user can deselect donors and can add others from 10 pre-selected stations; it seems that other stations cannot be added, and would have to be applied outside of WINFAP 4.

Important note: If you set up WINFAP-FEH 3 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 but not for pooling. This issue should not occur with WINFAP 4, which can detect the suitability flags in the NRFA dataset.

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 when working on very low risk studies.

Donor sites should be:

- close to the subject site;
- classed as suitable for QMED or shown to be suitable in a more in-depth review of data quality.

Similarity in catchment area, BFIHOST and other catchment descriptors included in the QMED regression equation is not essential. However, in view of the sometimes uncertain relationship between BFIHOST and runoff, similarity in geology or soil type may be relevant.

Consider using more than one donor.

In most circumstances, moderate the adjustment using the power term calculated from the distance between catchment centroids. If the subject and donor sites are on the same watercourses, or if there are multiple subject sites, check that this process does not introduce inconsistency.

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.

QMED from bankfull channel width

The issues

On some types of river you can use simple measurements of channel width to estimate QMED, either on their own (Method 1 below) or in conjunction with FEH catchment descriptors (Method 2).

These methods are not suitable for routine use. Instead, consider them when there is doubt or concern over the accuracy of an estimate derived from FEH methods. You will need to ensure that the channel is natural and satisfies the other criteria given below. Method 1 gives answers that are highly uncertain on average, but it is included here because it avoids any need to define the catchment area. This can be difficult occasionally, for instance, if a river is fed by spring sources and the groundwater flow directions are unclear.

The channel geometry method is most suited to perennial streams with stable banks that are not easily widened by floods. It is less likely to be accurate on flashy or ephemeral streams. You should not apply it on artificial channels; strongly channelised rivers (unless the channel system has adjusted to the new flow regime); reaches with bedrock banks; braided reaches, or reaches with large pools or locally steep gradients. It may not be reliable on streams where the channel width at bankfull is much less than 5m.

It is necessary to visit the river to assess its suitability, find representative cross sections and accurately measure the bankfull channel width.

Refer to Technical Guidance 12_17 for more information on these methods and to SC130009/R (Dixon and others, 2017) for a report on the research.

How to measure channel widths

Follow the steps below to measure the bankfull channel width for the purpose of estimating QMED on suitable types of river.

Step	Action
1	Select a reach that is relatively straight or on a stabilised reach of a meandering channel and at least 4-5 channel widths in length.
2	Select at least three sections with rectangular or trapezoidal shape, spaced at least one channel width apart with widths that are representative of the reach as a whole.
3	Select sections with similar bankfull levels on both banks and along the reach.
4	Flow velocities should be reasonably symmetrical across the section.
5	For stabilised reaches of meandering channels, locate the sections close to the point of inflection.
6	For reaches with weak to moderate riffle-pool sequences, select cross-sections in the straighter intermediate sections where flow velocities do not differ greatly across the width.
7	For well-developed pool-riffle sequences with no intermediate straight section, select at least two pool and two riffle sections or choose cross-sections on the leading edge of the riffles.
8	Identify the bankfull level by careful consideration of both banks over the entire length of the survey reach. Bankfull is defined as the elevation of the active (i.e. frequently inundated) floodplain. Use the height of the lower limit of perennial vegetation as a guide.
9	Measure the bankfull channel width using a tape measure or optical methods. Where channel banks are of different heights, keep the measurement horizontal, from the lower bankfull level across to the opposite bank.
10	Calculate reach values as an arithmetic mean of the widths at all sections.

Using channel dimensions to estimate QMED

Method 1: Estimating QMED solely from channel dimensions

Use this equation:

$$QMED = 0.226\ BCW^{1.90}$$

where BCW is bankfull channel width measured in metres and QMED is in m^3/s.

The equation explains 77% of the variation in QMED at 73 gauging stations to which it was fitted. The factorial standard error (FSE) is 1.60, indicating a much greater degree of uncertainty than the regression of QMED on catchment descriptors, for which the FSE is 1.43. So, on average you will get a worse result in comparison to using catchment descriptors, even without a donor adjustment. However, this method may provide a useful alternative perspective in troublesome cases.

Method 2: Estimating QMED from a combination of catchment descriptors and channel dimensions

Use this equation:

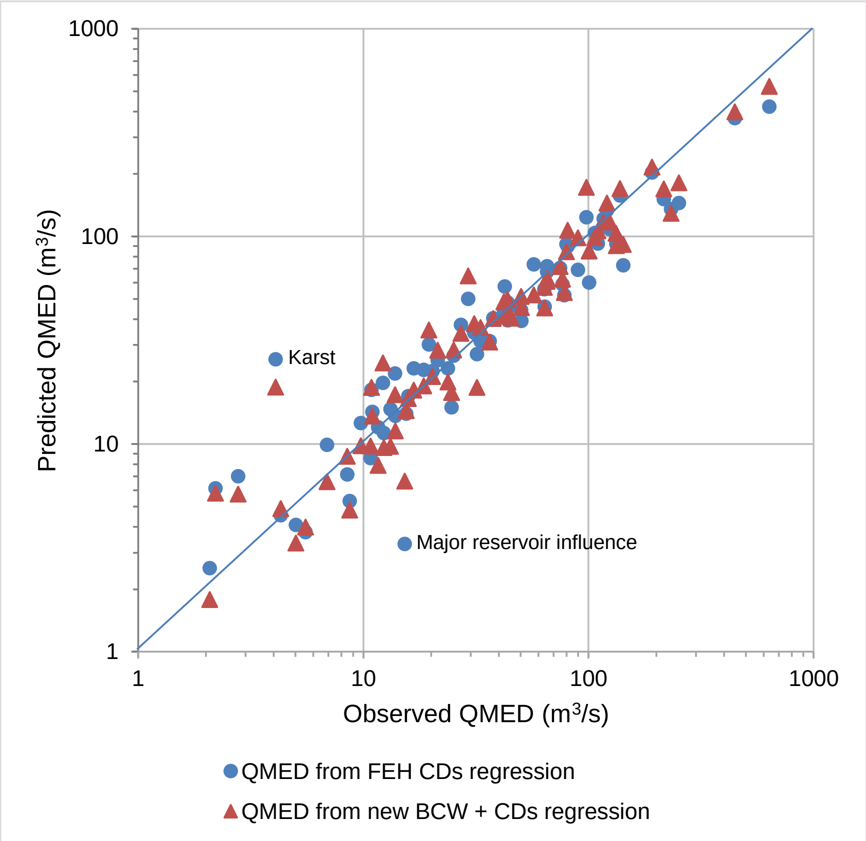
$$QMED = 2.527BCW^{0.661}0.0600^{BFIHOST^2}AREA^{0.6028}FARL^{2.181}0.266^{\frac{1000}{SAAR}}$$

where BCW is measured in metres and all other variables are FEH catchment descriptors. The regression explains 91% of the variation in QMED at the 73 gauging stations to which it was fitted. This is a good performance, although not as good as the 95% achieved by the current FEH regression equation for QMED.

The factorial standard error (FSE) for Equation 5 is 1.38, slightly lower than the 1.43 associated with the FEH regression for QMED. However, it is important to realise that the FEH regression was developed from eight times as many gauging stations.

The FEH local research found that Method 2, along with an urban adjustment where necessary, helped to improve some large under or over-estimates of QMED from the FEH regression (Figure 14).

Figure 14 Comparison of predicted and observed QMED at 73 gauging stations



Despite the evidence of good performance, you should not use Method 2 routinely. It has been developed from a much more limited dataset than the FEH Statistical method. Where there is little difference between the results of Method 2 and conventional FEH methods, this should help in reinforcing confidence in the FEH result. If Method 2 yields an increased estimate of QMED, you might prefer this result for some types of project where a conservative answer is desirable.

QMED from flow duration curve statistics

The issues

Only just over half of flow gauging stations in the UK are classed as suitable for estimating QMED. For subject sites at or near flow gauges where you cannot rely on the flow measurements in flood conditions, there is an alternative method of estimating QMED from a combination of flow duration statistics and catchment descriptors. The uncertainty in the estimate is lower than that of the FEH catchment descriptor regression, even after applying a data transfer, with the factorial standard error being 1.34.

The method is described by Wallingford Hydrosolutions (2016b). It is implemented in WINFAP 4 and can alternatively be applied in a spreadsheet or other software (as explained below).

Using flow duration curve statistics to estimate QMED

Use this equation:

$$\mathbf{QMED = 1.762Q5_{DMF}{}^{0.866}(1 + GRADQ5_{DMF})^{-0.775}DPSBAR^{0.265}0.2388^{BFI^2}}$$

where:

$Q5_{DMF}$ is the 5 percentile ordinate on the flow duration curve, i.e. the flow that is exceeded 5% of the time. DMF indicates that the flow duration curve is normally calculated from daily mean flow data.

$GRADQ5_{DMF}$ is the gradient of the flow duration curve between Q5 and Q10, assuming that the curve follows a log-normal distribution. To calculate this, you need to take the logarithm of the flows and convert the percentages to exceedance probabilities, then take the inverse of the standard normal cumulative distribution.

DPSBAR is the FEH catchment descriptor, mean drainage path slope.

BFI is the baseflow index calculated directly from gauged flow data. **Caution!** Do not confuse this with BFIHOST, or BFIHOST19.

Growth curves

Definition

A flood growth curve describes the relationship between peak flow and flood rarity (i.e. return period) for a specific river location. It can be used to find the rarity of a given flow, or the flow which is attributed to a given return period.

In the FEH method, the growth curve takes a value of 1.0 for a return period of 2 years, because the 2-year flow is QMED.

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).

When applying the FEH statistical method, 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). However, in some cases it is good practice to prefer the single-site growth curve if it can be improved by incorporating flood history.

WINFAP 4 identifies the subject site in the growth curve plot of all stations, which enables the at-site growth curve to be compared with the other stations.

Guidelines

Item	Guideline or advice
1	The FEH states that catchments within a pooling group should be essentially rural (**3** 6.1), i.e. URBEXT2000 < 0.03. WINFAP 4 provides an option that allows urban catchments to be included in groups, and applies the urban adjustment in reverse in an attempt to remove the effect of the urbanisation. This was developed in light of concerns that following the original FEH procedure meant excluding potentially useful small urban catchments, despite the fact that the effect of urbanisation on growth curves is generally small. It is often worth including urban catchments as long as they are similar in size to the target catchment and not too heavily urbanised. They are particularly valuable to include if on the same watercourse as the site of interest. If you include urban catchments in the pooling group, test the sensitivity of the results by comparing with an all-rural group. One concern over including heavily urban catchments in pooling groups is that occasionally their flood growth curve can be strongly influenced by local hydraulic characteristics, such as culverts that restrict conveyance during large floods. Such idiosyncrasies could have a large effect on the flood growth curve and they are not transferrable to other catchments; even a neighbouring catchment might have quite different hydraulic characteristics.
2	For a study with multiple flow estimation points, it is good practice to apply one pooling group to several points along a river. This helps promote spatial consistency.
3	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 in the group that are least similar to the subject site have little influence on the pooled growth curve because of the low weights allocated to them. WINFAP 4 plots the growth curves of all the stations in the selected pooling group, with the subject site (if gauged) in red. Review this figure and present the plot in the FEH Calculation Record.
4	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. **Important!** 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).

5	The review should assess physical and hydrological differences between subject and pooled catchments such as: • station locations and periods of record; • flood seasonality; • urbanisation and other anthropogenic activity (**3** 9, 21); • quality of high flow data; • geology; • local climate. Differences in AREA, SAAR, FARL or FPEXT are sometimes used as a reason for excluding stations, but since these four descriptors are used to select the group, it is inevitable that any replacement stations will be less similar in terms of these properties. It is good practice to remove stations if you think they duplicate another station on the same river with overlapping records. Some stations may be rejected for data quality reasons such as ratings not accounting for out of bank flow. Most such stations should have been automatically excluded through being classed as not suitable for pooling in the NRFA dataset. Some analysts are wary of including stations in Northern Ireland in pooling groups for sites in Great Britain, particularly those stations with low growth curves. The reasoning behind this may be partly a wish to not to derive estimates which are too low (the precautionary principle), perhaps that flows at some stations have been affected by arterial drainage schemes in the past, and perhaps that at some stations the estimate of little out-of-bank flow in the assessment of the indicative suitability may have been optimistic. Where estimates are important a number of pooling group options could be explored and reported, to help understand the sensitivity of the results.
6	It is common for analysts to remove stations from a group due to large differences in BFIHOST. This may be because in the original version of the FEH method, BFIHOST was one of the three descriptors from which the pooling group was selected. Subsequently, the SC050050 research found that BFIHOST had very little explanatory power for flood growth curves, with ten other catchment descriptors found to be more useful at explaining variation in the L-moment L-CV. Earlier research, including the FEH and Flood Studies Supplementary Report 4 (1977), consistently reported differences in flood growth curves on permeable and nearby impermeable catchments. They report that there is generally less year-to-year variation on the permeable catchments and hence flatter growth curves. Despite the findings of SC050050, there is a common perception that highly permeable catchments are likely to have different flood growth curves, perhaps showing greater skewness due to the occurrence of occasional floods that are many times higher than QMED, for example, during conditions in which the catchment acts more like an impermeable catchment. An example might be the flood of May 1920 at Louth in Lincolnshire, in which the reconstructed peak flow is thought to have been nearly 50 times QMED (Rodda and others, 1976). There do not seem to be many of these exceptional floods evident in the gauged period of record and so they may not be reflected in the sample L-moments. Some more recent research also supports the idea that BFIHOST is worth considering when refining pooling groups (Formetta and others, 2018). The

	research tested an alternative approach to constructing pooling groups, using flood seasonality in conjunction with just one catchment descriptor, BFIHOST. This procedure was found to provide a more accurate estimate of the growth curve than the current FEH method. Although the new method is not currently recommended for implementation, the findings might act as an encouragement to refine groups with the aim of making them more representative of the geology and soils of the subject catchment. However, the effect on the pooled growth curve is likely to be small.
7	A drawback of removing stations from the group is that any replacement stations will inevitably be less similar to the subject site, in terms of AREA, SAAR, FARL, and FPEXT, than those that were removed. An alternative is to accept a group smaller than the default size of 500 station-years. The uncertainty associated with pooling does not increase much until the number of years drops below 300. See Figure 6.3 in SC050050.

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.

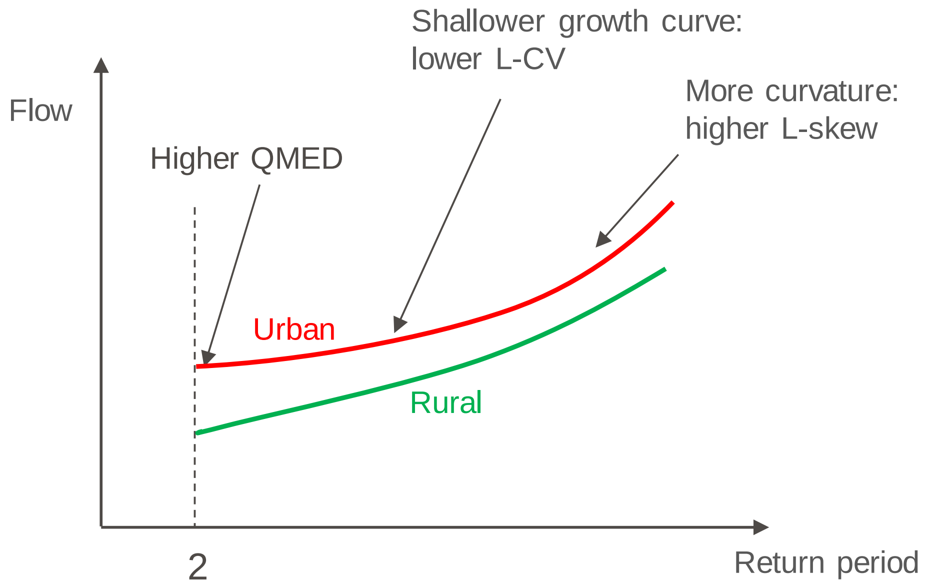
On average, the GL distribution is considered to perform better than the GEV for pooled growth curve derivation (**3** 7.3, 15.3 and 17.3.2). For some pooling groups, other distributions are found to fit better than the GL.

