2 Hydrology

2.1 Key issues

Hydrological analysis is an essential prerequisite for any project involving the implementation of works in a river or stream. The hydrology of the catchment defines boundary conditions and sources of risk, such as low flows affecting navigation or high flows causing flood or erosion hazards.

But although hydrological data appear to be an independent input to a design project, the quality of the data and the analysis are vital in providing a realistic understanding of risk. It follows therefore that uncertainties in the hydrological analysis should be understood and treated sensibly. The specialist hydrologist should be involved early in the design process to help with risk identification, data collection and design development (see Chapter 1 for an explanation of these steps in the design process).

Hydrological data in the UK are generally of high quality and hydrologists are trained to scrutinise data carefully, to exclude or recognise potential misinformation. Most hydrological analysis methods have been developed with a view to maximising the information gained from the available data and the analyst’s confidence in the results. Nevertheless, uncertainty is always present and the methods to quantify and even represent uncertainty are not all settled into routine practice. It is therefore difficult to provide general statements in answer to the question ‘how much uncertainty is there in a hydrological estimate?’ Hydrological analyses based on good practice and fair data should give us enough confidence to inform design decisions, but are likely to lead to a realistic band of uncertainty in water level estimates that is at least an order of magnitude greater than, for example, the precision of survey data. Uncertainty is discussed further in Section 2.7.

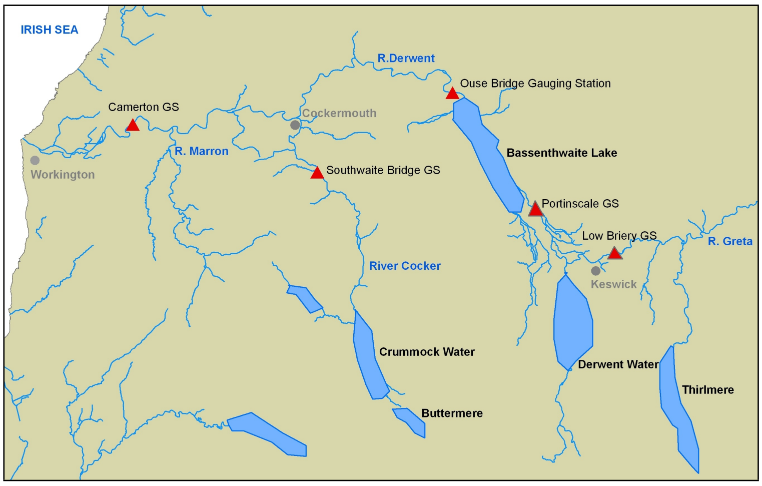
The hydrological analysis for a design should be guided by understanding the functional requirements for the project. Issues to consider include:

- Does the project call for analysis of high, low or mean flows? In practice, the answer may well be all three. For example, the design of a flood relief channel may have to consider low flow levels or velocities during a drought in order to assess the potential ecological impacts, or mean flows in order to assess the effect of the scheme on a nearby abstraction site.
- The range of design conditions relevant to the scheme. The analysis may concentrate on high or low flows, but could include sensitivity tests for alternative scenarios, such as climate change, land use change or urbanisation.
- Hydrology is fundamentally about understanding volumes and flows of water, but most design studies involve estimating water levels corresponding to specified conditions such as a ‘100-year’ flood level (see Section 2.4.1 for a discussion of the meaning of ‘T-year’ flood). The relationship between flow and level depends on the hydraulic conditions at a given location (see Chapter 7 for further discussion of hydraulic analysis).
- If storage is involved in high-flow analysis (whether natural storage on the floodplain or artificial impoundments), it is important to consider the volumes as well as the peak water levels and discharges. This means that a hydrograph is needed. Designers should be aware that, for flood analysis, the methods used to generate a ‘design hydrograph’ usually assess the probability in terms of the peak flow. The flood volume would not necessarily have the same probability.
- If the project site is extensive (for example, with river restoration works over a long reach), there may be a need to consider whether hydrological design conditions could vary significantly over the study site – especially around confluences.

- Are there significant influences on the site from non-fluvial sources such as drainage outlets, groundwater, tidal influence or pumping? Abstractions are important for a low flow analysis.

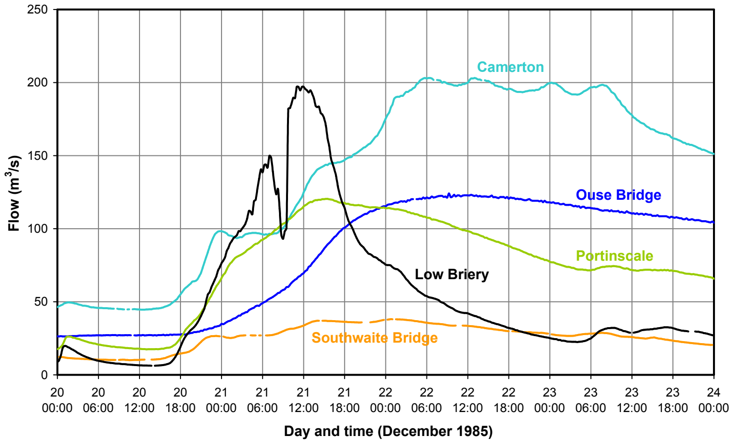
The presence of lakes and reservoirs in the catchment should be considered. Appropriate techniques are mentioned later in this chapter. The influence of lakes and reservoirs is illustrated in Box 2.1.

Box 2.1 Influence of lakes and reservoirs



The map shows the location of five gauging stations in the Lake District and the main features of the drainage network.

The catchments in this region are steep, impermeable and produce runoff very quickly after rainfall.



The graph shows flow data from the gauging stations for a storm event in December 1985.

It can be seen that the responses vary dramatically, even on the same branch of the river network, due to the influence of the lakes. For example, the very rapid rise and fall at Low Briery is attenuated to become a smooth, gradual hydrograph at Ouse Bridge, downstream of Bassenthwaite Lake.

