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Improving PMP and PMF estimation for UK reservoir safety

FCERM Research & Development Programme

Research Report: Phase 1

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Executive summary

The probable maximum flood (PMF) is the greatest fluvial discharge that is realistically possible under contemporary climatic conditions for a catchment. It is estimated from the probable maximum precipitation (PMP), which is the greatest depth of precipitation for a given duration that is meteorologically possible under contemporary climatic conditions for a catchment at a particular time of year.

The PMF is used to check the safety of the highest risk dams in the UK, where a breach of the dam could put lives in downstream communities at risk. It can also be used for assessing the safety of other very high-risk infrastructure.

Most methods and data used to estimate the PMP and PMF have not been updated since the Flood Studies Report was published in 1975. This report describes the first phase of a project that aims to assess the suitability of methods for estimating PMP and PMF - and develop new methods to improve the safety of our highest risk reservoirs. The aim of Phase 1 is to review options for alternative approaches to estimating PMP and PMF and recommend a way forward for future research developments.

The report includes a:

- catalogue of extreme floods and rainfall events in the UK
- worked example restating the method currently used to estimate PMF
- review of all aspects of methods for estimating PMP and PMF, looking at UK practice, overseas practice and research, including case studies comparing methods
- assessment of needs and opportunities for an improved method
- comparison of options for developing an improved method

The catalogue contains 324 events from a wide range of sources across the UK and Ireland. It includes events that exceeded defined flow and rainfall thresholds to build on the past work to identify extreme events. Eight rainstorms exceed current estimates of PMP, with 3 of these being recent long-duration rainfall totals in mountainous areas. Exceedances of estimated PMF are harder to find, with 5 possible candidates identified, all being uncertain estimates of peak flow made using approximate methods.

The worked example of the current method includes guidance on how to apply a method of calculating snowmelt published in 1997. Although this method is already recommended when calculating the winter PMF, it is often not fully applied by practitioners. A spreadsheet that applies the current PMP and PMF methods, including calculating snowmelt, accompanies this report.

The review of methods starts by discussing the concept and definition of a probable maximum. The validity and usefulness of the concept has been questioned widely, but despite this the PMF continues to be used in dam safety assessment across many countries. Its strength lies in its derivation from physical concepts in meteorology and hydrology. This complements the extrapolation of statistically-fitted rainfall and flood frequency curves which become increasingly uncertain for events of very low probability. The return period of PMP and PMF is an important issue in risk-based management of dam safety, for which it is necessary to quantify costs and benefits of alternative options. There are several methods available for associating a return period with the PMP, but extending this concept to the PMF becomes increasingly difficult and arbitrary. Another important issue that the review covers is the impact of climate change, which is not currently accounted for in UK methods.

The review then considers alternative methods for estimating the PMP, including novel approaches using numerical weather models that have so far only been applied in research projects rather than operationally. It discusses rainfall-runoff models, focusing on the need to account for changes in hydrological processes that may occur in extreme conditions. It also covers methods for assessing snowmelt, the effect of frozen ground, and the joint probability of these phenomena and extreme rainfall. It reviews the potential for including evidence of past floods gathered from field measurements of palaeoflood deposits.

It is important that a new method of estimating PMP and PMF has the confidence of those involved in managing reservoir safety. It should also stand up to scientific scrutiny. To achieve these aspirations, the method should incorporate important scientific advances and data sets, while being practical to apply and giving credible results that are useful in flood risk management. With these requirements in mind, a range of options are put forward and scored. The choice of options needs to be addressed in the context of the decision-making and regulatory framework in which the method is to be used. It also needs to be guided by the practicalities of time and budget. Several options are capable of achieving a substantial improvement. All need significant effort to develop, test and implement into a method that can be readily applied by practitioners for any catchments in the UK.

The recommended options form a family of modules which can be built on each other, allowing for some future enhancement and potentially better alignment with future methods of estimating UK flood frequency. These will take several years to develop.

1 Introduction

1.1 Background to project

Engineers check the safety of Category A dams (as defined in ICE, 2015), where a breach of the dam could put lives in downstream communities at risk, using the probable maximum flood (PMF). Category A dam spillways must be able to discharge the flow of the PMF without endangering the safety of the dam. The concept of the PMF is also relevant in other situations where flooding poses a risk to life, such as the design of infrastructure like nuclear power stations that need protecting from the most extreme floods.

Hydrologists estimate the PMF from a probable maximum precipitation (PMP) in combination with conservative assumptions about the initial soil moisture, time to peak and (in the winter) snowmelt and frozen ground. Most aspects of the methods and data used to estimate PMP and PMF in the UK have not been updated since the Flood Studies Report (FSR) was published in 1975 (NERC, 1975). The current methods do not account for the impact of climate change.

Calls for an update to PMF (such as by Faulkner and Benn, 2019) have pointed out that methods used to estimate floods with a defined probability in the UK are much more up to date. Concerns about the FSR methods for estimating PMP and PMF are strengthened by the reports of catastrophic rainfall and flood events exceeding estimates of the probable maxima (for example, Acreman, 1989; Stewart and others, 2013).

Another reason for rethinking methods of estimating extreme floods is that there have been several recent incidents in which reservoir spillways have been damaged during floods, threatening the structural integrity of dams. The most recent of these occurred at Toddbrook Reservoir, Derbyshire in August 2019. Following this, the government commissioned an independent reservoir safety review for England. The review report (Balmforth, 2021) recommended that the assurance of reservoir safety should be managed on the basis of risk, and that the present project should allow for the non-stationarity of climate.

1.2 Objectives

The overall objective of the project is to assess the suitability of the existing methods for estimating PMP and PMF, and develop new methods and guidelines to ensure that we understand the risk posed to our highest risk reservoirs from extreme flood events.

This report covers Phase 1, which reviews possible methods that could be used to update PMP and PMF estimation in the UK, and develops a preferred option to implement in future work.

The PMF is only one of many factors that contribute to managing the safety of high risk infrastructure. An awareness of the wider decision context is important. This report considers implications for the risk-based evaluation of reservoir safety. This requires estimating floods with a defined probability. Reservoirs are designed for floods with annual probabilities of exceedance as low as 0.0001, equivalent to a return period of 10^4 years.

