Flood Estimation Guidelines

Instruction: LIT 11832 Published: 23/12/2022

Audience: Environment Agency

Description: This document offers advice to help analysts carry out fluvial flood frequency estimation using the methods of the Flood Estimation Handbook (FEH), its updates and other recent publications. 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.

These guidelines are intended for:

- 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 the Summary and Introduction sections.
- Consultants carrying out work for us or carrying out work requiring our approval.

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Summary

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

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

Project managers must ensure that those carrying out flood estimation 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. You must take a risk-based approach when considering the required staff competence and the time needed to carry out a study.

What these guidelines offer

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

In line with the philosophy of the FEH, these guidelines offer few prescriptive instructions. In most situations, there is a choice of alternative data and methods, sometimes giving a wide variety of results. These guidelines don't tell users which data and methods to choose. Instead, they 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 catchments.
- how to record and justify the choice of method.

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

Overview of flood estimation methods

There are two principal techniques available:

- the FEH statistical method. An “improved” set of procedures has replaced most of the original 1999 FEH statistical methods for ungauged sites.
- the Revitalised Flood Hydrograph (ReFH1 and ReFH2) method. This has replaced the original 1999 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. This is expected to be updated in 2022.

Differences between the two techniques

The statistical method gives only a peak flow estimate for the design event.

The rainfall-runoff techniques (ReFH1, ReFH2 and original FEH) give an estimate of the full flood hydrograph for the design event.

Hydrologists often prefer the statistical method because it uses peak flow data directly, is based on a larger dataset and can more easily assimilate local data.

Using a hybrid method

If a flood hydrograph is needed, you can use a hybrid method to fit a hydrograph shape to the peak flow estimate 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, typically many thousands of years, from which individual design floods or sequences of design floods can be extracted. It avoids some of the assumptions of FEH methods and is worth considering on catchments where there are complex combinations of factors that affect flood levels.
- Direct rainfall. This involves modelling rainfall-runoff processes using a 2D hydraulic model to represent flow pathways across the catchment terrain. These models typically assume that all runoff occurs as overland flow. This is not a good assumption in most rural areas, and so the direct rainfall approach is most appropriate for surface water flood modelling in urban areas.

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.

Flood frequency is best estimated from gauged data. These guidelines offer advice on how to obtain gauged data and review data quality, in particular the accuracy of rating equations. The availability and the quality of gauged 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 gauged data is available. Selecting donor catchments is a subjective process. These guidelines offer advice on this drawn from the FEH, more recent research, and the accumulated experience of many users.

Confidence and uncertainty

By its very nature, flood estimation is an uncertain science, and this uncertainty is probably greater than many hydrologists realise. Even many weeks of work won't produce a definitive statement on the magnitude of a 1% probability flood or the rarity of an observed event. These guidelines offer advice on identifying sources of uncertainty. They provide methods for calculating confidence limits for flood estimates derived using standard FEH methods.

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 residual uncertainty 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.

Reviewing hydrology reports

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

The guidelines address these and other comments by including sections on assumptions and limitations (see Chapter 5: Assumptions, limitations and uncertainty), a flood estimation report template (LIT 11833) and a hydrology review template (LIT 17618).

The flood estimation report template 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.

1 Introduction

1.1 Purpose, scope and definitions

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. Other aspects addressed include levels of competence and supervision.

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 Template to enable robust recording and quality assurance of the results.
- a Hydrology Review Template for reviewing flood estimates.

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.

These guidelines are managed by the Flood Hydrology team within Evidence & Risk, part of Incident Management and Recovery. Send any comments or suggestions to FloodHydrology@environment-agency.gov.uk

Scope

These guidelines focus on methods used for flood estimation for river (fluvial) flood management and reservoir safety. The standard methods used for these applications are the FEH procedures and their successors. These guidelines cover the standard methods and their variations for different applications, including reservoir safety, lowland (pumped) catchments, small catchments, urban catchments and groundwater-dominated catchments.

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

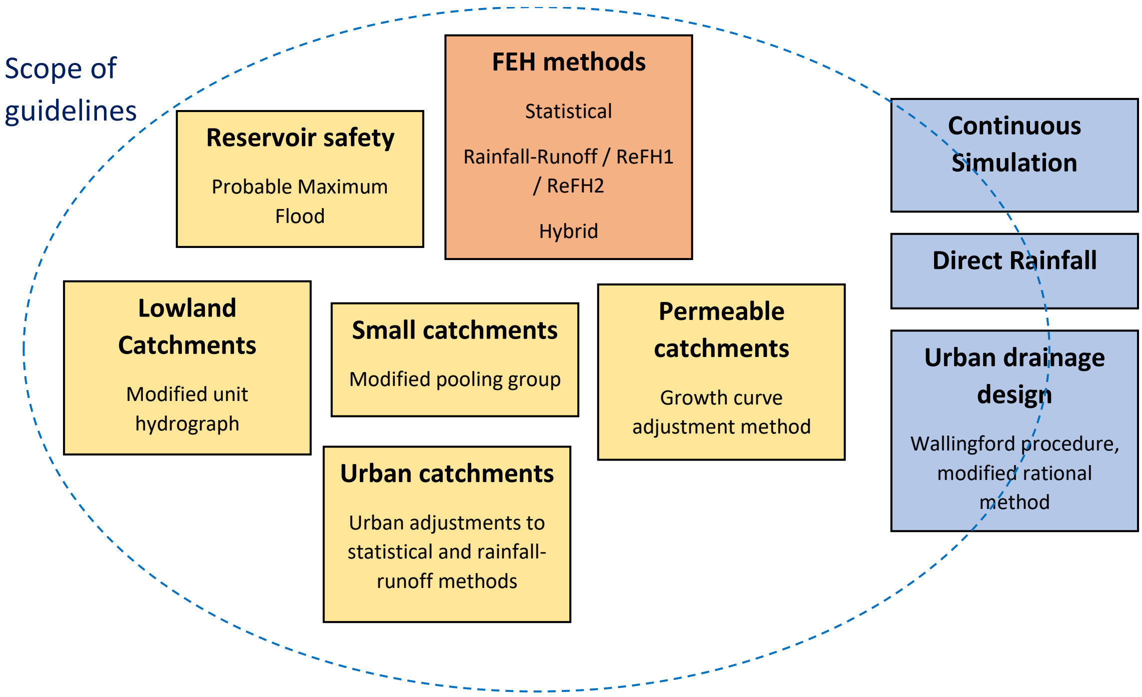


Figure 1: Diagram showing applications and methods covered by these guidelines

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.

! Important You must refer to the FEH and other relevant publications, in addition to these guidelines. These are referenced in these guidelines and listed in the References section.

Using alternative methods

You may sometimes need to depart from these guidelines and use alternative methods. When you do, the project scope or the proposal must make this clear and be confirmed by the Environment Agency's Project Manager. Your flood estimation report must explain and justify the decisions made. Alternative methods must be proven and accepted within the hydrological community (for example, peer-reviewed and published).

Defining the frequency of flooding: return periods

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

The FEH mainly uses a return period based on analysis of annual maximum (AMAX) floods (FEH Volume 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.

Presenting results to non-specialists

When presenting results to non-specialists, use the annual exceedance probability (AEP). Non-specialists may incorrectly associate the concept of return period with a regularity of occurrence rather than an average recurrence interval.

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).

Return period on AMAX scale (years)	AEP (%)	Return period on POT scale (years)
1.6	63	1
2	50	1.5
5	20	4.5
10	10	9.5
25	4	25
50	2	50
75	1.33	75
100	1	100
500	0.2	500
1,000	0.1	1,000

Table 1: Relationship between return periods and AEP

1.2 Obtaining the FEH reports and software

Obtaining the Flood Estimation Handbook (1999) report and updates

Information about the FEH is provided on the UKCEH website. Hard copies are available to purchase, and downloadable pdf files are available for free using the links on the website. The website has a list of FEH errata/corrigenda. Make hard-copy corrections to your copy of the FEH.

Updates to the FEH methods are available in the following reports, available online or on request from the Environment Agency.

- Science Report FD1919: FEH Catchment Descriptor URBEXT2000 (2005)
- 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).
- The Revitalised Flood Hydrograph Model ReFH2: Technical Guide (2019).
- Science Report FRS18087: Development of interim national guidance on non-stationary fluvial flood frequency estimation (2020).
- Science Report SC090031/R0: Estimating flood peaks and hydrographs for small catchments (Phase 2) (2022).

Software for undertaking FEH calculations

At the time of writing (June 2022), the latest releases of the web applications and software packages most commonly used to apply FEH methods are:

- FEH Web Service https://fehweb.ceh.ac.uk/. This is a pay-per-use application developed by UKCEH and administered by Wallingford HydroSolutions.
- WINFAP 5 (released in 2021). This is a licensed software product available from Wallingford HydroSolutions. https://www.hydrosolutions.co.uk/software/winfap-5/
- ReFH2.3 (released in 2019). This is a licensed software product available from Wallingford HydroSolutions. https://www.hydrosolutions.co.uk/software/refh-2/

Alternative implementations of some FEH methods are available. We do not mandate use of any particular software package, so long as you can demonstrate that any alternative software correctly implements the methods. The ReFH2 method is protected by commercial rights and can only be implemented using the Wallingford HydroSolutions software.

Examples of alternative software for FEH methods include:

- Various hydraulic modelling software packages which have the facility to implement the FSR/FEH/ReFH2 rainfall-runoff methods, such as FloodModellerPro. Currently, the ReFH2 method can only be accessed in conjunction with the Wallingford HydroSolutions ReFH2 licensed software.
- A package, UKFE, developed by Anthony Hammond in the R language, freely available from https://CRAN.R-project.org/package=UKFE. This implements the FEH Statistical method and the ReFH1 rainfall-runoff model, along with other utilities for flood estimation.
- The Open Hydrology Auto-Statistical software, freely available from https://github.com/OpenHydrology/OH-Auto-Statistical. This claims to implement an automated version of the FEH Statistical method.
- In-house software used by consultants.
- A spreadsheet developed for the Environment Agency to estimate the probable maximum flood, PMF (LIT 58205, available on request from the Environment Agency).

For some applications, older versions of the FEH software are adequate and may be preferable in some cases. For example, some studies may have a large number of subject sites, but WINFAP 5 is limited to analysing only one site at a time, while earlier versions could analyse multiple sites. Some analysts also prefer to handle most calculations within a spreadsheet rather than within the software packages.

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, meteorology, soil science and hydrology. An enquiring mind and a determination to challenge underlying assumptions in datasets and seek out facts are essential. Analysts need to think, at all stages, about the problem they are solving.

Attending training courses should provide some basic knowledge and competence, but it cannot fully equip you for undertaking or reviewing complex or high-risk flood studies. Skills are best acquired through supervised “on-the-job” experience and supported by reading the FEH reports and associated literature.

Competency framework

A competency 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. The competency framework 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.

All studies should be approved by an analyst who has not carried out or supervised the study. The competence criteria should be interpreted as minimum levels. 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.

Simple and routine studies

- Examples: Preliminary assessment, culvert capacity check, low risk development application
- Value of flood defence works or damages: <£50,000
- Indicative timescale for flood estimation: less than 2 days
- Analyst competence: Level 1 (hydrologist with minimum approved experience in flood estimation)
- Supervision and approval competence: Level 2 (senior hydrologist)

Moderately complex studies

- Examples: Small flood mapping study or medium-risk development application
- Value of flood defence works or damages: <£250,000
- Indicative timescale for flood estimation: 2 to 10 days
- Analyst competence: Level 2 (senior hydrologist)
- Supervision and approval competence: Level 3 (senior hydrologist with extensive experience of flood estimation)

Difficult studies

- Examples: Medium flood mapping study or outline business case
- Value of flood defence works or damages: <£2,000,000
- Indicative timescale for flood estimation: 2 to 4 weeks
- Analyst competence: Level 2 (senior hydrologist)
- Supervision and approval competence: Level 3 (senior hydrologist with extensive experience of flood estimation)

Very Difficult studies

- Examples: Major scheme design or high-risk project
- Value of flood defence works or damages: >£2,000,000
- Indicative timescale for flood estimation: more than 1 month
- Analyst competence: Level 3 (senior hydrologist with extensive experience of flood estimation)
- Supervision and approval competence: Level 3 (senior hydrologist with extensive experience of flood estimation)

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 to Environment Agency staff:

- 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 (hydrologist with minimum approved experience in flood estimation). 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.

Consultancy staff

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

1.4 Managing flood estimation studies

Project managers are responsible for defining the purpose of the flood estimates they need and ensuring that they are used appropriately.

Commissioning a flood hydrology study

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.

Consider installing temporary flow loggers at the start of a study, if the catchment is ungauged or has poor quality records. As little as 18 months of data can significantly improve confidence in flood estimates.

Method statements

For all but simple or routine projects, establish a breakpoint 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.

Allow sufficient time in your programme for the method statement to be checked and any changes to be agreed. A minimum of 4 to 6 weeks should be allowed for discussions and changes.

Reviewing calculations

Completing a flood estimation report 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 the project's needs. Allow sufficient time in your programme for the flood estimation report and calculations to be checked and any changes to be agreed. A minimum of 4 to 6 weeks should be allowed for discussions and changes.

The flood estimation report template (LIT 11833) 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, justify their decision making and allow calculations to be fully reproduced for checking.

Calculations should be checked using the hydrology review template (LIT 17618). This allows comments to be tracked and responses recorded.

Signing off responsibility

! Important You must sign off the results of the flood estimation to confirm that they are fit for the purposes of the study.

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

The calculations will be considered complete when all comments in the hydrology review template have been resolved to mutual agreement.

2 Hydrometric data and catchment descriptors

2.1 Hydrometric data

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 or low flows.

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.

Peak Flow Data

A peak flows dataset is hosted by the National River Flow Archive (NRFA). It is updated on an annual basis. Submit any errors or suggestions relating to the NRFA peak flows dataset to nrfa@ceh.ac.uk.

Use the NRFA Peak Flow dataset as your primary source for flood peak data. You can download the latest version from the link above. If using WINFAP software, you should make sure it is set up to read in the correct Peak Flow dataset when creating pooling groups.

The NRFA includes suitable flow measurement stations from all of the UK gauging authorities. The website provides information on each gauging station in the dataset, including:

- Annual maximum (AMAX) flow and level data.
- Peaks-over-threshold (POT) flow and level data.
- Flow rating histories.
- Photographs and commentary on the station structure.
- Guidance on the quality of data.

Indicative suitability

Stations are classified according to their indicative suitability for use in flood estimation. The categories are:

- “OK for pooling”: The station is able to measure extreme floods with reasonable confidence and can be considered for QMED estimation and inclusion in pooling groups in the statistical method. The criteria for inclusion in this category are that AMAX3 (the third largest annual maxima flow) is likely to be within 30% of its true value, or AMAX2 (the second largest annual maxima flow) if the record length is less than 13 years. The accuracy of AMAX1 (the largest annual maxima flow) must also be considered.
- “OK for QMED”: The station is able to measure up to moderate flows with reasonable confidence and can be considered for QMED estimation. The requirement for inclusion in this category is that QMED is likely to be within 30% of its true value.

The indicative suitability relates only to the quality of flow data at the station, not the record length or the nature of the catchment. This means that some stations classed as suitable should be avoided in some circumstances. For instance, station 27032, Hebden Beck at Hebden, is unlikely to be a suitable donor for QMED on nearby catchments because the upper part of the topographic catchment drains via a cave system which discharges into a neighbouring catchment. The consequence is that peak flows are lower than would be expected from the topographic catchment area.

The final choice of what stations to use for what applications is subjective. Hydrologists will have to balance similarity of catchments and flow statistics against the quality of flow data. There is further discussion on this in Chapter 3: Choice of methods.

Limitations of the NRFA Peak Flows Dataset

For some lower risk studies, you can use the NRFA peak flows dataset without any need for further review or searching for data.

If you are using the NRFA peak flows dataset in more detailed studies, there are limitations that you will 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 only gauges can be useful sources of evidence for flow magnitudes, for example for estimating time-to-peak.
- The dataset will typically lag a year or two behind the present, so there will often be the opportunity to update flood peak series. This is more worthwhile at times when NRFA is less up to date or when there has been a recent major widespread flood. If you are using WINFAP 5, consult the

software help to find out how to make changes to the flood peak dataset used in pooling. The procedure is different from that used in previous versions of WINFAP.

- Some stations have flow data in the NRFA that currently differ from the data held on the Environment Agency's WISKI database. These differences should be identified and explained where possible.
- The indicative suitability classification is a starting position for data quality. More detailed rating reviews are often worthwhile and can result in changes to the classification of stations.

Temporary flow loggers

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 (FEH Volume 3 Section 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 (FEH Volume 3 Section 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.

Visualising peak flow data

Visual examination of flood peak data is always worthwhile (*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 (FEH Volume 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 section 4.1 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 (FEH Volume 3 Section 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 other station(s) on the same or neighbouring river, or comparison with rainfall data. You may need to adjust statistical method estimates for non-flood years.

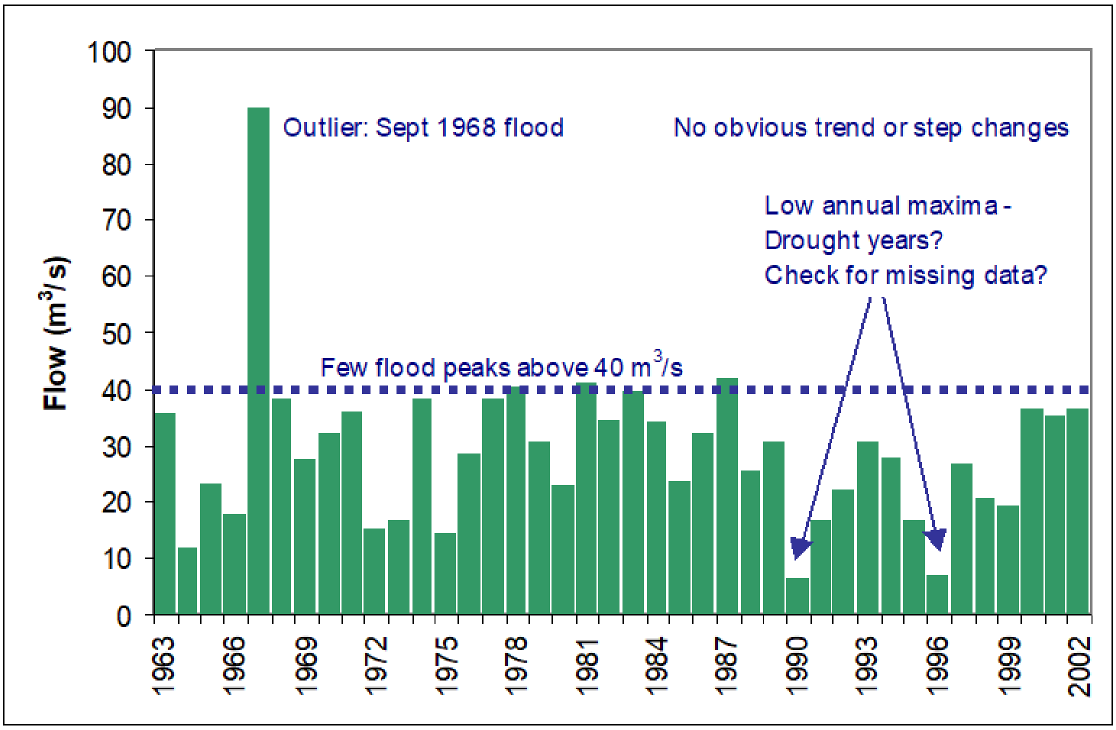


Figure 2: Example annual flood peak time series for the River Stour at Langham, Essex/Suffolk.

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 (*Figure 3*).

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 groundwater-dominated catchments, you can investigate the importance of baseflow, for example by plotting an annual hydrograph.

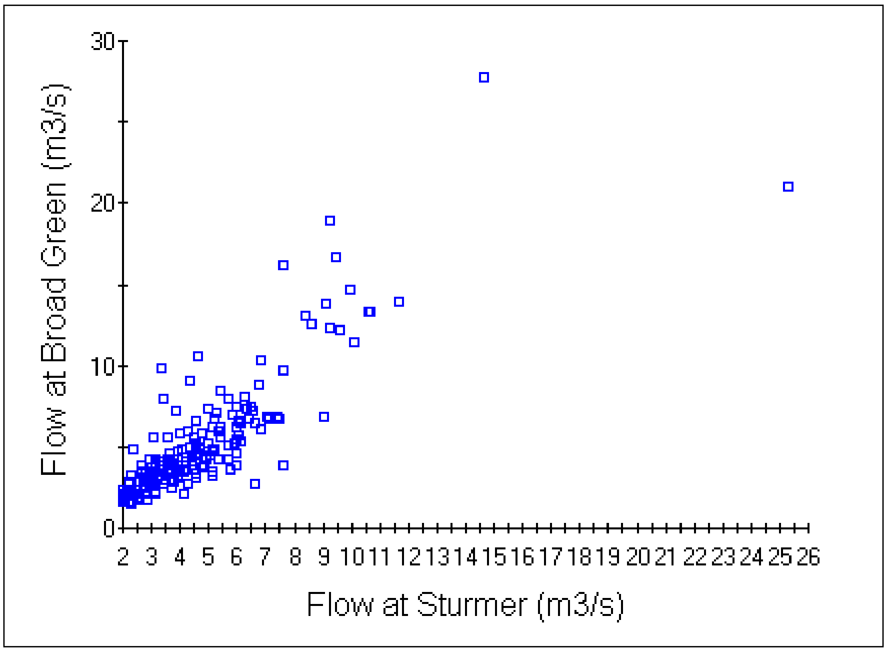


Figure 3: Example flood peak correlation plot, using flood peaks (from POT data) on adjacent tributaries of the River Stour in Essex/Suffolk. The catchments are similar in size, soils and geology. However, the Stour Brook at Sturmer is affected by urbanisation and a major flood storage scheme. The correlation 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

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.

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.

! Important Search for and use any more recent rating reviews or high flow spot 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.

Rating 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 already available, for example from another study.

Some studies also request 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 further guidance on rating reviews, see Ramsbottom and Whitlow (2003) and Environment Agency guidance LIT14089 "High flow rating curve development using hydraulic models".

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. Rather than being purely a statistical exercise, the review should consider the nature of the gauging station. 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.

Information about existing and closed stations and their history 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. Other sources of information may include station files held by UKCEH, reports of earlier flood studies, and reports of previous hydrometric improvements.

The information collected should include:

- The history of the station, such as its original purpose and any changes in the channel, structure, or rating equations.
- Whether the rating is solely theoretical, theoretical but checked by spot gaugings, or based solely on gaugings (empirical).
- If the rating is theoretical, how it was derived.
- If the rating is empirical, how it has been extrapolated for measuring flows above the calibrated range. 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) for further guidance on this.
- How spot gaugings are collected and whether the measurements include flow through parallel channels or the floodplain.