2.2 Processes in flood hydrology

2.2.1 Rainfall and snowmelt

For fluvial design calculations, it is necessary to consider the type of rainfall patterns most likely to generate the appropriate design conditions at the site. In general, smaller drainage areas, steeper slopes and more impermeable soils or geology tend to be more sensitive to a relatively short, high intensity rainfall event. Where the drained area is large, the slopes mild and the geology more permeable, shorter storm events are more likely to be attenuated by storage and by the time delays associated with longer flow paths within the catchment.

Rainfall processes are complex, but hydrologists often draw a distinction between long duration, low intensity, widespread rainfall and short duration, high intensity, localised storms. The former are perhaps more like large-scale frontal weather systems and the latter more like convective thunderstorms, but this physical interpretation is crude; for example, high intensity convective rain cells can be embedded within frontal patterns. Designers should note that rainfall amounts vary considerably within a storm and that, particularly for large catchment areas, point rainfalls may depart significantly from the average.

The difference in characteristic types of rainfall is reflected in hydrological design methods by using different typical storm profiles. In the UK, *Flood studies report* (FSR) (NERC, 1975) used summer (shorter and more peaky) and winter (longer and smoother) symmetrical profiles, with the summer profile recommended for urban catchments and the winter profile for rural catchments.

Snowmelt has been an important factor in some notable UK floods, especially where triggered by warm fronts and accompanying rainfall onto frozen ground (which has reduced infiltration capacity). There is little guidance available on when to consider snowmelt in design calculations, apart from the special cases of probable maximum precipitation (usually for reservoir design) given in Volume 4 of *Flood estimation handbook* (FEH) (Institute of Hydrology, 1999).

2.2.2 Runoff generation mechanisms in natural catchments

For hydrological design calculations, it is useful to think of a combination of runoff generation processes and runoff routing processes.

Runoff is typically generated in response either to rainfall rates exceeding the infiltration capacity of the soil or because the soil has already become saturated and cannot absorb more water. Runoff routing processes include channel flow, overland flow, pipe or macropore flow, and matrix flow through the soil or bedrock.

In design calculations, it has been traditional to regard the process by which river levels rise during or after a storm as a combination of a slowly varying baseflow (often associated with groundwater) and storm runoff (assumed to represent the rainfall during the event). In fact, runoff responses in nature are much more complex than this; isotope analysis at a range of scales has shown that more than half of the ‘runoff’ during a storm event can be ‘old’ (or pre-event) water that has been displaced by the storm rainfall. Not all of the ‘runoff’ generated in response to a rainstorm should be assumed to be overland flow.

2.2.3 Urban runoff

Urban areas typically have high runoff rates because of their higher proportion of relatively impermeable surfaces. For a fluvial design calculation, the questions are more likely to be about the impact of an urban area within the whole catchment than about the runoff produced by a localised urban area. However, runoff from an urban area is important for the design of sustainable drainage systems (SUDS) (see Chapter 10). In reality, the impact on design flows depends on:

- size and location of the built-up areas;
- efficiency of the drainage system;
- storm track and rainfall profile in a particular event.

Standard design methods do not take storm movement into account, although the statistical method given in Volume 3 of *Flood estimation handbook* does include an adjustment for urbanisation, and the FEH and ‘revitalised flood hydrograph (ReFH) event models (Kjeldsen *et al*, 2008) include an urban extent parameter; see ‘Key references’ for an explanation of ReFH.

In the case of the statistical method, urban adjustment is based on an empirical model and represents the net effect of urban areas within UK catchments, including any associated drainage or flood amelioration works. Only seven highly urbanised catchments could be used in the development and calibration of the ReFH method. Therefore, in the absence of additional local calibration data, there is less confidence about the design flows produced by the method than in rural catchments. For design calculations in the immediate vicinity of an urban-dominated catchment, it is worth considering the actual or design performance of the urban drainage network.

2.2.4 Storage

Storage has the general effect of attenuating the flood hydrograph, reducing its peak flow rate and spreading the volume out over a longer time span. This effect may be natural (for example, floodplain storage for overbank flows) or engineered as part of a flood alleviation scheme. It may also occur if floodbanks are overtopped (or breached), leading to water ponding up behind. It is worth looking at whether this could create significant storage volumes, for example if there are extensive low level agricultural floodbanks upstream of a site. It is also worth being aware of any significant flow or level thresholds where storage effects may start to have an impact on the hydrograph, such as the levels at which floodbanks or the natural topography are overtopped allowing the river to fill a storage area.

2.2.5 Groundwater

Groundwater flooding tends to be very prolonged and results not just in high river flows, but also in the appearance of many small spring lines or seeps that may be some distance from any permanent watercourse. Standard FEH methods include some allowance for permeable catchments when calculating river flows but, for sites that could be affected by emergent springs, little guidance is available. Perhaps the best approach is to seek anecdotal evidence of past flooding and to study historical evidence such as maps.

2.2.6 Tides and surges

For tidally influenced rivers, the most significant source of flood risk can be the combined effect of high tides and storm surge rather than fluvial flows. A coincidence of high tide, surge and fluvial flows is a worst case scenario. This joint probability problem is somewhat beyond the scope of ‘standard’ hydrological analysis methods. The analysis may require a matrix of simulations of water levels under different combinations of tidal and fluvial boundary conditions to determine combined probabilities. This analysis is likely to involve building a mathematical model of the river channel and running it with downstream water level boundary conditions derived from a tide/surge analysis and upstream boundary conditions derived from a hydrological analysis. Hydrologists should note that the backwater influence of a tidal boundary on water levels can extend upstream beyond the actual tidal limit.

2.3 Sources of data

2.3.1 Hydrometric data

River level and flow

Gauged river flow data are the most direct and important source of information for hydrological analysis. Local flow data are extremely valuable as they can greatly increase the confidence in the analysis compared with relying solely on generalised procedures.

High flow data

The accuracy of high flow records has a direct impact on the accuracy of flood estimation. It is therefore essential to understand how flow is measured at a gauging station and the likely limits in accuracy of high flows.