1.3 Overview of this report

There are 3 main components to this report, each of which can be read in relative isolation from the others. These are a:

- catalogue of extreme events (Chapter 2, supported by Appendices 1 to 3)
- restatement of the FSR method currently used to estimate PMP and PMF in the UK (Chapter 3)
- review of alternative methods and recommended options for future research. This is split across the following 4 chapters:
  - a review of all aspects of methods for estimating PMP and PMF, looking at UK practice, overseas practice and research, including an appraisal of the FSR method and some case studies comparing results of alternative methods
  - an assessment of needs and opportunities for an improved method
  - a comparison of options for developing an improved method

1.4 Terminology

This is a technical report, written for an audience with some understanding of the basic concepts and techniques of hydrology and meteorology.

The report uses the term 'return period' along with its inverse, the 'annual exceedance probability'. Spillways for the highest risk dams are designed for a return period of 10^4 years (10,000 years), which corresponds to an annual exceedance probability of 0.0001, or 0.01%.

There is a list of acronyms and other abbreviations at the end of this report.

2 Catalogue of extreme events

2.1 Purpose and scope

Historical events can provide the firmest evidence of the need to revise estimates of PMP and PMF. The work undertaken here builds on the comprehensive exercise carried out as part of project FD2613, Reservoir Safety – Long return period rainfall (Stewart and others, 2013), which compiled a set of 63 extreme rainfall events from across the UK with a duration of at least one hour. The aim of the cataloguing work is to implement a systematic approach for reviewing sources of rainfall and flow data which may contain information about events close to or exceeding PMP and PMF, with the contextual information contained in the catalogue providing a valuable picture of what is possible for such events.

Despite the application of this systematic approach, the catalogue is inevitably a partial, incomplete record. It has not been feasible to examine every source of information about every event. There is more knowledge, whether among professionals, students, local witnesses, historical records or written in the landscape, that remains untapped. Investigating even one event in detail could take weeks. It is also important to recognise that measuring extreme floods or, in some cases, rainfalls, can be difficult and uncertain.

2.2 Data sources

With a focus on events occurring since 2006 (to build on the work of Stewart and others (2013) which identified events occurring up to 2006), rainfall gauge records offered the opportunity to identify multiple events suitable for including in the catalogue. The cataloguing work was completed in late 2020 and so includes no events since 2020, although some sources used extended only to 2017 or 2018.

The temporal resolution of some of the digital data sets, with some data available at a 15-minute resolution provides a wealth of information that may not have previously been available. For data sources that could be reviewed programmatically, the full length of the data set was reviewed. Where events were identified in literature or flood chronologies, there was a focus on events with gauge information available (rainfall or flow).

2.2.1 Global Sub-Daily Rainfall data

The Global Sub-Daily Rainfall (GSDR) data set is a quality-controlled (QC) data set of hourly precipitation (Lewis and others, 2019). The UK sub-set of this data set incorporates data from about 1,900 rain gauges operated by the Environment Agency, Natural Resources Wales (NRW), the Scottish Environment Protection Agency (SEPA) and the Met Office (MO) for 1990 to 2014. These have been subject to a uniform QC procedure, which subjects the data to 25 quality checks in order to flag and remove suspicious data (Lewis and others, 2021). A sub-hourly extension to GSDR (GSDR-SH) has been developed for the UK. While containing fewer gauges (~1,300), it benefits from additional QC, possible due to the increased data resolution as well as updates that extend the data set period up to 2018 (Villalobos Herrera and others, 2022c). Data from both of these data sets was compared against the rainfall thresholds to obtain candidates to include in the events catalogue, and to verify candidates identified using the National River Flow Archive (NRFA).

The project was extended to include data for the Republic of Ireland. The same thresholds were applied to data for all gauges in the Republic of Ireland, but no events exceeding the thresholds were found. This partly reflects the limited availability of data, with only 36 Irish gauges in the GSDR.

2.2.2 UKGrsHP – Blended gauge and radar data

UKGrsHP (UK high-resolution gauge-radar-satellite merged hourly precipitation) is a new blended gauge-radar-satellite precipitation data set (Yu and others, 2020). The data set covers the period 2005 to 2014 at a high temporal (hourly) and spatial (~1 km) resolution. It is based on the idea that combining multiple data sources should provide more accurate gridded precipitation estimates than any individual data source.

UKGrsHP was first assessed for its potential to help with identifying events. This assessment revealed that many of the threshold exceedances in UKGrsHP are due to radar artefacts, rather than real events. Although the NIMROD radar inputs to UKGrsHP have been corrected for various limitations (Harrison and others, 2000), manual inspection indicated that a substantial number of artefacts from ground clutter, beam blockage and other errors are present in UKGrsHP. These issues were often easy to spot visually for individual hours or days, but their patterns were not enough to facilitate automatic error recognition. As the number of threshold exceedances was large (for example, 869 separate dates for the one-hour threshold for England and Wales alone), it was not possible to check the plausibility of each potential event manually.

Therefore, it was decided that UKGrsHP would potentially be better suited to providing additional detail on events identified from other sources, at least at this stage in its development. For 25 of the larger events identified from the literature search, GSDR and CEH Gridded Estimates of Areal Rainfall (CEH-GEAR), the corresponding periods in UKGrsHP were manually checked to see whether any likely errors were present. The events selected were those for which radar data are available. Two of the 25 events investigated were found to have plausible representations in UKGrsHP, that is, 23 of the events had radar or blending artefacts that meant the representation in UKGrsHP was unrealistic. Radar fields were either missing or missed the event in 15 of the 23 poorly represented events. Satellite data were incorporated but unhelpful in most of these cases. This issue particularly affects events in the earlier part of the blended data set. Several of the other 8 events showed poor underlying agreement between the radar and gauge data. It could be that some of the problems are at least partly improved in future extensions to the blended data set, as more recent years would benefit from upgrades to the Met Office's radar network.

For these 2 events, total event rainfall was calculated and mapped. The relevant periods of UKGrsHP for these events were saved in NetCDF format to permit further characterisation.