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

Item	Guideline or advice
1	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	Weights are calculated from record length 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, which differs from the original FEH method as implemented in WINFAP-FEH v1.
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 URBEXT2000 below the threshold of 0.030. There have been four versions of the urban adjustment for growth curves, although the fourth, used in WINFAP 4, is identical to the third but the equations are expressed in terms of URBAN rather than URBEXT2000 (Wallingford HydroSolutions, 2016a). So, the adjustment used in WINFAP 4 is essentially the same as that published by Kjeldsen (2010). The references are listed in Related documents. The Kjeldsen (2010) formulae for adjusting the L-moments are: $\text{L-CV}_{urban} = \text{L-CV}_{rural} \times 0.5547^{URBEXT2000}$ $\text{L-skew}_{urban} = ((\text{L-skew}_{rural}+1) \times 1.1545^{URBEXT2000}) - 1$ 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. See Figure 15. If you are carrying out calculations outside WINFAP-FEH, take care not to apply an urban adjustment to a single site growth curve.

Figure 15: Effect of urban adjustment on flood frequency 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 2T.

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.

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. You can find the details of the enhanced single-site method in Science Report SC050050.

WINFAP 4 allows users to apply enhanced single site analysis on urban catchments. The L-moments for the subject site are de-urbanised by applying the urban adjustment in reverse, before the pooling process. The pooled L-moments are then adjusted for urbanisation.

Guidelines

Item	Guideline or advice
1	The two basic approaches to improving on the extrapolation of single-site data are: • search for historic data (see below); • 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).
2	You should normally carry out an enhanced single-site analysis when deriving a growth curve for a site at or near a gauge with at least 8 years of good-quality flood peak data. Compare the resulting pooled growth curve with a frequency plot showing the annual maximum flows and a standard single-site growth curve. You need to make a reasoned decision about which growth curve is preferable.
3	Be aware that WINFAP will default to enhanced single-site analysis when you create a pooling group for a gauging station’s catchment descriptor (.cd3) file taken from the NRFA dataset, when the gauge is classed as suitable for pooling. If you create a .cd3 file by extracting the catchment descriptors from the FEH web service at the site of a gauge, the site will be treated as “ungauged” by WINFAP 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 does not report the relative weights used in enhanced single-site analysis.
4	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 effects of: • 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 AMAX data, but is a long way from the true underlying distribution (which we can never fully know). See the illustration in Figure 16. When AMAX flows are plotted on a frequency diagram, their position along the x axis direction is calculated from a plotting position equation. This uses only information on the ranks of the floods, and so can produce poor estimates of the return periods of the highest-ranking floods. 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.
5	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 1,000 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.
6	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

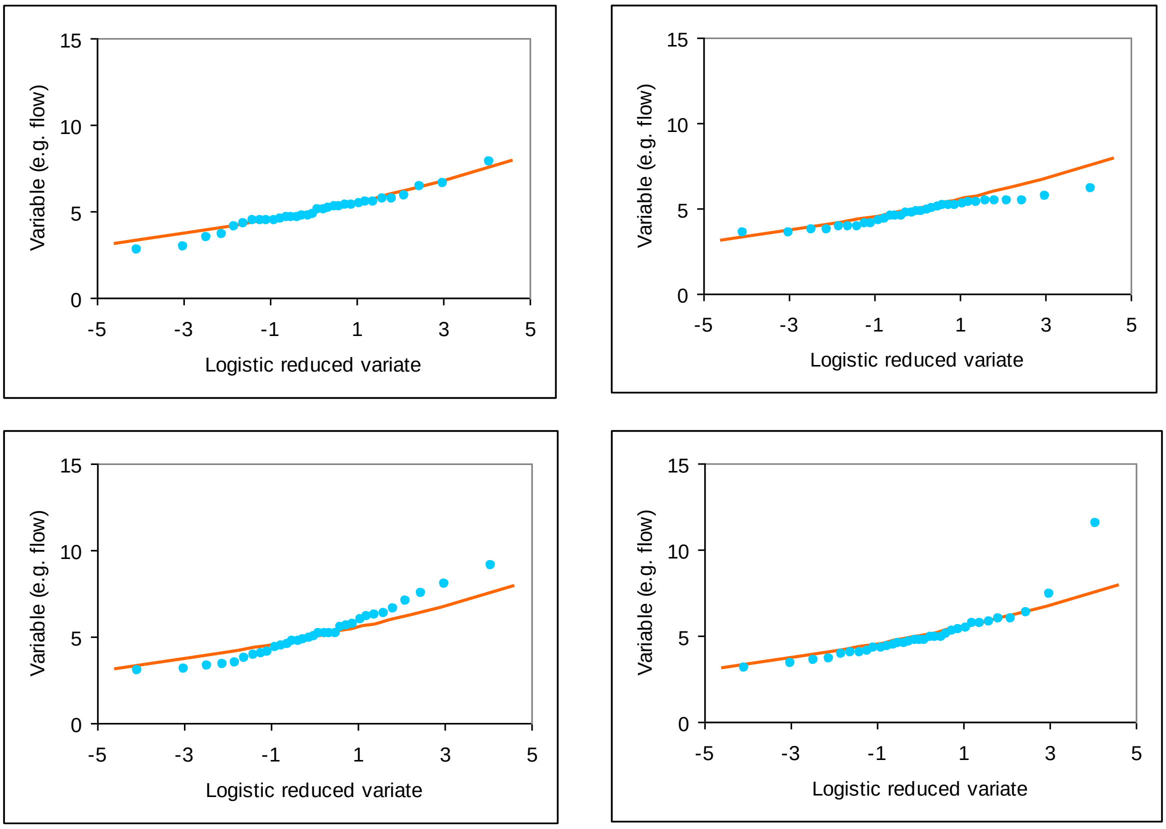
	should ensure a smooth variation in growth curve, choosing and applying the preferred growth curve(s) manually to all flow estimation points.

Figure 16: Should these curves fit the points?

This example illustrates how easy it can be to derive a single-site flood frequency curve that appears to fit the AMAX data, but is a long way from the true underlying distribution.

The graphs below show four plots of AMAX values of a variable (for example, river flow). Each plot has 33 years of data and 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, perhaps due to the gauged record covering an unusually flood-rich or flood-poor 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.

Growth curves incorporating historical flood data

Guidelines

Item	Guideline or advice

1	There are several ways of incorporating historical data formally into the frequency analysis. The choice of approach will depend on the type of information available. These methods can be applied in WINFAP 4 or other software. Refer to Technical Guidance 12_17 for more in-depth guidance and to Dixon and others (2017) for the scientific background to the guidance.
	
	The most favourable situation is when you are able to estimate peak flow rates for the historical floods. Use **Method 1a** in Technical Guidance 12_17.
	
	If you cannot estimate flow rates, use information on the impacts of the flood to develop a ranking and then apply **Method 1b** in Technical Guidance 12_17. Accounts in newspapers sometimes refer to the water level as being so many inches higher than a previous notable flood, or the highest since a given date. It is important to be able to identify a threshold flow from the gauged record, above which you are confident you have identified all historical floods in a given period of time.
	
	The information you need to apply these methods is:
	• Gauged annual maximum flows.
	• Either:
	    • flow rates for *k* historical flood events (method 1a) or
	    • evidence that *k* historical flood events have exceeded a threshold flow, X_0 (method 1b).
	• The length of the historical period represented by the events, *h*.
	• The threshold flow X_0 which is often named the perception threshold since it corresponds to the threshold above which a flood would have been large enough to be noted in historical sources or leave recognisable signs across the catchment.
	
	If the gauged flow record is shorter than 10 years and there is information available on a very large historic flood, you should not apply these quantitative methods because the resulting estimate is likely to be very biased. Use a qualitative approach (below) instead to learn from the information available on the historic floods.

2	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.
3	Consider how to reconcile the historic and pooled flood frequency curves. There are some ways you could consider for combining historical and pooled analysis, such as calculating the L-moments that correspond to the distribution parameters estimated from historical analysis and then including

	them in a pooled analysis, with a large weight given to the at-site data to reflect the long effective record length. A more informal approach would be to develop a weighted average of the historical and pooled flood growth curves.
4	Take particular care in cases when the historical flood data suggests that the preferred frequency curve is too high, because of the scope to overlook floods (Bayliss and Reed, 2001). The FEH suggests giving greater respect to historical flood data when they suggest that the preferred frequency curve may be too low.

4.4 Rainfall-runoff approaches

Topics in this section

This section provides guidance on flood estimation using rainfall-runoff models. The main focus is on applying such models for estimating a design flood event. It covers the FSR/FEH rainfall-runoff method, the ReFH1 method, released in 2006 and ReFH2, released in 2015 and updated in 2019 (ReFH2.3). Refer to the earlier advice on differences between ReFH1 and ReFH2 and how to choose between them. ReFH1 and ReFH2 use essentially the same rainfall-runoff model, referred to as the ReFH model.

Refer to FEH Supplementary Report No. 1 for details of the ReFH1 method. For information on the research, see Kjeldsen and others (2005). Refer to Wallingford HydroSolutions (2019a) for ReFH2. All these references are listed in Related documents.

The section starts with some general principles on the application of rainfall-runoff methods for simulating either observed or design floods. It then provides guidance and cautions on applying the methods. It explains the issues associated with the difference between lumped and distributed applications of the models. Finally, brief guidance on continuous simulation modelling is provided.

General principles

Design versus observed floods

The FSR/FEH and ReFH rainfall-runoff models can be used to simulate real or design floods. The difference between the two types of simulation is the inputs of the model.

For a real flood, use observed catchment-average rainfall and an initial condition that accounts for the antecedent weather conditions. In the ReFH model, this is controlled by Cini, the initial soil moisture

For a design flood, use the recommended combination of inputs, i.e. storm duration, depth, and temporal profile and initial soil moisture.

When applying these rainfall-runoff models, it is important to distinguish between:

- Model parameters, which represent an effectively fixed property of the catchment, such as its soil and geological composition. Cmax, the maximum soil moisture capacity, is an example of a parameter, as is the SPR in the FEH method. Parameters remain the same whether you are simulating a real or a design flood.

- Initial conditions, which can vary from day to day. Cini is an example, or CWI (catchment wetness index) in the FEH method. **Caution!** Initial conditions will differ between design and observed floods. A common mistake is to assume, often unintentionally, that the design Cini can be used for simulating a real flood.

Guidance on estimating parameters for rainfall-runoff methods

Item	Guideline or advice
1. First choice in ideal circumstances: All parameters from hydrometric data	Estimate the model parameters from hydrometric data when: • Suitable data are available near to the site of interest and • You judge that it is worth the effort and • Suitable hydrological expertise is available. Giving preference to local observations over generalised regression models is usually a wise move in hydrology. However, there are examples of practitioners ending up with very poor estimates of ReFH model parameters because they have made unwise decisions during the calibration process, such as putting too much trust in erroneous catchment rainfall values or flow data. Project managers: You should be aware that applications that involve estimation of parameters from observed data will take much more time than those that rely on catchment descriptors, and require suitably experienced and skilled staff. You can estimate the four parameters of the ReFH model using the ReFH2 Calibration Utility, a freely-available tool. The baseflow parameters are calculated by fitting recession curves to flow data. Cmax and Tp are calculated jointly by an optimisation method that requires catchment rainfall, flow, and evaporation data. The resulting parameters can be applied in either the original ReFH method or in ReFH2. The data needed are stream flow and catchment-average rainfall (usually at a time interval of 1 hour or 15 minutes) covering at least five floods (preferably more), plus daily rainfall and potential evaporation (PE), from the start of the year before the first flood event. Sources of PE data include the Met Office's MORECS or MOSES systems and CEH's CHESS (Climate, Hydrology and Ecology research Support System). You can obtain a quick estimate by assuming a sine curve for the seasonal variation of PE, in conjunction with a long-term mean value. However, this makes no allowance for unusual periods of weather during the calibration period. It takes some time to assemble the data needed, including calculating the catchment-average rainfall, getting it into the right format, loading it to the software and navigating the complex procedures for parameter estimation. There are tables of parameter values in reports on the development of ReFH and ReFH2 for a limited number of gauging stations. However, in the vicinity of most long-established flow gauges, the preferred method for peak flow estimation is likely to be the FEH Statistical approach. In this case, the role of ReFH2 might be limited to developing a

	hydrograph shape, or perhaps not even that if a characteristic shape is developed empirically from observed floods. Refer to FEH Volume 4 for guidance on estimating the parameters of the FSR/FEH rainfall-runoff model from hydrometric data.
2. Second choice: Time to peak from lag analysis	If there is no flow data or if time is short then you can estimate Tp from rainfall and river level data by lag analysis. When the ReFH model is being used primarily to provide a hydrograph shape, Tp will be the most influential parameter and so lag analysis is probably adequate as a method of parameter estimation. There has been no research into the relationship between lag time and Tp as defined in the ReFH model. Instead, FEH Volume 4 gives a formula for the time to peak of the instantaneous unit hydrograph: $Tp(0) = 0.879\ LAG^{0.951}$ Rather than using this equation directly to estimate Tp for the ReFH model, use it to derive an adjustment factor for Tp(0) by comparison with the estimated FEH model parameter, and then apply this factor to adjust the Tp parameter in ReFH. Refer to the row below for a complicating factor on urban catchments.
3. Third choice: Data transfer	The ReFH and ReFH2 research did not examine the value of data transfer for refining parameters. Faulkner and Barber (2009), listed in Related documents, have shown 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. 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. If the gauge measures water level only, an adjustment factor for the Tp parameter can be estimated by lag analysis (as above). **Caution!** Take care when comparing the catchment-descriptor estimates of the response time parameters Tp and BL with those estimated from hydrometric data if the catchment is urbanised. The parameters calculated by the ReFH2 software are for an as-rural catchment and so are not comparable with estimates from hydrometric data. One approach for handling Tp is to replicate the method used to develop the regression equation in ReFH2, multiplying the catchment-descriptor estimate by an urban component (see Table 2 in the ReFH2 report). The coefficient for the urban component is not given in the report. It is -3.36, i.e. multiply the as-rural Tp from the ReFH2 software by: $(1+URBEXT2000)^{-3.36}$ and then compare it with the observed Tp to calculate an adjustment factor.

4. Fourth choice – but sometimes the most sensible option: Catchment descriptors	Research (not yet published at the time of writing) has shown that there is limited loss of performance in the ReFH2 method when parameters are estimated solely from catchment descriptors. So, depending on the sensitivity of the study and the budget and time available, this may be a sensible approach. On ungauged watercourses this may be the only option available. When ReFH2 is being used to extend the growth curve, for example, by deriving a ratio of the 100-year to 1000-year flood, the results may be less sensitive to parameter choice, being influenced mainly by the gradient of the rainfall frequency curve.
5.Not generally recommended: combined hydrological and hydraulic calibration	A common way to calibrate the ReFH model is to do so in conjunction with a hydraulic model. This involves estimating parameters of rainfall-runoff models, usually for multiple sub-catchments by trial and error, trying to match observed flows or water levels at one or more points within the hydraulic model network. The approach might seem superficially attractive because it presents an opportunity to calibrate both the hydrological and hydraulic models. If the models can be shown to reproduce observed events well, so the argument goes, they can be expected to do well for design floods too. It allows for calibration of rainfall-runoff model parameters even at ungauged model inflows. Be aware of the following drawbacks to this approach: • Often the preferred method for estimating design flows is FEH Statistical, in which case the role of the ReFH model is to provide shapes for the design flood hydrographs. If you calibrate your hydraulic model using the combined hydrological-hydraulic approach, but then apply the model using design inflows generated from a different method, you can no longer be confident in the model calibration. For example, what if the rainfall-runoff model was predicting flows too large, so you over-compensated by setting Manning's n too small to match observed water levels? • The calibration method differs from that used to develop the ReFH and ReFH2 methods. • Trial and error is unlikely to identify parameters as accurately as other calibration methods, particularly given the large number of parameters (hydrological and hydraulic) that are available for adjustment. • The method can take a lot of time, particularly if it is applied within a 1D-2D model with long run times. Therefore, it is typically applied to a smaller number of floods; up to three floods is the number often specified in scopes for hydraulic model development. This is not enough to identify ReFH model parameters with confidence. On some watercourses, where flow and level are influenced by hydraulic factors such as backwater from tide locking, it may be the case that this combined hydrological and hydraulic model calibration approach is the only viable alternative to reliance on catchment descriptors.