At most sites, flow is assessed by measuring the water level and converting it to discharge using a rating curve. Rating curves are prone to uncertainty due to extrapolation and because many gauging stations are bypassed in flood conditions; this uncertainty is often far greater at flood flows than at low to medium flows. The case study in Box 2.2 features a gauging station in East Sussex under high and low flow conditions.

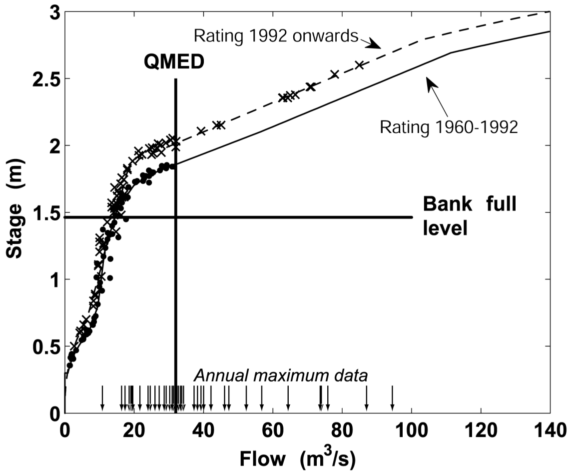
Box 2.2 Case study – gauging station under high and low flow conditions

River Ouse at Goldbridge gauging station, East Sussex

The top photograph shows the station at low flows and the bottom photograph shows the structure largely drowned out.

Note that this station is still regarded as producing useful high flow data because, even when the structure is drowned, the flow is contained within riverside banks and a relationship between water level and flow has been developed (the standing water visible in the background in the lower photograph is from overtopping downstream of the structure rather than bypassing).

Source: R Long, Environment Agency



HiFlows-UK rating curve for Goldbridge

The change in the shape of the rating above bankfull can be seen clearly. Note that there are two distinct sets of gaugings and rating relationships, corresponding to the periods before and after 1992, when the site was refurbished.

The annual maximum (AMAX) flows are plotted as vertical bars. There are check gaugings prior to 1992 up to the median annual flood (QMED; see Section 2.4.2) but not for higher flows, which are therefore based on extrapolation of the rating.

Higher check gaugings have been recorded since the datum changed in 1992, and seem to confirm the extrapolated rating. The AMAX data are therefore considered reliable.

It is vital to be aware of the shortcomings and range of accuracy of any rating curve. Section 3.2 of *Flood estimation guidelines* (Environment Agency, 2007) explains how to check a rating curve while guidance on extending the range of rating curves is given in an earlier report (Environment Agency, 2003).

Flood peak data

There are two main types of flood series:

- The annual maximum (AMAX) series is used for most FEH methods and consists of the largest observed flow in each *water year*.
- The peaks-over-threshold (POT) series consists of all distinct peak flows that are greater than a selected threshold flow. The FEH uses POT data mainly when the flow record is short (less than 14 years).

Visual examination of flood peak data is worthwhile for quality control and to aid understanding of the flood regime. Section 3.1 of *Flood estimation guidelines* (Environment Agency, 2007) gives guidance on what to look for.

Rainfall and flood event data

The main use of rainfall data in flood estimation is in estimation of the parameters of the ReFH method. Although these parameters can be estimated from catchment descriptors, more reliable values can be obtained on catchments for which flow and rainfall data are available for at least five flood events.

Unlike the older rainfall–runoff method described in FEH, ReFH does not include the provision to use river level data for deriving time-to-peak. Despite this, level-only stations can still provide valuable information, for example on the timing and duration of flooding. This can often be incorporated into the design of works such as flood alleviation schemes. For example, the relative timing of hydrographs at confluences is an important consideration when deciding where to site upstream flood storage (Chapter 10). If a flood storage reservoir is built on a tributary that naturally peaks first, the effect of the storage may be to make the flood peaks coincide at the confluence, thus increasing flood flows further downstream.

For flood event analysis on most UK catchments, it is necessary to obtain data from at least one recording raingauge, which typically provides rainfall data accumulated continuously at 15-minute intervals (or even more frequently). For very large catchments, daily data may be sufficient because the hydrograph may be much smoother and less ‘peaky’.

Flood event analysis needs to be based on catchment-average rainfall data. Radar rainfall data can help in averaging point measurements of rainfall.

Figure 2.1 shows data obtained at an example high flow flood event.

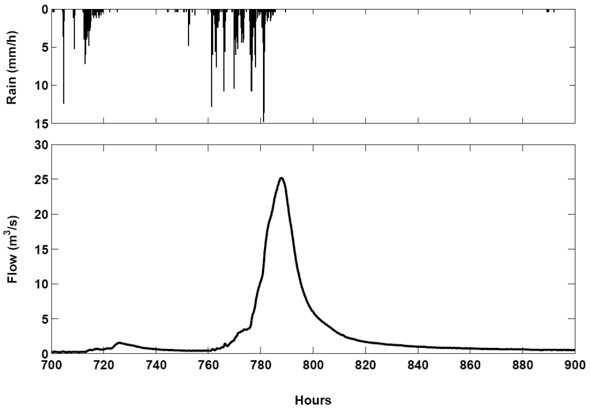


Figure 2.1 Flood hydrograph

Hydrograph showing a high flow event on the River Gaunless in October 2002

The top panel shows rainfall at 15-minute intervals; the lower panel shows flows recorded at the gauging station at 15-minute intervals. This is a responsive, upland catchment in north-east England. Note the rapid rise during the main event and also the greater impact of a sustained period of rainfall, causing saturated conditions.

Catchment water balance and low flow data

Daily mean flow data are useful to summarise overall water balance and yield for a catchment, or ‘low flow’ analysis. Typically, water levels (flow estimates for ultrasonic and electromagnetic gauges) are recorded at 15-minute intervals from which a mean flow can be calculated for each day.

In the UK, daily mean flows are usually computed for the water day (09:00 to 09:00 GMT), although calendar days (midnight to midnight) are sometimes used. Often it is useful to analyse longer aggregations of mean flow data, for example seven-day or monthly averages.