2.2.3 CEH Gridded Estimates of Areal Rainfall (CEH-GEAR)

CEH-GEAR (Tanguy and others, 2019) provided gridded estimates of daily and monthly areal rainfall for the United Kingdom from 1890 until 2017. For the time period from 2006 until 2017 all rainfall events exceeding the 24, 48, 72 and 96-hour thresholds, detailed in the section below, were extracted. The resulting threshold exceedances were then grouped where exceedances occurred in 1 km x 1 km cells adjacent to each other and classified as the same event. For each event, the maximum rainfall accumulation was then extracted for each storm duration. In a subsequent step, the initial thresholds were increased by 50%, which means they are still well below PMP for most parts of the UK, but bring the number of extracted threshold exceedances down to a more realistic number. By doing this, the first set of 1,342 events was reduced to 57 events. This number was then brought down to 21 events by classifying all threshold exceedances within the same area on consecutive days as the same event.

2.2.4 National River Flow Archive (NRFA)

Version 9 of the NRFA peak flows data set was released in 2020. It contains annual maximum flows up to water year 2018 to 2019 at most gauges, and also includes the floods of winter 2019 to 2020 in regions where they were extreme.

Floods were extracted from all gauges, irrespective of the quality classification of their flow data (that is, suitable for QMED, suitable for pooling or suitable for neither). It is expected that even the ‘suitable for neither’ gauges might provide more accurate measurements of extreme floods than some of those obtained from other sources for this project. The NRFA quality classifications were used to guide the selection of data quality scores for the catalogue.

2.2.5 Chronology of British Hydrological Events

The Chronology of British Hydrological Events (BHS, 2020) provides an abundance of information about floods and heavy rainfall events across the UK, including detailed descriptions of events and damage reports. Using the thresholds detailed in the section below the chronology was manually reviewed, and any events where rainfall totals or flows exceeded the thresholds were added to the catalogue. The focus was on events with gauged rainfall or flow data; events that were descriptive in nature were not included as it was difficult to determine whether these events had exceeded the thresholds in use.

2.2.6 British Chronology of Flash Floods

The British Chronology of Flash Floods (JBA Trust, 2020) provides a wealth of information about flash flood events across England, Scotland and Wales. Developed as part of the SINATRA (Susceptibility of catchments to INTense RAinfall and flooding) project, the purpose of the chronology is to support improved assessments of flash flood risk for a given location, and more generally of catchment vulnerability to flash flooding. It focuses on events occurring between April and October, reported in the British Newspaper Archives, and regional and local newspapers. The majority of winter floods are excluded from the chronology, although there are some exceptions, such as where it is not clear whether the events were flash floods or slow-onset floods (Archer and others, 2019).

Using the thresholds detailed below, the chronology was reviewed and any events where rainfall totals exceeded the thresholds were added to the catalogue. The work of Stewart and others (2013) reported events up to 2006. As a result, the manual review of the chronology mainly focused on events occurring after 2006. Where particularly large events occurring before 2006 were reported with reliable rainfall data that exceeded the rainfall thresholds, they were included if they had not already been included in the work of Stewart and others (2013). Rainfall data in the chronology were obtained from British Rainfall (to 1968), the Climatological Observer Link (from 1970), and informal rain gauges.

2.2.7 Literature

Papers were reviewed and events where either rainfall totals or flows exceeded the thresholds were added to the catalogue. Not all reviewed papers provided information on events exceeding those thresholds. However, the list below gives an overview of literature out of which events, including corresponding information on durations, rainfall totals and/or flows were extracted:

- Acreman (1989)
- Archer and others (2019)
- Archer and Fowler (2018)
- Barker and others (2016)
- Benn and Faulkner (2019)
- Bettes (2005)
- Bettes and Bain (2006)
- Bettes and Bain (2005)
- Blenkinsop and others (2017)
- Burt (2005)
- Cameron (2007)
- Chiverrell and others (2019)
- Clark (2003)
- Clark and Vetere Arellano (2004)
- Clark (2007)
- Collier, Fox and Hand (2002)
- Collinge, Thielen and McIlveen (1992)
- Fenn and others (2005)
- Flack and others (2019)
- Foulds, Macklin and Brewer (2014)
- Hand, Fox and Collier (2004)

- ICE (1949)
- Jones and others (2013)
- Kjeldsen and Prosdocimi (2018)
- Marsh (2020)
- NERC (1975)
- Rodda and others (2009)
- Stewart and others (2013)
- Warren and Stewart (2008)
- Wass, Lindsay and Faulkner (2008)
- Webb and Elsom (2015)

2.2.8 Quality assurance

Once events had been identified and data sourced, cross checks were implemented where data were available from more than one source.

Events identified in the CEH-GEAR gridded data were cross checked with the GSDR rain gauge data, by searching for the 10 nearest gauges to each GEAR location (within a 50 km radius). The temporal search window was also expanded by ±24 hours to account for any aggregation artefacts in the GEAR data. In the majority of cases, the values of rainfall from the GEAR data set were higher than any values at nearby gauges. This is a feature of the interpolation routine, which includes normalisation by annual average rainfall, the interpolation of which allows for altitude. There were 2 instances where gauge rainfall totals exceeded the CEH-GEAR interpolations by a few mm. The results of these checks are found in the event catalogue, in the 'GEAR – comparisons and checks' tab.

Some gauges in the GSDR data set showed similar rainfall accumulations within a short time frame, across a variety of durations. As these values appeared to be unusual, the underlying data were investigated further to confirm whether the rainfall accumulations were correct. Where the data were identified as incorrect, events were not included in the catalogue. One such example is a rain gauge at Nantyrwydd in Wales which reported the same rainfall accumulation on 3 days across a 2-week period, all with durations of between 5 and 6 hours. On further investigation, the gauge reported suspicious sub-hourly values, and all events associated with this gauge were discarded.

Some events identified in Acreman (1989) were cross checked against the gauges in the NRFA which have annual maximum flow data. Where peak flows from NRFA were significantly lower than those in the Acreman paper, the events were removed from the catalogue as they were not as outstanding as previously thought.

2.3 Method

To identify precipitation events to be included in the catalogue, rainfall thresholds were identified and applied to all available data. All events where these rainfall thresholds were exceeded have been added to the catalogue. For most sources, the rainfall thresholding work focused on events occurring from 2006 onwards.