<table>
<tr><th>Item</th><th>Guideline or advice</th></tr>
<tr><td>1. Design package</td><td>To estimate a design flood, it is necessary to provide the ReFH model with suitable inputs:
• Rainfall depth, including application of a seasonal correction factor (SCF) and areal reduction factor (ARF)
• Storm duration
• Storm temporal profile
• Initial soil moisture, Cini
• Initial baseflow BF0

You should consider these design event inputs as a complete package. The FEH, ReFH and ReFH2 rainfall-runoff methods were calibrated so that the recommended design inputs gave rise to an output hydrograph with a peak of the required return period. However, in some circumstances it can be wise to adjust some of the inputs, such as the storm duration. Refer to point 4 below.</td></tr>
<tr><td>2. Seasonality</td><td>You need to choose whether apply a winter or a summer storm. This choice affects the rainfall depth and profile, the initial soil moisture Cini and initial baseflow, BF_0.

Model versions ReFH2 to ReHF2.2 made no distinction between Cini for winter and summer seasons, but ReFH2.3 reintroduced a summer Cini following research by Stewart and others (2019). Although the research was motivated by a need to improve flood estimation on small catchments, this part of the analysis included data from larger catchments too and the recommendations are applicable to all catchment sizes. The guidance below is based on Stewart and others (2019) and WHS (2019a).

• If URBEXT2000 is ≥ 0.30,
• or if URBEXT2000 ≥ 0.15 and BFIHOST19 ≥ 0.65
  ○ then apply summer rainfall depths and Cini values along with either the 75% storm profile or 50% profile.
  ○ Analysis indicates that the 75% “winter” profile is marginally better despite the previous recommendations to adopt the more peaky 50% “summer” profile on urban catchments.
• In all other cases use winter storms.
In the FSR/FEH rainfall-runoff method, the choice of season affects only the storm profile and the relationship between flood and rainfall return periods.</td></tr>
<tr><td>3. Rainfall statistics</td><td>The ReFH2 method provides options to use either the original FEH99 rainfall frequency statistics or the replacement FEH 2013 statistics. You should use the FEH 2013 statistics in all circumstances unless you can justify reverting to the older data. The ReFH2 report recommends that FEH 2013 is preferred because it leads to good agreement with the enhanced single site estimates derived using the FEH Statistical method. Additionally, this method avoids the need to apply the physically unrealistic α correction factor necessary to reconcile the differing gradients of rainfall and flood growth curves when using FEH99 rainfall frequency statistics.</td></tr>
</table>

4. When to alter the defaults	In some situations, you should amend aspects of the design event. These include: • Storm duration - when generating inflows for a hydraulic model that covers a long section of watercourse, for a model of surface water flooding, or for reservoir routing. • Storm profile - the FEH storm 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). However, it is recommended to use alternative profiles when calculating design floods for reservoirs on large catchments. • Storm season – if local data indicate that the flood seasonality is different from the default (WHS, 2019a). • Initial soil moisture, Cini - when adjusting ReFH or ReFH2 outputs to achieve a match with results from another method. It is usually more logical to adjust Cini, which is part of the design event, than to adjust one of the model parameters.
5. Design floods from other rainfall-runoff models	Alternative rainfall-runoff models are occasionally used in conjunction with a design event approach in the UK, such as the NAM model in MIKE-11 or FRQSIM (used mainly in Greater London). FEH 2013 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. This would be far from straightforward.

When to apply ReFH2 with caution

Guidance

For estimating peak river flows in a typical catchment, often the results of the FEH Statistical method will be preferable. In some catchments with complex multiple influences on flood levels, continuous simulation might be a better choice. For developing a characteristic hydrograph shape, there are alternatives to ReFH2 such as empirical analysis of normalised hydrograph shapes from observed floods.

Exercise particular caution if considering ReFH2 in its current form (version 2.3) for:

- Large catchments. Design event methods that assume a storm covering the whole catchment are best avoided in such cases, and ReFH2 can overestimate, particularly where FPEXT is high. Usually peak flow data will be available on major rivers, favouring a statistical approach.
- Catchments where a significant flood attenuation effect is expected, unless applying ReFH2 to generate inflows for a hydraulic model that will route the flood hydrograph through the storage features. This is because the ReFH model takes no account of the presence of lakes, reservoirs or floodplains in a catchment.
- When designing flood storage or in other situations where project results are highly sensitive to volumes of flow. Take care to check the results of ReFH2 and considering the implications. These checks should include comparing volumes of both direct runoff and total flow with volumes of rainfall, and checking the duration over which the baseflow volume is calculated. Volumes for urban catchments should be treated with particular caution. ReFH2.3 has the ability to maintain a water balance,

which avoids some of the problems with runoff volumes, but checks are still worthwhile.

Earlier versions of ReFH2, and ReFH1, also have drawbacks on other catchment types, such as permeable catchments for ReFH1.

When hydrographs are required for catchments unsuitable for ReFH2, you may use the method to derive a hydrograph shape which could then be fitted to a peak derived by a more suitable method.

Software for applying the ReFH and ReFH2 methods

Modelling design floods

For ReFH2, use the ReFH2 software. The current version at the time of writing is ReFH2.3. The method is also implemented in hydraulic model and drainage design packages, but in every case, the package needs to run in conjunction with the ReFH2 software.

The ReFH2 unit in Flood Modeller Pro (version 4.4) has major limitations, providing little opportunity for the user to intervene. The user is unable to view or alter any model parameters or initial conditions. We recommend that it is best avoided in its current form.

ReFH2 is also implemented in InfoWorks ICM. This provides more flexibility than other implementations, including the ReFH2 software. ICM only implements the rural aspects of the ReFH2 method, which are used to model pervious areas. Users of the software are expected to use other methods for calculating and routing runoff from roofs, roads, etc.

For ReFH1, there are various options including the ReFH Spreadsheet. This was created by CEH for the Environment Agency, but it can no longer be downloaded from the CEH website. ReFH1 is also implemented in various hydraulic model packages.

Modelling real floods

Unlike earlier versions, ReFH2.3 can model real floods as well as design floods. Enter an observed rainfall event, with a sub-daily time step, and an antecedent daily rainfall series.

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 sub-catchment.

In practice, this decision is often dictated by the nature of the study. 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, set the storm duration 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 design event for ReFH1 and ReFH2.

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 sub-catchment. Using an individual design storm for each sub-catchment, with a duration set to the critical duration of the sub-catchment, 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 or sites by trial and error. This optimisation can be carried automatically in some packages. The critical duration is the one that gives the highest flow (or water level or storage pond volume) at the site of interest. For a model that covers a length of river, you may need to calculate separate critical durations for different flood risk areas.

When there is significant variability in rainfall patterns over a large area, you can derive the rainfall depth separately for each sub-catchment, 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 sub-catchment, beware that the ReFH model is being used well outside of its calibrated range. In some cases, it can overestimate flows as a result.

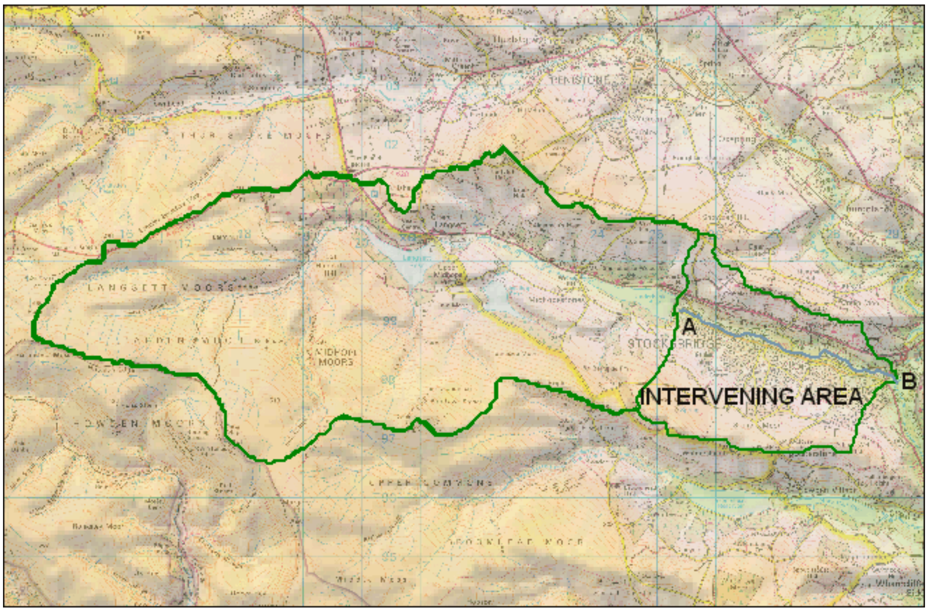
Guidelines

Item	Guideline or advice
1	A distributed approach is the natural choice for large or varied catchments and for those with floodplain or reservoir storage. However, 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 sub-catchments. All sub-catchments 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 sub-catchments, are usually treated as 'intervening areas' (see Figure 17).
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 17), or based on the descriptors of a significant watercourse within the intervening area. FEH **5** 7.2 gives advice on adjusting catchment descriptors. 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. Alternatively if the intervening area is less than 40km^2, you can estimate the ReFH2 model parameters from the “plot-scale” equations which use AREA in place of DPLBAR.

5	Estimate hydrographs for intervening areas by applying FEH methods to the derived catchment descriptors, as you would for any other sub-catchment. However, intervening areas are not real catchments, so the FEH methods are not strictly applicable to them. For this reason, the number of intervening areas should be 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. Subtract the upstream hydrograph 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 is 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 is important to check whether the reservoir can attenuate flood flows to such an extent that the site is more sensitive to heavy rainfall concentrated on the intervening area downstream of the reservoir than it is to a longer storm over the whole catchment.
8	The approach taken in the FEH and ReFH methods makes an assumption of complete dependence between rainfall amounts in different parts of the catchment. This is an increasingly unrealistic assumption for larger catchments.

Figure 17: Intervening area

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.



Continuous simulation - an alternative rainfall-runoff approach

Description

Continuous simulation of flows offers an alternative to design event methods such as ReFH2. The idea is run a long series of rainfall through a suitable rainfall-runoff model to produce a long flow series. Short simulations can use observed rainfall data but to estimate long return period floods it is usually necessary to produce simulated rainfall.

You can then rank the peaks of the flow series and analyse them to obtain design flows of the required return period. Alternatively, run the flow series, or a selection of events, through a river model and then rank the resulting water levels separately at each node to estimate the flood level for the required return period.

Advantages

Continuous simulation can be an attractive approach on complex catchments where flooding is affected by multiple influences. A simulation covering a period of several thousand years can be expected to include a rich variety of flood types, including those with high peaks, high volumes, multiple peaks and sequences of events.

Continuous simulation avoids the need to make difficult decisions and compromises over the types of flood to which different parts of the catchment are sensitive and how these might change as a result of alterations in the catchment. It can provide increased confidence by avoiding or mitigating unrealistic assumptions. It permits a more coherent, multivariate and probabilistic view of the flood hazard in comparison to using conventional hydrological frequency analysis methods.

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

Drawbacks

Continuous simulation modelling costs more and takes longer than other hydrological methods. It is usually necessary to calibrate a stochastic rainfall model for the catchment and rainfall-runoff models for each significant sub-catchment. Unless the catchment is small, the rainfall model needs to account for the spatial coherence of rainfall across the catchment. It may also be necessary to account for dependence between rainfall and other relevant input variables such as tide level or snowmelt.

Another typical requirement is a fast-running model of the river system, which can route the simulated flood hydrographs from potentially thousands of events through the channel, floodplains and any storage features such as reservoirs.

CS requires calibration data for both the rainfall and the rainfall-runoff models. The ideal requirement is a flow gauge towards the downstream end of each main tributary.

Tools and expertise for applying CS modelling are not widespread. Some companies have in-house software, but commercial software (that implements all steps of the process) is not available. One challenge is how to handle the large amounts of data that is generated, and how to select appropriate events for simulation in the river model without compromising on the aspiration to represent flood-generating conditions in all parts of the catchment.

Research and application

A research project developed methods of estimating continuous rainfall-runoff model parameters from catchment properties or by transfer from similar gauged catchments. See Calver and others (2005), listed in Related documents. However the findings have not yet been implemented.

Continuous simulation has been applied in practice 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. Four case studies of continuous simulation application in the UK are described by Lamb and others (2016).

5 Assumptions, limitations and uncertainty

5.1 Overview – common criticisms

Two common criticisms

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

- fail to acknowledge the assumptions and limitations of the methods used;
- 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 a way to choose an answer that suits their prejudices or their pockets.

The reasons why results may exhibit a certain level of uncertainty tend to be similar for many studies. For this reason, many may consider it pointless to list them. Additionally, many analysts would probably have difficulty identifying and describing all the assumptions that they implicitly rely on.

Why bother with uncertainty?

Does uncertainty matter?

While it is obvious to most hydrologists that their flood estimates are uncertain, there may be some 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 during the subsequent process of making decisions.

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, when there is too much uncertainty in a flood estimate, it may be wise to recommend that a proposed development is refused permission, because there's not enough information on its consequences, or at the very least, recommend that the uncertainty is managed by setting floor levels with an adequate freeboard. This is in line with the precautionary principle.

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.
For 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 and bias.

It also provides useful information for anyone reviewing the calculations and future users of the report.

For this reason, we require a section describing limitations in hydrological studies and hydraulic models as part of all reports produced.

5.2 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;
- can be tested;
- 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 1000-year growth factors are best estimated from a rainfall-runoff approach, given that the confidence is greater in rainfall growth curves thah in flood growth curves for longer return periods.

5.3 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 summarises the validity ranges for selected methods, based on information in the FEH 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	None	No limit if using current urban adjustment,	Each method has various types of catchment for

	applied up to 1000 years)		but other methods may be better when most flow is via sewer network	which it is not ideal – see Choosing between the FEH methods
ReFH (largely superseded by ReFH2)	Up to 150 years	Not suitable for very large catchments	Only reliable in its original form for URBEXT1990 <0.125	
ReFH2	Up to 1,000 years	Not suitable for very large catchments	No limit but other methods may be better when most flow is via sewer network	
FEH 2013 rainfall frequency	2 – 10,000 years	n/a	n/a	Durations 1 hour to 8 days

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

Guidelines

Item	Guideline or advice
1	**! Important** You should choose methods by following the guidance in Chapter 3, 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.

5.4 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 60 years in length.

- data uncertainty from the measurement of flood flows.
- model structure uncertainty from the choice of model, whether this is a hydrological model or a statistical model such as a flood frequency distribution.
- model parameter uncertainty stemming from the selection of parameters for a growth curve or a rainfall-runoff model.

Rather than just acknowledging that your results are uncertain, you should try to quantify the uncertainty and identify the main sources. This may help define any further work needed to reduce the uncertainty.

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. For instance, you might 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. If you want a higher level of confidence, such as 99%, then you need to use a wider range.

Refer to the guidance below on how to quantify uncertainty for the various FEH methods.

Confidence intervals for FEH statistical method at ungauged sites

It is possible to quantify uncertainty in the results of the FEH Statistical method in some standard situations. The confidence limits presented below express the natural and model parameter uncertainty. They do not include model structure uncertainty as they assume that annual maximum flows follow a Generalised Logistic distribution. As the confidence limits are estimated from gauged data, they do not allow for any bias due to climatic variability, and reflect the prevailing climate of the periods during which the data were gauged.

Also excluded is any bias associated with measurement of river flows during flood conditions. This bias could be significant if you use data mainly from a single site in your analysis, so it is important to understand the limitations of flow measurement and rating curves in flood conditions.

You can find confidence intervals for design flows at ungauged sites in the tables below. Table 4 is for rural catchments (URBEXT2000<0.03) and Table 5 is for moderately urbanised catchments ($0.03 \leq URBEXT_{2000} < 0.15$). Confidence intervals for heavily urbanised catchments are not provided because there are not enough suitable catchments with flood peak data to provide reliable statistics.

There are results for three situations, corresponding to the use of zero, one and six donor sites for adjusting QMED. The results were derived assuming that donor sites are chosen purely on the basis of geographical proximity.