- When spot gaugings were taken, and whether there has been any change to the hydraulic control or channel conditions since that time.
- 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 different flow dynamics on the rising and falling hydrograph limb, e.g., due to storing flood water).
- How the station is classified, according to the Gauging Station Data Quality system. This assesses whether measurements for flows around half of QMED are reliable (based on site and station factors) and checks spot gaugings. See Environment Agency R&D Report W6-058 (JBA Consulting, 2003).

You can summarise some of the information listed above on a plot showing the rating curve against flow gaugings (*Figure 4*), showing the scatter in the spot gaugings (an indication of uncertainty) and how far the rating has been extrapolated for measuring the highest flow on record (AMAX1) and 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 useful to plot the channel cross-section on a second x-axis.

You can statistically assess the accuracy of the rating, if necessary, but this should be done with caution. Goodness-of-fit statistics such as R2 tend to be dominated by the large number of low flow gaugings and may not reflect the quality of the rating for high flows.

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.

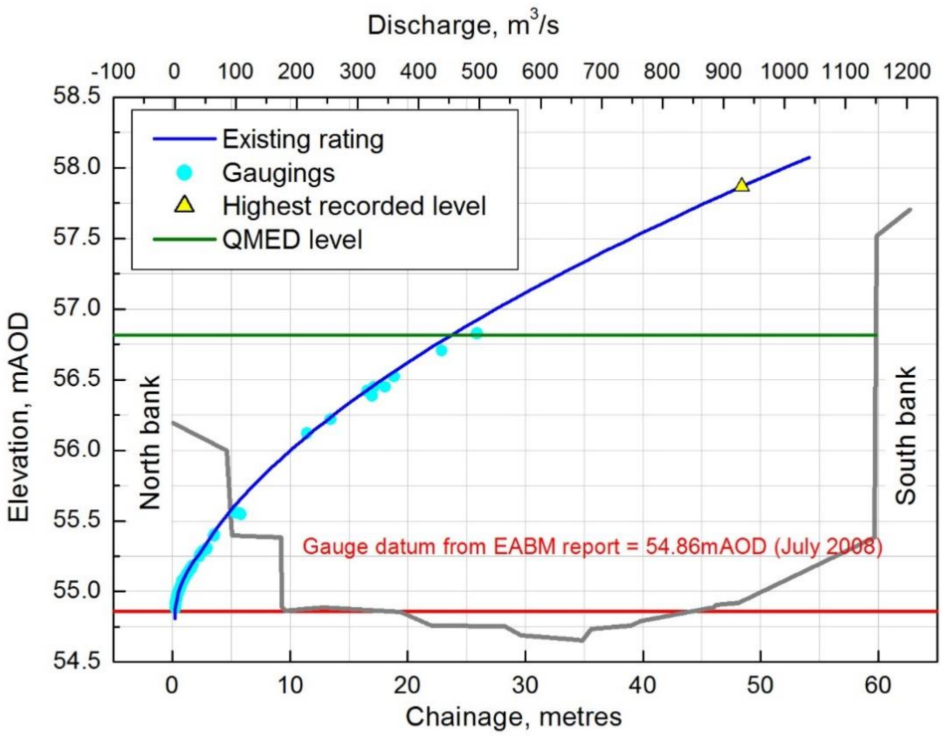


Figure 4: Example rating curve plot, showing the rating curve plotted against flow gaugings on the South Tyne at Haydon Bridge. The plot also shows in grey the channel cross-section at the gauge site, on the same vertical scale as the rating curve.

Results of the review

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

In some cases, it is appropriate to develop a new rating if there has been new high flow spot gaugings or other sources of evidence such as:

- A new hydraulic model that represents out-of-bank flow conditions.
- A new 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 Environment Agency's local Hydrometry and Telemetry team and ensure any revisions to the rating are fed back into both the Environment Agency's WISKI archive and the NRFA peak flows dataset.

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, and 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 in a project, if a new or improved hydraulic model of the reach that includes the gauging station is developed. 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

Flood event data (for example, flow or level hydrographs and rainfall timeseries) can be used to estimate model parameters for rainfall-runoff methods. 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. Refer to FEH Volume 4 Section A.4.3 for further guidance on data quality checks for flood event data.

Rainfall data

Flood event analysis must be based on catchment-average rainfall data. On smaller catchments with a nearby 15-minute recording rain gauge, 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 rain gauges (which are more numerous) can also help improve the averaging.

Radar-derived rainfall data can provide a valuable additional source of information. It may show cells of intense rainfall that were missed by rain gauges. Within the Environment Agency, HYRAD software provides catchment-average rainfall accumulations derived from radar. It also displays the “best rainfall observation” which merges point rainfall intensity measurements with radar images.

Evaporation data

Potential evaporation data is required to set the initial soil moisture when estimating model parameters from observed data or simulating observed events using the ReFH1 and ReFH2 models. 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 data sources described in the [Section 4.3 guidance on estimating model parameters for ReFH rainfall-runoff methods](#).

2.2 Flood history and palaeoflood data

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 (FEH Volume 1 Section C). Uncovering forgotten information can also add credibility to the analysis and contribute to public understanding of flood risk (FEH Volume 1 Section 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.

For detailed guidance on the value of historical reviews and the methods for acquiring and using historical data, refer to LIT 14710 "Using local data to reduce uncertainty in flood frequency analysis" and Bayliss and Reed (2001), and Section 4.2 guidance on incorporating historic data in single-site analysis.

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, 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 also 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 LIT 14710 “Using local data to reduce uncertainty in flood frequency analysis” for information and examples of how to incorporate palaeoflood data.

How to find and evaluate historical flood data

Sources of data

The main sources of historical flood data 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 website that can be searched by place name, river basin or date. There is also an interactive map search option, although many entries have not yet been georeferenced.
- The British Chronology of Flash Floods, developed for the SINATRA project (Susceptibility of catchments to INTense RAinfall and flooding) and extended by Archer and Fowler (2021). This rich resource includes nearly 8,000 entries describing flash floods and the impacts of hail and lightning, covering the period from 1700 to 2020.
- 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 the 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*).
- 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.

Figure 5: Flood marks on the River Tay at Perth.

Evaluating the historical information

Refer to Bayliss and Reed (2001) Chapter 3. Consider the format and authenticity of the information. When 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 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.

Define the period of time 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 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).

Understand the impact 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. However, you should not use the fact that the catchment or channel has changed as a reason 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.

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. In any case, extreme flows measured at gauging stations also 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.

Incorporate the historical flood data in the flood frequency analysis

Refer to the later section on incorporating historic data in statistical analysis.

2.3 Catchment descriptors

Ten catchment descriptors are used in FEH flood estimation procedures, allowing flows to be estimated in ungauged catchments. The definition and derivation of each catchment descriptor is provided in FEH Volume 5.

The numerical distribution of values for 943 gauged catchments is given for many descriptors in FEH Volume 5. This provides an indication of what the normal range of values might be. The other catchment descriptors are currently not used in the FEH methods but provide extra information for the analyst to use when comparing catchments.

! 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 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.

Source of descriptors

Catchment descriptors may be obtained from the FEH web service, which replaced the FEH CD-ROM in 2015. Descriptors must be purchased for each catchment or point required.

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. These are defined in Kjeldsen and others (2008).

Most catchment descriptors have not been updated from the FEH CD-ROM v3. The main differences (at the time of writing in June 2022) 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.

BFIHOST19

BFIHOST19 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, which may occur in the future.

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.

! Important Use BFIHOST19 in place of BFIHOST for all future work.

Checking and amending catchment descriptors

Do not use catchment descriptors obtained from the FEH web service without, at least, a rudimentary check of key descriptor values and update to URBEXT. You should also investigate any other local anomalies that might affect hydrological response, for example, unusual land cover or land use.

! Important You should take account of the derivation and purpose of catchment descriptors when making amendments and record any adjustments fully in the flood estimation report so that they can be checked and are reproducible.

Catchment boundaries

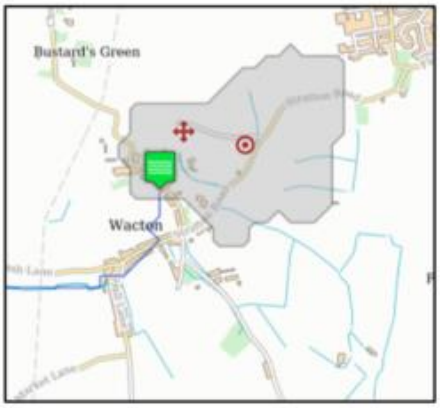
The FEH web service catchment boundaries are calculated from the Integrated Hydrological Digital Terrain Model (IHDTM). With a grid resolution of 50m, this is much coarser than newer terrain datasets such as LIDAR.

! Important 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.

It's particularly worthwhile to verify catchment boundaries:

- In small catchments (

FEH web service: catchment area is 0.55 km².



Catchment boundary from Nextmap DEM: area is 2.01 km².

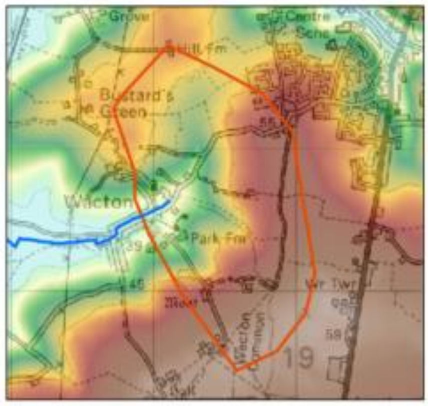


Figure 6).
- In flat or fenland areas.
- Where there are artificial influences such as reservoir catchwaters, diversion channels, canals, embankments, mines, or pumps.
- Where there may be groundwater interactions (consult geological and hydrogeological maps and memoirs).

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. Recalculate the catchment AREA to update the descriptor value to reflect the new catchment boundary.

It is most important to ensure that the AREA catchment descriptor 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.

FEH web service: catchment area is 0.55 km².

Catchment boundary from Nextmap DEM: area is 2.01 km².

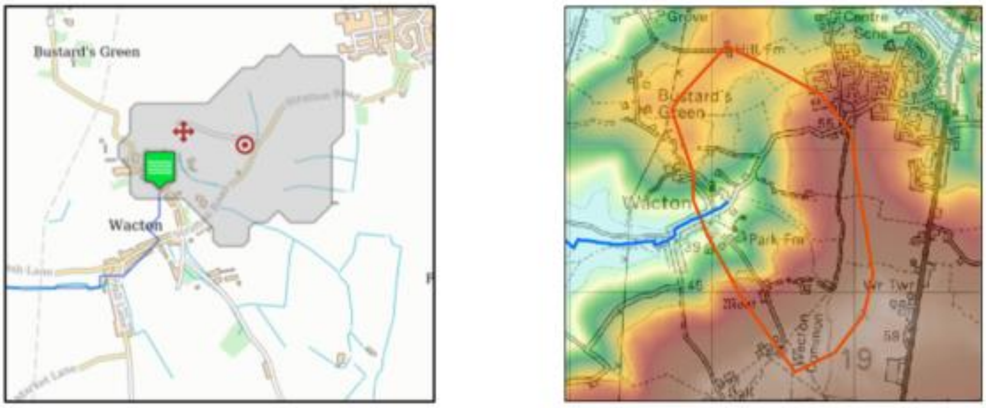


Figure 6: Maps showing a catchment boundary error at Wacton Stream, Norfolk.

Soil properties

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 (FEH Volume 5 Section 5.4).

The soil descriptors (SPRHOST, BFIHOST and/or BFIHOST19) should be recalculated if the catchment boundary significantly changes.

You can check soil characteristics against soil and geology maps. 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 FEH Volume 5 Table 5.1. To derive BFIHOST19, refer to the coefficients in Griffin and others (2019). Use BFIHOST19 in preference to BFIHOST in all new studies.

When reviewing older studies, you should beware of 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.

Take particular care to update SPRHOST when estimating floods for reservoir safety in catchments including soil HOST class 4. See Section 6.5 for more guidance.

Urban extents

Check the urban area defined by the FEH web service against current mapping. The FEH web service provides a layer which shows the urban areas defined by URBEXT1990 and URBEXT2000. This is often reasonable, and the only adjustment 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. The urban expansion factor (UEF) equations are:

- URBEXT1990
$$UEF = 0.8165 + 0.2254\ \tan^{-1}\{(Year - 1967.5)/21.25\}$$
- URBEXT2000
$$UEF = 0.7851 + 0.2124\ \tan^{-1}\{(Year - 1967.5)/20.32\}$$

The term within the parentheses { } is in radians.

To update the value, the original URBEXT1990 or URBEXT2000 value should be multiplied by the UEF calculated for the year of interest (usually the current year that the study is being undertaken in).

URBEXT should be fully recalculated if significant changes have been made to the catchment boundary, or if 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 (FEH Volume 5 Section 6.5.5 and Bayliss and others (2007)):

- URBEXT1990 = URBAN / 2.05
- URBEXT2000 = 0.629 URBAN

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).

Flood attenuation due to reservoirs and lakes (FARL)

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 or adjust for any significant changes to the catchment boundary, by manually calculating FARL following the procedure in FEH Volume 5 Section 4.3.

Drainage path length (DPLBAR)

If you make significant changes to the catchment boundary then it is also worth recalculating DPLBAR. This can be undertaken using the equation in FEH Volume 5 Section 7.2.4 or by deriving an exponent by regression on the catchment area for the specific catchment in question.

Checking and adjusting other catchment descriptors

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 (FEH Volume 5 Section 7.2.1). In this case, many of the catchment descriptors can be adjusted using a simple area-weighting method (FEH Volume 5 Section 7.2.2), with the exception of FARL and DPLBAR as noted above.

Refer to the section on distributed application of rainfall-runoff methods for important advice on estimating descriptors for intervening subcatchment areas.

3 Choice of methods

3.1 Overview

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.

There are two principal techniques for flood estimation available:

- The FEH statistical method.
- The Revitalised Flood Hydrograph (ReFH) rainfall runoff model, with two versions: ReFH1 and ReFH2.

ReFH2 uses a similar underlying rainfall-runoff model structure as ReFH1 for rural catchments, but with improved procedures for estimating model parameters and defining the design storm, and an improved method for urban catchments. In these guidelines, the model structure that underlies both ReFH1 and ReFH2 methods is referred to as the ReFH model.

Other FEH and non-FEH methods for flood estimation include:

- The FSR/ FEH rainfall-runoff method. This rainfall-runoff method reported in FEH Volume 4 is superseded for most applications by the ReFH model but is still used for some aspects of reservoir safety work.
- A precautionary method of estimating greenfield runoff using freely available data.
- Continuous simulation.
- Direct rainfall modelling.

Maxims for flood frequency estimation

The FEH offers six maxims (FEH Volume 1 Section 2.2), summarised below. Use the six maxims to guide all aspects of the choice of method.

1. Flood frequency is best estimated from gauged data.

2. 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.
3. 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.
4. The most appropriate choice of method is a matter of experience and may be influenced by the requirements of the study and the nature of the catchment. Most importantly, it will be influenced by the available data.
5. In some cases, a hybrid method, combining estimates derived from statistical and rainfall-runoff approaches, is appropriate.
6. There is always more information. An estimate based on readily available data may be shown to be suspect by a more enquiring analyst.

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 reconciliation of estimates by different methods is a skilled task. 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' (FEH Volume 1 Section 5.1).

As the sixth maxim 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. 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.

3.2 A framework for choosing a method in larger projects

This section describes a framework for decision-making in larger projects. Choice of method is important and rarely straightforward. 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 "sense-check" any flood frequencies indicated by the hydraulic model. If necessary, they revisit the calculations.

If analysts follow this framework, there should be a reduced 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.

Framework procedure

This procedure covers 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.

1. Assemble information:

    - The project scope.
    - Maps.
    - Hydrometric data.
    - Flood history.
    - Other local data.
    - Previous studies.
    - Catchment descriptors.

2. Think about:

    - The type of problem.
    - The type of catchment.
    - The type of data available.

3. Write a method statement and agree this with the client and the Environment Agency, if required.

4. Undertake analysis at selected locations.

5. Select preferred method. Record the choice of method and agree this with the client and the Environment Agency, if required.

6. Undertake analysis at all sites required. Record the calculations and results in a flood estimation report. Agree these with the client and the Environment Agency, if required.

7. Check results for sensibility and consistency. If relevant, apply flows in a hydraulic model. Check modelled water levels and flood extents against local expectations. If necessary, return to Step 5 and revisit choice of method.

The need to think

Step 2 in the framework procedure involves thinking about the many factors that influence choice of method. 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.
  For example: Is a hydrograph needed or will a peak flow suffice? How will the flows be applied to any hydraulic model? Is the flood estimate needed for a reservoir spillway assessment? What return periods are required?
- Type of catchment.
  For example: Is it large? Groundwater-dominated? Urban? Pumped? Are there disparate sub-catchments? (FEH Volume 4 Section 9.2) Is there a reservoir? (FEH Volume 4 Section 8) Are there extensive floodplains? (FEH Volume 1 Section 3.1.2)
- Type of data available.
  For example: Is there a flood peak record? How good are the high flow measurements? Are flood event data available? What about flood history?

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.

3.3 Preparing method statements

Step 3 in the framework involves preparing a method statement. 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 (FEH Volume 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.

! Important 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.

Preliminary choice of method and software

Include a preliminary choice of method, or methods, with reasons. You should also explain what software you will be using for the calculations and demonstrate its suitability if required.

3.4 Choosing between the FEH methods

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 (FEH Volume 1 Section 5.6).

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 LIT 14710 "Using local data to reduce uncertainty in flood frequency analysis" for ideas on how to find and exploit such data.

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.

The FEH discourages users from choosing a method based on reasons such as:

- It gives the highest or lowest flow (FEH Volume 3 Box 7.1).
- It gives results that match those from a previous study (FEH Volume 1 Section 5.8).

Factors favouring the statistical method

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, therefore it is often preferable to design event (rainfall-runoff) approaches (Volume 1 Section 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 km². 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 (rainfall-runoff) approach

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 flood properties 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 (e.g. flapped), with the flow of water impeded by downstream conditions.
- The study involves designing works to counter the effects of a new urban development and/or storm sewer design.
- Rainfall and flow or river level data are available for five or more flood events that could be used to calibrate model parameters.
- 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 long return periods (200 – 1000 years) or for reservoir safety applications.

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.

Factors favouring continuous simulation

Continuous simulation approaches 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, contributions from different tributaries, or interactions with the tide.
- 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.

Factors favouring direct rainfall approaches

Direct rainfall approaches might be favoured in these circumstances:

- Flooding is generated mainly by overland run-off, for example in urbanised areas where surfaces are mostly impermeable.

Choosing between ReFH rainfall-runoff approaches

There are two versions of the ReFH rainfall-runoff model: ReFH1 and ReFH2. Both use the same underlying model structure to represent rural catchments.

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

Differences between ReFH1 and ReFH2

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

- ReFH2.3 uses revised equations for estimating model parameters from catchment descriptors.
- ReFH2.3 can construct the design storm using the FEH 2013 rainfalls.
- ReFH2.3 uses 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.
- ReFH2.3 uses separate summer and winter initial soil moisture (Cini) equations, while ReFH1 does not differentiate initial soil moisture by

season. This means ReFH1 can give higher flow estimates for summer storms, as it uses a wetter initial soil moisture than ReFH2.3.

- ReFH2.3 does not use 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.
- The ReFH2.3 software includes alternative parameter estimation equations which are recalibrated to the plot scale for estimating pre-development greenfield runoff rates.
- The ReFH2.3 includes the option to close the water balance over the event that is being modelled.
- The ReFH2.3 includes the facility to represent different runoff characteristics of urban areas, based on papers published in 2009 and 2013. The default parameters to represent urban runoff have been revised.

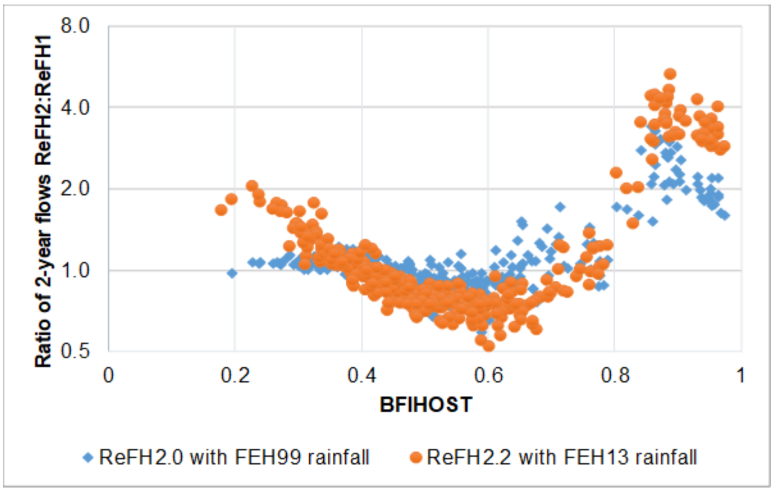
Comparing the performance of the ReFH1 and ReFH2.3 methods, the ReFH2.3 has reduced bias and factorial standard error when estimating QMED. In particular there is a very large improvement in performance on highly permeable catchments using ReFH2.3. There is an increase in peak flows for most low-BFIHOST and high-BFIHOST catchments and a decrease or little change in peak flows for BFIHOST of about 0.4 (*Figure 7*).

Choosing between ReFH1 and ReFH2

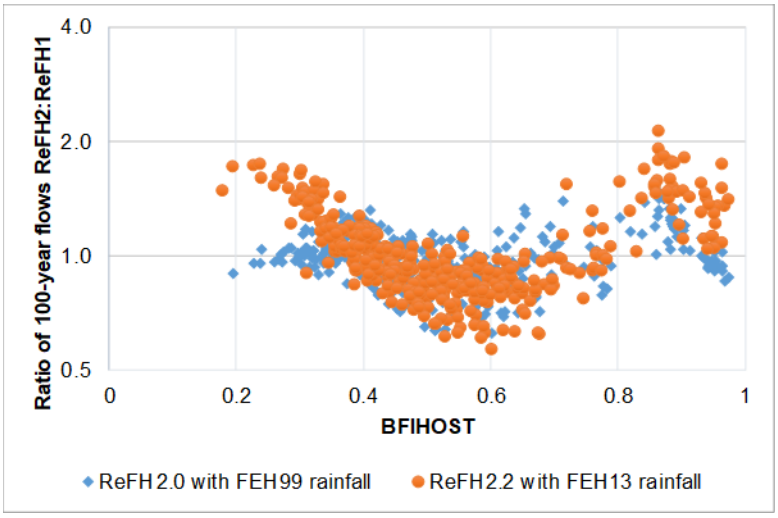
In most situations, apply the current version of ReFH2 in preference to ReFH1. Unlike ReFH1, ReFH2 is suitable for estimating design flood hydrographs on highly permeable catchments (BFIHOST > 0.65). It can also be applied at the plot scale.