For flow events, 2 flow thresholds were used, both based on peak flow measurements. Any events exceeding these thresholds were reviewed and, where appropriate, added to the catalogue. Further information about the thresholds and criteria used is provided in the section below. The review of flow data used all available data, and did not focus solely on events after 2006.

For events added to the catalogue, temporal profiles of rainfall for the duration of the event have been obtained (where rainfall records are available). The majority of these data come from the Newcastle University GSDR data set, which contains rain gauge data post 1970. Gauge data before this date are scarce.

2.3.1 Rainfall thresholds

After a review of previous methods of identifying events with near PMP rainfall, the decision was made to apply the same rainfall thresholds as used in work by Collier and others (2002) and Dempsey and Dent (2009). Consistency with this earlier work was desirable given that the aims of the rainfall cataloguing were to collate evidence about extreme events and update this earlier work, which led to the set of events reported by Stewart and others (2013).

These thresholds had been derived as follows, using results from the Flood Studies Report. For event durations up to one hour, the expected maxima for point rainfall amounts as a function of time were used; and for durations greater than one hour, the rainfall value for the 100-year return period was used (Hand and others, 2004).

A minimum event duration of 0.25 hours (15 minutes) and maximum event duration of 96 hours (4 days) were used. The maximum event duration was defined after consultation with members of the Project Advisory Group who have experience of the critical storm durations affecting reservoirs. Details of the thresholds used are shown in Figure 1 and Table 1.

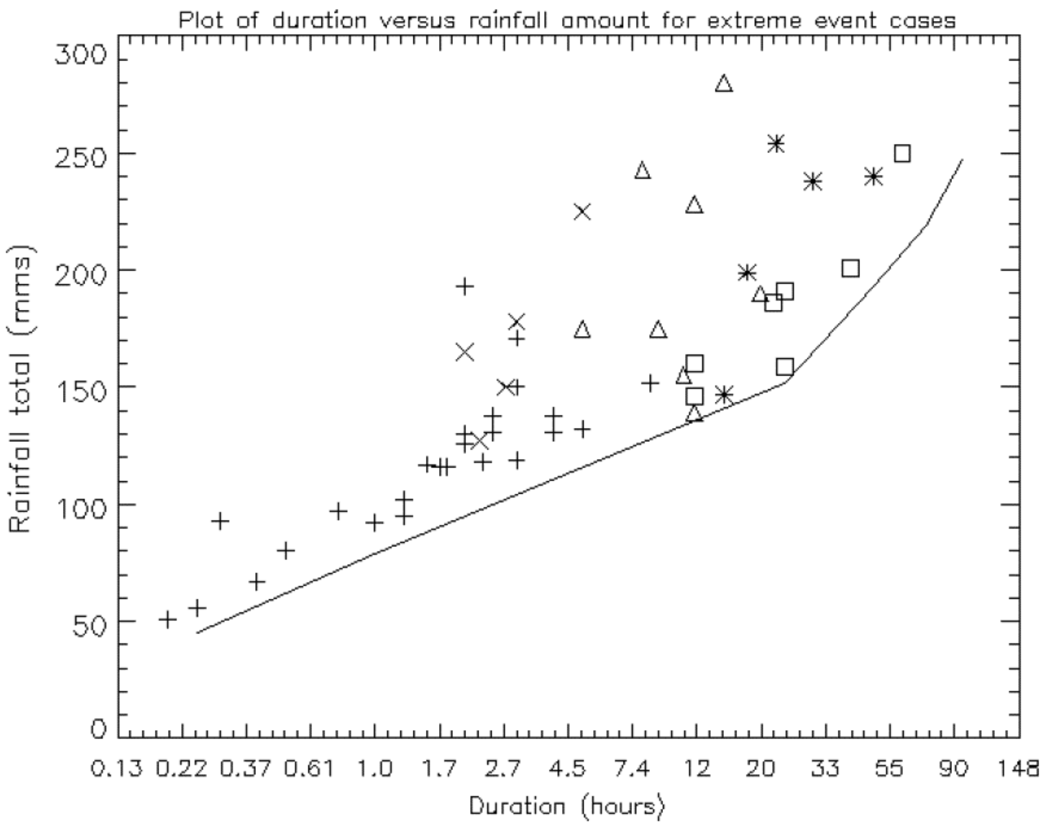

Figure 1: Plot of rainfall amount versus duration (on a logarithmic scale) (Collier and others, 2002). The symbols represent different types of rainfall: convective '+'; convective with frontal forcing 'x'; orographic '*', frontal (with embedded instability) '∆'; and frontal '□'. The solid line indicates the threshold used for extreme event classification (see Table 1 for rainfall values at a range of durations). The data points are events identified by Collier and others.

During extraction of data from some sources, it was found that the initial choice of threshold led to a very large number of events for durations longer than 24 hours (for example, 1,342 events were initially extracted from the CEH-GEAR data set) being included. To help focus the catalogue on truly extreme events, the catalogue entries were filtered using a higher threshold, increased by 50%, for durations over 24 hours.