Where to go for existing data

The main source of flood peak data is the HiFlows-UK dataset, which contains AMAX and POT level and flow data, rating histories, photographs and guidance on the quality of data for around 1000 gauging stations in England, Wales, Scotland and Northern Ireland. HiFlows-UK can be freely accessed via http://www.environment-agency.gov.uk/hiflowsuk. HiFlows-UK is being continually updated; details on the current version and its spatial and temporal coverage are available on the website.

Flood and rainfall event data for England and Wales are held on the Environment Agency's hydrometric archive (WISKI) and are available on request (a fee may be payable). For Scotland, the Scottish Environment Protection Agency (SEPA) is the measuring authority. In Northern Ireland it is Rivers Agency. The Met Office is another source of rainfall data. Internal drainage boards (IDBs) and occasionally local authorities may also have water level gauges for operational use.

The Environment Agency also has a network of level-only gauges for flood warning. The water level time series data could be converted to flow information if a stable rating curve can be established at such a site. While the quality of the ratings would have to be considered on a case-by-case basis, these sites could potentially provide information to help define flood flows.

The National River Flow Archive (NRFA) (http://www.ceh.ac.uk/data/nrfa/index.html) maintained by the Centre for Ecology and Hydrology (CEH) at Wallingford is the primary source of information for daily mean flows and monthly rainfall totals. Archived data have been processed through a number of quality controls and there is good supporting information to help assess data quality. In addition, the archive includes station summary sheets that provide a very good, concise overview of the data at river flow stations and of the catchment flow regime, plus spatial information summarising rainfall patterns, geology, land use and topography.

Temporary measurements

Given the value of local hydrometric data, it can be worthwhile installing temporary measuring equipment at the start of, or in anticipation of, a study for which flood estimates are expected to be needed.

Two years of flow data generally give a better flood estimate than one obtained solely from catchment descriptors (see below). Temporary flow loggers can be installed at many locations – particularly using modern ultrasonic devices, which require less invasive work in the river channel or banks than the installation of a gauging weir. Such flow data can also be valuable for calibrating a hydraulic model.

River level data can be obtained more easily, for example using small self-contained, submerged pressure sensors. Peak river levels for flood events may also sometimes be available from peak level recorders installed by the Environment Agency.

2.3.2 Catchment descriptors

Catchment descriptors summarise the properties of river catchments. They are needed for flood estimation at sites where there is no long, gauged record and for comparisons of hydrological similarity.

There are 19 original FEH catchment descriptors, nine of which are required by the flood estimation procedures. Version 2 of the FEH CD-ROM provides three additional catchment descriptors based on an improved and more recent land cover map (Bayliss *et al*, 2007). The principal new descriptor is URBEXT_{2000} (urban extent in the year 2000). This is defined differently from the previous URBEXT_{1990} and should therefore not be used in the original FEH equations for urban adjustments. Revised equations are available in version 2 of WINFAP-FEH (from Wallingford HydroSolutions Ltd; http://www.hydrosolutions.co.uk/feh.html).

Catchment descriptors from the FEH CD-ROM should not be used without at least a rudimentary check (see Section 3.5 of *Flood estimation guidelines*).

2.3.3 Flood history

The average length of river flow records is 30 to 40 years. Many design studies require a flood estimate for a return period of 100 years. The estimate will be very uncertain if derived solely from flow records at the site of interest. For example, the River Bollin at Wilmslow has 34 years of data. The 100-year flood derived from those data has a 95% confidence interval of 36–83 m^3/s (see Section 2.7 for a discussion about confidence intervals).

Historical information can be invaluable to help set the recent gauged record into a longer-term context. When quantitative information can be found (for example, flood marks on buildings), this can have a major influence on the selection of the final design flows.

Volume 1 C.3.3 of FEH recommends an informal method for incorporating historical flood data. More detail is given by Bayliss and Reed (2001), who review various methods for incorporating historical data in a flood frequency analysis and advocate the use of simple methods.

2.4 Design flood estimation concepts

2.4.1 Probability and return period

Most fluvial designs are sized to be able to withstand a flood of a given flow, Q. For example, a bridge or culvert would be designed to be able to convey that flow without surcharging. Q is known as the design flood. To work out the magnitude of Q, it is usual to start by considering how often it would be acceptable to have floods larger than Q. This frequency is often expressed as a return period, although probability is also used (see below).

The return period of a flood with flow Q is the average interval between floods that have a flow of at least Q. Strictly speaking, this is the return period on the peaks-over-threshold (POT) scale. There is an alternative definition based on annual maximum (AMAX) floods, which is used more widely in FEH. The annual maximum return period is then the average interval between years containing a flood of flow at least Q. The difference between the two definitions is only important at short return periods, less than about five years.

Flood frequency can alternatively be expressed in terms of an annual exceedance probability (AEP), which is the inverse of the annual maximum return period. For example, the 100-year flood can be expressed as the 1% AEP flood, which has a 1% chance of being exceeded in any year. This is recommended when presenting results to non-specialists who may associate the concept of return period with a regular occurrence rather than an average recurrence interval.

2.4.2 Flood frequency analysis

The relationship between flow and return period is known as the flood frequency curve. There are two common approaches to estimating the flood frequency curve:

- statistical analysis of flood peak data (single site or pooled analysis);
- design event approach, which uses a rainfall–runoff model.

These are described below.

On many catchments, either approach can be applied and may give very different results. Choosing between the approaches can be difficult, although in many cases the statistical analysis approach is preferable because it is more direct and is based on a larger dataset.

The choice of method should be guided by a method statement that considers issues such as the needs of the study, the nature of the catchment and the type of data available. Refer to Section 4 of *Flood estimation guidelines* (Environment Agency, 2007) for more information.

Single site and pooled analysis

Flood frequency curves are best derived by analysis of flood peak data (if available). FEH uses mainly annual maximum flows.

Ideally, a long record of flood peaks is available at the site of interest, in which case the curve can be derived from single site analysis. More typically, there are no data or insufficient data at the site of interest. In this case, the flood frequency curve can be derived by analysing data from a group of gauging stations on other similar catchments known as a ‘pooling group’.

Pooled analysis generally reduces the uncertainty in design flows, but involves some assumptions (that the catchments in the pooling group are representative of the subject site) which can introduce errors.