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

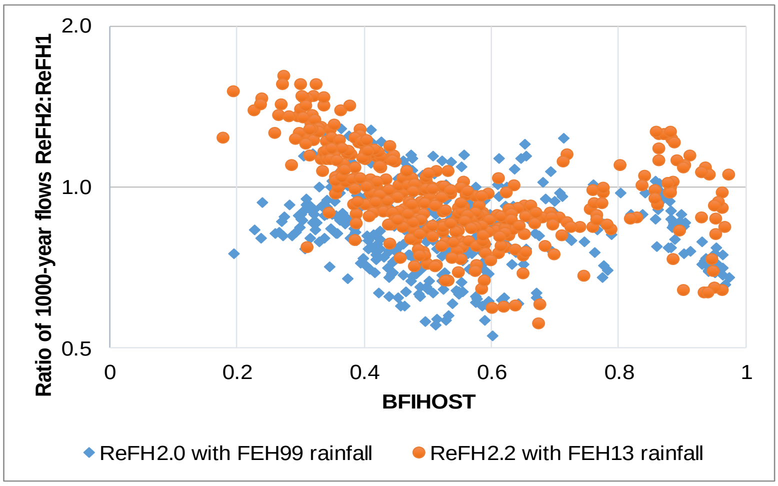
- When a rainfall-runoff method is being applied only to create the shape of the flood hydrograph, with peak flows estimated using another method (see hybrid methods). Caution should still be used when modelling distributed catchments with longer storm durations, where ReFH1 may over-estimate volume.
- When access to software creates difficulties with applying ReFH2, for instance if creating many inflows for a distributed 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 copy-paste errors and can create difficulties with testing critical storm durations. Scaling factors could be applied to match the peak flows estimated by ReFH1 to ReFH2 estimates, where differences are significant.



2-year return period



100-year return period



1000-year return period

Figure 7: Comparison of ReFH2 and ReFH1 for catchments across England and Wales as a function of BFIHOST, for return periods of 2, 100 and 1000 years.

Choosing water balance options in ReFH2.3

ReFH2.3 includes an option to close the water balance, 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 option available in the software for modelling observed floods. The option is not available for groundwater-dominated 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 (2019 a, b). In general, you should select the option to close the water balance.

When to apply ReFH methods with caution

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

- Large catchments. Design event methods that assume a uniform storm covering the whole catchment are best avoided in such cases, and ReFH2 can overestimate, particularly where FPEXT is high. 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. Usually, peak flow data will be available on major rivers, favouring a statistical approach.
- Catchments where a significant flood attenuation effect is expected, for example due to reservoirs, 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. For gauged catchments, comparisons to observed volume

frequency estimates can be used. 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 highly permeable catchments for ReFH1.

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

Hybrid methods

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 (FEH Volume 1 Section 5.6, FEH Volume 3 Section 10 and FEH Volume 4 Section 7.3). Hybrid methods are used commonly in hydrodynamic modelling studies.

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

(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, reducing the quality of 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. Do not use “fit to peak” options to scale hydrographs, as this can lead to significant overestimation of inflow volumes if longer storm durations are modelled. In distributed models, you could:

- Estimate catchment-wide uniform scaling factors, if attempting to reconcile modelled flows to a downstream statistical flow estimate.
- Estimate scaling factors for individual sub-catchments, by comparing statistical flow estimates for each sub-catchment with peak flow estimates from the design event method (using the critical duration storm relevant to each subcatchment). Then, change the storm duration to the catchment-wide uniform duration(s) identified as critical for the location of interest(s) and apply the scaling factors.

(b) Adjusting the parameters of the rainfall-runoff model until the simulated peak flows match the preferred values (FEH Volume 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 (FEH Volume 3 10.4)

This method involves constructing a symmetrical hydrograph to fit to the design peak flow, 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. This method may be preferable for catchments with significant storage (in aquifers, lakes or floodplains), unless the storage is to be modelled explicitly as part of the study.

The simplest approach is to use the shape of the largest flood on record. This is particularly attractive if the largest observed flood is thought to have a return period similar to that of the required design event.

Alternatively, 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 (*Figure 8*).
- Using a more sophisticated procedure, such as deriving the duration of exceedance of selected percentiles of peak flow, for example Archer, D., Foster, M., Faulkner, D. and Mawdsley, J. (2000).

It is worth checking for any tendency for larger floods to have a different shape than smaller floods, for example due to more floodplain attenuation or faster overland runoff processes.

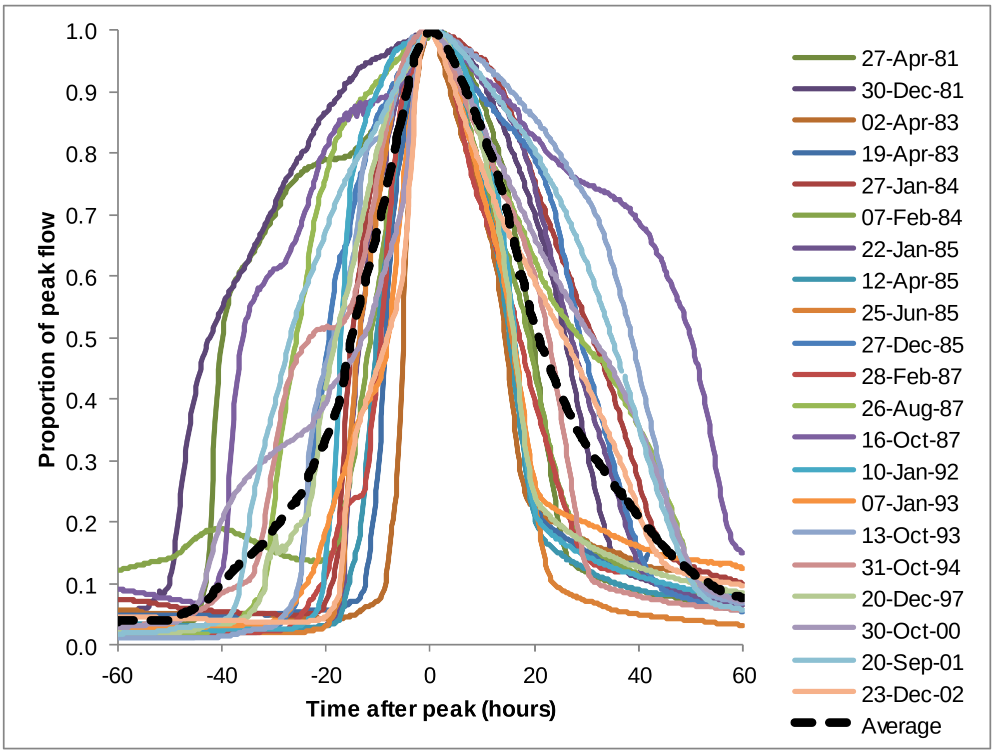


Figure 8: Flood hydrograph shapes for the River Ore at Beversham. 21 different floods are shown, normalised by their peak flow and aligned so that the peak occurs at the same time. The dashed line shows the average, calculated as the arithmetic mean of the proportional flow rate at each time step.

3.5 Checking results

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 below. 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.

- Are the results spatially consistent between upstream and downstream points and at confluences?
- 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 recommended, 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. For example, you can sometimes justify much higher growth factors on catchments containing areas of high permeability, where they are consistent with the flood history.
- 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?
- 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.
- Are the results consistent with the longer-term flood history?
- 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 decide the preferred method for flood estimation.

You can use the hydrology review template (LIT 11833) which includes the questions above and other possible questions. This template can be used by:

- Analysts checking their own work.
- Supervisors carrying out internal reviews.
- Project managers reviewing calculations.

4 Advice on flood estimation methods

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 are not intended to explain all aspects of flood estimation methods. 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.

4.1 Non-stationary methods

All the FEH methods (statistical and rainfall-runoff) 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. The statistical properties of the data series, for example its median and standard deviation, are assumed to remain constant through time. This means that the exceedance probability of any flow is constant throughout the period of record, i.e., the data represent a stationary process. Therefore, observations of past flood events can be used to represent the behaviour of present and future events. FEH methods are normally applied together with an allowance for the potential impacts of climate change, which are assumed to occur in the future.

If the flood frequency behaviour of a catchment is not constant over time (i.e., non-stationary), the peak flows are not identically distributed and so this fundamental 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.

The ReFH2 method also relies on an assumption of stationarity because it uses the FEH13 rainfall frequency statistics, derived from a stationary model of rainfall frequency. It also assumes that the way the catchment responds to rainfall, represented through the unit hydrograph, does not change over time.

The need to consider trends and other non-stationary behaviour is not new. Trend detection is mentioned frequently in the FEH (e.g., Volume 1 Section 12.5, Volume 2 Section 14.3, Volume 3 Chapter 21). In particular, FEH Volume 3 Chapter 21 provides guidance on detecting and account for trends and non-stationary behaviour in gauged records. Latest research has simply provided more accessible tools for undertaking non-stationary calculations (for example, *Figure 9*).

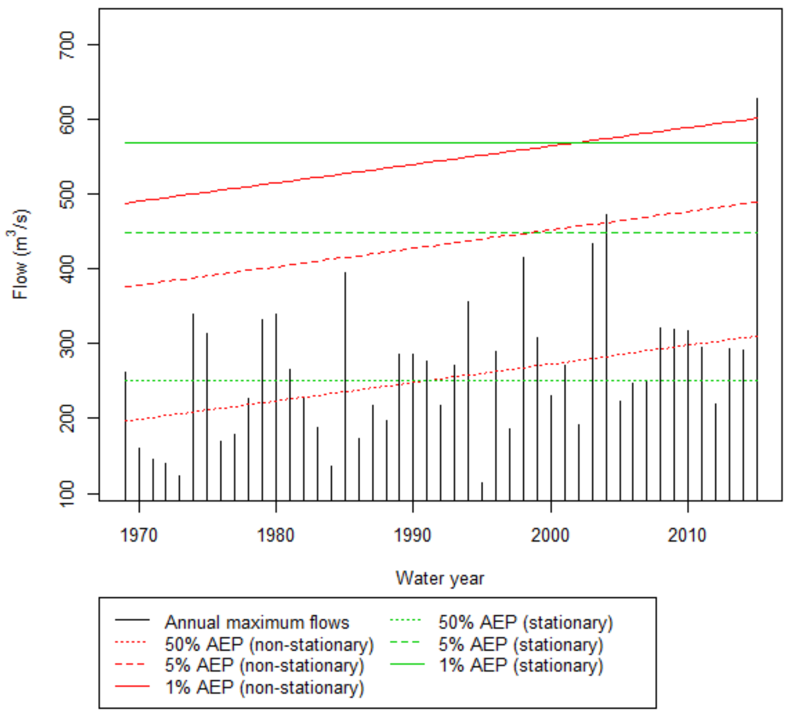


Figure 9: An example of non-stationary flood frequency analysis at the River Lune at Killington. The graph shows stationary and non-stationary estimates of flow for three probabilities. The non-stationary estimates increase over the period of record.

When to consider non-stationary methods

New research has introduced alternative methods of flood frequency analysis that allow for non-stationarity in annual maximum flows. Refer to the interim national guidance on non-stationary fluvial flood frequency estimation (Faulkner and Warren, 2020).

The current guidance on application of non-stationary methods is that they should be considered for use:

- In the appraisal of all fluvial flood alleviation projects submitting a short form business case or outline business case to the Environment Agency.
- In flood and coastal erosion risk management strategies if they have not already been submitted it to the Environment Agency for assurance and approval. For existing approved plans and strategies, we would not normally expect this advice to be applied until the next review, unless specific investment projects within them are planned before this.

For other projects, non-stationary methods are not currently required to be used. However, this does not replace the need for normal hydrological judgement. For example, if an analyst considers that the early part of a record is not representative of current conditions it would be good practice for the calculations to try to adjust or exclude it.

Therefore, consider non-stationary analysis:

- For the planning and appraisal of flood risk management schemes and for strategies.
- When there is a gauging station with a long record of reliable peak flows not far from your sites of interest.
- When you think the data may be non-stationary.

However, do not automatically abandon the assumption of stationarity in these circumstances.

Overview of interim national guidance

The interim national guidance on non-stationary fluvial flood frequency estimation provides:

- A guidance document for practitioners, which introduces the concepts of non-stationary analysis and provides a step-by-step guide to trend testing and non-stationary flood frequency estimation, including case studies.
- A software package, written in the R language, which allows hydrologists to easily carry out trend and change point detection and non-stationary flood frequency analysis using annual maximum flow data.
- A user guide to the R package.
- A science report explaining the development and testing of the methods and discussing results across the whole of England and Wales.

All of these are available from the FCERM research webpage, Development of interim national guidance on non-stationary fluvial flood frequency estimation.

The R package allows you to rapidly apply non-stationary analysis methods. There are two approaches available, one that models changes in flood frequency as a function of time and another which includes physical variables in the statistical model. The second approach can give a better model fit but it takes more effort to gather the data needed and to interpret the results.

Applying non-stationary methods

If you carry out non-stationary analysis, always do so alongside an equivalent stationary analysis.

The interim national guidance documents should be referred to in the first instance for details on non-stationarity methods and assumptions, and how to use the available R package tools.

We recommend a staged approach to assessing non-stationarity (*Figure 10*):

1. A scoping review to assess data availability and whether a significant trend is present. If so, continue to Stage 2.
2. Detailed analysis stage to check reasons for trend, calculate non-stationary flood frequency estimates and compare to stationary analysis. If significant impacts on flow estimates, continue to Stage 3.
3. Application of non-stationary findings to project.

An Environment Agency scoping template (LIT 56492) is available for recording the Stage 1 investigations to identify trends and step-changes.

Testing for trends and step-changes

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 and is available in the R package. 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.

Other tests that you could apply include the PELT and PETTIT tests for step-changes (both available in the R package), and the Mann-Whitney and Brown-Forsythe split sample tests (not currently available in the R package but can be implemented using other software tools). FEH Volume 3 Section 21.2 also suggests a number of methods for testing for non-stationarity.

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.

Visual assessment of trends in annual maximum flows and statistical trend tests are both useful initial screening steps. Neither are guaranteed to detect non-stationarity. So, if you have other reasons to suspect non-stationarity, consider applying non-stationary flood frequency analysis.

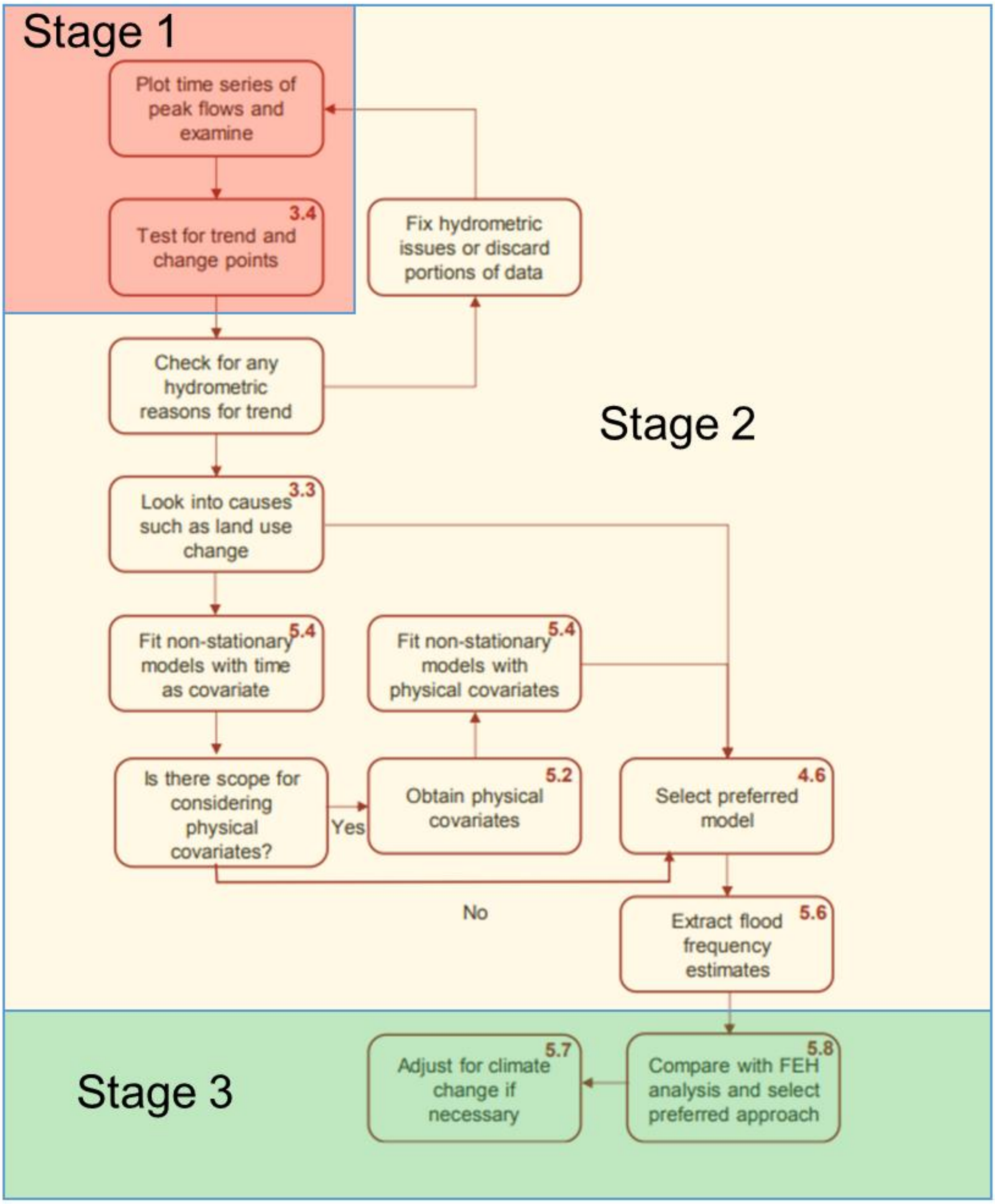


Figure 10: Process flow chart giving an overview of the steps to be followed during a flood estimation study where non-stationarity is a potential issue. The numbers in bold refer to sections in the Interim Guidance Practitioner Guide. Steps have been grouped into three stages for structuring non-stationarity investigations.

Identifying the cause of trends and step-changes

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 flows 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) and Hall and others (2014).

Consider the implications for flood frequency estimation

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 how you are planning to use the flood peak data, for example, as a subject site or donor, for estimating QMED only or for flood frequency analysis.

The aim is to estimate a flood frequency curve that is representative of present-day conditions. You should never extrapolate the trend into the future, as there is no guarantee that past changes will continue at the same rate.

If the trend or step-change 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 but are available in the interim guidance R package.

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. You should follow the interim guidance to make justified decisions over:

- Whether to vary the distribution location, scale, or both.
- Whether to vary properties with time, with physical covariates, or both.
- Which physical covariates to use and in what combinations.
- Which distribution gives the best fit to the data.

The non-stationary methods currently available can be applied only for statistical analysis at single gauged sites. There has been research into applying non-stationary analysis across a pooling group, but this has not yet developed a method recommended to be generally applied at ungauged sites.

Often a single site analysis is not the preferred method for flood growth curve estimation due to its high uncertainty and vulnerability to data quality issues at the site. However, there may be more confidence in QMED estimates at single gauged sites. Therefore, one option may be to use a non-stationary model for QMED, combined with a standard stationary pooled flood growth curve. A non-stationary QMED estimate could also be used as a donor for an ungauged site.

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), and the case study examples in the interim guidance practitioner guide.

4.2 FEH Statistical method

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.
- At pooled gauging stations to construct the pooled growth curve.

Figure 11 shows the main options for analysis in the FEH statistical method. There are other options that will also be preferable in some cases.

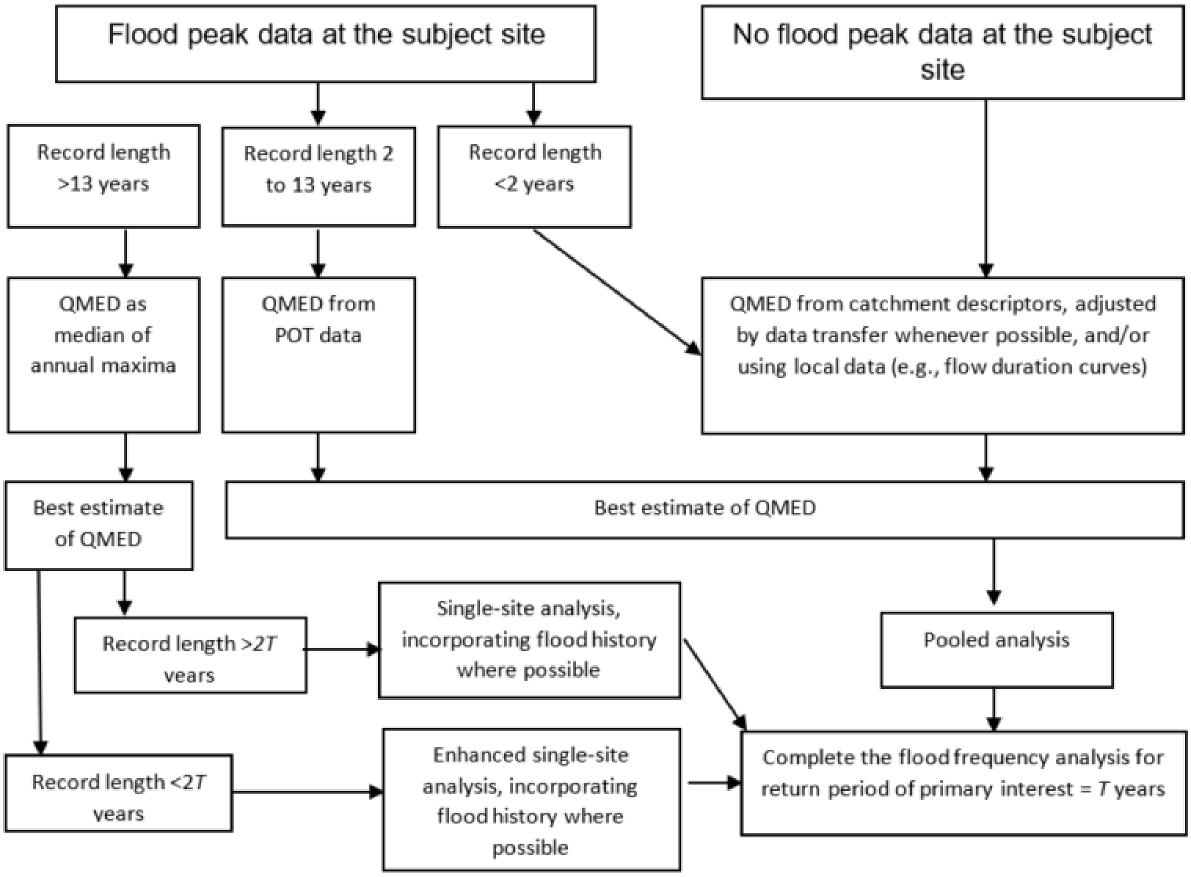


Figure 11: Flow chart for applying the FEH statistical method.

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 Peaks-over-threshold (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.

Software

The statistical method is usually applied using WINFAP. The current version of the software is v5, released in 2021. The core methods are similar to those in v3 but v4 and v5 have some additional options. Alternative software packages are also available, such as the UKFE R Package.