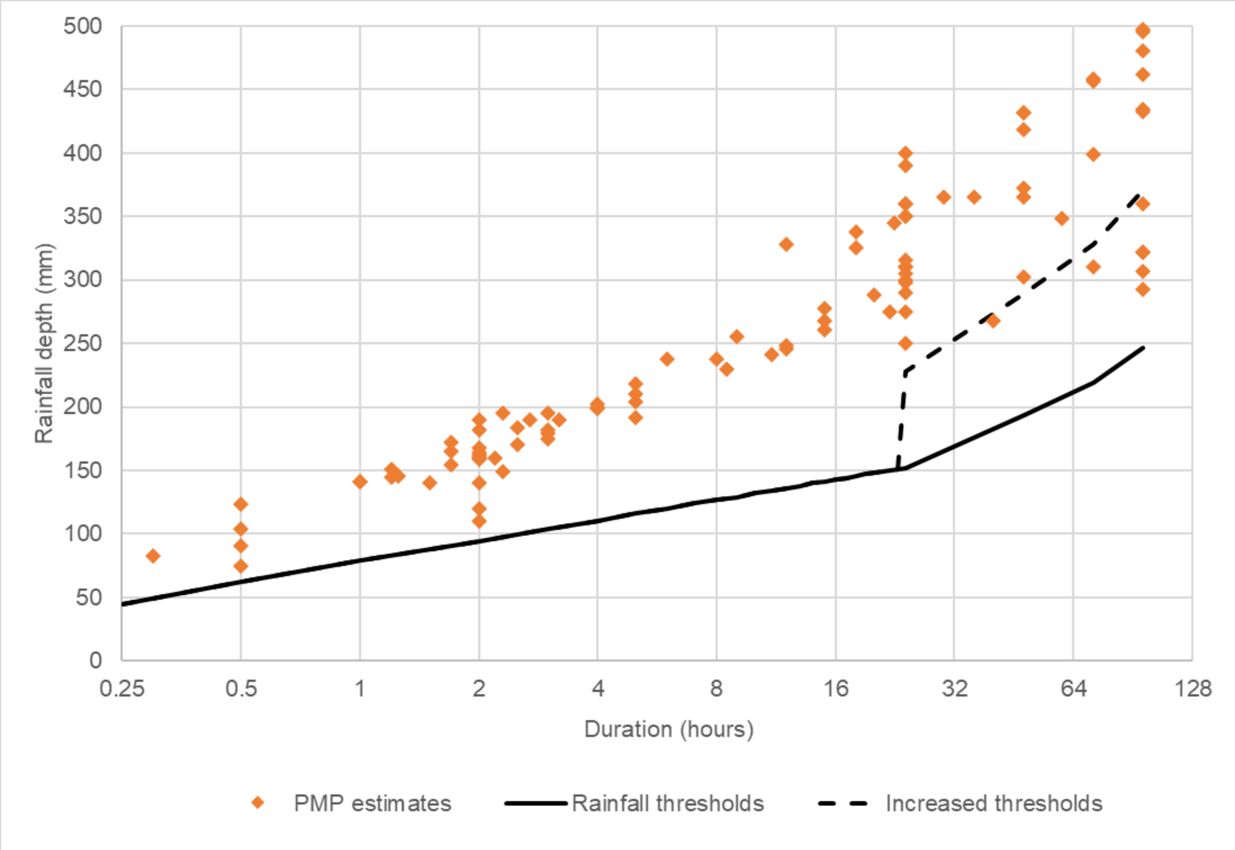

Figure 2: Plot of rainfall amount versus duration. The solid line indicates the thresholds used for extreme event classification (see Table 1 for rainfall values at a range of durations). The dashed line indicates the increased thresholds used for extracting extreme events from the GEAR and GSDR data sets. The points are estimates of PMP and are all above the line.

Figure 2 compares the original and increased threshold with estimates of PMP for a range of locations across the UK. Most PMP estimates lie above even the increased threshold. A drawback of using a uniform national threshold in conjunction with large data sets is the difficulty of striking a balance between the chance of missing some near-PMP events and including an unmanageably large number of events.

Table 1: Rainfall thresholds applied when identifying events to include in the catalogue (before any adjustments).

Duration (hours)	Threshold (mm)
0.25	45
0.5	62
1	79
24	152
48	193
72	219
96	247

2.3.2 Flow thresholds

It was necessary to define thresholds that would identify all floods that may have approached or exceeded current estimates of PMF, while avoiding including large numbers of smaller floods. To do this, 2 thresholds based on peak flows were defined, and events that exceeded either were included. One was based on peak flow per catchment area, Q/AREA (unit discharge) and the other on peak flow as a ratio of the median annual maximum, QMED (where available). Each has pros and cons, as listed below.

Q/AREA pros

The pros are that:

- it is compatible with most previous work such as Acreman (1989) and the Creager curve, which expresses the relationship between peak flow and catchment area
- the catchment area can be readily obtained for nearly all locations where a river has flooded or where a PMF has been estimated
- PMF values seem to follow a fairly clear pattern when plotted on a graph of Q/AREA vs AREA (Figure 3)

Q/AREA cons

It may pick up many more floods on wet upland catchments and could miss some extreme events on drier or more permeable lowland catchments. This is less of a concern than it might appear because the FSR method of estimating PMF is expected to give more conservative estimates on lowland than on upland catchments. This is because the FSR

PMP does not vary greatly with standard annual average rainfall (SAAR) and the method is not particularly sensitive to soil class (because of the frozen ground allowance for the winter PMF). So, we might expect more floods to approach the FSR PMF estimates in upland catchments than in lowland ones.

Q/QMED pros

It is a useful way of identifying extreme floods on drier, lowland or more permeable catchments.

Q/QMED cons

The cons are that:

- it would be necessary to estimate QMED for all locations where PMF has been estimated, estimating it from catchment descriptors in most cases
- it is not known whether PMF/QMED values will fall within a distinct range
- QMED is not always well estimated from catchment descriptors

Both thresholds are based on peak flow. Volume may also be an important consideration when considering floods that could have approached or exceeded the PMF. It is, in theory, possible for a PMF outflow from a reservoir to occur during a flood that does not exceed the PMF inflow to the reservoir. This is more likely for large reservoirs with small catchments, which provide a large degree of attenuation. They will tend to be sensitive to high-volume, long-duration floods, which may not produce a high peak inflow. Nevertheless, it was thought likely that the thresholds based on peak flow were set low enough to capture all events likely to have been close to or exceeded the estimated PMF.

The Q/AREA threshold was set empirically by plotting a straight line on a double log plot of Q/AREA against AREA that lay distinctly below a set of PMF estimates and yet was not exceeded by a large number of annual maximum floods in the NRFA peak flows data set. The threshold, shown on Figure 3, is defined by:

$Q/AREA = 5.14\ AREA^{-0.1334}$

This formula represents Q as proportional to $AREA^{0.87}$. This is very similar to the FEH regression equation for QMED, which uses $AREA^{0.85}$.