In FEH*,* pooled analysis is carried out in two steps:

1. Estimating the index flood QMED – the median of the set of annual maximum (AMAX) flood data. It has a return period of two years.
2. Estimating the growth curve which expresses design flows for other return periods as a ratio over QMED.

For more guidance, refer to FEH Volume 3 (Statistical procedures for flood frequency estimation) and Section 5.3 of *Flood estimation guidelines*. Note that the recommended procedures for flood frequency analysis could change as a result of further research since FEH was published. In particular, a review of the FEH’s statistical procedures has proposed an updated statistical model for QMED and changes to the approach taken to pooling data (which, in effect, emphasise geographical proximity). See Kjeldsen *et al* (2008) for further details.

The FEH statistical method is usually applied using WINFAP-FEH, although many of the steps can be carried out using alternative software such as spreadsheets.

Design event approach

Because rainfall records are more plentiful and generally longer than river flow records, flood estimation is often performed indirectly using a rainfall–runoff model. This ‘design event’ approach involves creating a design storm from the FEH rainfall frequency statistics and running it through a simple catchment model to produce a design flood.

An advantage of this approach over statistical analysis of flood peaks is that it produces a full flow hydrograph rather than just a peak flow. For this reason, the design event approach is often adopted when flood volumes or durations are important, for example in the design of flood storage areas or reservoir spillways.

For England and Wales, design floods can be modelled using the 'revitalised flood hydrograph' (ReFH) method, which has superseded the earlier FSR/FEH rainfall–runoff method for most applications. For some exceptions, see Section 2.5.

For more information on ReFH, refer to *FEH supplementary report 1* (Kjeldsen, 2007). For guidance on application of ReFH, refer to Section 5.4.3 of *Flood estimation guidelines*.

The ReFH model transforms a design rainfall event into a design flood. It has three components:

1. Loss model – removes losses such as those from evaporation and infiltration, leaving the net rainfall.
2. Routing model – converts the net rainfall into runoff using a unit hydrograph.
3. Baseflow model – routes the infiltration through a storage unit representing groundwater. The outflow from the storage is added to the runoff to produce the total flow in the river.

The model has four parameters, which are best estimated from rainfall and flow data if available for the site of interest. They can otherwise be estimated from catchment descriptors. Inputs to the model consist of a design rainfall event, and initial values for soil moisture and baseflow. ReFH uses different combinations of design inputs for winter and summer events.

ReFH can be applied using a free spreadsheet from CEH Wallingford (http://www.ceh.ac.uk/sections/hrr/SpreadsheetimplementationofReFH.html), but this allows only estimation of parameters from catchment descriptors. Figure 2.2 shows the structure of this model. A more comprehensive ReFH software package was released in July 2007 by Wallingford HydroSolutions (http://www.hydrosolutions.co.uk/feh.html). There is also a ReFH unit within version 2.5 of ISIS, with similar functionality to the ReFH spreadsheet.

An alternative approach to modelling is to create a hydrograph by applying a time profile to a statistically derived peak flow rate, based for example on a typical 'average' hydrograph profile.

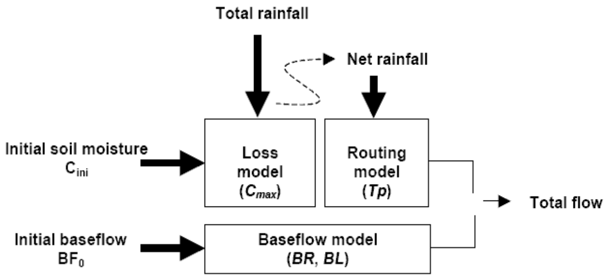


Figure 2.2 Structure of ReFH model

The model components and parameters are shown inside the boxes. The initial conditions are on the left. The main input is rainfall and the output is flow.

Reproduced from Kjeldsen (2007) with permission from CEH Wallingford

A disadvantage of design event methods is that they rely on some significant assumptions regarding the nature of the design storm and catchment wetness. There are an infinite number of combinations of conditions that might result in a flood with a peak flow of return period 100 years. In a design event method, it is necessary to pick a single combination of the various inputs to run through the model.

The design inputs to ReFH were selected by matching resulting flood frequency curves to results from the FEH statistical method using pooled analysis. But on any particular catchment, there is no guarantee that the combination of design inputs will result in a flood of the required return period. This is particularly true for:

- catchments that are not well represented in the ReFH dataset, such as heavily urbanised ones;
- catchments where the ReFH model could not calibrate well, such as permeable ones.

An alternative to the design event approach is to model a long time series of rainfall, resulting in a long flow series which can then be analysed statistically as if it were real data. This continuous simulation approach removes the need to decide what constitutes the design event. A national approach for continuous simulation has been produced by a joint Defra/Environment Agency R&D project (Calver *et al*, 2005).

For a more detailed discussion of approaches to calculating design floods using rainfall-runoff models, including the various assumptions that are made by different methods, see Lamb (2005).

2.4.3 Use of routing models

Rainfall–runoff methods can be applied in a 'lumped' fashion to the entire catchment upstream of the site of interest or in a 'distributed' approach, splitting up the catchment and routing the design flows from each subcatchment.

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.

It is usual practice to apply the same storm duration to each subcatchment. A realistic range of durations should be tried for the design storm to find the critical duration at the subject site by trial and error. The critical duration is the one that gives the largest flow (or, for some design studies, the highest water level or greatest storage pond volume) at the site of interest.

2.5 Special cases

2.5.1 Urban catchments

FEH methods treat urbanisation by adjusting aspects such as the index flood, the growth curve or the time to peak. Section 7.9 of *Flood estimation guidelines* (Environment Agency, 2007) gives advice on how to treat urban catchments. In summary, the statistical method can be used for catchments with URBEXT_{1990} up to 0.50, or URBEXT_{2000} up to 0.60. ReFH should currently only be used for $\text{URBEXT}_{1990} < 0.125$ or $\text{URBEXT}_{2000} < 0.150$.