The tables include results for two levels of confidence, 68% and 95%. These percentiles are chosen because they are calculated from the factorial standard error (FSE). The standard error is a measure of uncertainty in an estimate based on the data in a sample.

The results are presented as factors by which the estimated design flow should be multiplied to obtain confidence intervals. For example, for the 100-year flood on a rural catchment estimated using one donor:

- the lower 68% confidence limit is 0.69 times the best estimate;
- the upper 68% confidence limit is 1.46 times the best estimate.

For more information on the derivation and interpretation of these confidence intervals, refer to Technical Guidance 12_17 and the supporting science report, Dixon et al. (2017).

The amount of uncertainty shown in these tables 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 in comparison to the values at the upper and lower confidence limits.

Table 4: Confidence intervals for design flows at an ungauged site (rural only)

Return period (years)	No donor		One donor		Six donors	
Confidence level	68%	95%	68%	95%	68%	95%
2	0.69-1.45	0.48-2.10	0.70-1.42	0.50-2.02	0.71-1.40	0.51-1.97
5	0.68-1.46	0.47-2.13	0.70-1.43	0.49-2.04	0.71-1.41	0.50-1.98
10	0.68-1.47	0.46-2.15	0.70-1.43	0.49-2.05	0.71-1.41	0.50-1.99
20	0.68-1.47	0.46-2.17	0.69-1.44	0.48-2.07	0.71-1.42	0.50-2.01
50	0.67-1.48	0.45-2.20	0.69-1.45	0.48-2.10	0.70-1.43	0.49-2.03
100	0.67-1.49	0.45-2.23	0.69-1.46	0.47-2.12	0.70-1.43	0.49-2.05
200	0.67-1.50	0.44-2.25	0.68-1.47	0.47-2.15	0.69-1.44	0.48-2.08
500	0.66-1.51	0.44-2.29	0.68-1.48	0.46-2.19	0.69-1.46	0.47-2.12
1000	0.66-1.53	0.43-2.33	0.67-1.49	0.45-2.23	0.68-1.47	0.46-2.16

Table 5: Confidence intervals for design flows at an ungauged site (moderately urbanised)

Return period (years)	No donor		One donor		Six donors	
Confidence level	68%	95%	68%	95%	68%	95%
2	0.63-1.59	0.39-2.54	0.63-1.58	0.40-2.51	0.63-1.59	0.40-2.53
5	0.61-1.64	0.37-2.68	0.62-1.62	0.38-2.64	0.61-1.63	0.38-2.65
10	0.60-1.66	0.36-2.75	0.61-1.64	0.37-2.70	0.61-1.64	0.37-2.70
20	0.60-1.68	0.36-2.82	0.60-1.66	0.36-2.76	0.60-1.66	0.36-2.75
50	0.59-1.71	0.34-2.91	0.59-1.69	0.35-2.85	0.59-1.68	0.35-2.83
100	0.58-1.73	0.33-3.01	0.58-1.72	0.34-2.94	0.59-1.71	0.34-2.91
200	0.57-1.77	0.32-3.13	0.57-1.75	0.33-3.06	0.58-1.74	0.33-3.02
500	0.55-1.82	0.30-3.33	0.55-1.80	0.31-3.26	0.56-1.79	0.31-3.20

1000	0.53-1.88	0.28-3.52	0.54-1.86	0.29-3.45	0.54-1.84	0.30-3.38

Confidence intervals for FEH statistical method at gauged sites

Because of the number of options, there is not a straightforward way of quantifying uncertainty in design flows at gauged sites for all circumstances. In general, you can expect the uncertainty to be lower than that for an ungauged site. However, there are two parts of the procedure for which you can currently quantify uncertainty:

- estimating QMED: use Table 12.4 in FEH Volume 3.
- estimating a single-site flood growth curve: use the resampling method in WINFAP.

Refer to Technical Guidance 12_17 for more information.

There is no straightforward way of quantifying confidence intervals for an enhanced single-site growth curve.

Confidence intervals for ReFH/ReFH2

It is more difficult to quantify uncertainty in design flows estimated from the ReFH rainfall-runoff model. One approach, which has not yet been achieved, would be to combine the uncertainty in the rainfall frequency statistics with the uncertainty due to the estimation of rainfall-runoff model parameters and that due to the composition of the design event package. Refer to Dixon and others (2017) for a fuller discussion of the issues.

Wallingford HydroSolutions (2019c) evaluates the performance of ReFH2 by comparing its results with those from an enhanced single-site analysis at gauging stations. The factorial standard errors from ReFH2 are comparable to those observed for the FEH pooled statistical method when the catchment is treated as ungauged.

6 Application-specific guidance

In this chapter

This chapter provides an overview of issues that an analyst should consider when assessing how to approach flood estimation in a specific application or catchment type.

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

6.1 Catchment-wide studies and hydrodynamic models

Hydrodynamic models

Most of the Environment Agency's hydraulic models of rivers are hydrodynamic. This means that they represent how flow varies with time. These models require inflow hydrographs, as opposed to steady-state models that need only peak flow values.

The issue: striking a balance

Hydrodynamic 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 hydrodynamic 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
For 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

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 hydraulic model. At each point of interest in the model, it is necessary to decide how to strike the balance described above. **Caution!** A common error is failure to check the peak flows within a hydraulic model against those estimated in the hydrological study.

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 such thing as a 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). Despite this, project scopes usually call for modelling of a design flood throughout the length of a hydrodynamic model. The longer the length of river covered by a hydrodynamic river model, the bigger the challenge. This is due to the need to reconcile flows or levels within the model domain with those estimated from the flood frequency analysis. This process can become complex and frustrating, involving uncomfortable compromises along the route due to the fact that a catchment-wide design flood event is ultimately not achievable. One way around this is to limit the length of model reaches.
4	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, you will also need to ensure that for each site of interest, you apply a uniform storm duration and areal reduction factor across all sub-catchments.

Combined model calibration

Some studies use a combined rainfall-runoff and river model to help to derive parameters for the ReFH 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 river model. Refer to the section on ReFH calibration for advice on the drawbacks of this approach.

Additional factor: spatial consistency

FEH methods are intended for application at particular (subject) sites because they are calibrated against flood data at particular (gauged) sites. They are not guaranteed to give spatially consistent results if applied to multiple sites along a river system. Additional inconsistency can be introduced by applying donor sites. See Figure 18.

There are some additional factors to consider in larger scale studies. The most important is spatial consistency. A report on automation of the statistical method addressed this; see Morris (2003). It suggests some rules for spatial consistency, including:

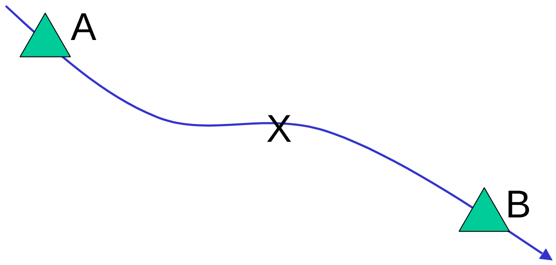
- sudden increases in flood estimates should only occur at confluences;
- flood estimates should not decrease in the downstream direction unless there are clearly defined physical causes (such as floodplain attenuation);

- 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.

Figure 18: Donor sites and spatial consistency

In the map below, if donor A is used to adjust QMED for all points upstream of X and donor B used for points 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.



6.2 Direct rainfall modelling

Overview of the issues

An approach to rainfall-runoff modelling that became popular after the widespread adoption of 2D hydraulic models is “direct rainfall” or “blanket rainfall” modelling, where rainfall is applied to the hydraulic model grid. The flood water is then routed overland using the shallow water equations.

This is widely used for the mapping of surface water flooding. It is sometimes regarded as a preferred approach for fluvial flood estimation on lowland catchments where the concept of flow estimation at a point on a watercourse can be difficult to apply, and contributing areas may be unclear. It has also been used to assess the effectiveness of natural flood management measures which are often small-scale distributed measures in the landscape.

Direct rainfall can appear enticing to hydraulic modellers and project managers, some of whom have a notion that it replaces the requirement for the development of hydrological models, and so reduces project costs and durations (Hall, 2015).

Another attraction in comparison with lumped rainfall-runoff models such as the FEH or ReFH models is that direct rainfall modelling allows detailed spatial variation of the rainfall input and, potentially, the loss rate. A distributed modelling approach offer the potential to represent dynamic interactions between tributaries as a result of proposed risk reduction measures.

However, direct rainfall models are often applied uncritically, apparently without considering whether they adequately represent hydrological processes and whether they can be justified empirically by comparison with flow measurements. Some modellers may not understand that there are other distributed hydrological models that may be preferable.

There are several major issues and questions regarding direct rainfall models, including:

- Does overland routing of flow adequately represent the processes by which river flow is generated?
- How are losses modelled?
- How is the double counting of depression storage avoided?
- How sensitive are the results to the grid size and parameters of the 2D model?
- How has the distributed hydraulic roughness parameter set been developed and does the channel have a realistic value? Use of land-cover land-use data to set distributed roughness can result in large errors (Medeiros and others, 2012), which might be improved with at least some ground-truthing.
- How are watercourse channels represented in the model grid? For example is LiDAR data assumed to represent channels, or is it necessary to add in ground-based survey cross-sections?
- How is baseflow modelled? Can some of the water lost to the model domain when calculating runoff be re-introduced (for example by adding an internal inflow boundary along the river reach)?
- Can you be confident that a rainfall depth for a given return period will generate a flood depth or extent of the same return period?
- What evidence is there that direct rainfall modelling generates river flow that matches observed events at gauging stations?
- For ungauged catchments, is the direct runoff response similar to that predicted by ReFH for a range of probabilities?

Some of these issues are explored below.

Analysts: When contemplating or reviewing direct rainfall modelling, first develop an understanding of the issues described in this section. Take great care with the method statement, considering whether the proposed modelling approach represents the physical processes that control the type of flooding you are trying to model.

Major assumption: overland flow routing

Direct rainfall modelling avoids using a unit hydrograph. It generally models flow over the surface of the ground only. Some models allow for infiltration, but the infiltrated water is generally lost from the model domain. Overland flow is a valid way of representing inundation of floodplain areas (the purpose for which these models were originally designed), but not necessarily a good representation of the way runoff is generated across a catchment.

Important! This assumption that runoff finds its way overland into a river is rarely correct in most UK catchments outside heavily urbanised areas. In temperate climates, most rapid runoff occurs via flow through shallow soil layers rather than overland. Indeed, tracer tests have shown that in some catchments, nearly all the water that enters the river following a storm is “old water” that has been stored in the soil and is displaced by piston flow as new water infiltrates further up the hillslope.

There are many distributed or semi-distributed hydrological models that represent subsurface flow routes in addition to overland flow. These can improve representation of processes such as interaction between surface and sub-surface flows, or re-infiltration of saturation excess overland flow further downslope, and can be integrated into 1D or 2D models. Refer to Hankin and others (2016) for guidance on the suitability of different models, such as Dynamic TOPMODEL, SWAT and Mike SHE.

Calculating losses: two approaches

In direct rainfall modelling, it is necessary to allow for losses, such as interception or infiltration. There are two basic approaches to this:

1. Pre-calculation of losses, leading to a "net rainfall" grid which represents runoff depths across the catchment. The losses can be calculated using a variety of methods including fixed percentage runoff, initial and continuing loss rates, or using the loss components of rainfall-runoff models such as ReFH.
2. Use of infiltration equations to calculate losses dynamically within the hydraulic model code. Examples are the Horton or Green & Ampt equations.

Commercial flood modelling packages such as Flood Modeller Pro, TUFLOW, InfoWorks ICM and a forthcoming release of HEC-RAS offer various of the options mentioned above for calculating losses. In general, they do not provide evidence to support the applicability of the methods that they implement. The onus is on the modeller to justify the approach he or she chooses.

Both of the basic approaches listed above have advantages and disadvantages.

Approach 1 has an advantage over more physically-based techniques of calculating runoff (or infiltration), in that rainfall-runoff models such as ReFH are designed and calibrated from well-established datasets (rainfall, river flow and potential evaporation). No equivalent datasets, with national coverage, are available for parameters such as infiltration or surface runoff, which are generally measured over small scales and short durations at experimental sites or in the laboratory.

A drawback of Approach 1 is that the definition of runoff used in the ReFH model, and other conceptual models, depends on the way the fluvial flood hydrograph is separated into baseflow and quick flow, and does not have any direct physical interpretation.

An assumption associated with Approach 1 is that all the net rainfall will find its way across the digital terrain model and into the river system, with no water being held back in depressions. This assumption is unlikely to be correct. Extra losses will occur due to depression storage in the model grid or mesh, and so you can expect some double-counting of losses. The amount of depression storage can depend critically on the grid resolution (Figure 19 shows an example). For further guidance on this issue, refer to Engineers Australia (2012). The approach can be improved with wetting-up of the model grid or potentially infilling depressions, although that is not desirable when trying to understand flow accumulation.

Approach 2 generally involves the application of idealised equations that apply at a specific point and take no account of the heterogeneous nature of soils. In reality, features such as macropores, fissures, and field drainage can account for a large proportion of runoff generation. There is little information available on which parameter values to apply in infiltration equations at a catchment scale and how to estimate them from soil mapping data.

On the other hand, infiltration equations allow for continued infiltration after the rainfall ceases and they represent the greater infiltration that can be expected where water is ponded (Caddis and others, 2008). They avoid relying on the assumption mentioned above under Approach 1.

The way in which losses are represented may need to depend on the primary purpose of the modelling, with different considerations applying for surface water and fluvial modelling.

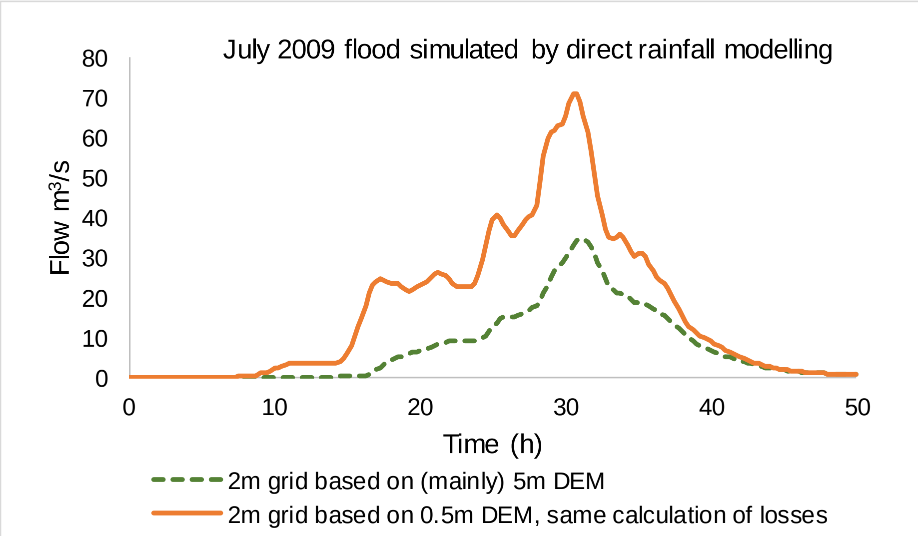
Figure 19: Sensitivity of

The graph shows two hydrographs simulated by direct rainfall modelling on a 37km^2 catchment in the northern Pennines. Both the volume of runoff and

predicted runoff volume to grid resolution

the peak flow change by a factor of two depending on the source of terrain data used by the model. High-resolution 0.5m LIDAR data, resampled to a 1m grid, identifies many more connections and flow paths, leading to a large decrease in depression storage.

The findings highlight the critical dependence of process representation on model scale.



Direct rainfall for fluvial flood modelling: baseflow and combined probability

As well as the above issues, you also need to work out how to calculate baseflow when using direct rainfall to represent fluvial flooding. One approach would be to use ReFH2 to calculate baseflow and add it to the river channel at the upstream end of the hydraulic model reach. Potential issues include:

- The need to keep baseflow topped up as the catchment size increases along the model reach;
- The fact that, as mentioned above, the definition of runoff and baseflow in the ReFH model does not have any direct physical interpretation. However, you may decide this is less of an issue if you have also used ReFH to calculate the net rainfall.