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.

QMED from peak flow data

When you estimate QMED from flood peak data, the gauged record at the subject or donor sites should be of sufficient length and quality (FEH Volume 1 Section 5 and Volume 3 Sections 2.2 and 12).

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. See earlier section on non-stationary methods. The FEH recommends that QMED is always adjusted for climate variation if the station's record is shorter than 14 years (FEH Volume 3 Sections 2.2 and 20).

The presence of tied values (identical annual maxima) in a flood series can compromise the estimate of QMED (FEH Volume 3 Section 2.3). You can identify these by examining the ranked flood peak data.

QMED from catchment descriptors

You should only consider estimating QMED from catchment descriptors alone as a last resort. Use the donor adjustment method and local data to reduce uncertainty wherever possible.

The QMED regression equation for estimating QMED from catchment descriptors provided in FEH Volume 3 has been superseded in 2008 by a revised equation in Science Report SC050050. You should always use this revised equation for estimating QMED from catchment descriptors.

The revised equation, which estimates QMED as if the catchment were rural, is:

$$QMED = 8.3062\ AREA^{0.8510}\ 0.1536^{\frac{1000}{SAAR}}\ FARL^{3.4451} 0.046^{BFIHOST^2}$$

Adjust this rural estimate of QMED for urbanisation where needed. Refer to the section on adjusting statistical estimates for urbanisation.

The equation was developed from data on 602 rural catchments, with catchment descriptors covering the following ranges:

- AREA: 1.6 - 4590 km²
- 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 more guidance on calculating confidence intervals from the FSE.

Use BFIHOST19 in place of BFIHOST in this equation. For most catchments this substitution changes QMED by less than 20%. On some small catchments the change can be much larger. The largest changes can be expected for very small catchments that comprise HOST class 11. For this HOST class, BFIHOST19 is 0.27, compared with the original BFIHOST value of 0.93. This leads to an 11-fold increase in QMED. This HOST class, which represents drained peat soils with shallow groundwater present, is only observed in 0.55% of the HOST dataset. It is frequently co-located with highly permeable soils, and this is thought to be a reason why the coefficient of BFIHOST for class 11 in the original classification is particularly poorly estimated.

The model for QMED cannot account for all catchment features. Avoid using it on artificially drained fenland catchments. You should not rely on the QMED equation when FARL<0.9 due to reservoirs (FEH Volume 3 Sections 3.3 and 13).

Improving QMED estimates using donor adjustment

QMED estimates from catchment descriptors can be improved by transferring data from nearby gauged catchments (donors). You should carry out data transfer in all cases where QMED is estimated at an ungauged site.

The main area where difficulty or disagreement can arise in QMED estimation is in the selection of donor catchments. Donor adjustment remains a process with no universally agreed rules and there is scope for disagreement even between experienced hydrologists. Since data transfer is 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.

In general, donor sites should be:

- Close to the subject site.
- Classed as suitable for QMED or shown to be suitable from a more in-depth review of data quality.

It is not essential for donor and subject sites to be similar in catchment area, BFIHOST and other catchment descriptors included in the QMED regression equation. However, in view of the uncertain relationship between BFIHOST and runoff, some analysts prioritise donors that are more similar in geology or soil type. You should consider using more than one donor. In most cases, you should moderate the adjustment using distance between catchment centroids (where this does not introduce an inconsistency between multiple subject sites).

Estimates of QMED can change significantly as a result of some donor transfers. However, the reduction in uncertainty as a result of applying data transfer is modest. *Figure 18* in Section 5.4 illustrates how the factorial standard error reduces only very slightly when donor adjustment is applied.

Adjusting QMED using a single donor

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 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:

$$QMED_{s,adj} = QMED_{s,cds}\left(\frac{QMED_{g,obs}}{QMED_{g,cds}}\right)^{a}$$

$$a = 0.4598\exp\left(-0.02d_{sg}\right) + 0.5402\exp\left(-0.4785d_{sg}\right)$$

where:

- $QMED_{s,adj}$ is the adjusted QMED at the site of interest.
- $QMED_{s,cds}$ is the initial estimate from catchment descriptors at the site of interest.
- $QMED_{g,obs}$ is the estimate from observed data at the gauging station (donor site).
- $QMED_{g,cds}$ is the estimate from catchment descriptors at the gauging station (donor site).
- “a” is a power term that reduces with distance between the catchment centroids.
- d_{sg} is the distance in km between the catchment centroids s (site of interest) and g (gauged donor site).

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, and the power term “a” is less than 0.1 when the inter-centroid distance is greater than about 76 km (*Figure 12*).

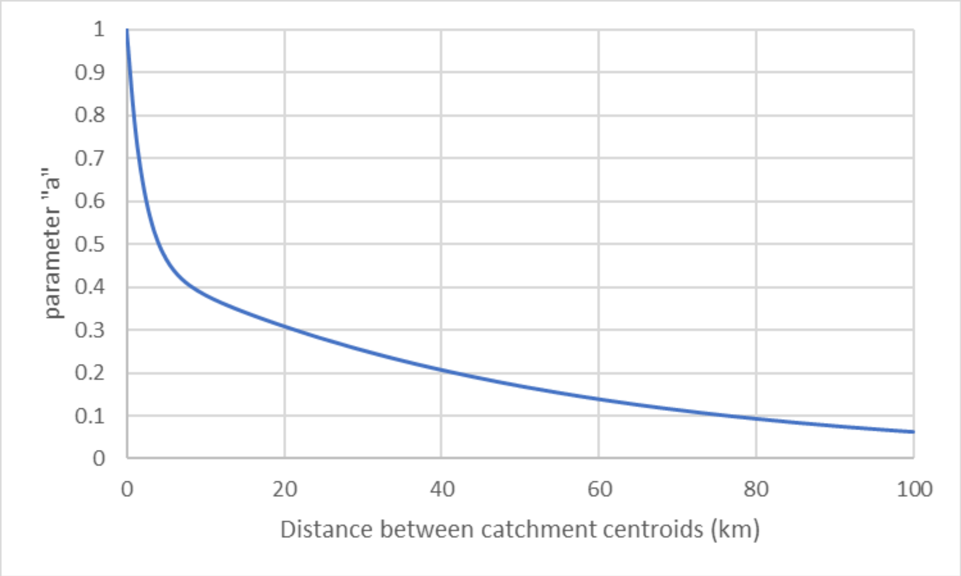


Figure 12: Graph showing the relationship between the distance between catchment centroids and the power term “a”.

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.

Adjusting QMED using multiple donors

In some cases, there will be several suitable donors, perhaps at similar distances from the subject catchment. WINFAP versions 4 and 5 allow you to use multiple donors, by default choosing six. 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.

WINFAP versions 4 and 5 enable you to automatically identify the nearest donors and calculate the moderated adjustment factor. WINFAP selects six donors using the procedure in a publication by Kjeldsen and others (2014). You can also select other donors 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. 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.

If using WINFAP version 3, beware that if you set the software 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 versions 4 and 5, which can detect the suitability flags in the NRFA dataset.

If you prefer a less automated approach, you can carry out data transfer using two donors outside WINFAP. Use the equations below to calculate the weights α1 and α1. They are taken from Kjeldsen (2019).

$$QMED_{s,adj} = QMED_{s,cds}\left(\frac{QMED_{1,obs}}{QMED_{1,cds}}\right)^{\alpha_1}\left(\frac{QMED_{2,obs}}{QMED_{2,cds}}\right)^{\alpha_2}$$

$$\alpha_1 = \frac{\rho_{s1} - \rho_{12}\rho_{s2}}{1 - \rho_{12}^2}$$

$$\alpha_2 = \frac{\rho_{s2} - \rho_{12}\rho_{s1}}{1 - \rho_{12}^2}$$

$$\rho_{ij} = 0.4598\exp\left(-0.02d_{ij}\right) + 0.5402\exp\left(-0.4785d_{ij}\right)$$

Where:

- The subscript s refers to the subject site.
- The subscripts 1 and 2 refer to the donor sites 1 and 2.
- ρij is a function of the distance dij between the centroids of catchments i and j (various combinations of the subject and two donor sites).

Donor adjustment and urbanisation

By default, WINFAP version 5 applies the urban adjustment in reverse at every donor station, whether it is urban or rural, to “de-urbanise” the gauged catchment before calculating the donor adjustment using rural QMED estimates from catchment descriptors. You should apply the “de-urbanised” donor adjustment to the rural QMED estimate from catchment descriptors for the subject site, before finally applying an urban adjustment appropriate to the subject site. You can choose to use the observed unadjusted QMED donor adjustment value instead of the de-urbanised value but be careful not to double-count the effects of urbanisation.

Reasons for selecting donors

More recent research on small catchments (SC090031) has supported the findings of SC050050. It recommends that multiple donors are selected purely on the basis of proximity, because screening donor catchments by their physical characteristics can lead to a poorer estimate.

For many hydrologists, this finding is counterintuitive, and they have continued to apply judgement and to implement elements on the original FEH guidance to select donors. For example, in common practice, there is a reluctance to use large catchments as donors when the subject catchment is small. 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)."

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 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.

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).

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. In general, you should:

- 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 (FEH Volume 3 Section 4.6). The FEH recommends avoiding urbanised donors, even for an urbanised subject catchment.

However, WINFAP versions 4 and 5 allow urban donors, applying the urban adjustment for QMED in reverse (by default) 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.

- Only use donor sites with good quality flood data, which will generally mean the site is classed as suitable for QMED. A review of the rating is worthwhile for high-risk studies.
- Avoid using donor sites where the topographic catchment area is not a good indication of the area that contributes runoff during floods around QMED. This includes some gauges on catchments affected by karst features or flow diversions.
- Prefer donor sites with longer records to those with short records, especially if the short records are thought to cover an atypical period in terms of flood frequency.
- 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.

Checking donor adjustments for consistency

Check adjusted estimates of QMED to ensure they are consistent with observations at upstream or downstream gauging stations. This is particularly important in catchment-wide studies.

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 having unrealistic step changes in flow estimates. In these cases, you should ignore the moderation term and use a more appropriate adjustment factor.

QMED from bankfull channel width

On some types of rivers, 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). Refer to LIT 14710 “Using local data to reduce uncertainty in flood frequency analysis” for more information on these methods and to SC130009/R (Dixon and others, 2017) for a report on the research.

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 the standard 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 in some circumstances, 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 essential to undertake a site visit to the river to assess its suitability, find representative cross sections and accurately measure the bankfull channel width.

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 rivers.

1. Select a reach that is relatively straight or on a stabilised reach of a meandering channel and at least 4 to 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.

    - The sections should have similar bankfull levels on both banks and along the reach.
    - The sections should have reasonably symmetrical flow velocities across the section.
    - For stabilised reaches of meandering channels, locate the sections close to the point of inflection.
    - 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.
    - 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.

3. 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 (frequently inundated) floodplain. Use the height of the lower limit of perennial vegetation as a guide.
4. 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.
5. Calculate reach values as an arithmetic mean of the widths at all sections.

Method 1: Estimating QMED solely from channel dimensions

Use this equation:

$$QMED = 0.226\ BCW^{1.9}$$

where BCW is bankfull channel width measured in metres and QMED is in m3/s.

The equation explained 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 explained 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 catchment descriptor equation alone (*Figure 13*).

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 standard catchment descriptor 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 projects where a conservative answer is desirable.

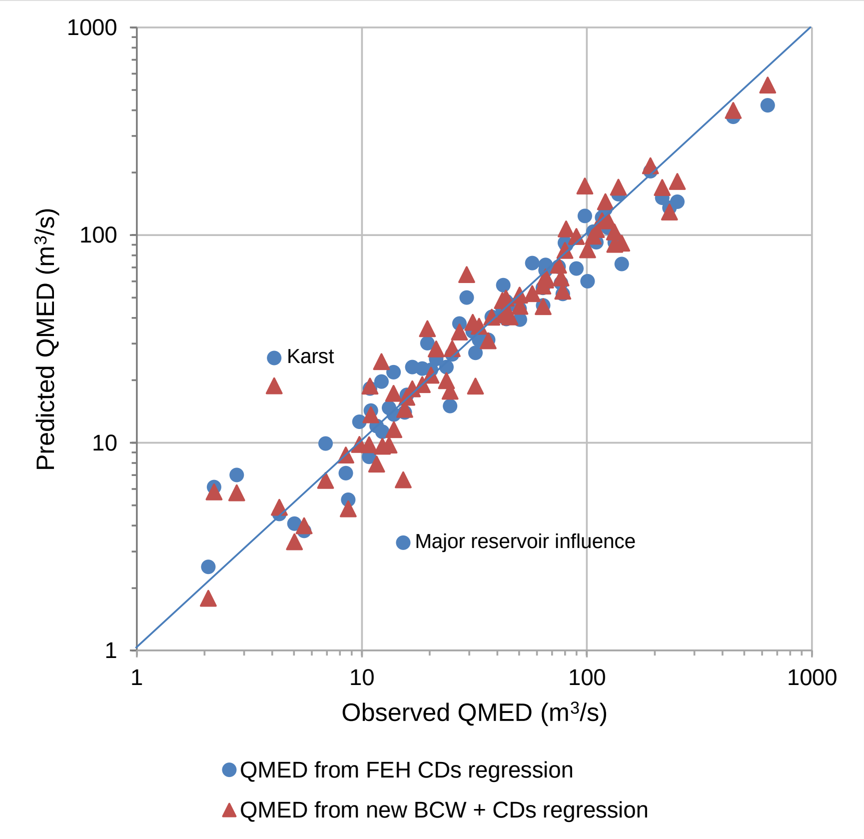


Figure 13: Comparison of predicted and observed QMED at 73 gauging stations, using (1) the FEH catchment descriptor alone and (2) the combined bankfull channel width and catchment descriptor equation.

QMED from flow duration curve statistics

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 versions 4 and 5 and can alternatively be applied in a spreadsheet or other software.

Using flow duration curve statistics to estimate QMED

Use this equation:

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

where:

- $Q5_{DMF}$ is the 5th 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 5% and 10% to exceedance probabilities of 0.05 and 0.10, then take the inverse of the standard normal cumulative distribution for those two probabilities. This gives a formula which is approximately:

$$GRADQ5_{DMF} = \frac{(log_{10}Q5_{DMF} - log_{10}Q10_{DMF})}{-0.3633}$$

- 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

The flood frequency curve for a river location relates the size of a flood flow to the rarity of the flood. It can be used to find the rarity of a given flow, or the flow which is attributed to a given return period.

The growth curve represents a re-scaling of the flood frequency curve using an index flood, which is QMED in the FEH statistical method. Therefore, the growth curve has a value of 1.0 at the 2-year return period, because the 2-year flow is QMED.

In the FEH statistical method, the growth curve is calculated separately to QMED. The two are then multiplied together to estimate the flood frequency curve to give design peak flow estimates for selected return period events, or to estimate the rarity of an observed flow.

At ungauged sites, a pooling group should be created to estimate the growth curve. You should not use regional growth curves (for example, the Flood Studies Report regional growth curves).

At gauged sites, you can use the flood peak data to estimate the growth curve, either as a single-site analysis or in combination with a pooling group. You can also include historical flood data in the analysis to improve the growth curve estimate.

Choice of distribution

Growth curve calculations are based around fitting a statistical distribution to flood peak data, either at a single site or for multiple sites in a pooling group.

There is no way of knowing which distribution the correct choice is, because the underlying 'parent' distribution is unknown.

The FEH found that, on average, the Generalised Logistic (GL) distribution performed better than the GEV for pooled growth curve derivation (FEH Volume 3 Sections 7.3, 15.3 and 17.3.2). For some pooling groups, other distributions are found to fit better than the GL.

Winfap 5 makes available the "Kappa 3" distribution, which represents a compromise between the GL and GEV distributions. The GL, GEV, and Kappa 3 are all three-parameter distributions that are special cases of the overarching four-parameter Kappa distribution, with different fixed values for the fourth parameter, h:

- GL distribution: h = -1
- "Kappa 3" distribution: h = -0.4
- GEV distribution: h = 0

Kjeldsen and others (2017) found that the Kappa 3 distribution gave an acceptable fit for 90% of pooling groups across the UK, a better performance than other distributions including the GL. It was the best-fitting distribution for 37% of pooling groups, with the GL in second place at 27%. For catchments larger than 1000km² other distributions were found to be commonly preferable to the Kappa 3.

On average, choosing the Kappa 3 rather than the GL leads to a very slight reduction in design flood estimates, of about 2%.

! Important You should usually select the distribution that gives the best fit. This may vary between different pooling groups within a single project. Use the goodness of fit test in WINFAP for pooled growth curves. For single-site growth curves, use alternative ways of judging fit, one of which is visual assessment on a flood frequency plot.

Estimating growth curves using pooling groups

Pooling data from hydrologically similar sites provides more data and enables more reliable estimates of the growth curve for rarer floods (FEH Volume 3 Sections 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 (FEH Volume 3 Sections 6, 11.5 and 16) or where historic data has been incorporated into a single site analysis. WINFAP 5 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.

WINFAP and other software will automatically create a pooling group for a subject site based on similarity in catchment descriptor space. Science Report SC050500 introduced new methods for selecting and weighting stations in a pooling group. This improved method is implemented in the latest versions of WINFAP and should always be used in preference to the original FEH method.

A new pooling method was introduced for small catchments through Science Report SC090031. This method is implemented in Winfap 5. See Section 7.1 for further guidance on using the small catchments pooling method.

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 to promote spatial consistency.

Including urbanised sites in pooling groups

The FEH states that catchments within a pooling group should be essentially rural (FEH Volume 3 Section 6.1), i.e. URBEXT2000 < 0.03. The pooling procedure aims to produce a best estimate of the as-rural growth curve, which can subsequently be adjusted for urbanisation if needed.

WINFAP 4 and 5 provide an option that allows urban catchments to be included in pooling groups by applying the urban adjustment for growth curves 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 urban catchments. You can change the default threshold value of URBEXT2000 above which stations will be excluded to include more urbanised sites (default value of 0.03). This threshold value represents the level above which you do not have confidence in the generalised procedures for de-urbanising L-moments. By default, de-urbanisation is applied to all catchments in the pooling group, even if only essentially rural catchments are included in the group.

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.

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.

If you include urban catchments in the pooling group, test the sensitivity of the results by comparing with an all-rural group.

Reviewing pooling groups

You should always review the stations included in the pooling group (FEH Volume 3 Sections 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.

Where estimates are important a number of pooling group options could be explored and reported, to help understand the sensitivity of the results to pooling group composition.

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 (FEH Volume 3 Sections 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 (FEH Volume 3 Section 16.2.3).

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 anthropogenic activity (FEH Volume 3 Sections 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.

Including highly permeable catchments in pooling groups

It is common for analysts to remove stations from a group due to large differences in BFIHOST or BFIHOST19. 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.

Earlier research, including the FEH and Flood Studies Supplementary Report 4 (1977), consistently reported differences between flood growth curves on highly permeable and nearby less permeable catchments. They report that there is generally less year-to-year variation on the more permeable catchments and hence flatter growth curves. However, 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.

Despite the findings of SC050050, there is a common perception that highly permeable catchments are likely to have different flood growth curves, perhaps due to the occurrence of occasional floods that are many times higher than QMED. There is some evidence for this in the peak flow dataset, which shows a significant difference between the distributions of L-CV on high and low BFIHOST catchments (JBA Consulting, 2022).

Research by Formetta and others (2018) also supports the idea that BFIHOST is worth considering when refining pooling groups. 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.

A drawback of removing stations from the group due to differences in BFIHOST 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).

Calculating the pooled growth curve

The pooled growth curve is calculated from weighted averages of the L-moments at each station in the group. 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. Therefore, moving catchments up or down the ranking order does not alter the weights. This differs from the original FEH method, in which the station ranking affected the calculation.

You should adjust the pooled growth curve for urbanisation where needed. Refer to the section on urban catchments.

Growth curves for sites with flood peak data

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
- any unusual characteristics of the catchment compared with others in its pooling group.

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 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). 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 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.

An improvement on visual comparison of extreme value curves with AMAX flows plotted using plotting positions is the extreme rank plot (Hammond, 2019). This overcomes the problems of comparing one frequency model (the fitted distribution) with another (the plotting position formula). The ranks of the observed data are known. Rather than attributing return periods to the observed data, ranks can be attributed to the modelled distribution. The extreme rank plot constructs a distribution of probable flows for each rank in accordance with the fitted distribution. The way in which the observed AMAX flows fit within the modelled distribution of flows at each rank provides an indication of how well the model represents the underlying distribution of the observed AMAX. You can implement the extreme rank plot using the UKFE R package.

In some cases, the difference between the single-site and pooled curves is so wide that it is clear something is wrong. For 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.

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 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 14 shows 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 figure shows 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 GL 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.

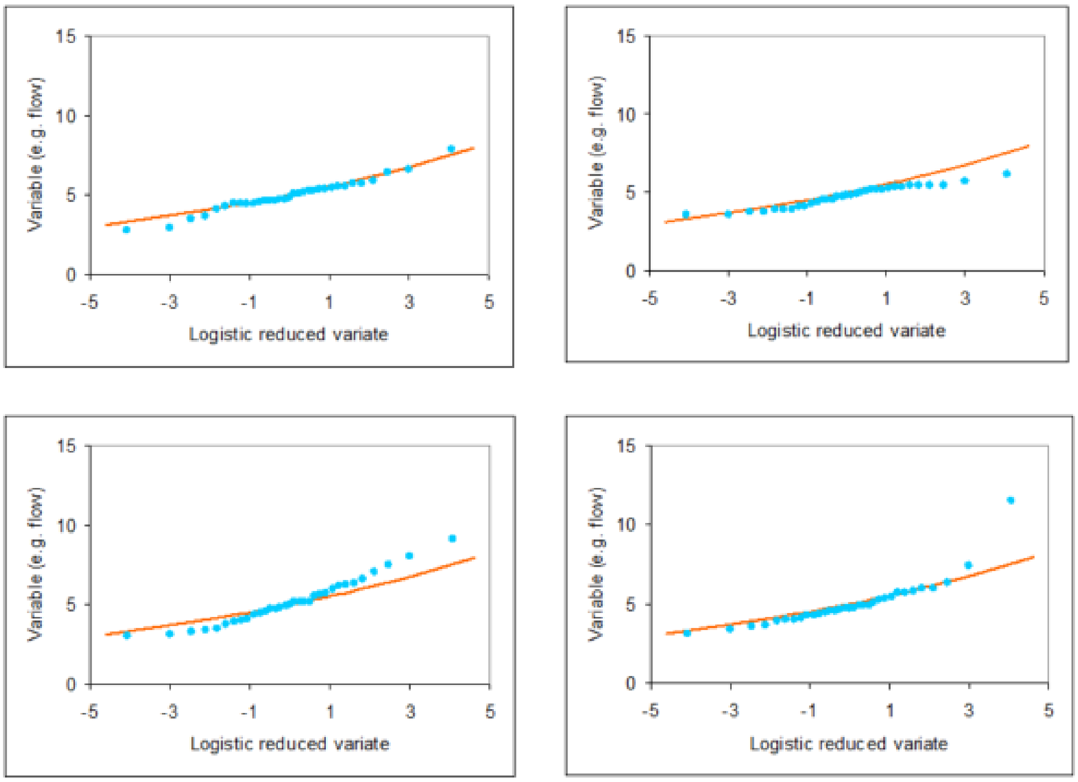


Figure 14: Four examples of fitting growth curves to flood peak data

To apply the illustration 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.