FEH methods should not normally be applied on heavily urbanised catchments. Sewer design methods such as the 'modified rational' (for peak flows) or the Wallingford hydrograph method are more appropriate for deriving flows from the catchment component served by urban sewers.

2.5.2 Small catchments

Flood estimation on small catchments is more uncertain, mainly because most gauging stations are on medium or large catchments. FEH methods apply for catchments down to 0.5km^2.

For smaller areas, there are alternative methods available such as those given in Institute of Hydrology Report 124 (Marshall and Bayliss, 1994) or ADAS Report 345 (ADAS, 1982). Another option worth considering is simply scaling down an FEH estimate by area. No single approach can be recommended unequivocally. See Section 7.8 of *Flood estimation guidelines* for guidance on the pros and cons.

2.5.3 Permeable catchments

Flood estimation on highly permeable catchments (usually chalk or limestone geology) requires particular care. Significant floods tend to be infrequent, but they can be unexpectedly severe when they do occur. This means that relatively short gauged records need to be interpreted with caution. Design event methods such as ReFH are generally unsuitable.

An understanding of the catchment geology and hydrogeology can be valuable when estimating floods in permeable catchments. In particular, it is important to establish the possible processes that might lead to flooding. See Section 7.10 of *Flood estimation guidelines*.

2.5.4 Reservoirs

The FEH statistical method accounts for lakes and reservoirs in a general way, using the catchment descriptor FARL to reduce QMED when water bodies are present in the catchment. The QMED equation should not be relied on when FARL is below around 0.9 due to the presence of impounding reservoirs unless they are kept permanently full and thus act like natural lakes. If flood peak data are available downstream of the reservoir and close to the site of interest, they can be used to estimate QMED directly and thus implicitly account for the effects of the reservoir.

In the absence of suitable flood peak data, the ReFH method should be used on catchments with a significant reservoir influence, along with a flood routing calculation that determines the outflow from the reservoir. Unless the subject site is directly downstream of a single reservoir, it is necessary to incorporate this in a flow routing model to allow for inflows from the rest of the catchment.

2.5.5 Pumped catchments

The hydrology of pumped catchments is fundamentally different from that of typical gravity-drained catchments, because:

- the catchment boundaries tend to be man-made rather than natural;
- the water-table is lowered by drainage;
- watercourses are often artificial;
- flows are affected by pump operations.

For these reasons, prediction of design flows from catchment descriptors is unlikely to be successful.

None of the FEH procedures are intended to be applicable to lowland pumped catchments.

Most studies continue to use a variation of the FSR rainfall–runoff method, which involves using a trapezoidal unit hydrograph shape with a time-to-peak estimated from local data or set to 24 hours. Pumped catchments can also be modelled using the continuous simulation approach, routing flows through the drainage network using a hydraulic model that incorporates pump operating rules.

2.6 Low flow analysis

2.6.1 Water level and flow control

Low flow conditions in rivers and streams are of fundamental importance to the ecological status of the watercourse. Any change in the seasonal pattern of flows, for example due to exploitation of a groundwater source or abstraction of water from the river, may lead to irreversible changes to the stream ecology. Low flow analysis is also important when considering the construction of works in rivers and streams (for example, a weir), and for river restoration schemes for which an understanding of hydrological variation is important in determining appropriate restoration works. Methods of low flow analysis are outlined below.

2.6.2 Flow duration curves

A flow duration curve (FDC) represents the relationship between the magnitude and duration of stream flows; duration in this context refers to the overall percentage of time that a particular flow is exceeded. The shape of the FDC for any river therefore strongly reflects the type of flow regime and is influenced by the character of the upstream catchment including geology, urbanisation, artificial influences and groundwater. Figure 2.3 shows the flow duration curves for two contrasting rivers.

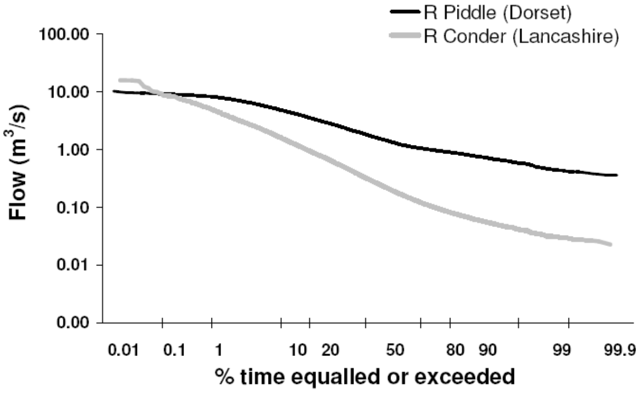


Figure 2.3 Flow duration curves for two contrasting rivers

This graph shows the impact of catchment type on FDC shape.

The River Piddle is a chalk stream with a relatively limited seasonal variation in flow, being sustained by groundwater baseflow throughout the year and having few high flow events due to the permeable nature of the catchment.

In contrast, the River Conder is an upland stream with a 'flashy' flow regime. Its FDC has a much steeper gradient, reflecting the greater range of flows experienced. In particular there are more extreme high and low flows at this site.

The FDC is a very useful tool for assessing the overall historical variation in flow, though one drawback is that it offers little information about the timing or persistence of low flow events.

The FDC has a wide range of applications including:

- setting river flow objectives;
- scenario evaluation (in respect of the impact of artificial influences such as water abstraction or effluent releases);
- hydropower assessment;
- evaluation of sediment or contaminant loads;
- structure design (for example, a structure can be designed to perform well within some range of flows, such as those exceeded between 20 and 80% of the time or such that it does not alter the low flow regime).

In practice, FDCs are used mainly in relation to the setting of environmental flow objectives. The Q_{95} flow (the flow exceeded 95% of the time according to the FDC) has been used historically in the UK to represent the low flow in a river. Abstraction conditions have sometimes been set to protect this flow; for example, abstraction is permitted provided the flow is greater than the Q_{95}.