Some projects combine direct rainfall models on some sub-catchments with conventional rainfall-runoff models elsewhere. For instance, urban or low-lying sub-catchments may be represented using direct rainfall. You need to think about how to combine the inputs from the different models to give an output of the required probability / return period. One approach would be to apply a consistent design rainfall hyetograph as the input to both the direct rainfall and the conventional models.

Direct rainfall for surface water flood modelling

Surface water flooding is a difficult phenomenon to model convincingly apart from on paved surfaces. The volume of runoff during a storm, and the route it takes, depend on detailed local features of both the surface and subsurface, which are not feasible to represent in a model. There is little systematic measurement of runoff before it is concentrated in watercourses, so it is difficult to validate predictions of runoff rates.

Direct rainfall modelling is a natural choice for representing surface water flooding. Think carefully about the best approach to calculate losses. If you choose Approach 1 (above), you are likely to end up applying a model that has been calibrated from river flow data. There may be an implicit assumption that the quick flow component of the river flood hydrograph predicted by the rainfall-runoff model is generated from overland flow which causes surface water flooding as it finds its way to the river. As mentioned above, this is unlikely to be correct.

When to consider direct rainfall modelling

In light of the issues discussed above, on fluvial flood studies, avoid direct rainfall modelling using the shallow water equations as much as possible. However, it is sometimes worth considering for:

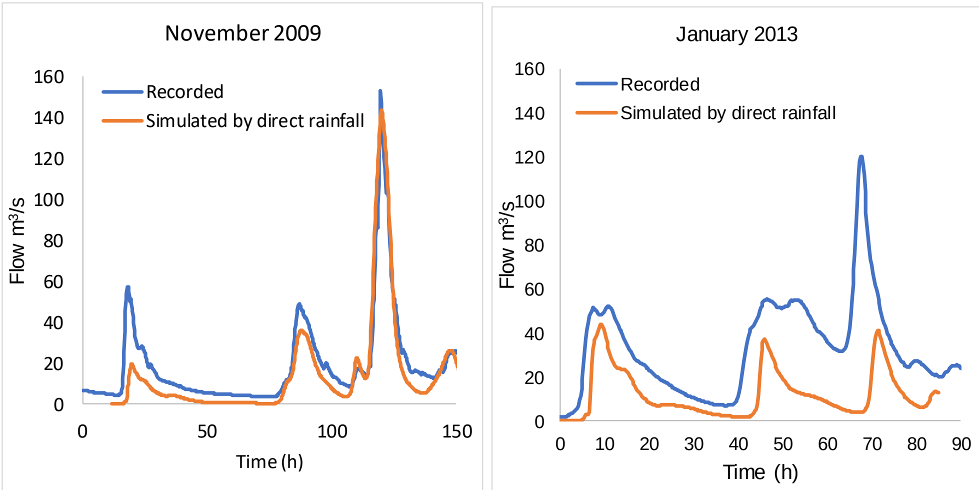
- Heavily urbanised areas where most runoff will be overland on paved surfaces. Allow for the influence of the storm drainage systems and culverts. Compare the resulting flow hydrographs with those estimated using FEH methods.
- Lowland areas where there is permanent standing water or near-saturated soils, so that most runoff will occur on the ground surface. Again, compare the results with those from FEH methods intended for lowland catchments. Be careful not to double-count the depression storage.
- Mixed catchments in which some sub-catchments are either heavily urbanised or low-lying. Use standard hydrological approaches for the rest of the catchment and assess the joint probability of the various model inputs before combining them.
- Gauged catchments, where you can check that the model is matching observed flood hydrographs over a variety of recorded events.

In all cases, test the sensitivity of the modelled water levels or flood extents to the design storm duration. You may need to run a variety of durations and merge the results.

Figure 20: Comparing direct rainfall predictions with recorded flows

The pair of graphs below compare observed flood hydrographs with those simulated from a direct rainfall model. This is for a 170 km^2 catchment in the Northern Pennines. Losses were calculated using the ReFH rainfall-runoff model, with the initial soil moisture, Cini, set based on antecedent rainfall and potential evaporation data.

The direct rainfall model shows a good fit for the highest peak in the Nov 2009 flood. It shows a general tendency to underestimate the flow volume, probably due to water being stored in depressions within the model grid. The Jan 2013 peak flow is underestimated by a factor of three. This highly WEM variable calibration performance indicates the unpredictable performance of direct rainfall models and the importance of calibration.



6.3 Joint probability and multivariate analysis

The issues

Joint probability problems occur frequently in flood management because flood hazard is often affected by more than one variable. For example:

- A location might flood from an event that combines a large volume of flood water (which fills up a floodplain or reservoir) and a high peak flow.
- In the vicinity of a confluence, water levels may be affected by flows on both rivers.
- Upstream of a flapped outfall, the peak flood level will depend on the duration for which the flap is closed and the volume of water that accumulates upstream of the outfall over this period.
- On tidal reaches of rivers, water levels are influenced by a combination of river flow and tide level.
- A road or railway line might be closed due to flood conditions on any one of a number of rivers that are crossed.

Refer to Figure 21 for a real-world example.

In all these examples, the influencing variables are unlikely to be completely independent, and nor will they be completely dependent. This partial dependence introduces some difficulty with the solution of joint probability problems. Approaches to solving such problems include:

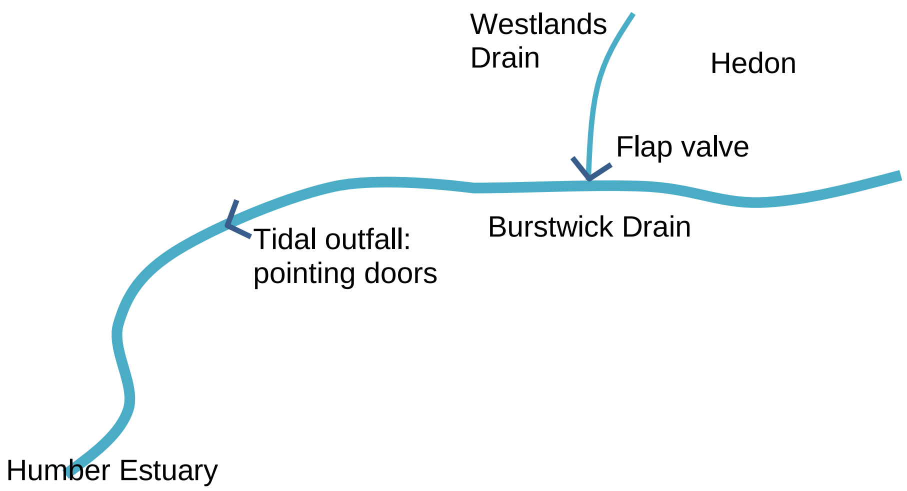
- If there is a long record of the “output variable” (the quantity of interest such as water level at a site of flood risk), there may be no need to analyse the causal variables. A frequency analysis of the “output variable” may be sufficient. However, there could be a risk that the period of record does not include any critical combinations of the input variable which could lead to unusually extreme values for the output variable.
- A hydrological and/or hydraulic model could be used to continuously simulate the output variable, based on either long-term observed or stochastically generated records of the input variables. The stochastic model(s) would need to account for the dependence of the input variables. Refer to Continuous simulation.
- Statistical methods can analyse the characteristics of the input variables and their relationships with each other, producing outputs such as combinations of return periods of the input variables that will yield a given return period of the output variable (See below).

Figure 21: Example joint probability problem: flood risk in Hedon, East Yorkshire

Burstwick Drain flows into the Humber Estuary. Pointing doors open to allow the drain to discharge during low tides. Westlands Drain is a tributary, which discharges into Burstwick Drain via a flap valve.

This means that flood levels on Westlands Drain are affected by:

- The volume and rate of runoff over the catchment of Westlands Drain;
- The amount of storage available within the drain and a connected flood storage area;
- The duration of closure of the flap valve, which depends on the relative water levels on Westlands Drain and Burstwick Drain. The level of Burstwick Drain depends on:
    - The volume and rate of runoff over the catchment of Burstwick Drain;
    - The hydraulic characteristics of the drain, largely its volume;
    - The duration of closure of the tidal outfall, which depends on the relative water levels upstream and downstream of the outfall. The downstream level depends on:
        - Astronomical tides;
        - Surge tides.



A flood study of Burstwick Drain used continuous simulation modelling in an attempt to resolve some of the joint probability issues, although tide levels were not included in the simulation.

Complicating factors

There are several complicating factors associated with joint probability analysis. One is the possibility that the dependence between the input variables can **change with their magnitude.** For example, day to day river flows and sea levels may be fairly independent (sea levels being influenced mainly by astronomic tides) and yet in extreme conditions they could be much more dependent (tidal surges being caused by atmospheric depressions which also bring rainfall and hence flood flows).

It is also important to consider **timing effects**, such as the duration over which the input variables can be extreme. For example, on a large slowly-responding river, a flood could last for days or weeks, and so have a higher probability of coinciding with an extreme tide compared to a flood on a rapidly responding urban catchment.

Another consideration is that the dominance of the various input variables can **change with location**. For example, in an estuary, water levels are likely to be influenced mainly by the tide at the seaward end and mainly by river flows further upstream. It is often necessary to investigate a number of combinations of the input variables, each combination having the same joint return period. This allows you to find which combination gives the critical condition, such as the highest water level, in which location.

Multivariate statistical analysis

There are many methods that have been developed for joint probability analysis. Some of these are applied in research and are not necessarily easily accessible to practitioners in flood risk management.

Practitioner guidance published by Defra as part of project FD2308 in 2005 (Hawkes, 2005) provided a few methods including the "desk study approach", a spreadsheet which requires as input high and extreme values of two input variables, together with a simple measure of the dependence between them, denoted using the variable χ. A companion technical report, Hawkes and Svensson (2005) explains how to calculate the dependence measure χ from hydrometric data.

More recent research has applied a more sophisticated statistical model of joint probability, known as the Heffernan and Tawn model. Reports on Science Project SC060088 (Keef and others, 2011) explain why the model was chosen.

The Heffernan and Tawn model uses two parameters per variable to express the dependence between two (or more) variables. One of the parameters represents how the dependence changes with the magnitude of the variables. The model can be used to represent any combination of environmental variables. In contrast, the FD2308 uses a single parameter (χ) for a pair of variables.

The model has been used widely in recent years to create "event sets": spatially consistent scenarios of flooding across large areas, which are of interest to the reinsurance and emergency planning sectors (see Towe and others, 2018). It can also be used to set inflows to river models, for example, at confluences.

Like the χ dependence measure, you can apply the Heffernan and Tawn model where there are observations of the input variables, covering an overlapping period. You can implement it using the Multivariate Event Modeller, outlined below.

Multivariate Event Modeller

The Multivariate Event Modeller (MEM) tool implements the Heffernan & Tawn model with user-supplied data sets to estimate the joint probability of extreme events with combinations of up to ten variables. Refer to the user guide produced for project SC140002 by Hunter and others (2018).

The MEM tool is aimed at those interested in joint probability assessment, including hydrologists, hydraulic modellers and coastal engineers. It can be used to:

- Understand and view the relationships between the largest values of a combination of variables in space and time.
- Calculate the dependence parameter, χ, for a pair of variables, which can then be used in the joint probability desk study spreadsheet
- Find the probability of an observed or hypothetical extreme event at multiple locations and/or in multiple variables.

Figure 22 shows an example of the outputs.

The input variables can represent any concurrently sampled quantities, including river flow, river level, rainfall, wind speed or tide surge. The data needs to be at a daily time step, with no missing periods. Either daily mean or daily maximum values can be analysed.

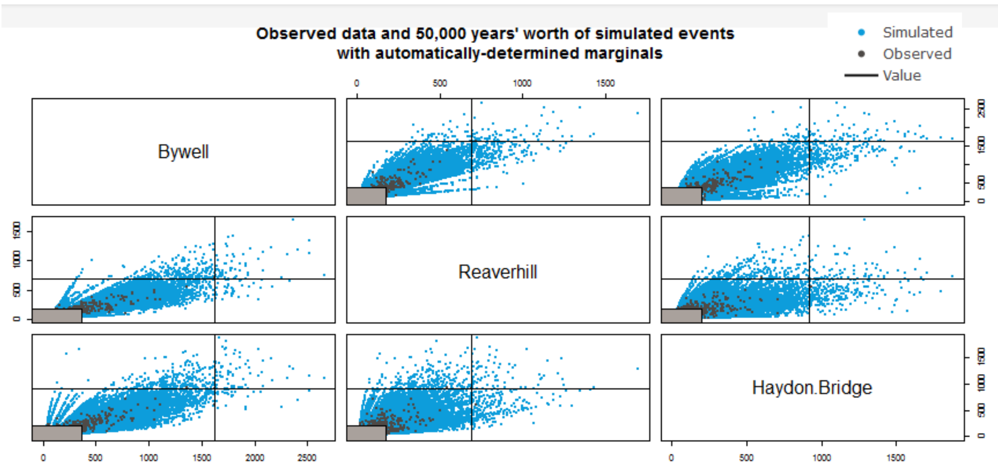
The MEM can automatically fit a statistical distribution for the annual exceedance probabilities in each variable (a "marginal distribution"), using a Generalised Pareto Distribution (GPD) fitted to POT data. However, another option is to import a distribution. This enables the joint probability analysis to incorporate flood frequency curves derived using FEH methods. **Caution!** The decision about whether to choose the distribution fitted by the MEM or to import an FEH distribution can have a major effect on the results. FEH distributions can incorporate pooled information, which may make them more robust, but even a single-site analysis of the same record using a GPD fitted to POT data can produce very different results from an FEH curve fitted to annual maximum flows, even at short return periods.

When applying the MEM, you need to carefully consider sampling uncertainties, the robustness of the input data, and timing issues. It is recommended that the MEM is compared with other methods, including the FD2308 joint probability method, FEH outputs, and historical precedents to ensure a robust analysis. One feature of the MEM is that it analyses concurrent values of the input variables, with no allowance for any possible time lags, for instance between peak flows on catchments that respond at different rates.

The MEM does not currently produce a range of input combinations for a specified output probability or return period. However, you can use trial and error within MEM to develop this type of information.

Figure 22: Example outputs from the MEM tool

The scatter graphs show pairs of events at three gauging stations on the Rive Tyne and its two tributaries, the North and South Tyne. The black dots are observed events and the blue ones are obtained by fitting the Heffernan and Tawn model to the observed data and then simulating events spanning a period of 50,000 years.



In the table below, the user has entered the peak flows at the three gauges for a particular flood.

The results are shown to the right: the joint probability of the three peak flows is 0.71%, expressed as an AEP. The table shows the encounter probabilities for a range of time spans up to 50 years.

	AEP (%)	Value
Bywell	2.70	1620.78
Reaverhill	4.10	688.47
Haydon.Bridge	5.60	914.60

The joint probability of the event in the table in any given year based on a simulation of 50,000 years is 1 in 140 (0.712% chance).

There are 357 simulated events that exceed your event. It is recommended that at least 10 simulated events exceed your event to account for uncertainty in the joint probability estimate. If this is not the case, you can simulate a larger event set.

The encounter probabilities for your event are given in the table below. If a value of 100% is shown, this should be interpreted as meaning a very high probability, i.e. close to 100% but not necessarily exactly 100%. The converse applies for values displaying as 0%.

Years	Percentage chance
1	0.71
5	3.51
10	6.9
25	16.36
50	30.04

Selecting likely combinations of input variables

Multivariate analysis can result in a large number of combinations of return periods for the influencing variables ("marginals"), which combine to give an identical joint return period. It is necessary to work out which combinations are more likely. Some may be physically very unlikely to occur, such as extreme conditions on one watercourse combined with a minor flood on another.

There are ideas on how to select combinations in research articles including Bender and others (2015) and Gräler and others (2013).

From a practical point of view, a useful starting point is to test the sensitivity of modelled water levels to different influences, such as flow on two tributaries or flow and tide level.

Joint probability in the absence of hydrometric data

Often not all the watercourses involved in a joint probability situation have river level or flow records. In some cases it may be possible to substitute local rainfall records accumulated over an appropriate duration. For example, on a small urban catchment, you might assume that there is a close dependence between the rainfall depth over the critical duration and the peak flow, and so substitute rainfall for flow data in a joint probability analysis. To create inputs for the MEM tool, you might calculate daily maximum values of (say) the 3-hour rainfall total.