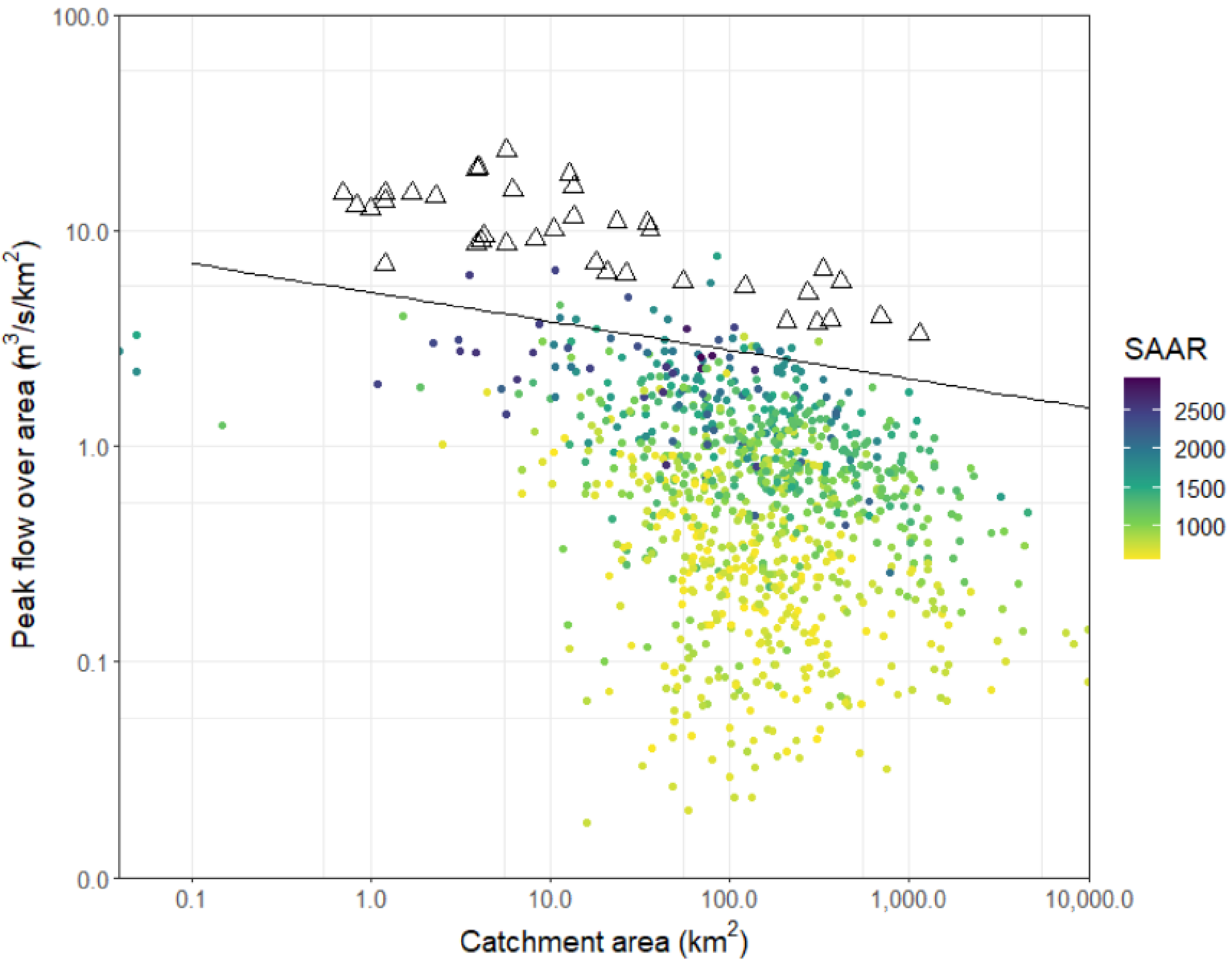

Figure 3: Plot of the Q/AREA threshold for extracting floods. Points are the largest flow at each gauging station in the NRFA peak flows data set. Triangles are PMF estimates

The PMF estimates in Figure 3 are taken from Acreman (1989), Reed and Field (1992) and a small number of projects carried out by JBA. They come from a wide range of catchment types, with SAAR ranging from 680 mm to 2,300 mm. Eight of the PMF estimates are on catchments with SAAR ≤ 800 mm. The catchment areas range from below 1 km^2 to above 1,000 km^2.

Figure 3 shows that there is a distinct relationship between annual rainfall and Q/AREA. Most floods with high values of Q/AREA occur on catchments with high SAAR, for example, upland, wet catchments. This is not surprising, but it is a useful reminder that the Q/AREA threshold will tend to detect mainly floods in upland areas.

The Q/QMED threshold was defined by extracting the top-ranking flood in the annual maximum series at every gauging station in the NRFA peak flows data set. Each flood was expressed as the ratio Q/QMED, and the 99th percentile of the ratios was calculated. This gave a value of 7.60, which was used as the threshold. The threshold is illustrated in Figure 4.

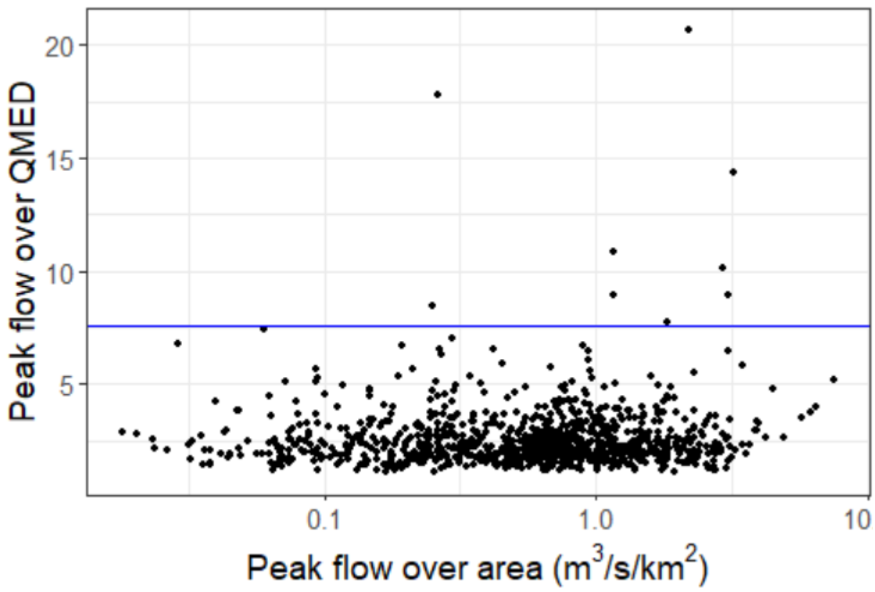

Figure 4: Largest flow at each gauging station in the NRFA peak flows data set, comparing ratio over catchment area to ratio over QMED. Line shows the threshold of 7.6 for Q/QMED

Figure 4 compares Q/QMED with Q/AREA for the largest annual maximum flow at each gauge. The plot shows that the addition of the Q/QMED threshold leads to some floods which are not extreme in terms of Q/AREA being included in the catalogue. These tend to be lowland, low-rainfall catchments.