There are two basic approaches to improving on the extrapolation of single-site data:

1. Add data from other sites by pooling, using the enhanced single-site analysis method.
2. Search for and include historic data to extend the gauged record.

You should attempt both approaches in many hydrological studies. A paper by Guame (2006) compares different approaches to extrapolating flood growth curves.

The enhanced single-site method

The enhanced single-site method gives more weight to the subject site in a pooling group. You can find the details of the enhanced single-site method in Science Report SC050050.

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. Do this by ticking the box in WINFAP 5 labelled “Use at-site data” in the Pooled and QMED analysis dashboard.

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.

WINFAP 4/5 allows users to apply enhanced single site analysis on urban catchments. By default, 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.

In WINFAP 5, when the subject site is urbanised, you can choose whether to de-urbanise the subject site, the pooling group or both. The default is to de-urbanise both. Consider changing this when there are specific local reasons why you think that the impact of urbanisation on the catchment may not be well represented by the FEH urban adjustment to the growth curve. For instance, the catchment may have SUDS measures intended to mimic a more rural type of flood response. In such cases, consider de-urbanising the pooling group but not the subject site.

Be aware that WINFAP will default to enhanced single-site analysis when you create a pooling group for a gauging station’s catchment descriptor file taken from the NRFA dataset, when the gauge is classed as suitable for pooling. If you create a 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 pooling group, but without the extra weight used for enhanced single-site analysis. WINFAP does not report the relative weights used in enhanced single-site analysis.

Incorporating historic data in single-site analysis

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 and 5 or other software.

Refer to the LIT 14710 “Using local data to reduce uncertainty in flood frequency analysis” for more in-depth guidance and to Dixon and others (2017) for the scientific background to the guidance.

The information you need to apply these methods is:

- Gauged annual maximum flows (minimum 10 years).
- Either:
    - Peak flow rates for historical flood events; or
    - Evidence that historical flood events have occurred and an indication of their relative severity.
- The length of the historical period represented by the events.
- The threshold flow 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.

The most favourable situation is when you are able to estimate peak flow rates for the historical floods. Use Method 1a in LIT 14710. If you cannot estimate flow rates, use information on the impacts of the flood to develop a ranking and then apply Method 1b in LIT 14710. 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.

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.

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.

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.

Take particular care in cases when the historical flood data suggests that the single-site or pooled 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 single-site or pooled frequency curve may be too low.

Adjusting growth curves to remove the influence of non-flood years

For some catchments, there are years in which no floods occur, and the annual maximum flow (if any) is due to baseflow alone. This is most common on catchments with low rainfall, but it can occur on other types of catchments too.

Including non-flood annual maxima in a flood frequency analysis can introduce a bias. It can result in a fitted growth curve that is bounded above (that is, the growth factors reach an upper limit).

The FEH provides a way of adjusting L-moments to remove the influence of unusually low annual maxima. It refers to this as a 'permeable adjustment' but it is equally applicable on any catchment with low annual maxima. The adjustment generally has a fairly small effect on growth curves.

The adjustment procedure applies only to the GL distribution. Apply the adjustment procedure when you are fitting a single-site growth curve to a dataset that includes annual maximum flows smaller than 0.5QMED. Consider applying the adjustment for pooled analysis as well, when you think it is likely to make a significant difference to the results. This might be the case if there are several low values in the annual maximum series at gauges that rank highly in the pooling group.

Refer to FEH Volume 3 Section 19 for details of the adjustment. The calculations for adjusting L-moments are not carried out by WINFAP. It is necessary to solve the equation for the shape parameter (FEH Volume 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. This only adjusts L-moments for gauges with SPRHOST < 20%, which was the recommended threshold in the FEH. The spreadsheet provides adjusted L-moments for each station in a pooling group, along with the resulting pooled growth curve. It does not offer the option of enhanced single-site analysis and does not carry out any de-urbanising of L-moments. The UKFE R-package also implements the adjustment.

The adjustment can occasionally result in the shape parameter, k, of the GL distribution ending up close to zero. When this happens, it may be more appropriate to fit the 2-parameter Logistic distribution. The FEH does not provide the equations necessary to estimate the distribution's parameters from the adjusted L-moments, but they can be derived using the same principles as those for the GL distribution and can be solved analytically.

Adjusting statistical method estimates for urbanisation

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 (FEH Volume 3 Section 9). Remember that this these adjustments are UK-average factors and cannot account for local circumstances which can vary greatly between different urban areas.

You should not routine apply the FEH methods to extremely heavily urbanised catchments (URBEXT2000>0.6). You should not use the Statistical method to predict the future effect of urbanisation (FEH Volume 3 Section 9.1). For more advice, refer to Section 7.2 on urban catchments.

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.

Adjusting QMED estimates for urbanisation

To adjust QMED for urbanisation, multiply the rural estimate of QMED (from catchment descriptors after adjustment 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 versions 4 and 5 use a revised adjustment method which overcomes a problem with the implementation of the urban adjustment in Winfap version 3. It also provides more flexibility in that it relates the adjustment more directly to the physical characteristics of urban areas. The adjustment is described in Wallingford HydroSolutions (2016a). Use this revised adjustment in all cases.

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

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

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. This set to 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:

$$URBAN = 1.567\ URBEXT2000$$

- PRUAF is the percentage runoff urban adjustment factor, calculated from the second equation.

Similar 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). There is no current guidance that links parameter values to specific drainage characteristics. If you alter any of the default parameters, state what value you have used and why.

When using WINFAP 4, take care when conducting enhanced single-site analysis for an urban gauged 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. You should also select the 'Show urbanised Flood Frequency results' check box. The flow results provided are then the observed QMED and the urban adjusted growth curve. Other combinations of options can give QMED estimates that are unlikely to be appropriate and may double count the effects of urbanisation. WINFAP 5 avoids these problems, as options for de-urbanisation of QMED and the growth curve are independent of each other.

Adjusting growth curves for urbanisation

Urbanisation typically has a smaller influence on the growth curve than on QMED.

There have been four versions of the urban adjustment for growth curves. The current version, used in WINFAP 4 and 5, 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 4/5 is essentially the same as that published by Kjeldsen (2010).

The Kjeldsen (2010) formulae for adjusting the L-moments are:

$$LCV_{urban} = LCV_{rural} \times 0.5547^{URBEXT2000}$$

$$LSKEW_{urban} = \left((LSKEW_{rural} + 1) \times 1.1545^{URBEXT2000}\right) - 1$$

The interpretation is that for urbanisation correlates with a decrease in L-CV values and an increase in L-SKEW values. These changes tend to reduce the gradient of the growth curve at lower return periods and increase the gradient at higher return periods (*Figure 15*).

To carry out the urban adjustment in WINFAP 5, tick "Show urbanised results" in the Pooled and QMED analysis dashboard. If you are carrying out calculations outside WINFAP, take care not to apply an urban adjustment to a single site growth curve.

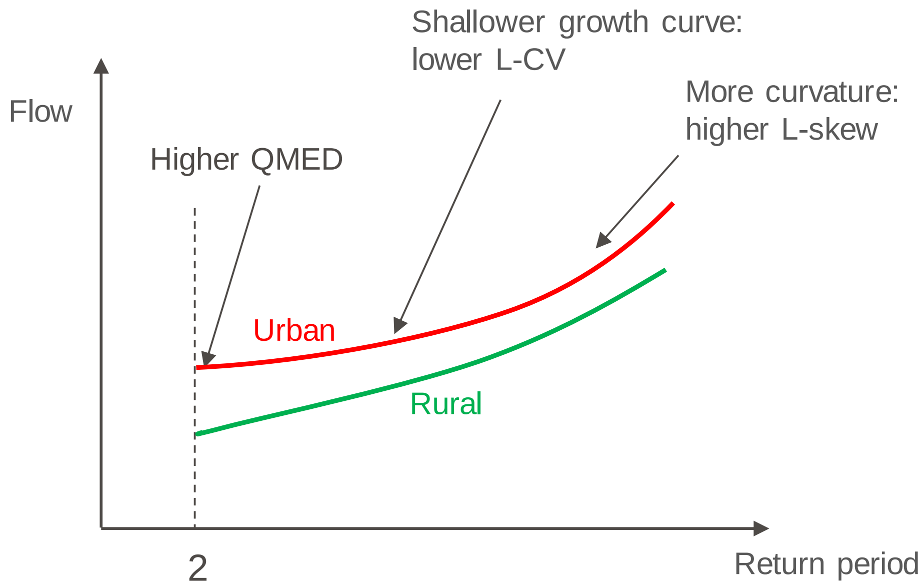


Figure 15: Effect of urban adjustment on flood frequency curves

4.3 Rainfall runoff approaches

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 ReFH1 method, released in 2006 and ReFH2, released in 2015 and updated in 2019 (ReFH2.3). The FSR/FEH rainfall-runoff method is only covered briefly as it is superseded by the ReFH methods in most cases.

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, but with different parameterisation. The FEH Supplementary Report No. 1 provides details of the ReFH1 method. For information on the research, see Kjeldsen and others (2005). Refer to Wallingford HydroSolutions (2019a) for ReFH2.

Lumped and distributed approaches

A fundamental decision in any rainfall-runoff model is whether to apply it:

- in a lumped fashion to the entire catchment upstream of the site of interest.
- 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.

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. 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. You can compare distributed model estimates to lumped estimates, for example statistical estimates at gauging stations, as a check on model performance.

Intervening areas

Areas draining directly to the modelled watercourse, or containing numerous small sub-catchments, are usually treated as 'intervening areas' (*Figure 16*).

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 16*), or based on the descriptors of a significant watercourse within the intervening area. FEH Volume 5 Section 7.2 gives advice on adjusting catchment descriptors.

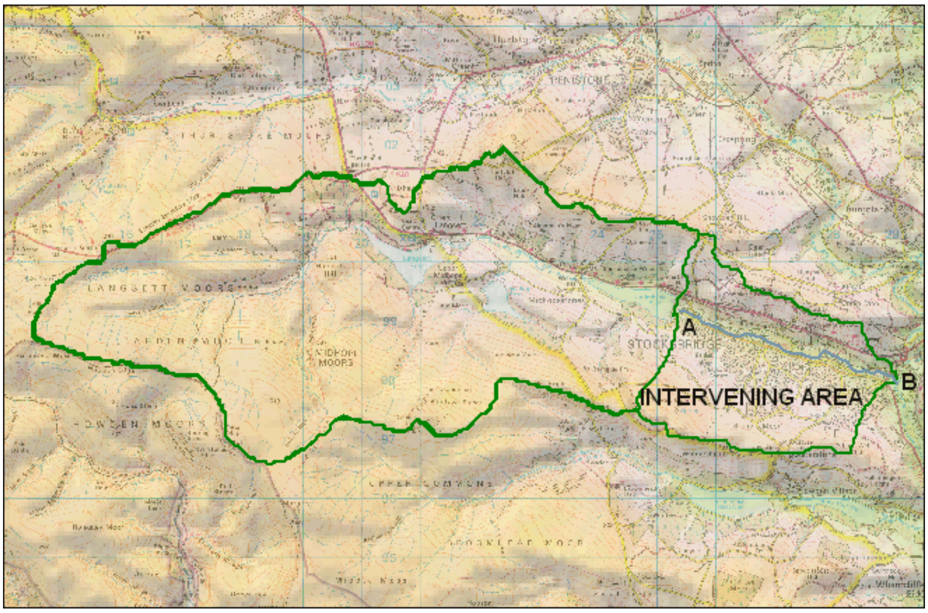


Figure 16: An example of an intervening area at Little Don at Stocksbridge, South Yorkshire. The intervening area is the catchment at B minus the catchment at A. *© Crown Copyright. All rights reserved. Environment Agency, 100026380, (2009).*

Take care over the estimation of 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 40km², you can estimate the ReFH2 model parameters from the "plot-scale" equations which use AREA in place of DPLBAR.

It is difficult to estimate design rainfall inputs from FEH13 for intervening areas. The FEH web service does not provide the parameters of the FEH13 rainfall frequency model. If there is significant variability in rainfall patterns between sub-catchments, you should use the area-weighting method to estimate the rainfall depth for intervening areas. Alternatively, it may be sufficient to copy the design rainfalls table from a nearby representative catchment.

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.

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 and does not include negative flows. This method is only appropriate for small intervening areas, to avoid confusion between genuine inflows and the transformation of the flood wave as it travels downstream due to hydraulic effects.

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.

Software

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 5.0) 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. 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. See Section 6.7 for further guidance on analysing observed events.

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. ReFH1 is also implemented in various hydraulic model packages and is available in the UKFE R package.

ReFH rainfall-runoff model inputs

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

- Initial conditions, which can vary from day to day. Cini is an example, or CWI (catchment wetness index) in the FEH method.
  ! Important 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.
- Model parameters, which represent a (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. Model parameters remain the same whether you are simulating a real or a design flood.

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 to the model.

For a real flood, use observed catchment-average rainfall for the event and an initial condition that accounts for the antecedent weather conditions. In the ReFH model, the initial conditions are specified using Cini, the initial soil moisture, calculated from antecedent rainfall. This can be calculated in the ReFH2 software. It is also necessary to set an initial baseflow, BF0. Within ReFH2, the BF0 is set according to Cini and cannot be directly set by the user.

For a design flood, use the recommended design combination of inputs in terms of storm duration, depth, temporal profile, and initial soil moisture. These will be estimated from catchment properties.

Estimating model parameters for ReFH rainfall-runoff methods

There are five options for estimating model parameters, in order of preference:

1. All parameters estimated from hydrometric data (first choice in ideal circumstances)
2. Time to peak estimated from lag analysis
3. Data transfer
4. Catchment descriptors (sometimes the most pragmatic choice)
5. Combined hydrological and hydraulic calibration (not generally recommended)

First choice: Estimating model 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.

! Important 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.

There is currently no ideal software for estimating the parameters of the ReFH2.3 form of the model. The ReFH calibration utility, a freely available tool, is able to optimise model parameters to fit observed data from multiple events. However, it uses the ReFH1 form of the model. It is not well suited to the changed model structure related to the water balance formation of ReFH2.3. It may be useful for producing first pass estimates of model parameters.

It is possible, although with some awkwardness, to use the ReFH2.3 software to estimate model parameters by trial and error for one event at a time. The following advice may help you in this process:

- Use the parameters from catchment descriptors as an initial guess.
- Consider having multiple copies of the software open, each one running for a different observed event.
- Use the same set of parameter values across all events.
- Export the modelled hydrographs for each event and use external software, such as a spreadsheet, to compare the modelled and observed hydrographs.
- Calculate measures of fit and use your judgement to adjust the parameter set to improve the fit.

The data needed for parameter estimation 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. Refer to FEH Volume 4 Section A.4.3 for further guidance on data quality checks for flood event data.

Sources of PE data include the Environment Agency’s PET (potential evapotranspiration) and PETI (potential evapotranspiration with interception correction) datasets. These datasets comprise:

- Daily data from 1st January 1961 covering England and Wales
- PET and PETI for a reference crop (short well-watered grass)
- 1km grid aligned with the Met Office HadUK grid
- Three levels of data quality
- Updated each month with provisional climate data and final climate data
- Timeseries data that can be extracted for points, bounding boxes and multiple polygons.

Use PETI in preference to datasets such as MORECS and MOSES. For more guidance on how to obtain this data, see Potential Evapotranspiration (PET) Datasets Environment Agency guidance.

You can otherwise obtain a quick estimate for PE 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. When modelling an observed event in the ReFH2 software, the only option is to use the sine curve.

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 carrying out numerous runs to achieve calibration.

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.

Second choice: Estimating 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. Where possible, choose single peaked events. For multi-peaked events, consider using POT event separation rules (FEH Volume 3 section 23.5.1) to identify if the data should be split into separate events.

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:

$$Tp(0) = 0.879LAG^{0.951}$$

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 section on data transfer below for a complicating factor on urban catchments.

Third choice: Data transfer

The ReFH and ReFH2 research did not examine the value of data transfer for refining parameters. Faulkner and Barber (2009) 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. Alternatively, if the gauge measures water level only, an adjustment factor for the Tp parameter can be estimated by lag analysis (as above).

! Important 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 but is -3.36. Therefore, multiply the as-rural Tp from the ReFH2 software by this adjustment factor:

$$Tp\ urban\ adjustment\ factor = (1 + URBEXT2000)^{-3.36}$$

and then compare your urbanised Tp with the observed Tp to calculate a donor adjustment factor.

Fourth choice: Catchment descriptors

Research (Vesuviano and others, 2020) 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.

Fifth choice: 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:

- 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.
- 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 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.

ReFH rainfall-runoff model inputs for design events

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 you should amend aspects of the design event:

- Storm duration - when generating inflows for a hydraulic model that covers a long section of watercourse, in a distributed model, 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' (FEH Volume 2 Section 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 (FEH Volume 2 Section 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.

Design rainfall

The depth-duration-frequency (DDF) model provided with the FEH (1999) was replaced in 2015 with the FEH 2013 (FEH13) rainfall model. (Stewart and others, 2013). Both the FEH99 and FEH13 rainfall statistics are available for catchments via the FEH Web service. They enable the estimation of design rainfall depths for any location in the UK or the return period of an observed rainfall.

Use the FEH13 rainfall statistics in preference to FEH99 for all applications unless you have evidence that FEH99 should be preferred in a particular location. 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.

An updated DDF model is expected to be released later in 2022/early 2023, to be known as FEH22. This should be used in preference to FEH13 and FEH99 when it is available, as it includes additional years of data and new stations. Wait until the ReFH2 Cini design equation has been recalibrated before using the ReFH2 method with the FEH22 rainfall. For further guidance on transition arrangements please contact the National Flood Hydrology team.

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. However, these are extrapolated below the 1-hour rainfall data used to develop the DDF model, so have a higher uncertainty.

You should use sliding durations to estimate design rainfall totals. These are durations that start at any time (FEH Volume 2 Section 2.5). The FEH Web service gives the option to adjust rainfall depths to convert between fixed (duration measured at discrete times only) and sliding durations. You should only normally use fixed durations if you are estimating the return period of a rainfall event that has been measured at hourly or daily rain gauges (e.g., where the duration is fixed to the 24-hour period between 9am on each day).

The FEH Web service will also provide rainfall estimates at a point and averaged across a catchment. Catchment-averaged rainfall will always be smaller than point rainfall estimates, as it is less likely for an extreme rainfall event to occur across a whole catchment compared to at a single point. This effect is more pronounced for larger catchments and shorter durations. Flood estimates for catchments should use the catchment-averaged rainfall. This is calculated by the FEH Web service which applies an areal reduction factor to the point rainfall based on the catchment area (see formula in FEH Volume 2 Section 3.4). You should 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.

You may need to amend the areal reduction factor and storm duration if using a distributed approach for catchment-wide studies. The areal reduction factor should reflect the whole catchment area to the location of interest. This is less important if using a hybrid approach with peak flows scaled to statistical estimates.

You will also need to choose whether to apply a uniform rainfall depth across all sub-catchments in a distributed model. It is not essential to use identical rainfall depths in all sub-catchments, although it can be worthwhile doing so when there is little variation in rainfall characteristics, to avoid introducing a spurious level of detail. You will need to copy the rainfall DDF data from the whole catchment .XML file into the sub-catchment .XML files.

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. For example, this may reflect the larger rainfall totals for the 1% (1 in 100) AEP event in upland areas compared to lowland areas in a large catchment.

It is difficult to estimate design rainfall inputs from FEH13 for intervening areas. If there is significant variability in rainfall patterns between sub-catchments, you should use the area-weighting method to estimate the rainfall depth for intervening areas. Alternatively, it may be sufficient to copy the design rainfalls table from a nearby representative catchment or use a point estimate for small intervening catchments.

Storm duration

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.

In a **distributed** rainfall-runoff application, it is vital to apply an identical design storm (in terms of storm season, 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 could 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 hydraulic modelling 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 and run separate critical durations for different flood risk areas.

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.

Seasonality, storm profile, initial soil moisture and initial baseflow

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, BF0.

ReFH versions 2.0, 2.1 and 2.2 made no distinction between Cini for winter and summer seasons, but ReFH2.3 reintroduced a summer Cini following research by Stewart and others (2022). 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.

You should use winter storm rainfall depths, Cini and initial baseflow values and storm profiles in for all catchments, unless:

- URBEXT2000 ≥ 0.30; or
- URBEXT2000 ≥ 0.15 **and** BFIHOST19 ≥ 0.65

For these catchments, refer to the guidance below on modelling urban catchments using ReFH or ReFH2 methods.

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.

Modelling urban catchments using 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. 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. In the statistical method it is known as PRIMP. IRF can alternatively be interpreted as the fraction of the impervious surface that is positively drained, sometimes known as the effective impervious area. Its value can depend strongly on the spatial configuration of urban areas within the catchment (Vesuviano and Miller, 2018). In the water balance version of ReFH2.3, the runoff from the rest of the impervious surface is routed via depression storage DS into the rural part of the model (*Figure 17*). 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 0.4 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. If you calculate a revised value for the urban area in the catchment using high-resolution land-use data, it would be appropriate to increase the value of IF accordingly (Vesuviano and Miller, 2018).

The Tp scaling factor is generally below 1 (default value 0.75 in ReFH 2.3), 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.

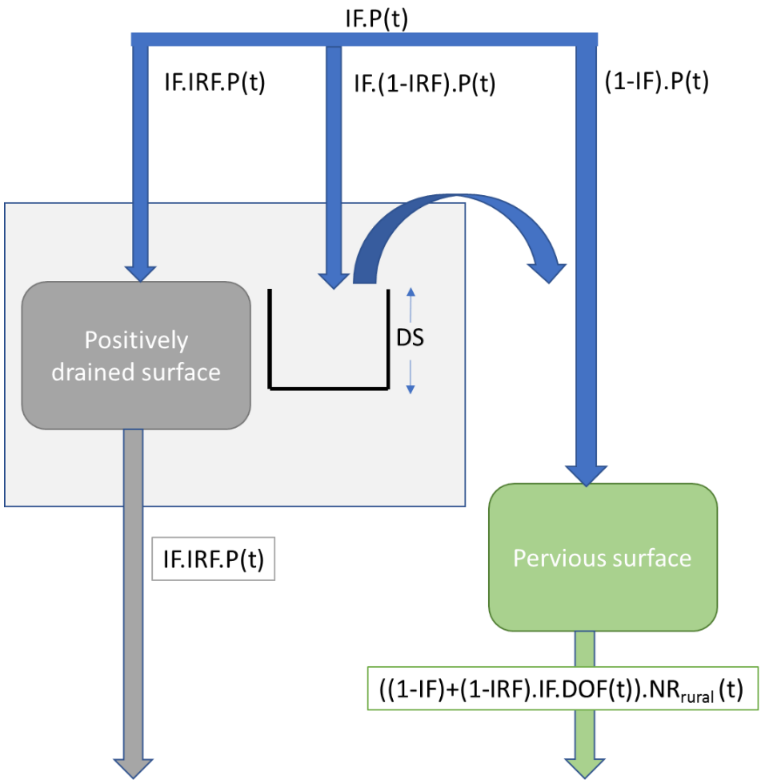


Figure 17: The losses component of the ReFH2 model version 2.3 that closes the water balance. DOF(t) is the Depression Overflow Factor, which takes a value of 0 until the precipitation depth exceeds the depression storage, DS, and then a value of 0 for subsequent rainfall. NRrural is the rural net rainfall, calculated from the ReFH2 rural losses model. Source: Wallingford HydroSolutions (2019a)

Recommended approaches for different levels of urbanisation

The recommended values for the parameters, and for the seasonality of the design storm, depend on both the urban extent and BFIHOST, as shown below:

1. Slightly to moderately urbanised catchments, URBEXT2000 < 0.15

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

2. Heavily urbanised catchments, 0.15 < URBEXT2000 ≤ 0.3

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

    For catchments in this range, the small catchments research project 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 (Refer to SC090031 (Stewart and others, 2022) for the reasons behind these recommendations).