Summary guidance on handling joint probability

Almost every type of flood is influenced by multiple causes. However, in many cases, when you are interested in flood risk at a single location, joint probability issues need not cause you much extra work. This may be because:

- In some cases, one cause dominates. For instance, on a heavily urbanised catchment, antecedent soil moisture may have little influence and so the dominant influence on flooding is the rainfall intensity (although hydraulic factors such as blockage could also be influential). If you are concerned about flood risk at a confluence, a sensible first step is to use hydraulic methods to test how sensitive water levels are to flow on the two rivers. Also, ask if there are any sensitive receptors in the reaches where joint probability is an issue.
- In other cases, the joint probability of the causative factors will be implicitly represented in a record of the output variable. For instance, there may be a long record of river flow or level at the site of interest.

Even the ungauged catchment version of the FEH Statistical method accounts in a generalised way for joint probability effects, since it analyses observed flood peak data.

- If you are applying a method like ReFH2, some joint probability aspects can be avoided because they have already been dealt with. When the design event composition was created, the initial soil moisture variable was calibrated so that the modelled flow (for a 2-year return period) matched observed flood frequency. Spatial joint probability issues are handled, very roughly, by the application of the areal reduction factor for rainfall.

  However, design event methods make the crude assumption that rain is simultaneous over the catchment, and this assumption becomes increasingly unrealistic for large catchments. ReFH2 can give an initial indication of the expected flood response from a smaller tributary during a flood on a larger river by applying the same longer-duration storm on both catchments. This is a simplification that ignores effects such as movement of storms and localised convective rain cells.

  This issue becomes important in considering flood mitigation strategies that involve extensive, distributed measures. This is particularly relevant for natural flood management, where a system of measures that may work well for one specific “design storm” scenario could be ineffectual or even increase risk for other plausible rainfall patterns. See the winning entry to the Defra Floods Competition 2016 by Hankin and others (2017).
- Where more than one input variable has a significant influence on flood risk at a sensitive receptor, and you are not confident that the approaches listed above adequately represent the joint probability, consider carrying out a statistical joint probability analysis using the MEM tool. This will only be possible if there are concurrent records of the input variables.
- Although the MEM tool is user-friendly and does not require any programming skills, it is important to understand the statistical principles that it is implementing.

6.4 Short return period and seasonal flood estimates

Two types of return period

Estimates of flow for high-frequency floods are needed in development control, where there is often a need to estimate the 1-year return period flood. Other applications include water level management plans for conservation sites and planning of construction work in river channels.

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

- the AMAX 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. Refer to Table 1 for a conversion.

Return periods of 1 year or less are meaningless on the AMAX 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 AMAX-scale return period, which is 1.16 years. You can calculate the design flow for this return period using an appropriate FEH method.

Similarly, annual exceedance probabilities become meaningless for events that are expected to occur once a year or more frequently. There is no such thing as the 100% AEP flood. The AEP is the inverse of the return period on the AMAX scale, not on the POT scale.

An alternative way of estimating short return period floods, particularly where short flood peak records are available, is to analyse POT data. The Flood Studies Report presents one method in Volume 1, section 2.7.5. Alternatively, you could fit a Generalised Pareto Distribution.

The types of method described above have attracted criticism for ignoring the dependence between successive flood peaks, which has been found to result in slight overestimation of design flows See Archer (1981a).

Seasonal flood estimation

Seasonal estimates of peak flow for a given return period can be important when planning construction work or investigating the impacts of water levels on seasonally-dependent ecological features or agricultural crops.

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

The peaks over a threshold database provide information for seasonal analysis. Archer (1981b) provides a practical method of such an assessment.

Alternatively, the ReFH and ReFH2 methods provide separate summer and winter flood estimates.

6.5 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 current guidance (at March 2019).

For detailed guidance, refer to FEH Volume 4 and ICE's Floods and Reservoir Safety (2015). You can also find relevant background information in:

- Reservoir Safety – Long Return Period Rainfall (CEH, 2011)
- Flood Studies Report (NERC, 1975)
- Flood Studies Supplementary Report 10: A guide to spillway calculation for a cascade of reservoirs (IH, 1983)
- Reservoir flood estimation: another look (IH Report 114, 1992)
- Design, operation and adaptation of reservoirs for flood storage (Environment Agency, 2016)

Analysts: you should ensure that you are familiar with the methods and up-to-date with the guidance.

Description

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

Guidelines

Item	Guideline or advice
1	**Important!** Flood estimation for reservoir safety is a specialist subject, often requiring knowledge of procedures that are not used in river flood estimation. Calculations require great care and should be thoroughly checked. You should check catchment descriptors manually. It is sometimes necessary to calculate the flow contributions from catchwater channels. Carry out a field visit to establish whether drainage paths are likely to change in an extreme event.
2	The Reservoirs Act 1975 as modified by the Flood and Water Management Act 2010 provide a safety regime for raised reservoirs with a capacity greater than 25,000m^3 in England and 10,000m3 in Wales . Separately from the legislation, dams are divided into four categories, A to D, based on the consequences of a breach. This is described in Floods and Reservoir Safety (Institution of Civil Engineers, 2015). The design standard for the spillway depends on the category (see Table 6). The dam category is determined by by the inspecting panel engineer. The design flood and the safety check flood of the required return period are derived for the catchment flowing into the reservoir and then routed through the reservoir, allowing for the reservoir lag effect in the storm duration. There are special considerations for cascades of reservoirs or dams with other types of flood storage within their catchments. Where the reservoir surface area is less than 5% of the catchment area it is usual to include the surface area as part of the overall catchment area for estimating inflows. Where the area is larger than 5% of the catchment a separate allowance should be made for direct rainfall.
3	There are specific methods prescribed for reservoir safety calculations. The 4th edition of the Floods and Reservoir Safety guide was published before the release of the ReFH2 method and so does not mention it. The current recommended methods are summarised in a table published by Pether and Fraser (2019) and summarised below. Although the design inputs to the FSR/FEH rainfall-runoff model were developed in the 1970s and have not been updated to incorporate the FEH 2013 rainfalls, on balance, it is thought preferable to use the most recent design rainfalls, even in an old rainfall-runoff model. Guidance on the choice of rainfall-runoff model is expected to evolve. The ReFH2 model has now been tested for the 10,000-year flood and the PMF, and the findings are expected to be published in 2019 or 2020. Initial indications are that the choice between the FEH and ReFH2 rainfall-runoff models can make a large difference to the

	results, with ReFH2 often, but not always, giving lower peak flows when the same rainfall input is applied to both models. In general, you can expect the ReFH2 method to provide more accurate estimates than the FSR/FEH rainfall-runoff model, at least up to the 1000-year return period. The reason why the FEH runoff model continues to be recommended for longer return periods is largely historical precedent rather than because there is any information indicating that it performs better. However, in reservoir safety work, it is advisable to be extra cautious, and so in some cases, it will be preferable to adopt the model that gives the higher flow estimate. Discuss the choice of approach with the Panel Engineer.

Current recommended methods

Return period (years)	150	1000	10,000	PMF
Rainfall statistics	FEH 2013	FEH 2013	FEH 2013	FSR
Rainfall-runoff model	FEH / ReFH / ReFH2	FEH / ReFH2	FEH	FEH

4	No matter which rainfall-runoff model you are using, estimate the parameters from local data if available. Consider also deriving a unit hydrograph rather than relying on the synthetic unit hydrographs in the FEH and ReFH rainfall-runoff models. Many reservoirs have water level records from which it may be possible to estimate the time to peak parameter (Tp), as long as you take into consideration reservoir lag effects. Make sure you do not double count the lag effect. When estimating Tp, watch out for any tendency for it to reduce with increasing rainfall intensity. Refer to the examples in Faulkner and Benn (2016). Consider removing smaller events from the analysis so that the resulting estimate better represents extreme flood conditions.
5	Some reservoirs have long critical storm durations. This can be because their catchment is large or because of a large storage volume, perhaps due to the presence of upstream reservoirs. Once the rainfall duration exceeds several days, it is not appropriate to use a symmetrical unimodal storm profile. Instead, adopt the temporal pattern of the most severe sequence of storms over the required duration that has been observed locally. Refer to FEH **2** 4.3 for more guidance.
6	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 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; • reduce the time to peak of the unit hydrograph by one third to account for the more rapid response of an exceptional flood; • when applying the winter PMP, set the standard percentage runoff to a minimum of 53% to account for frozen ground;

	• when applying the winter PMP, you should consider snowmelt (refer to step 7 below); • increase the catchment wetness index to allow for greater antecedent rainfall; • use a different storm profile constructed by nesting PMP depths over different durations.
7	For the PMF, add snowmelt to the event precipitation and the antecedent rainfall. **Caution!** Analysts frequently underestimate the snowmelt contribution. The FEH provides maps of melt rate and snow depth but the map of melt rate is potentially confusing. It shows the 5-year return period rate, but the recommendation in the FSR is to use the 100-year melt rate in conjunction with the PMP. The meaning of the contours on the FEH map is not clear. It is more advisable to use snow melt rates from Hough and Hollis (1997), as recommended by ICE (2015). There is a more detailed map of melt rates in the paper, but again this is for a 5-year return period and needs to be scaled up to a 100-year return period. This requires some ingenuity. The most straightforward approach is to: • Estimate the 5-year return period 24-hour melt rate from the regression equation based on altitude and Northing on the second row of Table 7 in Hough and Hollis (1997); • Convert this to a 100-year return period using the Gumbel distribution parameters from a representative climate station in Table 2 of the article (take great care with the treatment of p, the probability of years with no snow lying for the appropriate duration, unless p=0); • Add an allowance for energy provided by incoming rainfall, assuming 0.0125 mm of melt per mm (of rain) per °C, as recommended in the article. The rain depth is the PMP and you need to make a suitably conservative assumption for a winter temperature. Unless you have specialist knowledge of the topic, it may be preferable to seek expert advice. There is a need for a more straightforward procedure for snowmelt calculation.
8	You can do the PMF calculations in Flood Modeller Pro, 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 6: Dam categories

Dam category	Potential effect of a breach	Safety check flood: the inflow above which the safety of the dam cannot be assured	Design flood: the inflow that must be discharged with a safety margin
A	Endangering lives in a community	PMF	10,000-year flood

B	Endangering lives not in a community, or causing extensive damage	10,000-year flood	1000-year flood
C	Negligible risk to life and limited damage	1000-year flood	150-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	150-year flood

6.6 Estimating long return period floods (200-1000 years)

The issues

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.

Because we cannot validate estimates of long return period floods against observations, it is difficult to know which method provides the most reliable estimates.

There are some reasons for thinking that design event methods are preferable at long return periods. There tends to be greater confidence in rainfall frequency curves compared to flood frequency curves for long return periods. This is due to the greater availability of long rainfall records and the spatial consistency of extreme rainfall, which allowed the FEH and FEH 2013 rainfall growth curves to be extended to long return periods using a model of spatial dependence. This is why design event methods are exclusively recommended for reservoir safety calculations.

Guidelines

Item	Guideline or advice
1	If they are suitable for the catchment, apply both the FEH Statistical and ReFH2 methods when estimating long return period floods. Compare the answers and consider which method is more strongly supported by local data.
2	Take particular care when using a GEV distribution in the statistical method. This can lead to a growth curve with an upper bound, or with low skewness, in which the estimated 1000-year flood can be little higher than the 100-year flood. In such cases, it may be wise to avoid extrapolating the curve too far. It can help to calculate the ratio of the 1000-year to the 100-year floods.
5	If you need flood estimates for a range of return periods up to 1000 years, it may often be the case that you prefer the statistical method for the shorter return periods. If you choose ReFH2 for the longer return periods, to avoid a discontinuity in the results, you could consider using ReFH2 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.
6	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.
7	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.

6.7 Post-event analysis

Guidelines Post-event analysis may be required to assess the severity of a flood.

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. Always explain how the assessment was made and what data it was based on. Simple factual statements about the ranking of the event and the period of record provides an immediate perspective.
2	Be aware of the complexity of the relationship between the rarity (return period) of: • the rainfall, including the variation of return period with the duration and spatial extent over which rainfall depths are evaluated; • the peak river flow, including the variation of return period between different points in the catchment; • the impacts of the flood. The return period of the rainfall may be very different from that of the flood, especially on catchments that are larger, more permeable or of mixed geology or land use. Prior catchment wetness plays an important role here, as does the sensitivity of different parts of a catchment to different storm durations. The return period of the impacts of the flood, for example its spatial extent, its depth or its economic cost, may be sensitive to not only the peak flow but also the volume of the flood, its interaction with other factors such as the tide, the management of infrastructure such as reservoirs and flood storage areas, and the performance of defences.
3	It is usual to start by estimating the return period of the rainfall. Calculate a catchment average rainfall, bearing in mind that some relevant raingauges may be outside the catchment. Include data from daily storage gauges as well as recording gauges. One approach is to apply the temporal profile from the closest recording gauge at each daily gauge. Also consider including data from radar, particularly if the catchment is not well covered by raingauges or if the storm was

	highly localised. HYRAD provides catchment-average rainfall accumulations. It also displays the “best rainfall observation” which merges point rainfall intensity measurements with radar images. Use the FEH 2013 rainfall statistics to estimate the return period.
4	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. In some cases, you may need to commission an in-depth study to improve the rating curve before it is possible to estimate the peak flow. This may need to account for morphological changes in the channel or floodplain at the gauging station during the event. Consider calculating a percentage runoff to help assess whether the flood hydrograph is realistic. If the volume of flow implies a runoff rate near or greater than 100%, you may need to re-assess the rating.
5	It is most common to estimate the return period of a flood in its immediate aftermath. This risks introducing a bias. The study is only being carried out because a large flood has occurred. Research at Lancaster University is looking at ways of avoiding this bias. As a simple sensitivity test, repeat the analysis with the recent flood excluded from the fitting of the flood frequency curve.
6	Another aspect to consider is the bias inherent in estimating flood frequency and return period, particularly using a single site analysis (**3** Add. Note 11.2). This occurs because methods like the FEH are designed to give an unbiased estimate of the flow for a given return period, rather than the return period for a given flow. Seek expert advice when there is a need to make an adjustment.
7	The ReFH model can assist in event analysis when there is no recorded flow data. Use the model to simulate the flood hydrograph and then estimate the return period of the peak. This is preferable to making the crude assumption that the return period of the flood is identical to that of the rainfall. The data required to simulate an observed event is: • catchment-average event rainfall; • catchment-average daily rainfall from the start of the year preceding the flood; • potential evaporation. Refer to the earlier section on modelling real floods using ReFH2. In most cases, it is sensible to use ReFH2 for deriving the flood frequency curve as well as for simulating the flood. Any errors in model parameters can be expected to be cancelled out (to some extent), as described in the FEH (**4** 5.4.2).

7 Unusual catchments

7.1 Small catchments and greenfield runoff

The issues

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. Older methods have often been used instead, but subsequent research has shown that FEH methods should be preferred.