Both the Q/AREA and the Q/QMED thresholds were used to select floods from NFRA. 39 events exceed the Q/AREA threshold and 10 events exceed the Q/QMED threshold. Of these, 3 events exceed both thresholds, so the total number of exceedances is 46.

An initial review led to 27 of these floods being excluded. Reasons for this included:

- floods that are not much higher than several other events at the gauge - this can occur on some upland catchments, where the Q/AREA threshold is too low to identify truly extreme events
- clear evidence of overestimation due to rating curve extrapolation, as judged by the comments in the NRFA database
- not the highest flood on record at the gauge - since no exceedances of estimated PMF were eventually found in the NRFA data set, we can be confident that floods smaller than those included will also not have exceeded PMF

The excluded floods are listed in Appendix 3. Further reviews looked at any overlap between the floods obtained from the NRFA data set and those obtained from other sources.

2.3.3 Data quality

All events in the catalogue are accompanied by a data quality flag, scoring the data by reliability of source. Flags have been added for either rainfall or flow data, and the values used can be found in Table 2 for rainfall data, and Table 3 for flow data. In both instances, a value of 1 represents the highest quality data.

Table 2: Rainfall data quality flags

Rainfall data source	Data quality flag	Number of catalogue entries
Met Office standard gauge **British Rainfall record**	R1	338
Informal rain gauge **(for example, as detailed in flood chronologies)**	R2	119
Interpolated grid/radar data	R3	59

Table 3: Flow data quality flags

Flow data source	Data quality flag	Number of catalogue entries
Data from gauge suitable for pooling	F1	12
Data from gauge suitable for QMED	F2	4
Data from flow gauge not suitable for QMED	F3	0
Data from level gauge (informal rating)	F4	1
Flow estimated from hydraulic methods based on flood debris or boulder size, or from a model	F5	34

2.3.4 Events which have been excluded

There are some events which were previously reported as extreme, but as a result of revised data, are no longer deemed to be extreme events. As a result, the events no longer meet the requirements for inclusion in the catalogue and have been removed.

One example was the event reported on the River Findhorn at Divie and Dorback in 1970 (Acreman, 1989). The peak flows used in the report have been revised and reduced since publication and have been removed from the catalogue.

Another example are the events extracted from the GSDR data set which were taken from the gauge at Nantyrwydd (ID: EA059R0433W). Those events were disregarded due to quality issues. The data looks fine at an hourly level, but it shows obvious errors when the original sub-hourly data is considered.

Furthermore, the event at Portmoak on 13/08/2007 was excluded from the catalogue. The gauge is in lowland eastern Scotland, adjacent to Loch Leven. The time series for the event shows almost uninterrupted rainfall for 96 hours. There were no QC flags from the original SEPA data to examine, however the Met Office Daily Weather Summaries suggest that the days in question had predominantly westerly flows with dry interludes, especially in the east. Based on this, the available data appears suspicious and the event was, therefore, excluded from the catalogue.

The event on 23/11/2003 at King's Cliffe was initially added after expanding the search to the hourly GSDR, but has been removed by the sub-hourly QC performed by Newcastle University in creating the data set and was, therefore, excluded from the final event catalogue. The exceedance was identified at the 96-hour duration, but on further examination of the GSDR data, it became clear that there were errors in the rainfall recorded and PMP was not in fact exceeded at this or shorter durations. For this reason, the event was removed from the catalogue.

2.4 Additional data for selected events and catchments

Reservoir flood studies do not consider PMF in isolation and so it is desirable to have consistency between the hydrological methods used to estimate PMF and those for smaller floods. Existing reviews of the current UK method for estimating PMF have identified 3 issues that appear to need further research: acceleration of flood response time, allowance for frozen ground, and quantifying snowmelt. Examining antecedent rainfall and soil moisture may also be beneficial. Additional data (temperature data, snow data, soil moisture and flow) were collected for a selection of events for use in the future analysis of these issues.

2.4.1 Criteria for selection

Several criteria were applied to select the events for which additional data would be sought. The criteria were:

- events post 1960 (when soil moisture data are available)
- events where peak flow data is recorded at a nearby flow gauge
- a range of geographical locations across Great Britain and Northern Ireland

30 events were selected, listed in Table 4 and shown in Figure 5. For these events, temperature, snow, soil moisture and flow data were obtained, for use in future analysis.

Table 4: Events for which additional data were obtained

Date	Location	Source
30/09/1960	Alphin Brook, Exeter	Acreman (1989)
08/08/1967	Dunsop Water	Stewart and others (2011)
06/11/1967	Esk at Sleights	NRFA
15/09/1968	Eden at Penhurst	NRFA
15/07/1973	Wye, Pant Mawr	Acreman (1989)
24/09/1976	Polperro	British Chronology of Flash Floods, Acreman (1989)
15/08/1977	Severn at Hafren Flume	NRFA
30/10/1977	Ettrick Water at Brockhoperig	NRFA
04/08/1978	Allt Moor	Acreman (1989)
05/10/1978	Oykel	Acreman (1989)
28/12/1978	Six Mile Water, Ballyclare	Acreman (1989)
14/06/1979	Caldwell Burn, Berryscaur	Acreman (1989)
25/09/1981	Ardessie	Acreman (1989)
12/07/1982	Chulmleigh	Winter (1982)
17/07/1983	Ireshopeburn Farm	British Chronology of Flash Floods
17/07/1983	Honister Pass	British Chronology of Flash Floods
26/08/1983	Hermitage	Acreman (1989)