3. Very heavily urbanised catchments, URBEXT2000 > 0.3

- Treat the catchment as urban:
  - Estimate the urban parameters IF, IRF, DS and TpFactor where possible using local data, or use default values where no local data is available. It is worth first carrying out a sensitivity analysis before using local data. Refer to Wallingford HydroSolutions (2019a).
  - Use a summer rainfall depth and initial soil moisture, Cini, along with the 50% "summer" storm profile.
- Consider allowing for the influence of sewer flow pathways (see below).

These recommendations stem from the small catchments research, SC090031 (Stewart and others, 2022).

! Important 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 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.

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. Imports of water from sewers outside the topographic must be estimated using other methods (e.g., sewer models).

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 to 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. This refers only to the urban area where sewers drain out of the topographic catchment.

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 or import of water to the catchment via urban drainage systems, it may be simpler to assume that exports and imports roughly balance.

Alternative rainfall-runoff models

Alternative (non-FEH/ReFH) models can be used. These include

- Design event models, such as the NAM model in Mike-11, or FRQSIM. 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 (FEH Volume 2 Section 4.1). The onus is on the analyst to demonstrate that this is so, if using an alternative rainfall-runoff model. This may be far from straightforward.
- Continuous simulation models, such as PDM models.

Continuous simulation modelling involves running a long series of rainfall through a suitable rainfall-runoff model to produce a long flow series. You can then rank the peaks of the flow series and analyse them statistically to obtain design flows for the required return period. The flow series could also be run through a hydraulic model to estimate water levels which could also be ranked and analysed to estimate the design flood level for the required return period.

Short simulations can use observed rainfall data but to estimate long return period floods it is usually necessary to produce a simulated rainfall timeseries to run through the rainfall-runoff model. The simulated rainfall timeseries depth-duration-frequency statistics should be compared to the latest FEH rainfall DDF model to identify any differences and if necessary correct for bias.

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 floods 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. 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. It permits a more coherent, multivariate and probabilistic view of the flood hazard in comparison to using conventional hydrological frequency analysis methods.

However, 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 within reasonable timescales.

Continuous simulation 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. However, in catchments with good quality gauged records, the statistical method may be preferred.

It is more challenging to apply continuous simulation in ungauged catchments. 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). However, the findings have not yet been implemented.

Tools and expertise for applying continuous simulation 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.

Section 3.4 provides some guidance on where continuous simulation methods should be considered. 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

Why bother with uncertainty?

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?

Impacts of uncertainty on decision making

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. Sensitivity 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 of risk

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. Questions may be asked about why the initial estimate was so “wrong”. But 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 importance of uncertainty has been recognised in many Defra / Environment Agency reports and strategies.

The Flood and Coastal Risk Management Modelling Strategy 2010–2015 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.

Report SC120014 “Accounting for residual uncertainty” (2017) states: “Uncertainty is pervasive in all data and information. To make well-informed choices about how best to respond to this uncertainty, it must first be understood.”

A recent project (JBA, 2022b) investigating the relative importance of hydrological uncertainties within the flood modelling chain identifies the direct influence of uncertainty on real world flooding issues ranging from flood defence design and cost benefit analysis to mapping, real time forecasting, warning and resilience to climate change. The project identified that in the majority of case studies, hydrological aspects were the largest source of uncertainty.

Why we should acknowledge assumptions and limitations

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, who may want to know if they can re-use the modelling for other applications.

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 do not need re-listing

Many flood studies share 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.

These types of assumptions do not need re-listing in every study because they are obvious, they are often 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 to understanding.

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 are listed below. These are not necessarily recommended in any particular case, but it may help to list assumptions grouped under similar headings.

Assumptions about data

Examples:

- 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

Examples:

- 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

Examples:

- 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 than 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.

The validity ranges for selected methods, based on information in the FEH and other publications, are as follows. These are ranges over which the methods are 'principally intended to be used' or ranges covered by the data used to develop the methods. This is not to say you should never use the methods outside the ranges given. Each method also has various types of catchment for which it is not ideal, see Section 3.4 Choosing between the FEH methods.

- FEH statistical:
    - Return period limits: 2 to 200 years (but has been applied up to 1000 years)
    - Catchment area limits: none
    - Urbanisation limits: no limit if using current urban adjustment method, but other methods may be better when most flow is via sewer networks.
- ReFH (largely superseded by ReFH2)
    - Return period limits: up to 150 years
    - Catchment area limits: not suitable for very large catchments
    - Urbanisation limits: only reliable in its original form for URBEXT1990<0.125.
- ReFH2
    - Return period limits: tested up to 10,000 years (Stewart and others, 2019)
    - Catchment area limits: not suitable for very large catchments
    - Urbanisation limits: no limit but other methods may be better when most flow is via sewer networks.
- FEH13 and FEH22 rainfall DDF model
    - Return period limits: 2 to 10,000 years
    - Duration limits: 1 hour to 8 days, although durations shorter than 1 hour can be derived with caution.
    - Represents national scale patterns and very localised high intensity rainstorms may not be well represented at this scale.

! Important You should choose methods by following the guidance in Chapter 3, rather than by elimination using the limitations above.

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, groundwater-dominated 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. See Chapter 7 for further guidance on unusual catchments.

5.4 Assessing uncertainty

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 ultimately 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.

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 and the UKCEH guide on uncertainty in FEH methods (Griffin and others, 2021) on how to estimate confidence intervals for various FEH methods.

Another aspect of uncertainty in the results is bias, and this may not be revealed by confidence intervals. For instance, flood frequency estimates may be biased if they are based on measurements made during an unusually flood-free period, or if they are derived using a stationary frequency distribution when in reality the flood generating processes are non-stationary. There may also be bias due to errors in the measurement of river flows during flood conditions. The bias could be significant if you use data mainly from a single site in your analysis. You should attempt to identify if your results may be biased, for example by comparing against longer records, testing for trends, and understanding the limitations of flow measurement and rating curves in flood conditions.

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

Confidence intervals for the FEH statistical method at ungauged sites

It is possible to quantify uncertainty in the results of the FEH statistical method in most situations. Different methods for evaluating uncertainty make different assumptions and produce different results.

You can find confidence intervals for design flows at ungauged sites in the tables below. *Table 2* is for rural catchments (URBEXT2000<0.03) and *Table 3* is for moderately urbanised catchments (0.03 ≤ URBEXT2000 < 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.

The uncertainty reduces only very slightly as a result of adjusting QMED using donor sites. *Figure 18* illustrates this. This is not the same as saying that donor sites have an insignificant effect on the results. They can have a very large effect. The confidence intervals make no allowance for the distance of the subject site from the donor site(s). You can have higher confidence in estimates made using a donor site that is shortly upstream or downstream of the subject site.

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 2: Confidence intervals for design flows at an ungauged site (rural catchments)

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

Table 3: Confidence intervals for design flows at an ungauged site (moderately urbanised catchments)

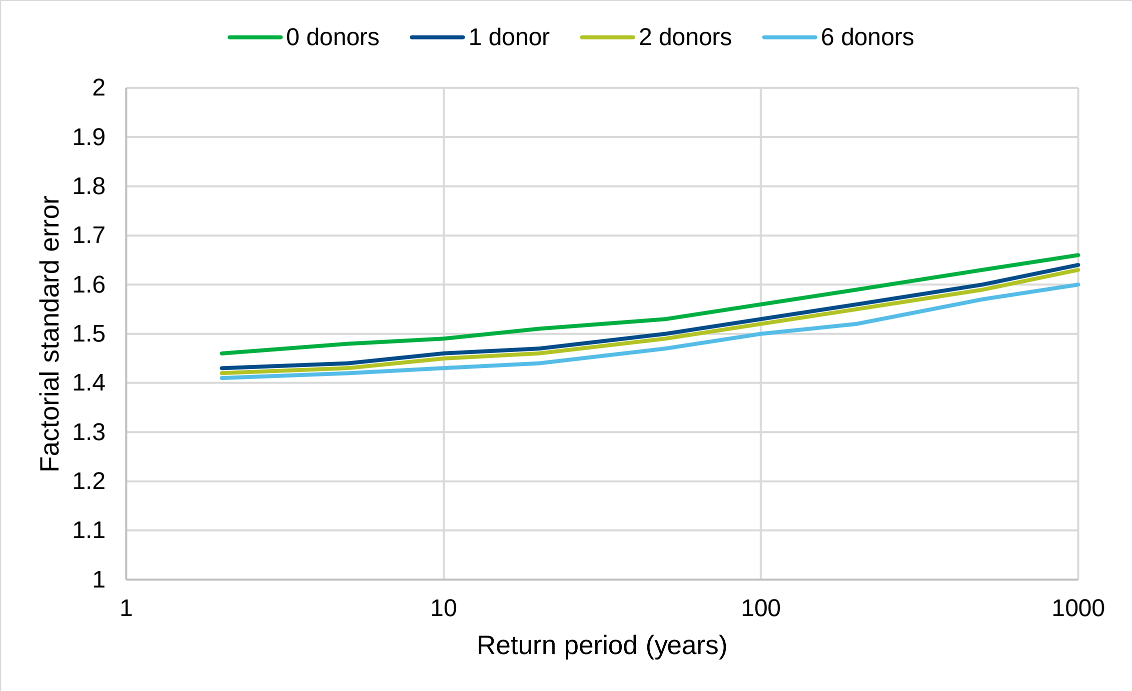


Figure 18: The effect of the number of donor sites on uncertainty for rural catchments, measured by factorial standard error, for return period events from 2 to 1000 years.

The confidence limits presented above are derived using a combination of the uncertainty in the QMED regression, the differences between pooled and single-site growth curves and the sampling error in the single-site estimates. For more information on the derivation and interpretation of these confidence intervals, refer to LIT 14710 and the supporting science report, Dixon and others (2017).

The results for rural catchments were derived from a sample of 637 stations, as explained in the science report. The confidence intervals for moderately urbanised catchments were derived using the same approach applied to a sample of 114 stations, but not written up in the science report. The smaller sample size available for moderately urbanised catchments means that the confidence limits are less accurately defined. This explains why for some return periods the confidence limits for 6 donors appear slightly wider than those for smaller numbers of donors.

The confidence limits 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.

Hammond (2021) derived alternative confidence limits for ungauged sites using bootstrapping, which is a non-parametric method that does not rely as much on assumptions about the distribution of the data. The confidence limits from Hammond (2021) are similar to those presented here for short return periods but they indicate more uncertainty at longer return periods. For the 100-year return period the 95% confidence interval with no donor is a factor of 0.39 to 2.58 times the best estimate, compared with a factor of 0.45 to 2.23 in *Table 2* for rural catchments. Refer to the later section for a brief discussion of bootstrapping.

Neither method of deriving confidence limits is able to account for the uncertainties associated with bias.

The amount of uncertainty shown in these tables may be surprising and worrying for some 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.

Confidence intervals for FEH statistical method at gauged sites

It is not possible to present equivalents to the above tables of confidence limits for flood frequency estimates that incorporate at-site gauged data. This is because the confidence limits depend on the record length, the value of QMED and the L-moments and/or distribution parameters. However, you can calculate confidence limits using easy-to-apply approximate formulae. Use these when:

- You have estimated QMED from at-site annual maximum flows; and
- You have estimated a growth curve using a GL distribution fitted either by single-site or enhanced single-site analysis.

Start by calculating the variance of the design flood estimate for return period T years, $var(Q_T)$. Choose an appropriate method below depending how you have estimated the growth curve.

1. Variance for single site analysis

   If you have fitted a GL distribution to at least 20 years of data, use this equation, from Kjeldsen (2021):

$$var(Q_T) = \frac{(QMED\ \times \beta)^2}{N} \exp\left(a_0 + a_1 y + a_2 y^2 + a_3 y^3\right)$$

   where:

   - $QMED$ is the median of the annual maximum flows.
   - β is the scale parameter of the GL growth curve (standardised by QMED).
   - N is the number of annual maximum flows at the site.
   - y is the logistic reduced variate for return period T: $y = \ln(T-1)$

   The values of the four parameters depend on the L-skewness of the annual maximum flows. Calculate them by linear interpolation between the rows in *Table 4*.

L-skewness, t_3	a_0	a_1	a_2	a_3
-0.45	1.2888	-0.4104	0.2114	-0.0181
-0.3	1.3441	-0.4287	0.2172	-0.0177
-0.25	1.3668	-0.3687	0.2082	-0.0164
-0.15	1.3805	-0.2282	0.1885	-0.0146
-0.05	1.3757	-0.0464	0.1760	-0.0139
0.05	1.3348	0.1785	0.1684	-0.0140
0.15	1.2970	0.4152	0.1607	-0.0137
0.2	1.2819	0.6006	0.1743	-0.0150
0.35	1.2903	0.7375	0.1928	-0.0161
0.45	1.2831	0.9136	0.1901	-0.0155

Table 4: Parameter values for use in single-site variance calculation (Kjeldsen, 2021)

2. Variance for enhanced single site analysis

Use this equation, from Hammond (2021):

$$var(Q_T) = \frac{(QMED \times LCV)^2}{N} \exp\left(1.3125 + 0.599y + 0.00399y^2\right)$$

where:

- $QMED$ is the median of the annual maximum flows.
- LCV is the L-coefficient of variation of the annual maximum flows at the site (not from the pooling group).
- N is the number of annual maximum flows at the site.
- y is the logistic reduced variate: $y = \ln(T-1)$

This method is implemented in the UKFE R-package.

3. Calculating confidence intervals from variance

The 95% confidence interval for the design flood Q_T is:

$$Q_T - 1.96\sqrt{var(Q_T)}\ ;\ Q_T + 1.96\sqrt{var(Q_T)}$$

On average confidence limits at gauged sites are much narrower than those presented in *Table 2* and *Table 3* for ungauged sites. This is mainly due to the fact that QMED at the gauged site is estimated directly from the annual maximum flows and so is not subject to the large uncertainty associated with the regression on catchment descriptors.

This procedure can sometimes give negative values for the lower confidence limit if $var(Q_T)$ is high. If this occurs, set the lower confidence limit to zero to avoid a physically meaningless result.

Alternative method for gauged sites: bootstrapping

Alternatively, you can derive confidence limits using random resampling (bootstrapping). This gives a site-specific estimate that avoids the approximation mentioned above and is applicable to any distribution. Bootstrapping is implemented in WINFAP for single-site analysis and in the UKFE R-package for both single-site and enhanced single-site.

The implementation of bootstrapping in WINFAP is not directly supported by a published reference. Bootstrapping is not mentioned in the relevant FEH volume (Volume 3) although Volume 2 does present a bootstrapping approach for deriving confidence limits for rainfall frequency curves. The bootstrapping in WINFAP only derives confidence limits for the flood growth curve and so does not allow for the uncertainty in estimating QMED.

Bootstrapping has some drawbacks, and in some situations needs a record length of about 100 years to provide reliable estimates. It is not straightforward to choose a method for quantifying uncertainty. You can find more information about this topic in Kjeldsen and others (2014), which compares three methods of uncertainty estimation: analytical solutions, Monte-Carlo simulation and bootstrapping.

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

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.

! Important In all cases, you will need to carefully consider the specific requirements of the study when developing your method statement.

6.1 Catchment-wide studies and 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.

Hydrodynamic models and 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 rainfall-runoff approaches 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.

Reconciling flow estimates

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 (FEH Volume 1 Section 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 due to the fact that a catchment-wide design flood event is ultimately not achievable. It is often necessary to strike a balance between two extremes:

1. Excessive reliance on the hydraulic model. For example, ignoring flood peak data at gauging station sites within the study reaches.

2. Imposing the design flows on the model. For example, adjusting inflows so that the model reproduces the preferred flow estimates at all downstream points in the system.

One way around this is to limit the length of model reaches.

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 inflow locations 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.

! Important A common error is failure to check the peak flows within a hydraulic model against those estimated in the hydrological study. This is necessary to confirm the design event is being appropriately modelled at the key areas of interest.

Applying FEH methods in catchment-wide studies

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.

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.
- The flood estimates at, and close to, gauging sites should be consistent with the gauged record unless there are valid reasons to the contrary.

For some studies, it may be useful to undertake joint probability analysis to understand the frequency of flooding due to combinations of flows from major tributaries.

Statistical method considerations for catchment-wide studies

Additional inconsistency can be introduced by applying different donor sites and pooling groups in catchment-wide studies. For example, in *Figure 19*, 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.

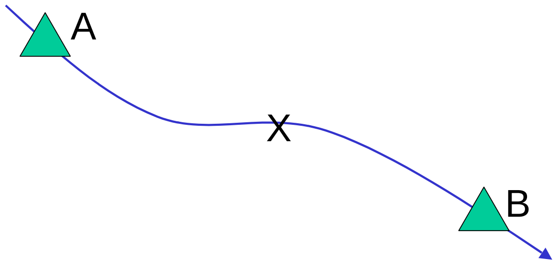


Figure 19: Donor sites and spatial consistency.

Using donor sites can also introduce 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 (flow reconciliation).

For similar reasons, and to save time, it is usually advisable to apply the same pooling group at several sites on the same watercourse.

Rainfall-runoff method considerations for catchment-wide studies

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 depth and duration appropriate for the catchment draining to that site (FEH Volume 1 Section 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. This may result in a number of different design storms being modelled to give critical results at different locations in the catchment.

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.

6.2 Direct rainfall modelling

Overview

An approach to rainfall-runoff modelling that has become 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 water, usually after subtraction of losses, 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 at the landscape scale.

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

Direct rainfall can appear enticing as it may appear to replace the requirement for the development of hydrological models and so reduces project costs and durations (Hall, 2015). However, direct rainfall models are often applied uncritically, without considering whether they adequately represent hydrological processes and whether they can be justified empirically by comparison with flow measurements. If a distributed spatial approach is being sought, there may be other distributed hydrological models that are more suitable, that are specifically designed to represent the processes by which runoff is generated. Such models also apply rain to a digital elevation model, but do not assume that all runoff is generated by overland flow.

Direct rainfall modelling for fluvial flood estimation

When choosing a direct rainfall approach to assess fluvial (river) flooding, the following should be considered:

- Does overland routing of flow adequately represent the processes by which river flood flows are generated?
- How will losses to evapotranspiration and infiltration be modelled? Do these vary spatially and temporally?

- 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? Use of land-cover land-use data to set distributed roughness can result in large errors (Medeiros and others, 2012).
- 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 further below.

Important! 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

Most direct rainfall models currently represent 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. Direct rainfall models are therefore using physics-based equations to model a physical process that may not actually occur in most of the catchment.

Even a direct rainfall model that is calibrated to match observed flood hydrographs at a downstream location may be unsuitable for predicting impacts of interventions such as land use change if the physical processes are not correctly represented. For example, a direct rainfall model of a chalk catchment might show that introducing surface runoff attenuation features could lead to a reduction in peak river flows, yet in reality surface runoff would probably not occur and so the features would not store any water.

Conceptual models, such as ReFH do not rely in the assumption of overland flow as they do not attempt to represent physical processes. There are also 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, TUFLOW, InfoWorks ICM and 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 they choose.

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

Approach 1 has an advantage over some more physically-based techniques of calculating runoff (or infiltration), because the loss components of 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 (the quick flow component does not necessarily represent overland flow).

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 may 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 20*) and will also depend on whether the 2D model code allows for sub-grid sampling of the topography. The approach can be improved with wetting-up of the model grid or potentially infilling depressions, although that is not always desirable when trying to understand flow accumulation (Engineers Australia, 2012).

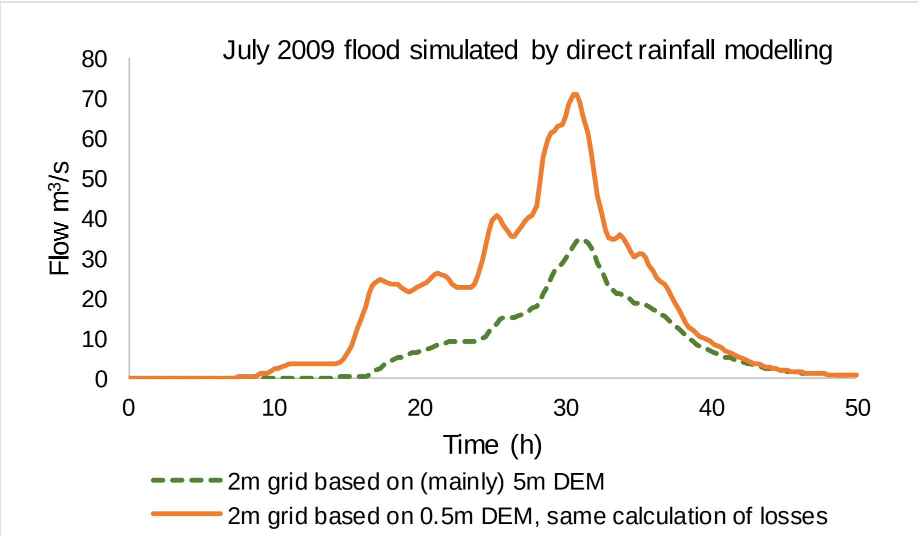


Figure 20: Sensitivity of predicted runoff volume to grid resolution. The graph shows two hydrographs simulated by direct rainfall modelling on a 37km² catchment in the northern Pennines. Both the volume of runoff and the peak flow change by a factor of two depending on the source of terrain data used 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.

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 and the complexity of subsurface flow pathways. 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.

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. See the CIWEM Integrated Urban Drainage Modelling Guide v2.01 (May 2021) for more advice on combined models.