River ecology requirements are often more complex than this and other values may be used to control abstractions. The influence of potential abstractions from the river and/or discharges into the river can be reviewed by constructing an influenced FDC which can then be compared to the target, enabling identification of flow ranges where further abstraction might be permitted. For example, it may be desirable to keep the flow regime of a particular river as natural as possible and a target of 90% of the natural flow across the full range of flow might be stated. This means that the combined effect of any artificial influences should not result in a change in flow regime such that the actual flow duration curve deviates from (drops below) the natural by greater than 10% at any point.

2.6.3 Low flow frequency analysis

A low flow frequency analysis evaluates the probability of flows occurring and remaining below a specified (low) design threshold for a given length of time. Customarily the analysis is carried out with regard to the minimum discharge aggregated over a period of *d* days in each year – the 'd-day annual minimum' or *AMIN[d]* – derived from daily flow series.

In the UK case, this is best applied on the basis of calendar years to avoid splitting low flow periods lasting from late summer through autumn; the Environment Agency has published guidelines which document how to apply the approach in detail (see Zaidman *et al,* 2002).

Application of a Type 3 generalised extreme value (GEV) or Weibull distribution allows the quantiles of the low flow distribution to be determined and the return periods of any design events estimated.

Regional frequency methods have also been developed to utilise flow data from similar sites to improve estimates for short-record sites and to enable low flow frequency estimation to be undertaken at ungauged sites; see Tallaksen and van Lanen (2004) for an introduction to this subject.

2.6.4 Naturalisation

Few rivers have a wholly natural flow regime, unaffected by human activity. Naturalisation is the process by which the flow record is manipulated to remove those human influences that are quantifiable such as consumptive abstraction and effluent discharges. Such impacts are predominantly felt in the low to medium flow range and, while they may be often ignored for flood design, take on greater significance when evaluating mean or low flow conditions.

Where there are artificial influences on river flows, the naturalised data should be used for assessing yields, low flow extremes or trends. This is to ensure that the analysis represents the flow regime of the catchment rather than the artificial influences, which could be highly variable. Results from the naturalised analysis can then be adjusted to represent artificial influences. The adjustment may be based on current data or on assumed scenarios such as increased abstractions.

It is recommended that naturalised data should be sought directly from the measuring authority, as the procedure requires detailed records of artificial influences over the period of interest and consideration of the quality of the gauged record. The latest guidance on these methods is given in Environment Agency publications (2001 and 2005).

2.7 Confidence and uncertainty

2.7.1 Sources of uncertainty

Uncertainty is often broken down into different components:

- **natural uncertainty** – from the inherent variability of the climate;
- **data uncertainty** – from errors in the measurement of river flows;
- **model structure uncertainty** – from the choice of model such as the selection of a growth curve distribution function;

- **model parameter uncertainty** – from selection of parameters, for example for a growth curve, rating curve or rainfall–runoff model.

It is almost always admitted that uncertainty is present in any hydrological design analysis, yet there is very little consensus about how to represent or communicate the uncertainty, or about how to respond to it in terms of design decisions.

It is useful to think of uncertainty as arising from a combination of natural randomness and ‘knowledge uncertainty’, which reflects imperfections in our understanding of nature or our ability to measure or model it. The two things are hard to separate in practice because natural randomness obviously contributes to our knowledge uncertainty, but the distinction helps us to identify the relevant sources of uncertainty. Chapter 1 includes a discussion about the treatment of uncertainty within the fluvial design process as a whole. Here, we are concerned with specific issues about the expression of confidence and uncertainty in a hydrological estimate.

Knowledge uncertainty is important in our choices of model structure (for example, which statistical distributions are used for flood frequency analysis) and in the quality of measured data (for example, is the rating curve ‘right’?). Natural variability and ‘noise’ are important in terms of sampling error (is the record long enough to provide a firm estimate of the T-year flood?) or more generally the ability to estimate model parameters.

2.7.2 Quantifying uncertainty

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

There are no widely available straightforward techniques for assessing confidence intervals for flood estimates. FEH provides confidence intervals for some components of flood estimates, but does not suggest any techniques for combining them together and accounting for the other sources of uncertainty. It is important to quote what information is available about the uncertainty of design flows, for example looking up confidence intervals for QMED in Chapters 12 and 13 of FEH Volume 3.

When communicating confidence intervals, it is worth thinking about what they mean. The confidence band for a given level of uncertainty (such as 95% or 99%) may be wide, but this does not mean that the true answer is thought to have an equal chance of being anywhere within that interval. Instead, it is usually most likely to lie closer to the ‘best estimate’ than to the edge of the confidence band. Confidence intervals with a smaller coverage probability will often be much narrower, yet may still be considered as the range within which the answer is most likely to exist. (For example, the Intergovernmental Panel for Climate Change regards an event that has a 66% probability as being ‘likely’ and this semantic interpretation of a probability could also be used to interpret a confidence interval). Figure 2.4 shows a flood frequency curve with confidence limits.

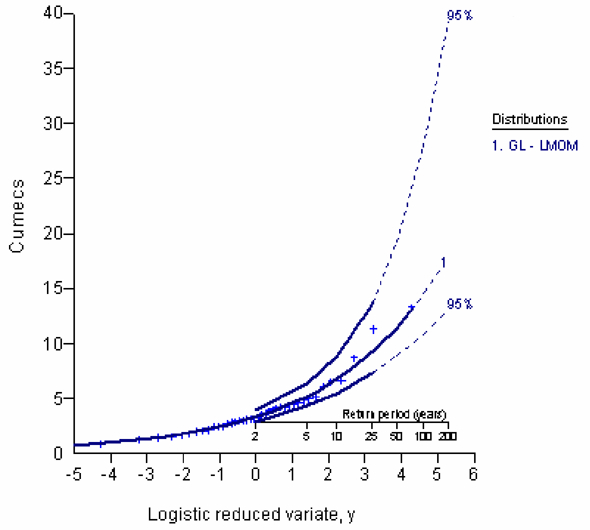


Figure 2.4 Flood frequency curve with confidence limits

The crosses represent annual maximum flows over 40 years and the middle line is a single site flood frequency curve fitted to them. The 95% confidence interval can be seen to expand rapidly for return periods greater than 25 years.