Reasons for uncertainty on small catchments

Flood estimates are particularly uncertain on small catchments (below about 25 km^2) because:

- there is a shortage of such catchments in the NRFA dataset used to derive the regression equations for ungauged sites and to select pooling groups and donor catchments;
- digital catchment descriptors are more difficult to derive for small catchments, which is why the FEH dataset does not include catchments smaller than 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

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	The SuDS Manual (Woods Ballard and others, 2015) gives detailed guidance on estimating runoff for both greenfield and developed sites. Refer to the manual for advice on the design of site drainage and runoff storage.
3	Guidance on choice of method for flood estimation on small catchments was developed in Science Project SC090031: Estimating flood peaks and hydrographs for small catchments. In accordance with the report on Phase 1 (Faulkner and others, 2012) we recommend that you: • Derive flood estimates on small catchments from FEH methods (Statistical or ReFH2) and not from older methods. • Check 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, derive flow estimates by applying FEH methods to the nearest suitable catchment

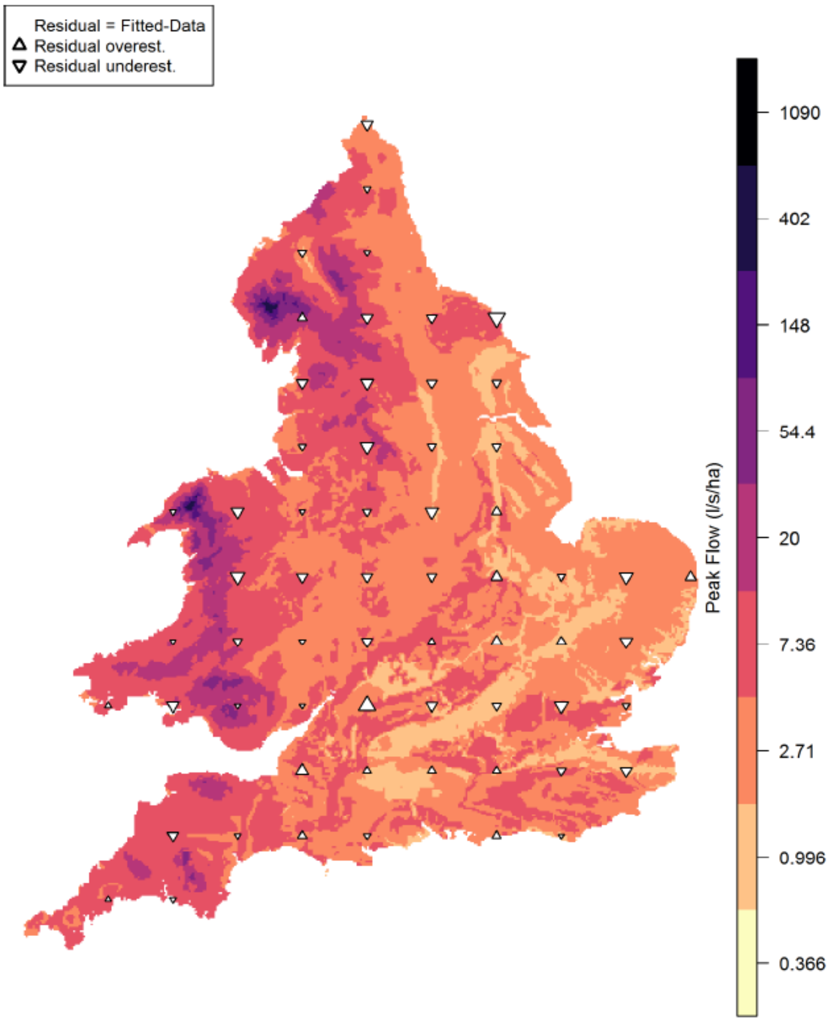
	above 0.5 km^2, and then scale them down by the ratio of catchment areas. • When translating FEH estimates from catchment scale to plot scale, assess whether the study site is representative of the surrounding catchment area. These recommendations continue to apply, but see point 3 below for some new developments.

4	Phase 2 of SC090031 is due to be completed in 2019. The draft final report (Stewart and others, 2019) makes the following recommendations for catchments and plots:
	FEH Statistical method for small catchments
	• Use the standard FEH regression for QMED. Adjust QMED using a single donor catchment, chosen on the basis of proximity. On average there is no advantage in choosing a small donor catchment.
	• For catchments smaller than 40km^2, select a pooling group using a new similarity measure that considers only AREA and SAAR. At the time of writing, this procedure is not implemented in any commercial software and so most practitioners are expected to continue using the standard FEH pooling method on small catchments.
	ReFH2 method for small catchments
	• Use the standard form of the current version of the ReFH2 method, including the lower limit of 1 hour for Tp.
	The SC090031 research developed new recommendations for seasonal inputs to ReFH2 and their dependence on urban extent. These apply to all catchment sizes and are explained in the section on inputs for simulating design flood events.
	ReFH2 method for plot-scale application
	• Use the option available in ReFH2 to estimate model parameters at the plot scale. This avoids the need to define the DPLBAR and DPSBAR descriptors which are meaningless for plots of land that do not contain a watercourse network.
	• When estimating greenfield runoff rates and storage volumes, use a winter storm.
	• ReFH2 can be used to assess the effect of site development on peak flows and runoff rates. The ReFH2 technical guidance explains how to apply the method in that case, calculating post-development runoff by:
	    • setting the urban area to equal the total amount of impervious surface planned for the development;
	    • setting the impervious fraction to 1, since all this area is impervious;
	    • increasing the impervious runoff factor to 1 (100% conversion of rainfall to direct runoff).
	    • The “urbanised” results section then provides the peak runoff and volume from the planned development.
	    • Set the storm duration to 6 hours if you want to calculate the storage requirement for a 6-hour storm, which is often needed in development planning.

	Alternative precautionary method for plot-scale application • Open-source data have been used to develop grids of greenfield runoff rates for return periods of 1, 2, 30 and 100 years across England and Wales. In addition, runoff rates and volumes are provided for the 100-year event of 6-hour duration which is a requirement mentioned in the SuDS Manual for the calculation of long-term storage. • All of the estimates are intended to be precautionary, providing preliminary results for use at the planning stage of new developments. • Although the results were intended to be conservative (i.e. to underestimate greenfield runoff and overestimate runoff volumes), the estimates are generalised and subject to considerable uncertainty. At some locations the runoff rates will not be precautionary in comparison with FEH methods. **Important note on generalised methods** • Seek as much relevant information on local circumstances as possible and always exercise judgement in the application of generalised methods.
5	You may come across studies that continue to use older methods. The most commonly used alternative method on small catchments was Institute of Hydrology Report 124 (IH 124). 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 practitioners to avoid IH 124. Some practitioners use the UK SuDS online tool (developed by HR Wallingford) for estimating greenfield runoff. The tool offers two options described as the IH 124 or FEH Statistical methods. For the latter, the user needs to supply BFIHOST or the dominant HOST class. The only aspect of the FEH method that appears to be implemented is the regression for QMED. There is no use of donor catchments and no pooled growth curve. Instead, growth factors are calculated using the Flood Studies method. More reliable results could be achieved using standard FEH methods.

Figure 23: Example map of greenfield runoff

The map is an example output from SC09001, showing the precautionary estimate of greenfield runoff for a 30-year return period in l/s/ha.



7.2 Urban catchments

The issues

Urbanisation has a widespread and significant effect on flood frequency. 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 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.

The FEH has much to say on the effects of urbanisation on flooding (**1** 8, **3** 9, **3** 18, **4** 9.3, **5** 6).

Guidelines

Item	Guideline or advice
1	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 developed and undeveloped areas both contribute significant amounts of runoff. The approach to flood estimation needs particularly careful thought when there is a mixture of rural and urban areas in the catchment. This needs to be considered when developing the conceptual model (see Preparing method statements).
2	The degree of urbanisation of a catchment is measured using URBEXT2000 (used in the Statistical and ReFH2 methods) or URBEXT1990 (used in the ReFH and Rainfall-Runoff methods). For information on the differences between URBEXT1990 and URBEXT2000, refer to Bayliss and others (2007), listed in Related documents.
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).

Slightly to heavily urbanised catchments (URBEXT2000 up to 0.6)

Choice of method in urban catchments

Either the FEH Statistical method or ReFH 1/2 methods can be applied, unless other characteristics of the catchment indicate otherwise. If choosing ReFH1, apply it in conjunction with the urban catchment extension of the method. You might choose to give preference to the results from ReFH 1/2 when:

- there is a major difference between the boundaries of the topographic and sewer catchments; and
- you need estimates of high probability floods for which much of the flow is expected to be via the sewer system; and
- there is no flow data suitable for statistical analysis; and
- there is time and budget available to define the sewer catchment boundaries.

Phase 2 of the small catchments research, SC090031 (Stewart and others, 2019) found that on average the ReFH2 method gave a slightly reduced bias and lower factorial standard error than FEH Statistical when estimating QMED on small catchments.

Where there is water level data you should incorporate this in the estimation process via a lag analysis which may lead to a preference to the results from ReFH 1/2 over those from the statistical method.

You can find guidance below on how to apply the FEH methods in urban catchments.

Option 1 Statistical Method

Use the Statistical method in accordance with the guidance given earlier, with an urban adjustment applied.

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

Option 2 ReFH or ReFH2 methods

The original version of ReFH was not suitable for urban catchments. Subsequent research led to an urban extension of the model which has been widely implemented, and is incorporated in ReFH2. See Wallingford HydroSolutions (2019a).

The urban component of the ReFH model introduces three extra parameters, with a fourth for ReFH2.3 when the water balance option is chosen (Figure 24). In the ReFH2 software they are called:

- Impervious runoff factor, IRF
- Imperviousness factor, IF
- Tp scaling factor
- Depression storage, DS

IRF is the proportional runoff from impervious surfaces, i.e. buildings, roads etc. It can alternatively be interpreted as the fraction of the impervious surface that is positively drained, and in the water balance version of ReFH2.3, the runoff from the rest of the impervious surface is routed via depression storage into the rural part of the model (Figure 24). This is intended to represent percolation through cracks or runoff from the edge of paved surfaces. The default for IRF is 0.7 (i.e. 70%).

IF is the proportion of urban areas that comprise impervious surfaces, the default being 0.3, or 0.4 in the water balance configuration of ReFH 2.3. It is also necessary to provide a value for the urban area in the catchment, but the ReFH2 software calculates this automatically from URBEXT2000 and the catchment area.

The Tp scaling factor is generally below 1, allowing for faster routing of runoff from impervious surfaces.

DS is depression storage expressed as a depth of runoff, with a default of 0.5mm.

The recommended values for these parameters, and for the seasonality of the design storm, depend on both the urban extent and BFIHOST, as shown below. These recommendations stem from the small catchments research, SC090031 (Stewart and others, 2019). You can alter the default values using local data, for example from detailed mapping. It is worth first carrying out a sensitivity analysis. Refer to Wallingford HydroSolutions (2019a).

Caution! ReFH2 can produce unexpected results on some catchment types, with the predicted runoff volume apparently decreasing slightly as urbanisation increases. This can happen on catchments with lower BFIHOST, where even the rural parts of the catchment are producing relatively large runoff volumes. For this reason, if flood volumes are important to the needs of your project, treat the results of ReFH2 with caution and explore the sensitivity of the results to parameter values.

Slightly to moderately urbanised catchments, URBEXT2000 < 0.15

Treat the catchment as rural and use a winter design storm.

Heavily urbanised catchments, 0.15 < URBEXT2000 ≤ 0.3

For catchments in this range, the small catchments research found that flood frequency estimates were more accurate if the catchment was treated as rural. This is a counterintuitive result, but it reflects the difficulty of generalising the complex and locally-specific effects that urban development has on flood flows. The analysis demonstrated that the influence of urbanisation on QMED is only apparent on very heavily urbanised catchments with URBEXT2000>0.3. Although the research was motivated by a need to improve flood estimation on small catchments, this part of the analysis included data from larger catchments too and the findings are applicable to all catchment sizes.

Treating the catchment as urban will give a conservative estimate. If this is desirable for the needs of your project, follow the procedure below.

- Increase the Tp scaling factor to 1 because there is no evidence for enhanced routing of urban runoff in these catchments.
- If the catchment is permeable (BFIHOST19 is > 0.65) use a summer storm; otherwise use a winter storm.

Refer to SC090031 (Stewart and others, 2019) for the reasons behind these recommendations.

Very heavily urbanised catchments, URBEXT2000 > 0.3

Treat the catchment as urban:

- Use the default Tp scaling factor as defined above.
- Use a summer rainfall depth and initial soil moisture, Cini, along with either the 75% storm profile or 50% profile. Analysis indicates that the 75% “winter” profile is marginally better, despite the previous recommendations to adopt the more peaky 50% “summer” profile on urban catchments.
- Consider allowing for the influence of sewer flow pathways (see below).

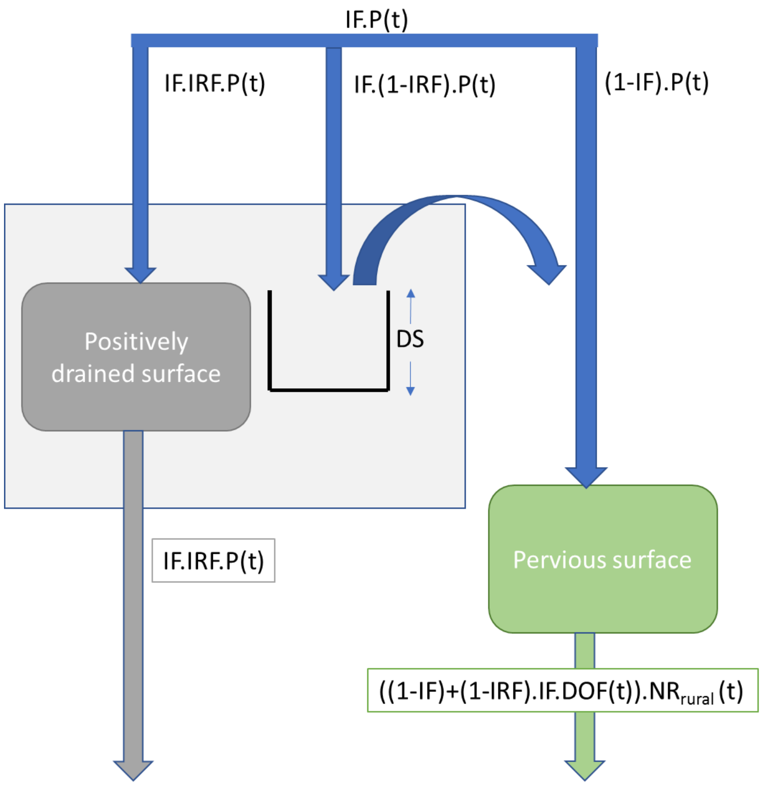
Figure 24: The losses component of the ReFH2 model, version that closes the water balance

Source: Wallingford HydroSolutions (2019a)

The figure shows how runoff is calculated from precipitation, P(t). The parameters IF, IRF and DS are defined above.

DOF(t) is the Depression Overflow Factor, which takes a value of 0 until the precipitaiton depth exceeds the depression storage, DS, and then a value of 0 for subsequent rainfall.

NRrural is the rural net rainfall, calculated from the ReFH2 rural losses model.



Influence of sewers in ReFH2

In ReFH2, there is an opportunity to allow for sewers that remove water from the topographic catchment. During development and testing of the ReFH2 method, the influence of sewers was ignored. There is little evidence relating to the benefits of allowing for the influence of sewers, although a case study for the Dead River in Surrey showed the importance of the sewer system in controlling modelled flood flows for frequent events. See Beskeen and others (2011).

The ReFH2.3 software does not allow the addition of flow from sewers that drain into the watercourse from outside the topographic catchment. This functionality is due to be added to version 2.4.

To define the area draining to sewers, you need to obtain locations of combined sewer overflows and storm sewer outlets, and the extent of the sewer network draining to these locations. 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.

In ReFH2.3, the sewer capacity needs to be specified as a discharge in m^3/s, along with an area in km^2 for the portion of the urban area that is "served by sewers", UASS. It is important to realise that this refers only to sewers that drain out of the topographic catchment. The feature is due to be enhanced in v2.4.

You will need to strike a balance between the potential gain in accuracy and the time needed to gather the extra information. Unless there is a major export of water from the catchment via urban drainage systems, it may be wiser to assume that exports and imports roughly balance and that, because imports cannot be modelled, exports should be ignored.

Extremely heavily urbanised catchments and drainage design

Recommended methods

For extremely heavily urbanised catchments (URBEXT2000>0.6):

You should not routinely apply the FEH flood frequency methods to these catchments (**5** 6.5.5). For deriving flows from urban sewered areas, it may be more appropriate to use sewer design methods or other alternatives listed below. However, these alternative methods have drawbacks too.

Urban drainage modelling is largely outside the scope of this guide. Refer instead to CIWEM Urban Drainage Group's rainfall modelling guide (2015) and drainage modelling code of practice (2017). There is also useful guidance in the SuDS Manual (Woods Ballard and others, 2015).