When to consider direct rainfall modelling for fluvial flood estimation

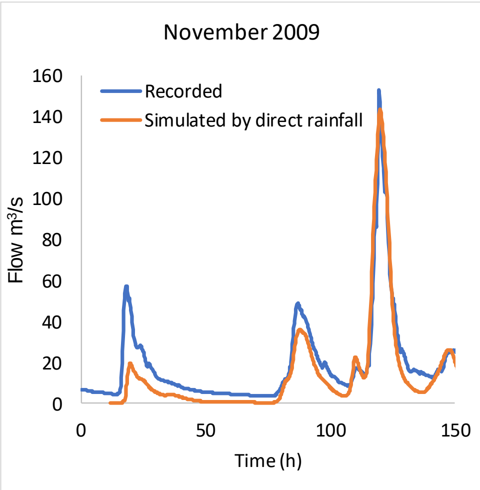
In light of the issues discussed above, on fluvial flood studies, avoid direct rainfall modelling using the shallow water equations as much as possible. However, it is sometimes worth considering for:

- 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. However, avoid using calibrated direct rainfall models to test scenarios that involve changes to the runoff response of the catchment.

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.

For example, *Figure 21* compares observed flood hydrographs with those simulated from a direct rainfall model. This is for a 170 km² 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 variable calibration performance indicates the unpredictable performance of direct rainfall models and the importance of calibration.



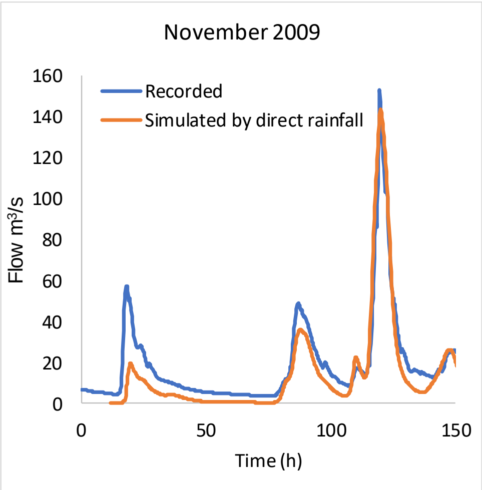


Figure 21: Comparing direct rainfall predictions with recorded flows

Direct rainfall modelling for surface water flood estimation

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 currently 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 in urban areas. 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. See the CIWEM Integrated Urban Drainage Modelling Guide (2021) for more advice on surface water flood modelling considerations.

6.3 Joint probability and multivariate analysis

Overview

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.

In all these examples, the influencing variables are unlikely to be completely independent, but 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:

- Using statistical methods to analyse the characteristics of multiple 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. This is known as multivariate analysis.
- 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.

Figure 22 shows a real-world example. 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.

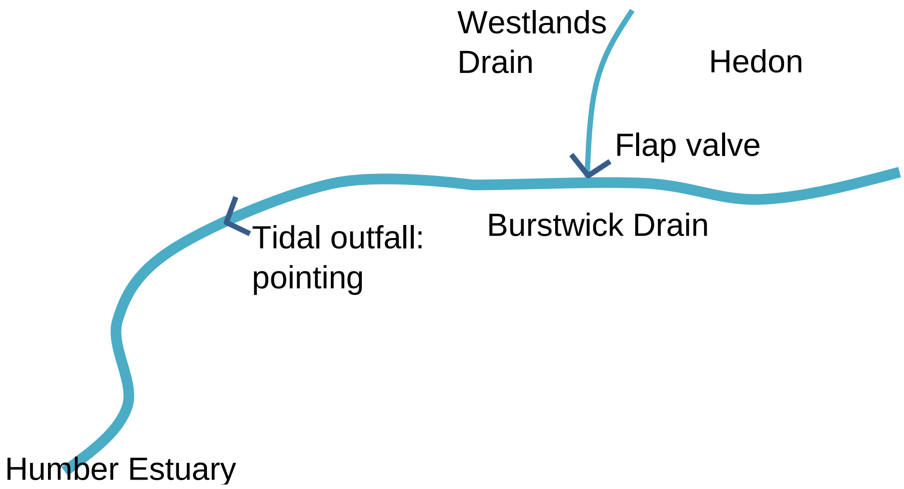


Figure 22: Example joint probability problem: flood risk in Hedon, East Yorkshire

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 itself 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 itself 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. For a large model, different combinations may give the critical condition in different locations.

Is joint probability analysis always necessary?

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.

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.

The limitations of design event methods with a uniform and simultaneous storm assumption become 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 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 multivariate analysis. This will only be possible if there are concurrent records of the input variables.

Multivariate analysis for joint probability assessments

There are many statistical methods that have been developed for joint probability analysis. Some of these are applied in research and are not 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 observed 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.

The Multivariate Event Modeller (MEM)

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 currently not fully accessible to all users. There is some limited access available through the Environment Agency for use on Environment Agency projects. Plans for making the MEM tool fully available online to all users are currently under development at the time of writing, in mid-2022.

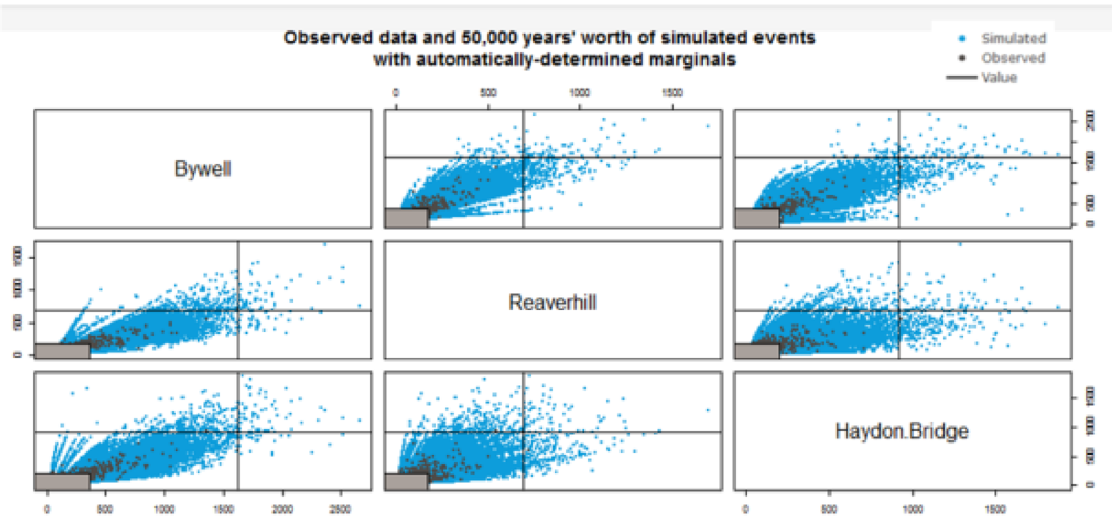
The MEM tool is aimed at those interested in joint probability assessment, including hydrologists, hydraulic modellers and coastal engineers. It can be used to:

- 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 FD2308 joint probability desk study spreadsheet.
- Find the probability of an observed or hypothetical extreme event at multiple locations and/or in multiple variables.
- Find potential combinations of multiple variables that have a required joint probability.

Figure 23 shows an example of the MEM tool outputs. 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, 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.

The input variables to the MEM tool 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 tool 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.



	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

Figure 23: Example outputs from the MEM tool

! Important 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.

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. When applying the MEM tool, you need to carefully consider sampling uncertainties, the robustness of the input data, and timing issues. It is recommended that the MEM tool 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 tool 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 tool 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 the MEM tool to develop this type of information.

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.

Multivariate analysis 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.

6.4 Short return period and seasonal flood estimates

Short return periods

Short return period events are defined here as events with a return period that is more frequent than 1 in 2 (an AEP greater than 50%).

Estimates of flow for high-frequency floods are sometimes needed in development control, where there may be 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).

For estimating flows that are not floods, for example the mean flow, or flow percentiles such as Q10 (the flow which is equalled or exceeded for 10% of the time), refer to low flow estimation methods guidance (e.g., IoH report 108, [Introduction to Qube - Qube User Guide (hydrosolutions.co.uk)]).

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. It may be important to consider flood seasonality when comparing observed event return periods to modelled design events.

6.5 Flood estimation for reservoir safety

The Reservoirs Act 1975 as modified by the Flood and Water Management Act 2010 provides a safety regime for raised reservoirs with a capacity greater than 25,000m^3 in England and 10,000m^3 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 (*Table 5*). The dam category is determined by the inspecting panel engineer.

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	Probable Maximum Flood (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

Table 5: Dam categories

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.

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.

This section gives a brief overview of the methods available and the current guidance (at May 2022). For detailed guidance, refer to FEH Volume 4 and ICE's

Floods and Reservoir Safety (2015). A full worked example is included in Project FRS19222 “Improving Probable Maximum Precipitation and Probable Maximum Flood estimation for reservoir safety” (available on request). 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)

Estimating design and safety check floods

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.

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) (*Table 6*).

! Important You should ensure that you are familiar with the methods and up to date with the latest guidance.

Current recommended methods				
Return period (years)	150	1000	10,000	PMF
Rainfall statistics	FEH13	FEH13	FEH13	FSR
Rainfall-runoff model	FEH or ReFH or ReFH2	FEH or ReFH2	FEH	FEH

Table 6: Current recommended methods for estimating design and safety check floods for reservoir safety (Floods and Reservoir Safety, 4th Edition)

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. A new rainfall dataset, FEH22, will be released at the end of 2022. This includes updated rainfall estimates for 150, 1,000 and 10,000 year events. Although in general we recommend that FEH22 is used in preference to FEH13, there may be some circumstances where a different approach is warranted. For reservoir safety design, you may wish to take a precautionary approach and use the highest rainfall estimate from FEH13 and FEH22.

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 (Stewart and others, 2019) and the PMF (Pucknell and others, 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.

The estimation of the PMF is set out in FEH Volume 4 Chapter 4. It is a version of the FSR/FEH rainfall-runoff method, with the following changes:

- the design rainfall event is the probable maximum precipitation, PMP. This is estimated from a procedure (FEH Volume 4 Chapter 4.3) based on information from maps and tables.
- you should estimate both summer and winter PMPs to see which gives the larger flood.
- use a different storm profile constructed by nesting PMP depths over different durations.
- reduce the time to peak of the unit hydrograph by one third to account for the more rapid response of an exceptional flood.
- increase the catchment wetness index to allow for greater antecedent rainfall.
- when estimating the winter PMF, set the standard percentage runoff to a minimum of 53% to account for frozen ground.
- when estimating the winter PMF, you should consider snowmelt (see below).

A full worked example is included in Project FRS19222 “Improving Probable Maximum Precipitation and Probable Maximum Flood estimation for reservoir safety” (available on request).

Rain falling directly on the reservoir

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.

Catchwater drains and changes to catchment boundaries

It is sometimes necessary to calculate the flow contributions from catchwater channels, which divert flow into a reservoir from neighbouring catchments. You should use hydraulic methods to estimate channel capacities and consider the maximum flow that could be conveyed into the catchment by the catchwater channels and any overland flow pathways.

Carry out a field visit to establish whether drainage paths are likely to change in an extreme event. It may be necessary to consider changes to the catchment boundaries in extreme events, for example if flows downstream in neighbouring catchments become constrained in an extreme event causing overtopping into the reservoir catchment. Discuss the potential for temporary debris dams affecting flow pathways with the Panel Engineer.

Estimating model parameters

Standard guidance on flow estimation methods is still applicable, refer to Chapter 4.

No matter which rainfall-runoff model you are using, estimate the parameters from local data if available, rather than relying on catchment descriptors alone. 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. You may be able to estimate reservoir inflow hydrographs from outflow and level records using reverse routing methods.

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.

If using catchment descriptors, you should always manually check their values. Take particular care when the catchment includes soil HOST class 4. This HOST class has an SPR of 2% which has been observed to significantly underestimate runoff rates for some soil types (Davison, 2005; Price and Torenga, 2016). You should adjust SPRHOST estimates to allow for higher runoff rates from this soil type. Where possible, use site data to estimate this adjustment. You should agree the method for adjusting SPRHOST with the Panel Engineer.

Storm duration should be estimated taking into account reservoir lag (FEH Volume 4 Section 8.2.1). Be careful if using timesteps of less than 0.25 hrs for short duration storms (e.g., <2 hours). This can produce uneven hyetograph shapes. Plot the hyetograph to check for this effect and if necessary, use a longer timestep.

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 24 hours, it may not be 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. The ICE guide recommends considering this for reservoirs with catchments greater than 100 km^2. Refer to FEH Volume 2 Chapter 4.3 for more guidance.

When modelling long critical storm durations for the probable maximum flood, please note that the Flood Studies Report rainfall tables only extend to 192 hours. When calculating the PMF, you have to include antecedent rainfall of a duration of 5 times the input design storm duration. This limits the maximum storm duration to about 38 hours. Although some software will allow you to model longer durations, you should carefully check the assumptions made regarding antecedent rainfall.

Snowmelt

For the winter PMF estimate, add snowmelt to the event precipitation and the antecedent rainfall.

! Important 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 Hough and Hollis (1997). 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 event rain depth is the PMP, and you need to make a suitably conservative assumption for a winter temperature. Use the antecedent rain depth to estimate snow melt in the antecedent period.
- Take into account the available depth of snow. If the total melt rate is greater than the available depth of snow, centre the melt over the PMP storm.

Unless you have specialist knowledge of the topic, it may be preferable to seek expert advice. A full worked example is included in Project FRS19222 “Improving Probable Maximum Precipitation and Probable Maximum Flood estimation for reservoir safety” (available on request).

Software

You can do PMF calculations in Flood Modeller Pro. Some consultants continue to use the Micro-FSR software, which was developed by the Institute of Hydrology to support the FSR methods. Neither of these currently implement the full Hough & Hollis snowmelt method.

A spreadsheet is available on request from the Environment Agency to support the Hough & Hollis method (LIT 58205). This includes a number of assumptions and limitations which you should understand before applying the spreadsheet to your site. The spreadsheet can be unlocked to change these assumptions if appropriate for your site.

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 rainfall-runoff 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

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.

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. It can help to calculate and compare the ratio of the 1000-year to the 100-year floods.

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.

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.

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.

6.7 Post-event analysis

Overview

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

Take care not to quote hasty over-precise assessments for rainfall and flood rarity. Consider using a range rather than a single value, to indicate the uncertainty in return period estimates. 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.

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.

Estimating rainfall return period estimates

It is usual to start by estimating the return period of the rainfall. Calculate a catchment average rainfall, bearing in mind that some relevant rain gauges 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. Always undertake checks and quality assurance on the rain data before using it to estimate return periods.

Also consider including data from radar, particularly if the catchment is not well covered by rain gauges 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. However, be aware that rainfall DDF models have not been developed using radar data and this increases the uncertainty of the return period estimate.

Use the FEH 2013 rainfall statistics (or latest rainfall DDF model) to estimate the return period. If your rainfall data has been measured at sub-hourly intervals (e.g., 15-minute resolution), you should use sliding durations. You should only normally use fixed durations if you are estimating the return period of a rainfall event that has been measured at hourly or daily rain gauges (e.g., where the duration is fixed to the 24-hour period between 9am on each day).

Take care when comparing observed events to modelled design events on the basis of rainfall return periods (for example, comparing the observed events for a rainfall event with an estimated return period of 1 in 50, to the results of a model run for the design 1 in 50 event). If a catchment is rural, the modelled design event may include a seasonal correction factor to adjust rainfall amounts for winter conditions. Therefore, for the same return period, the modelled design event may have used a smaller rainfall, and may have smaller flood extents, than an observed event with that return period. To allow a fair comparison between observed events and design model results, the observed rainfall return period may need to be seasonally adjusted.

Estimating flow return periods

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.

It is most common to estimate the return period of a flood in its immediate aftermath, but this could introduce 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.

Another aspect to consider is the bias inherent in estimating flood frequency and return period, particularly using a single site analysis (FEH Volume 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.

The ReFH model can assist in event analysis when there is no recorded flow data. Refer to the earlier section on ReFH rainfall-runoff model inputs. 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 for the same time period.

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 (Volume 4 Section 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 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 km² 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 km²) 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 km².
- 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.

Estimating floods for small catchments

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. Seek as much relevant information on local circumstances as possible and always exercise judgement in the application of generalised methods.

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. 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.

In accordance with the SC090031 Phase 1 report (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 km², derive flow estimates by applying FEH methods to the nearest suitable catchment above 0.5 km², 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.

The report on Phase 2 of SC090031 is due to be released in 2022. The recommendations for catchments and plots are summarised below.

FEH Statistical method for small catchments

Use the standard FEH regression for QMED. Adjust QMED using a single donor catchment, usually chosen on the basis of proximity. On average there is no advantage in choosing a small donor catchment or using catchment characteristics to select donors.

For catchments smaller than 40km², pooling groups can be derived using a revised similarity distance measure (SDM) intended for small catchments. This SDM considers only AREA and SAAR and gives less weight to AREA. It is implemented in WINFAP v5. WINFAP chooses the small catchments SDM by default for catchments smaller than 25km². For catchments between 25 and 40km² the user has the option to select the small catchments SDM. Usually, this option is worth selecting, although analysts may find it useful to compare the impacts of choosing this method against the standard approach.

If you are carrying out a project that includes several flow estimation points along a river, some on small catchments and some on larger ones, use your judgement to decide whether to apply the small catchments SDM. It can lead to a discontinuity in peak flows if you switch from the standard SDM to the small catchments version once the catchment area drops below 40km².

Comparisons undertaken by the Environment Agency using a sample of 4003 catchments from England with an area less than 40 km^2 and using NRFA v11 have indicated that on average, using the small catchments pooling method leads to higher flow estimates. In some cases, changes can be up to a 50%

increase in peak flow. The largest increases occur for catchments with a higher FPEXT (floodplain extent), i.e., flatter catchments with a wide floodplain extent.

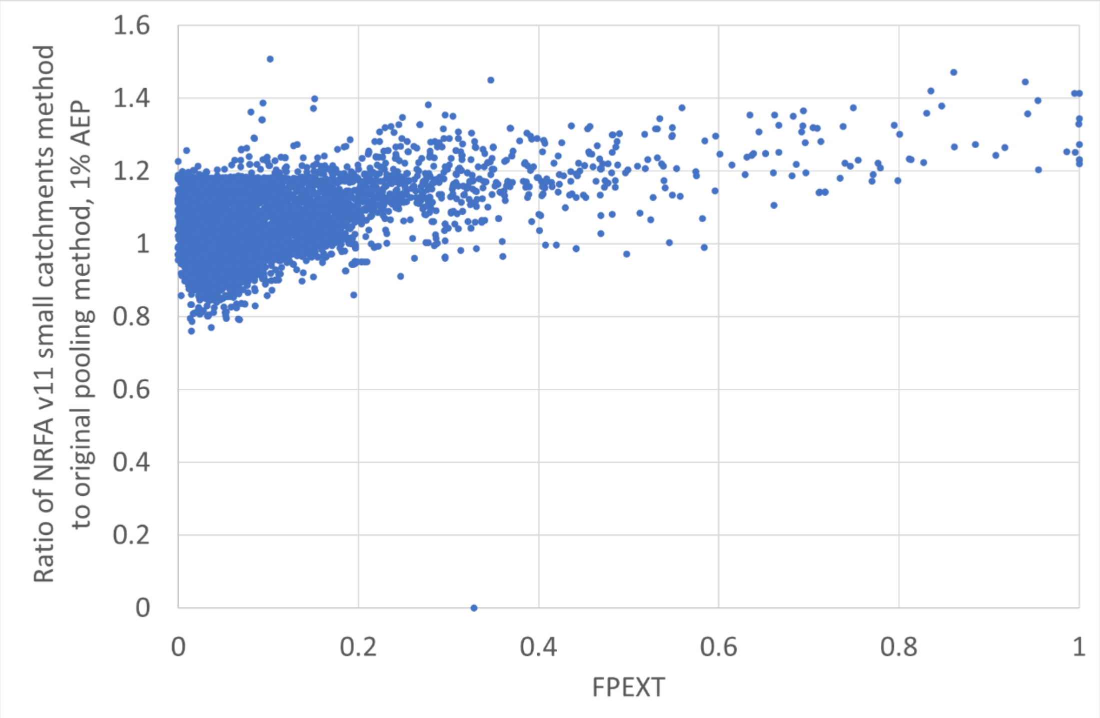


Figure 24: Correlation between FPEXT and the impacts of using the small catchments pooling method compared to the original pooling method for the 1% AEP event, for 4003 sample catchments

The revised SDM reduces uncertainty in pooled estimates of long return period floods, and increases variation between pooling groups for small catchments, helping to better differentiate between hydrologically-dissimilar small catchments. Take extra care when reviewing a pooling group created using the small catchments SDM, as it ignores some catchment descriptors that had no systematic effect in the data used in the research but are nevertheless known to affect flood peaks (for example, FARL).

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.

Estimating greenfield runoff rates

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.

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 is implemented is the regression equation for QMED. There is no use of donor catchments and no pooled growth curve. Instead, growth factors are calculated using the Flood Studies method regionalised growth curve. More reliable results could be achieved using standard FEH methods: using QMED with the small catchments pooling group method applied (see above) or using ReFH2 at the plot scale.

ReFH2 method for plot-scale application

The SC090031 research developed alternative parameter equations to support application of ReFH2 to drainage design at the “plot” scale (for example, a development site that does not encompass a whole catchment). These equations use AREA as an alternative descriptor to DPLBAR, and SAAR as an alternative to DPSBAR. 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.

The option to use the plot-scale equations can be selected in the ReFH2 software. When estimating greenfield runoff rates and storage volumes, use a winter storm and associated initial conditions.

ReFH2 can also 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 preliminary 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 (*Figure 25*). 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.

These estimates are intended to be precautionary, providing preliminary results for use at the initial stages 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. Detailed design should not use this preliminary method.