It is important to realise that a wide confidence interval does not necessarily mean that the best estimate, shown by the middle line, is wrong. It is much more likely to be correct than those values at the upper and lower confidence limits. The analyst should report the best estimate and the confidence limits (not forgetting to quote the coverage probability, which is 95% in this example).

The uncertainty for greater return periods could be reduced by pooled analysis or by consideration of the longer-term flood history.

As researchers identify more sophisticated methods for representing uncertainty in hydrology, so there is a need for practical guidance on how to use this information. Sometimes it is argued that it is not useful to delve too deeply into the uncertainty about a design flow estimate because the analysis is too difficult, or because the resulting uncertainty appears so wide as to damage the credibility of the estimate, or maybe because the information does not seem to be useful.

These arguments are discussed in a Flood Risk Management Research Consortium (FRMRC) report on tools for uncertainty evaluation (Pappenberger *et al,* 2006). The main difficulties in presenting uncertainty in fluvial design calculations can be practical ones; the relevant analysis methods are often not conveniently available within standard software tools and there is often not a definitive view about which method to use.

Some attempt to characterise uncertainty should be viewed as part of the scientific process of presenting complete information about the hydrological analysis. Indeed, it can undermine the credibility of the analysis if uncertainties are not recognised, and the results are later used with more (or possibly less) confidence than is justified. Therefore, reasons for citing uncertainty information in hydrological analysis are:

- as a measure of confidence in the results (which can, for example, show the improvement brought by additional data);
- to help judge between alternative estimates or scenarios (for example, are two competing estimates really significantly different when compared with the uncertainty in each one?);
- to avoid the sense that the results of the analysis are fixed and absolute, which can cause difficulty later if results are revised because of new data or an updated methodology;
- as an aid to sensitivity analysis and understanding the robustness of the design.

Whatever the uncertainty analysis shows, hydrologists should still report their best estimate as the basis for the design calculations. However, uncertainty may come to be integrated in risk-based calculations using methods such as Monte Carlo simulation or Info-gap theory as tools to use these techniques – which are already appearing in the strategic planning context – become more accessible.

Perhaps the best advice to designers of works in the fluvial environment is not to focus on a single design flow value, but to carry out sensitivity tests to make sure the design is robust for the likely range of flow conditions (see also Chapter 1). For example, if the project hydrologist has recommended a design flood flow of 22.5 m^3/s, with 95% confidence that the value lies in the range

18.5–27.0 m^3/s, then the designer should at least test the design for 27.0 m^3/s. If this higher flow value results in unacceptable consequences (for example, major infrastructure is flooded) then the design should be reappraised or further investigation of flood hydrology should be initiated.

2.8 Climate and land management change impacts

2.8.1 Guidance on climate change impacts

Planning Policy Statement 25: Development and flood risk (CLG, 2006) includes recommended ‘indicative sensitivity’ ranges for the potential effects of climate change on peak rainfall intensities and peak river flows with a range of design life horizons up to the year 2115. These values take the form of adjustment factors, which range from +10% to +30%. The source and appropriate use of these numbers is discussed in a supplementary note to FCDPAG3 project appraisal guidance (Defra, 2006).

Although the current guidance for climate change provides country-wide data, there is increasing evidence that impacts vary regionally, or even from catchment to catchment. The next generation of climate change scenario data for the UK (UKCIP09) will have greater regional detail, more information about uncertainties and permit more specific impact studies.

2.8.2 Impacts of land management change

There has recently been a growth in interest in the possible impacts of land management on river flows and especially floods. A joint Defra/Environment Agency project (O’Connell *et al*, 2005) reviewed the science base and concluded that analyses of historical data have not been able to demonstrate the impact of land use management on flood runoff due to a variety of other factors including:

- variability in the hydrological data;
- the rarity of flood events relative to the record length;
- measurement uncertainties;
- possible impacts of other changes (such as climatic).

There is no unique, generally accepted, design of model suitable for predicting land management impacts, and it is not known exactly which data are essential to predicting impact. But there are studies indicating that, at least at small scales, land management and especially practices that degrade soil condition, can increase runoff rates. Hence, there is no definitive guidance on how or even whether to consider land management scenarios in fluvial design calculations. Readers are advised to keep abreast of outputs from this active research area.

Key references

General

Shaw, E M (1994). *Hydrology in practice,* 3rd edition. Chapman & Hall (reprinted 2004 by Routledge).

This is a standard hydrology textbook with a focus on methods relevant to the UK. It covers processes, data and analysis methods for floods, water resources and groundwater. The text is currently undergoing a major revision and a new edition is planned for 2009.

Flood hydrology

Environment Agency (2007). Flood *estimation guidelines*, Version 2. Environment Agency.

These guidelines (which can be obtained by emailing enquiries@environment-agency.gov.uk and paying a small fee) offer advice on making the most of the material in the *Flood estimation handbook* and later publications, as well as older methods of flood estimation. The guidelines aim to ensure a consistent and robust approach, repeatability of results and systematic recording of the decisions made. They include a calculation record to be used in all Environment Agency studies and a checklist to aid the review of results.

Institute of Hydrology (1999). *Flood estimation handbook.* Institute of Hydrology (reprinted 2008 by the Centre for Ecology and Hydrology).

The handbook (commonly referred to as FEH) is the main source of information and guidance on current UK methods for flood estimation. Its five volumes present clear guidance to users as well as comprehensive supporting material on theory. Copies are now distributed by Wallingford HydroSolutions Ltd on behalf of CEH. The methods described in FEH can be implemented using the range of FEH software products also available from Wallingford HydroSolutions.

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The 'revitalised flood hydrograph' (ReFH) method was developed after FEH was released and largely supersedes the latter's rainfall–runoff method. *FEH supplementary report 1* describes the method and gives guidance on its application.

Low flow hydrology

Tallaksen, L M and van Lanen, A J (2004). *Hydrological drought: processes and estimation methods for streamflow and groundwater,* Developments in Water Science 48. Elsevier BV.

This textbook describes the standard techniques in low flow hydrology as well as some more advanced ones. Although aimed at a European audience, it includes a detailed summary of the methods currently applied for low flow estimation in the UK.

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