- The **modified rational method** is used for sewer design within the Wallingford Procedure (National Water Council, 1981). It includes formulae to aid estimation of the two key parameters. Time of concentration is divided into time of entry and time of flow through 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 **Wallingford hydrograph method** is a version of the FSR rainfall-runoff method which is used in sewer network modelling software. A version of this method is commonly applied to model runoff from impervious surfaces in integrated urban drainage studies. There are various options for calculating the percentage runoff parameter. Refer to CIWEM Urban Drainage Group (2017). Reports on these types of models do not always explain the method that was applied to calculate runoff and its assumptions, instead tending to focus on the hydraulic modelling of the pipe system. It is important to probe in cases where this information is lacking.
- **FRQSIM** is a rainfall-runoff model 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. It has been used on many catchments, but in recent years, many FRQSIM models have been replaced with versions of the ReFH model.

  The catchment is separated into 'node areas', based not only on topographic information, but also on drainage networks. FRQSIM uses a time-area method to produce synthetic unit hydrographs (SUH). A separate SUH is produced for paved and open areas and to represent gardens and verges within urban areas. Separate loss models can be applied for the paved and open areas. The model assumes that capacity of the surface water drainage network will restrict peak flows and that any rainfall above the assumed capacity will be stored in the model and released over subsequent time steps. Overland flow routes for excess water are likely to be impeded by buildings and walls.

  FRQSIM has been seen to give design flows much higher than those from FEH methods, including at locations where the latter are based on local flood peak data. In any event-based method for estimating design flows, it is necessary to ensure that the composition of the design event gives rise to a peak flow of the required return period. It is not clear that FRQSIM achieves this (see Onof and others, 1996).

For more information, refer to the user guide, FRQSIM Hydrological Model.

7.3 Permeable catchments

Importance of understanding processes

An understanding of the catchment geology and hydrogeology is 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. Consult colleagues in hydrogeology teams. Seek reports on groundwater modelling studies, which generally cover interactions with river flow.

Reasonably high BFIHOST values can come from a range of rock types, including chalk, limestone, and some sandstones, and such rock types may be variable in their runoff properties, so that the BFIHOST value may not represent actual runoff well.

If the catchment is gauged, look at flow data over a period of several years to understand the relative contributions of baseflow and rapid runoff, which sometimes appears as a “spike” superimposed on the baseflow response. Try to work out which parts of the catchment are generating the rapid runoff.

Importance of historical information

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. Put particular effort into seeking and interpreting historical flood data that pre-dates gauged flow records.

Why to prefer statistical methods

Design event methods are generally thought less appropriate 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 general apply to the ReFH2 method, although its results on highly permeable catchments are greatly improved compared with those from ReFH1.

The FEH Statistical method is normally a more appropriate choice on highly permeable catchments. However, it is important to be aware of two issues, explained below.

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 of overestimation are more common, with several Chalk catchments showing overestimation by a factor of 3-5, and some, such as the Rivers Ver and Mimram, closer to a factor of 10. Some of these flow gauging stations are not classed as suitable for QMED in the NRFA dataset and so were not included in the fitting of the QMED regression equation. However, rating reviews have indicated that the flow measurements are of reasonable quality.

In some cases, it is possible to explain the underestimation of QMED from local hydrogeological circumstances, such as groundwater equipotential lines indicating subsurface flow passing into a neighbouring surface water catchment.

Subsurface flow will also pass beneath the gauging station. Extremely intense rainfall may result in surface runoff when infiltration capacity is exceeded, and runoff from impermeable clay-with-flints or till on interfluves may only reach the stream network in exceptional events.

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 months of data may enable you to estimate design flows with more confidence in comparison to 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.

Refer to the earlier section on review of pooling groups for advice on whether to modify groups to allow for permeability.

The guidelines below introduce some other aspects of flood estimation on highly permeable catchments.

Guidelines

Item	Guideline or advice
1	Some studies carry out separate frequency analysis of the rapid runoff and baseflow components of the flood hydrograph. This can lead to difficulty when combining the results of the analyses, because you need to allow for the dependence between the two components.
2	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. 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 by writing code. A spreadsheet that carries out the adjustment is available from the Wallingford HydroSolutions website. The adjustment generally has a fairly small effect on growth curves.
3	Where the lower part of a catchment has higher BFIHOST values than the upper catchment, the increase in QMED from the regression equation may be less than some analysts might expect. In such cases other information may be useful, such as channel width and information on the extent and locations of past flooding.
4	Where full hydrographs are needed, you can implement a hybrid approach. Where flow data is available, it may be preferable to estimate a hydrograph shape empirically using the methods described earlier. Take care because flows can stay high for weeks or months on groundwater-fed rivers, and it may not be correct to assume that the hydrograph shape can be scaled to match a given peak flow.
5	The volume and duration of floods are important factors to consider. Bradford and Goodsell (2000) investigated flood volumes on permeable catchments and 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 it is for flood peaks.
6	Flood estimation by continuous simulation is worth considering on permeable catchments, particularly where there is a shortage of flood peak data near the sites of flood risk. It is a particularly attractive prospect in catchments with mixed geology, or highly permeable catchments that contain urban areas from which rapid runoff occurs. 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).

Examples of continuous simulation studies on permeable catchments include:

- Bentley Ings, a small catchment with limestone headwaters, an urban mid-catchment and a lower pumped catchment (see Lamb and others, 2016);
- River Darent, a catchment with complex heterogeneous geology and land cover (project carried out by JBA Consulting under the WEM Framework, 2018);
- Seven chalk catchments in Hampshire (project carried out by JBA Consulting under the WEM Framework, 2015).

The Hampshire study concluded that continuous simulation cannot be recommended outright for the case study catchments, at least not without modifying the stochastic rainfall model to simulate realistic variability of depths over several seasons. Where there is a long observed series containing some extreme events, the project recommended that single-site analysis seems the most robust method of estimating a flood frequency curve, and that this should be combined with an assessment of historical flooding, with particular attention paid to any mention of extreme events, such as those due to rainfall on frozen soil.

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;
- acquire local flow data (even a very short record) if possible rather than relying on catchment descriptors for estimation of design flows;
- adjust single-site growth curves to account for non-flood years in the dataset when SPRHOST<20%.

7.4 Catchments containing reservoirs

In this section

This section is about flood studies for sites downstream of reservoirs when the reservoir and its safety is not the subject of the study. See also Flood estimation for reservoir safety.

Description

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

- to reduce QMED;
- 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** 13.7.4). FARL makes no distinction between reservoirs, where the water level may be below the spillway, and lakes, which generally have a continuous outflow.

Reservoirs act to attenuate flood hydrographs even when they are at full capacity.

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 ReFH2 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 use a flow routing model to allow for inflows from the rest of the catchment.

Guidelines

Item	Guideline or advice
1	Many hydraulic 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 original ReFH method can overestimate the flow, sometimes giving a runoff volume that exceeds the rainfall volume. This problem should not occur in ReFH 2.3 when the water balance option is selected. However, it is still important to check that the results are realistic. • 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.
2	The design of operating rules for both on-line and off-line flood storage reservoirs or washlands 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. It is important to test the effectiveness of flood storage schemes using a variety of flood event types, rather than a single unimodal design storm. One approach is to test the scheme using a selection of observed floods or sequences of floods. There is an example for the River Aire washlands in Pelleymounter and Falconer (1992).

7.5 Pumped and other low-lying catchments

The issue

The flow characteristics of pumped catchments are fundamentally different to those of typical gravity catchments. 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.

The boundaries of such catchments 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.

Flood hazards on such watercourses tend to be influenced more by the volume of runoff than by peak discharge rates.

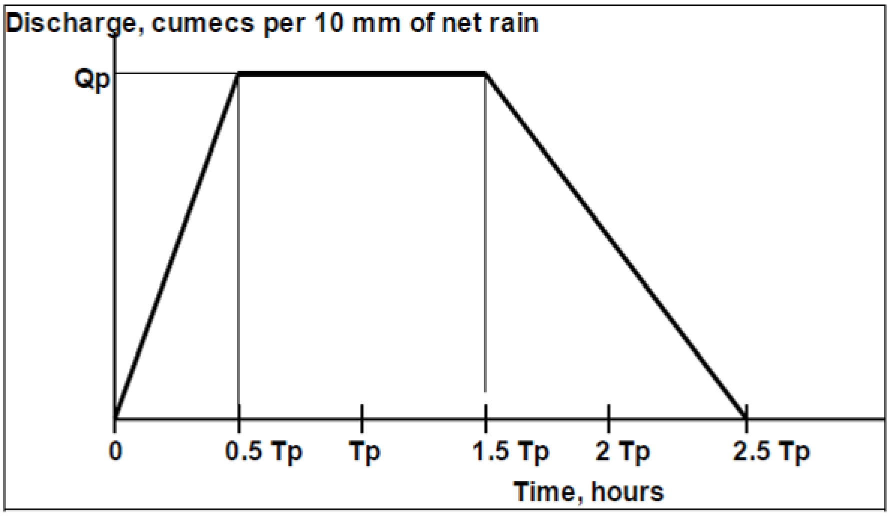
Guidelines

Item	Guideline or advice
1	The most important, and often the most time-consuming, aspect of flood estimation in lowland catchments is to derive the catchment boundary. LIDAR terrain data can be helpful, but is often not sufficient, because the contributing area may be determined by the connectivity of drainage ditches. Seek information from previous studies, internal drainage board maps, catchment engineers and field visits. Understand the role of high-level carriers and watch out for low-level drains that pass underneath high-level ones, rather than connecting into them. In some places, the direction of flow can reverse depending on the hydraulic gradient, which may be determined by the switching on of pumps or the state of the tide.
2	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. In light of the factors listed above, it is nearly always best to avoid using the FEH Statistical method on lowland catchments (**3** 13.7.4).
3	Instead, apply rainfall-runoff methods. ReFH2 is a natural first choice. Although few lowland watercourses have continuous flow records, many have logs that record when pumps were switched on. From these, and knowledge of the pump capacities, you can often calculate the volume of runoff and investigate the water balance. Pumped catchments are particularly sensitive to volumes of runoff, so it is important to estimate runoff characteristics as accurately as possible. Where feasible, adjust the catchment descriptors or the Cmax parameter by trial and error until predicted runoff volumes or percentages are consistent with observations. It may be possible to 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. Refer to the guidance in SC090006 (Flikweert and Worth, 2012). **Caution!** The HOST classes in some lowland areas appear to underestimate the volume of runoff, perhaps because they do not account for the shallow water table or the presence of field drainage systems. The unit hydrograph in the ReFH model was derived from flow data on gravity-drained catchments. On lowland catchments, the

	flow can be impeded by backwater effects, meaning that the standard unit hydrograph may be too peaked. To some extent, this attenuation effect is accounted for by the inclusion of the drainage path slope (DPSBAR) in the estimate of Tp. When DPSBAR is small, Tp will be longer and so the unit hydrograph will be more drawn-out. Consider the alternative unit hydrograph described in points 4 and 5 (below).
4	Some studies 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. An Environment Agency science project, SC090006 (Flikweert and Worth, 2012) updated the earlier guidance but the basic method is unchanged. In summary, when using the tailored version of the FSR rainfall-runoff method: • Use 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 25). 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 FEH triangular unit hydrograph or 1.80/Tp using the ReFH unit hydrograph. • Estimate SPR by back-calculation from rainfall and pumping station data in preference to using soil mapping. • Estimate time to peak preferably from local data or else (as a last resort), setting it to 24 hours, rather than using catchment descriptors. • Calculate a critical rainfall duration by iteration. • Be 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 local notable rainfall sequences. • Account separately for runoff for upland or urban areas. In theory, you could also apply the trapezoidal unit hydrograph in the ReFH model. This alternative was not mentioned in SC090006. A difficulty is that the ReFH2 software does not allow you to input a user-defined unit hydrograph. The older ReFH Design Flood Modelling software does, but this is no longer available for purchase.
5	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 under-estimate 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. This is rarely carried out in practice.
6	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).
7	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.
8	Another alternative 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. Refer to the section on direct rainfall modelling.
9	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.

Figure 25: Trapezoidal unit hydrograph, from Science Report SC090096



8 Audit trail

8.1 Flood estimation calculation record

Purpose

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

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

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.

8.2 Filling in the calculation record

Description

The calculation record consists of a series of tables for you to fill in. The most important aspects to record are those that deviate from the default methods.

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

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.

8.3 Presenting results and interaction with hydraulic modelling teams

Guidelines

Item	Guideline or advice
1	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	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.

	An example is using too many significant figures, such as quoting the 100-year flood as 145.7m^3/s. • to acknowledge 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 using phrases such as '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.
4	Estimating design flows rarely marks the end of a project. In many cases, the flows are used as the input to a hydraulic model. If you are not going to be doing the modelling, you should provide enough information for the modeller. Discuss with the modeller how the flows are going to be applied to the model, bearing in mind the range of approaches outlined in the sections on hydrodynamic modelling and lumped or distributed application of rainfall-runoff methods. There will often be a need to check or re-visit the flow estimates after a trial application to the model. This might involve agreeing a critical storm duration or set of durations. If initial model runs show unrealistic flood levels or outlines, there may be a need to revise the hydrology, the hydraulics, or both. Refer to the guidelines on choice of method.

8.4 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 NRFA peak flow 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.

List of acronyms

Acronyms The table lists acronyms that are related to flood estimation.

Acronym	Full expression
ADVP	Acoustic Doppler Velocity Profiler
AEP	Annual Exceedance Probability
AMAX	Annual Maximum
AREA	Catchment area (km^2)
BFI	Base Flow Index
BFIHOST	Base Flow Index estimated from soil type
CFMP	Catchment Flood Management Plan
Cini	Initial soil moisture content, used in the ReFH model
CMAX	Maximum soil moisture content, a parameter of the ReFH model
DDF	Depth Duration Frequency
DEM	Digital Elevation Model
DPLBAR	Mean drainage path length in a catchment
DTM	Digital Terrain Model
FARL	FEH index of flood attenuation due to reservoirs and lakes
FEH	Flood Estimation Handbook (1999), also used more generally to refer to successor methods
FEH99	Flood Estimation Handbook rainfall frequency statistics, released in 1999
FEH 2013	Revised rainfall frequency statistics, released in 2015
FSR	Flood Studies Report (1975)
FSR/FEH	The FSR rainfall-runoff method, restated in the FEH but essentially unchanged
GEV	General Extreme Value (a statistical distribution, fitted to AMAX data)
GL	General Logistic (a statistical distribution, fitted to AMAX data)
GPD	Generalised Pareto Distribution (fitted to POT data)
HOST	Hydrology of Soil Types
MEM	Multivariate Event Modeller
MORECS	Meteorological Office Rainfall & Evaporation Calculation System

MOSES	Meteorological Office Surface Exchange Scheme
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
POT	Peaks Over a Threshold
PROPWET	FEH index of proportion of time that soil is wet
QMED	Median annual maximum flood (with return period 2 years)
R&D	Research and Development
ReFH	Revitalised Flood Hydrograph, a rainfall-runoff model
ReFH1	Version 1 of the design event method using the ReFH model
ReFH2	Version 2 of the design event method using the ReFH model
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, a parameter of the ReFH model
Tp(0)	Time to peak of the instantaneous unit hydrograph, a parameter of the FSR/FEH rainfall-runoff model
URBEXT1990	Original FEH index of fractional urban extent
URBEXT2000	Updated version of urban extent, defined differently from URBEXT1990
WINFAP-FEH	Windows Frequency Analysis Package - FEH version (Version 4 drops the FEH suffix)

Related documents

Supporting documents

197_08_SD01 Flood estimation calculation record.

197_08_SD02 Checklist for reviewing flood estimates

Internal guidance

12_17 Using local data to reduce uncertainty in flood frequency estimation (2017).

260_05 Understanding and Communicating Flood Risk.

296_05 Guidance - 1000 year flow estimates for Flood Consequence Assessments - Wales only.

414_07 Accessing Hydrological Data and Information.

Other documents

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Annex: History of these 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 2000.
2	Produced by the Environment Agency with the help of JBA Consulting. Included new material, such as advice on non-FEH methods, reservoir safety methods, guidance on uncertainty and a checklist for reviewing calculations. 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.
5	Produced by the Environment Agency. Includes research and datasets released since 2012. Issued in 2015.
6	Produced by the Environment Agency. One page added to mention recent updates. Issued in 2017.
7	Produced by the Environment Agency with the help of JBA Consulting. Includes research, guidance and datasets released since 2015, along with developments in good practice that emerged from the user community. Major new topics include FEH 2013, ReFH2, small catchments research, FEH Local, direct rainfall and joint probability. Issued in 2020.