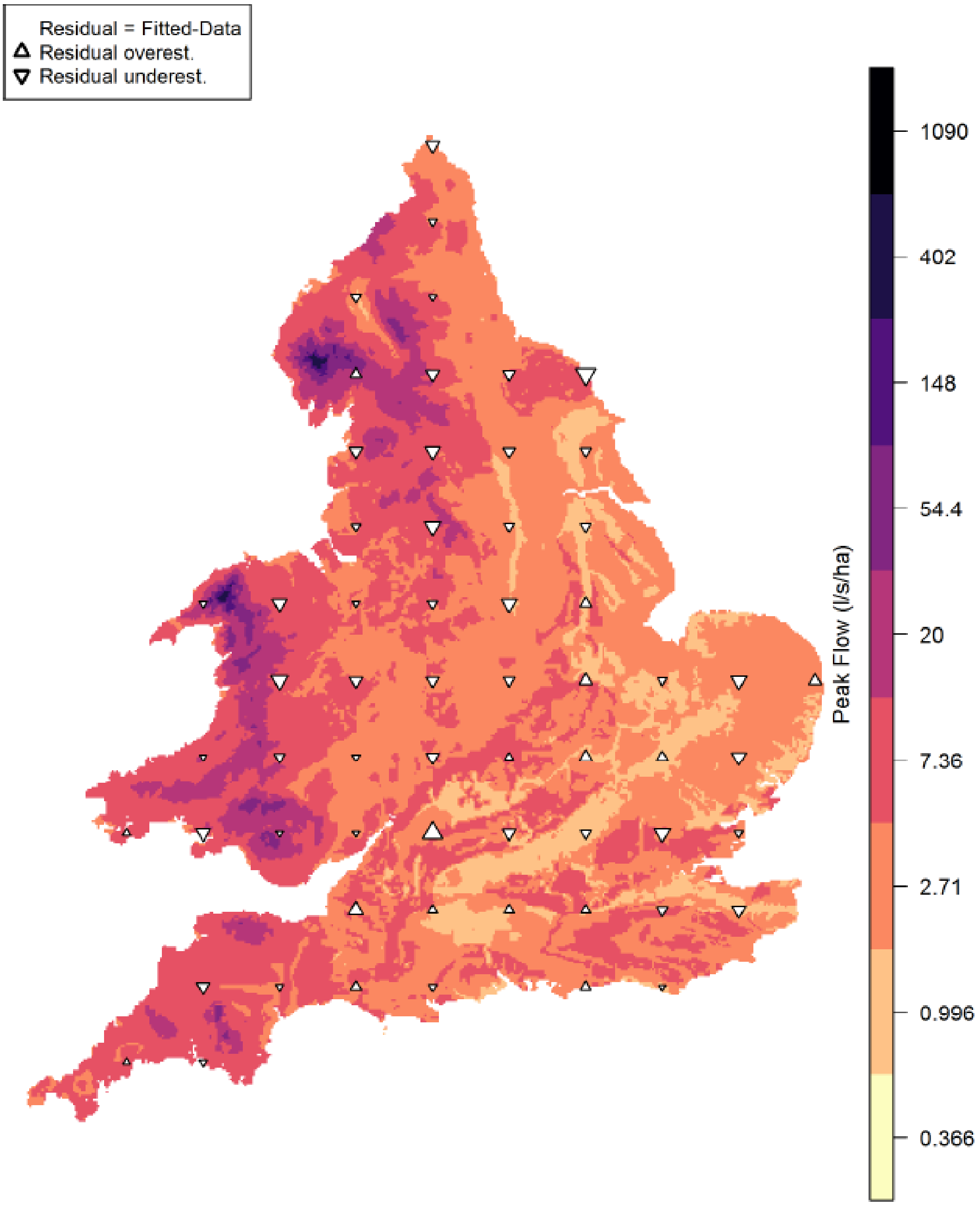


Figure 25: Example map of greenfield runoff. The map is an example output from SC09001, showing the precautionary estimate of greenfield runoff for a 30-year return period in l/s/ha.

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 (influenced by the soils and vegetation), the type of development, the way in which it is drained (including the extent of any SuDS measures), the location, spatial concentration and connectivity of the urbanisation. The FEH has much to say on the effects of urbanisation on flooding (FEH Volume 1 Chapter 8, Volume 3 Chapter 9, Volume 3 Chapter 18, Volume 4 Section 9.3, Volume 5 Chapter 6).

Urbanisation does not always necessarily increase flood flows. There are examples of heavily urbanised catchments that produce flood flows similar to or even lower than rural catchments. Vesuviano and Miller (2018) show that a 6km^2 catchment in Swindon dominated by suburban housing has a QMED, estimated from POT data, lower than the as-rural estimate of QMED made from ReFH2.

Because flood generation on urban catchments is so sensitive to local circumstances, you cannot expect to get a very reliable estimate of the flood frequency curve using generalised methods. These include the UK-average urban adjustments in the FEH Statistical method, and the additional parameters used in the ReFH model. 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 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.

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 degree of urbanisation of a catchment is represented in ungauged catchments using the catchment descriptors URBEXT2000 (used in the Statistical and ReFH2 methods) or URBEXT1990 (used in the ReFH and FEH Rainfall-Runoff methods). For information on the differences between URBEXT1990 and URBEXT2000, refer to Bayliss and others (2007).

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).

Slightly to heavily urbanised catchments (URBEXT2000 up to 0.6)

Either the FEH Statistical method or ReFH2 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 ReFH2 over those of FEH Statistical 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, 2022) 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 ReFH2 over those from the statistical method.

See Section 4.2 for further guidance on adjusting statistical method estimates for urbanisation, and Section 4.3 for further guidance on modelling urban catchments using ReFH.

Extremely heavily urbanised catchments and drainage design (URBEXT2000 > 0.6)

You should not routinely apply the FEH flood frequency methods to these catchments (FEH Volume 5 Section 6.5.5). For deriving flows from urban sewered areas, it may also 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 the CIWEM Integrated Urban Drainage Modelling Guide v2.01 (May 2021).

There is also useful guidance in the SuDS Manual (Woods Ballard and others, 2015).

The Modified Rational Method

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

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 (2021). 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

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 Groundwater-dominated catchments

Definition, extent, and further reading

A groundwater-dominated catchment is one in which the river flow is dominated by baseflow much of the time. This implies a close connection between surface water and groundwater. We use a minimum threshold of 0.66 for BFIHOST or BFIHOST19 to identify groundwater-dominated catchments for flood studies.

Most catchments above this threshold are in the south and east of England. The majority, and those with the highest BFIHOST, are dominated by outcrops of chalk. Others are found in areas of Jurassic limestones and Triassic sandstones. Groundwater flow processes can also play an important role on karst catchments, not all of which have a high BFIHOST.

Refer to a review of flood frequency estimation in groundwater-dominated catchments (JBA Consulting, 2022) for an in-depth look at the challenges, examples of floods, the performance of FEH methods and suggestions for improved practice and research.

In summary, you should:

- develop an understanding of the hydrological and hydrogeological processes that might result in a flood.
- be aware that significant floods can happen in groundwater-dominated catchments, but they tend to be infrequent.
- acquire local flow data (even a very short record using temporary flow loggers) if possible, rather than relying on catchment descriptors alone for estimation of design flows.
- carry out a review of historical floods.
- use the statistical method in preference to a rainfall-runoff technique.
- take great care with identifying suitable donor sites for QMED.
- understand the degree to which the project outcomes will be sensitive to flood volume, and explore methods to estimate hydrograph volume, duration, and shape.

Importance of understanding processes

You should develop an understanding of the catchment geology and hydrogeology when estimating floods in groundwater-dominated catchments. Establish the possible processes that might lead to flooding. Try to understand the balance between surface and underground flow processes, and how it changes between events.

Relevant processes and their consequences could include:

- runoff from intense rainfall on scarp slopes.
- a surge in baseflow due to a unusually high water table following prolonged autumn and winter rainfall.
- rapid groundwater movement through shallow highly-fractured zones of an aquifer.
- prolonged flooding dominated by baseflow.
- karst flow.
- snowmelt.
- surface runoff from rain falling on frozen ground.
- runoff from impermeable or urban areas of the catchment.
- ephemeral streams (winterbournes) which flow only in the winter, or only in some winters.
- some unusually small or large annual maximum floods.

Is there evidence that different processes operate during smaller and larger floods? If so, you should consider whether it is valid to fit a single flood frequency distribution to the whole set of annual maximum flows.

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. 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, and it may change between events. 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.

Importance of historical information

Significant floods tend to be infrequent on groundwater-dominated catchments, but they can be unexpectedly severe when they do occur. This means that you need to interpret gauged records with caution, being aware that an extreme flood could result from physical processes that have not operated during the gauged period and so could be several times higher than the highest flow in the annual maximum series.

Therefore, longer-term flood history is particularly valuable in groundwater-dominated catchments. Put particular effort into seeking and interpreting historical flood data that pre-dates gauged flow records.

Why to prefer statistical methods

Design event rainfall-runoff methods are generally thought less appropriate for highly groundwater-dominated 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 highly permeable catchments are not really suitable for design flood analysis using an event-based method.

These comments apply to both the ReFH1 and ReFH2 methods, although the ReFH2 results on catchments with high BFIHOST are greatly improved compared with those from ReFH1.

The FEH Statistical method is normally a more appropriate choice on groundwater-dominated catchments. However, it is important to be aware of the issues below.

Issue 1: Large uncertainty in QMED

The FEH regression equation for QMED (from Science Report SC050050) can over-estimate by a long way on some groundwater-dominated catchments (JBA Consulting, 2022). In some cases, all on Chalk catchments, the estimated QMED is more than 4 times higher than the value derived from flow data.

Potential reasons for overestimation of QMED on these catchments include:

- The topographic contributing area overestimating the hydrological catchment.
- The BFIHOST or BFIHOST19 value being unrepresentative of the hydrological response of the catchment.
- Depression of the groundwater table due to abstraction.
- The parameterisation of the QMED equation.

In some areas, large overestimation of QMED occurs not far from gauges that show significant underestimation. For this reason, take great care when estimating QMED at ungauged locations with high BFIHOST19. We suggest that you:

- Avoid choosing donors on catchments with much lower BFIHOST19.
- Look at QMED adjustment factors on several surrounding catchments with similar geology.
- Use the following types of information to help guide the choice of donor(s):
    - Groundwater flow directions, and differences between topographic and hydrological catchments. This information is available from

    - sources including the NRFA and BGS geological and hydrogeological maps and reports on groundwater modelling studies.
    - Whether streams are perched above the water table or not.
    - Spatial configuration of geology, such as whether the valley bottoms are drift-free.
    - Differences between BFI and BFIHOST19. This information should be available even at flow gauges without suitable annual maximum flow data.
    - Consistency of QMED adjustment factors on surrounding catchments with similar geology.

- Seek additional local sources of flow data, such as gauges that provide flow duration curve statistics, from which QMED can be estimated. You could treat these as additional candidate donor stations.
- Use judgement to decide how and whether to apply the distance moderation factor for data transfer.
- 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.

Issue 2: Pooling groups

In the original FEH method, pooling groups for groundwater-dominated catchments were generally composed of gauged catchments with similar groundwater dominance. 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.

Issue 3: Non-flood years

For some groundwater-dominated catchments (and other, mostly low-rainfall 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 bias the flood growth curve. Refer to the section on adjusting growth curves to remove the influence of non-flood years.

Issue 4: Separating quickflow and baseflow components

Some studies carry out separate frequency analysis of the rapid runoff and baseflow components of the flood hydrograph. This is worth considering, as long as you use a multivariate statistical model to allow for the dependence between the two components.

Estimating hydrograph volume, duration, and shape

The volume and duration of floods are important factors to consider. Understand the degree to which the project outcomes will be sensitive to flood volume. In a flood mapping study on a baseflow-dominated catchment it might be suitable to ignore flood volumes and run a hydraulic model in steady state. On the other hand, for examining flood storage options or for a catchment in which permeable headwaters flow into a low-lying river, volumes could be critical.

Bradford and Goodsell (2000) investigated flood volumes on highly 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.

Where full hydrographs are needed, you can implement a hybrid approach. Consider whether an empirical analysis of hydrograph shapes using the methods described earlier might give a more realistic design flood hydrograph than the ReFH2 method, which can produce hydrographs with an initial baseflow of zero. Take care with the empirical analysis 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.

Consider flood estimation by continuous simulation on groundwater-dominated catchments with suitable flow data for model calibration, particularly in any of these situations:

- the catchment contains a mixture of low and high-permeability geology.
- the catchment contains urban areas from which rapid runoff occurs.
- the project involves assessing options for flood storage, because continuous simulation provides a much more rigorous test of options than a single design flood event.

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). Refer to JBA Consulting (2022) for examples of continuous simulation studies on groundwater-dominated catchments.

7.4 Catchments containing lakes and reservoirs

Description

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

Lakes and reservoirs have an attenuating effect on flood peak flows and hydrograph shapes. Reservoirs act to attenuate flood hydrographs even when they are at full capacity.

Choice of methods

The choice of method for catchments with significant influence of lakes and reservoirs will depend on the local data available and the requirements of the analysis.

FEH Statistical method

The FEH statistical method can account for lakes and reservoirs in a general way using the catchment descriptor FARL, or with more accuracy if flood peak data are available downstream of the reservoir and close to the site of interest.

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

If no flood peak data are available, the FEH statistical method uses 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 (FEH Volume 3 Section 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.

ReFH method

Hydrograph shapes downstream of reservoirs should be estimated using observed data where possible.

When using catchment descriptors alone, be aware that the ReFH/ReFH2 method does not account for the influence of lakes and reservoirs. You can use it to estimate the inflow to a lake or reservoir, along with a flood routing calculation (for example using a spreadsheet or hydraulic modelling software) to determine the outflow from the reservoir (FEH Volume 4 Chapter 8). Unless the subject site is directly downstream from a single reservoir, it will be necessary to use a distributed approach with a routing model to allow for inflows from the rest of the catchment.

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 (FEH Volume 4 Section 8.2, Volume 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 (FEH Volume 4 Section 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.

Designing and operating flood storage reservoirs

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

Overview

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

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.

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. Therefore, it is nearly always best to avoid using the FEH Statistical method on lowland catchments (FEH Volume 3 Section 13.7.4).

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).

! Important The HOST classes in some lowland areas with highly permeable soils appear to underestimate the volume of runoff when compared to pumping records, perhaps because they do not account for the shallow water table or the presence of field drainage systems. You should check that model behaviour reflects operational experience (for example, frequency, timings, and duration of pump operations; flood frequency and extents).

FSR rainfall-runoff method for pumped catchments

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 using a variation of the FSR rainfall-runoff method first published in 1987 that includes a trapezoidal unit hydrograph. See Samuels (1993) and IWEM (1987) Part 1). An Environment Agency science project, SC090006 (Flikweert and Worth, 2012) updated the earlier guidance but the basic method is unchanged. In summary:

- Use a trapezoidal unit hydrograph shape, which reaches the peak flow at 0.5 Tp and remains at that flow until 1.5 Tp (*Figure 26*). 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.

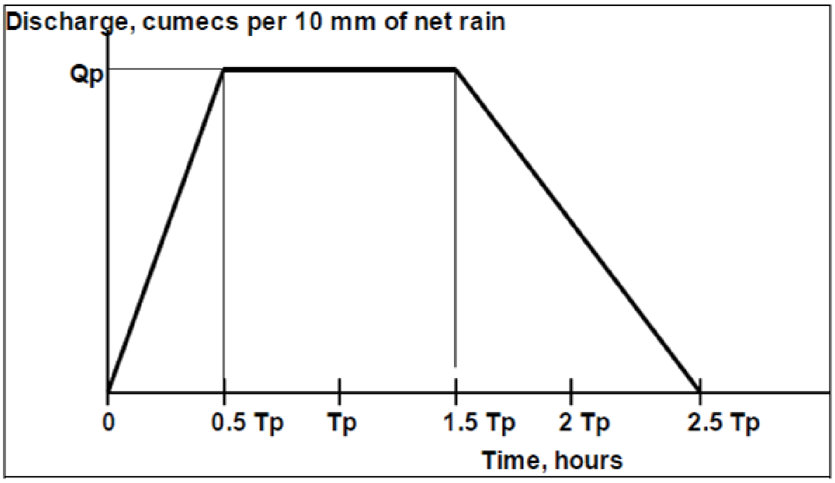


Figure 26: Trapezoidal unit hydrograph, from Science Report SC090096

Inflows for hydraulic models

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 apply caution if using 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.

Alternative methods for pumped catchments

An alternative method of flood estimation on pumped catchments is 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).

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 uses the pump capacity as an upper limit on the outflow.

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 around losses and subsurface flows in the hydraulic model development. Refer to the section on direct rainfall modelling.

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.

8 Audit trail

8.1 Flood estimation calculation record

Purpose

The flood estimation report template (LIT 11833) 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).

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

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

Filling in the calculation record

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. You can modify the template, if required, for such situations as non-stationary flow estimates and reservoir safety PMF calculations.

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 enough detail to allow the calculations to be reproduced by others.

Recording the data used

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.

Submitting digital files for review

If you are submitting work commissioned by the Environment Agency or for review by the Environment Agency, you should be prepared to submit on request input data, output data and project files (where these exist) from the software you have used in the flood estimation, in support of the calculation record.

Input data includes:

- Catchment descriptor files exported from the FEH web service in the formats required by the software you have used. Use the subject site names or codes to name these files.
- Any altered version of the NRFA peak flow dataset, such as additional gauges, updated flood peak series or alterations from rating curve updates. Submit the entire dataset rather than just the altered files, so that it can be directly used in software such as WINFAP.
- Hydrometric timeseries used to estimate rainfall-runoff model parameters.

The type of project or calculation file to submit depends on the software you have used.

- For WINFAP 5, submit the project file, which has the extension ".wxml". There will be a separate file for each subject site that you have analysed within WINFAP 5. Use the subject site names or codes to name the project files.
- For older versions of WINFAP, submit the project file with extension ".feh4" or ".feh". These may contain several subject sites.
- For ReFH2, submit project file for each subject site, with extension ".rxml". Use the subject site names or codes to name the project files.
- For calculations carried out in hydraulic modelling packages or drainage design software that interfaces with ReFH2 or applies the ReFH1 method, submit the files from the modelling package, which will probably also be required for review of the hydraulic modelling.
- Submit any spreadsheets used as part of the calculations.
- Submit any code written in R or other languages, for example used in conjunction with the UKFE package.
- When you have used other software, submit whatever files are available that you believe will be useful in auditing the calculations.

Be aware that the Environment Agency may ask for evidence that the software you have used is correctly implementing the FEH methods. This could take the form of comparisons with the results of software that the Environment Agency has checked and reviewed. It is your responsibility to demonstrate that the software you have used implements methods correctly.

If you have used code or spreadsheets that are subject to intellectual property right restrictions, make this clear in your submission. The Environment Agency will not pass this material on to third parties.

Relevant output data may already be included in the project file but include any other outputs that will be necessary for checking the calculations. When you have applied the ReFH2 software, include CSV output files containing hydrographs.

Submit the digital files in a logical structure, dividing them into folders if necessary.

8.2 Presenting results

Presenting to non-specialists

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.

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.

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 real-time press releases.

Providing flow estimates for hydraulic modelling studies

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.

List of acronyms

Acronym	Full expression
AEP	Annual Exceedance Probability
AMAX	Annual Maximum
AREA	Catchment area (km^2)
BFI	Base Flow Index
BFIHOST	Base Flow Index estimated from soil type, using the method published in IH Report 126 (1995)
BFIHOST19	Base Flow Index estimated from soil type, using the revised method published in 2019
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
DS	Depression Storage
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
IF	Imperviousness factor
Kappa 3	3-parameter version of the kappa distribution, with the fourth parameter fixed to -0.40
MEM	Multivariate Event Modeller
MORECS	Meteorological Office Rainfall & Evaporation Calculation System
MOSES	Meteorological Office Surface Exchange Scheme
PETI	Potential Evapotranspiration with Interception correction
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

Acronym	Full expression
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)

History of these guidelines

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. Applicable to work in England, Wales and Northern Ireland. 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.
8	Produced by the Environment Agency with the help of JBA Consulting. Includes updates since 2019, such as guidance on applying new features in WINFAP 5 and guidance on non-stationarity. Template updated to latest Environment Agency version. Issued in 2022.
9	Minor edits and corrections following comments and suggestions received from the practitioner community. Issued in January 2023.

Timeline of developments since release of FEH

The table below describes some of the main developments that have affected the way practitioners carry out flood frequency estimation in England, since the release of the FEH in 1999. It is far from comprehensive and excludes most updates to flood peak datasets, which have been numerous. It also excludes most academic publications apart from those that have been implemented by significant numbers of practitioners.

Year	Type	Development
2005	Commissioned report	Publication of report on ReFH method
2005	Software	Release of ReFH spreadsheet
2005	Data	Release of HiFlows-UK dataset. This was the first version of HiFlows-UK; before this FEH users either used the original FEH flood peak dataset (ending in 2005) or various locally updated versions of it.
2006	Commissioned report	Release of report on URBEXT2000
2006	Software	Release of v2 of FEH CD-ROM. This gave URBEXT2000 and improved catchment boundaries.
2007	Software	Release of v2 of WINFAP-FEH. The main change was updating urban adjustment to use URBEXT2000.
2007	Software	Release of ReFH Design Flood Modelling Software. This enabled estimation of ReFH parameters from hydrometric data and application of ReFH for simulation of observed events
2008	Commissioned report	Publication of revised FEH statistical method in SC050050. It included a new regression equation for QMED, new data transfer procedure and new procedure for pooling. This remains the current version of the core method.
2009	Software	Release of software for applying revised statistical method (v3 of WINFAP-FEH and FEH CD-ROM)
2009	Journal paper	Publication of paper on amended version of ReFH that represents runoff volumes in urban catchments
2010	Journal paper	Publication of paper on revised urban adjustments for statistical method
2012	Commissioned report	Publication of guidance on flood estimation in pumped catchments
2013	Journal paper	Publication of paper on further extensions to ReFH model for urban catchments
2014	Journal paper	Publication of paper on the benefits of using multiple donor sites for QMED (Kjeldsen and others, 2014)
2015	Software	Release of ReFH2 software
2015	Software and data	Release of FEH web service and FEH13 rainfall DDF data

Year	Type	Development
2015	Software	Release of ReFH 2.1. This allowed use of the FEH13 rainfall statistics, with FEH99 as an alternative.
2016	Software	Release of ReFH 2.2, a relatively minor update.
2016	Software	Release of ReFH2 calibration utility
2016	Software	Release of WINFAP v4. This made little change to core methods. The main additions were: fitting flood frequency curves to historical or palaeoflood data, joint with AMAX flows; estimating QMED from channel width in combination with catchment descriptors; estimating QMED from low flow statistics at gauges not suitable for calculating flood flows; ability to carry out enhanced single-site analysis at urban catchments; revised urban adjustment with more flexibility; option to apply multiple donor sites.
2017	Commissioned report	Release of FEH Local guidance on uncertainty and use of local data in flood estimation.
2017	Journal paper	Publication of Kjeldsen and others (2017) on the use of the kappa distribution for flood frequency estimation
2019	Data	Release of BFIHOST19
2019	Software	Release of ReFH 2.3. This made changes to the urban runoff model; added conservation of mass; added Cini for summer conditions. Accompanied by technical reporting of method enhancements.
2020	Commissioned report	Release of interim national guidance on non-stationary fluvial flood frequency estimation.
2021	Software	Release of WINFAP v5
2022	Software	Release of spreadsheet that carries out PMF estimation using the FSR/FEH method.
2023	Commissioned report	Anticipated release of Small Catchments R&D report
2023	Data	Anticipated release of FEH22 rainfall DDF data and ReFH2.3-FEH22 recalibrated software

References

Environment Agency controlled content

These documents are available internally to Environment Agency staff via content cloud. You can request them via the Environment Agency's customer contact centre.

- LIT 11833 – Flood Estimation Report Template
- LIT 17618 – Hydrology Review Template
- LIT 14089 – High flow rating curve development using hydraulic models
- LIT 58205 – Probable Maximum Flood calculation spreadsheet
- LIT 14710 – Using local data to reduce uncertainty in flood frequency estimation (Technical Guidance 12_17).
- LIT 56492 – Non-stationarity scoping template
- LIT 16157 – Understanding and Communicating Flood Risk (Policy 260_05).

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