Date	Location	Source
20/05/1986	West Stream, Lyons Gate	Acreman (1989)
11/08/1986	Crooked Oak, Knowstone	Acreman (1989)
18/10/1987	Sawdde at Felin-y-cwm	NRFA
02/10/1981	Muick, Invermuick	Acreman (1989)
21/08/2000	Erch at Pencaenewydd	NRFA
30/07/2002	Trout Beck at Moor House	NRFA
19/06/2005	Rye at Broadway Foot	Wass and others (2008); NRFA
25/06/2007	Dearne at Barnsley Weir	NRFA
25/06/2007	Heighington Beck at Heighington	NRFA
06/09/2008	Derwent at Eddys Bridge	NRFA
05/12/2015	Kent at Sedgwick	NRFA
23/08/2017	Abhainn Roag at Mill Croft	NRFA
16/02/2020	Taff at Merthyr Tydfil	NRFA

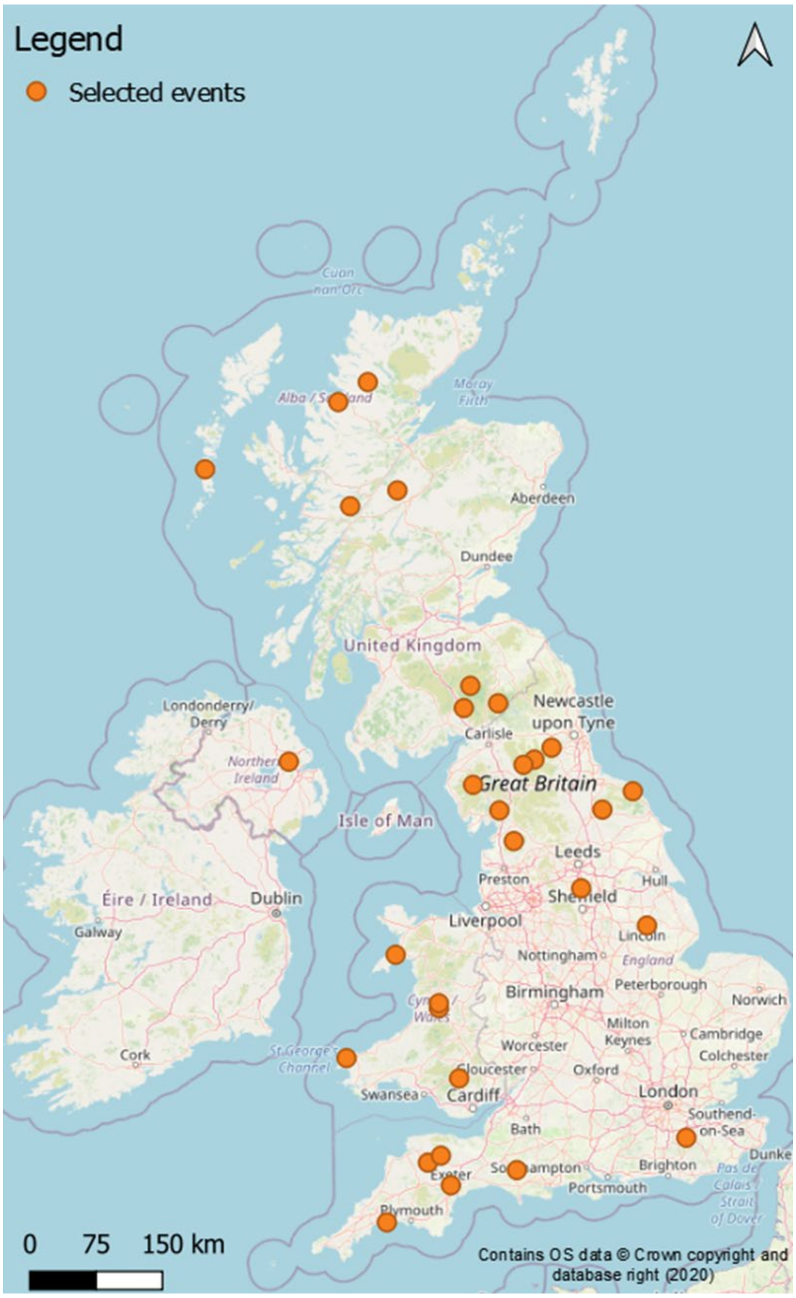

Figure 5: Location of events selected for extracting extra data across the UK

Figure 5 shows a map of the UK with 30 orange dots at the locations of individual events selected for extracting extra data. These are located in Scotland (8), England (16), Wales (5) and Northern Ireland (1).

2.4.2 Soil moisture

The purpose of the task is to derive the soil moisture for each of the selected catchments before the identified extreme events. This information may be used in a future investigation of patterns with regards to antecedent conditions associated with extreme floods.

The soil moisture values have been derived using 2 different soil accounting models, CERF and DAYMOD, described in Appendix 1.

Both CERF and DAYMOD were run for the period 1955 (before 1961 ‘average’ PE data was used) to 2017 for the identified catchments.

The soil moisture values were then obtained from each model run for the event identified within the catalogue.

For CERF, this is the addition of the soil moisture storage plus the probability distributed moisture store and is in the form of a soil moisture deficit. A value of 0 indicates the soil is saturated. Data is extracted for the day before the event.

For DAYMOD, this is in the form of a soil moisture depth, so a value of 0 indicates the soil is unsaturated, while a value of CMAX (the maximum soil depth) indicates saturation. The data provided is the starting soil moisture value for the day of the flood.

While the models are similar in many ways, it should be noted that DAYMOD is a far simpler structure and is parameterised using CMAX only. No site-specific calibration has been completed and the default parameterisation was used. Further commentary on comparisons between the 2 models, and their outputs is provided in the appendix.

2.4.3 Temperature and snow cover

Temperature and snow depth data were obtained from the Met Office MIDAS Open: UK Land Surface Stations Data. Observations are available at a large number of stations across Great Britain and Northern Ireland, with records available from 1853 to 2019. There are 1,592 stations with temperature observation data, and 1,587 stations with weather observation data. Their geospatial distribution is shown on 2 maps of the UK in Figure 6.

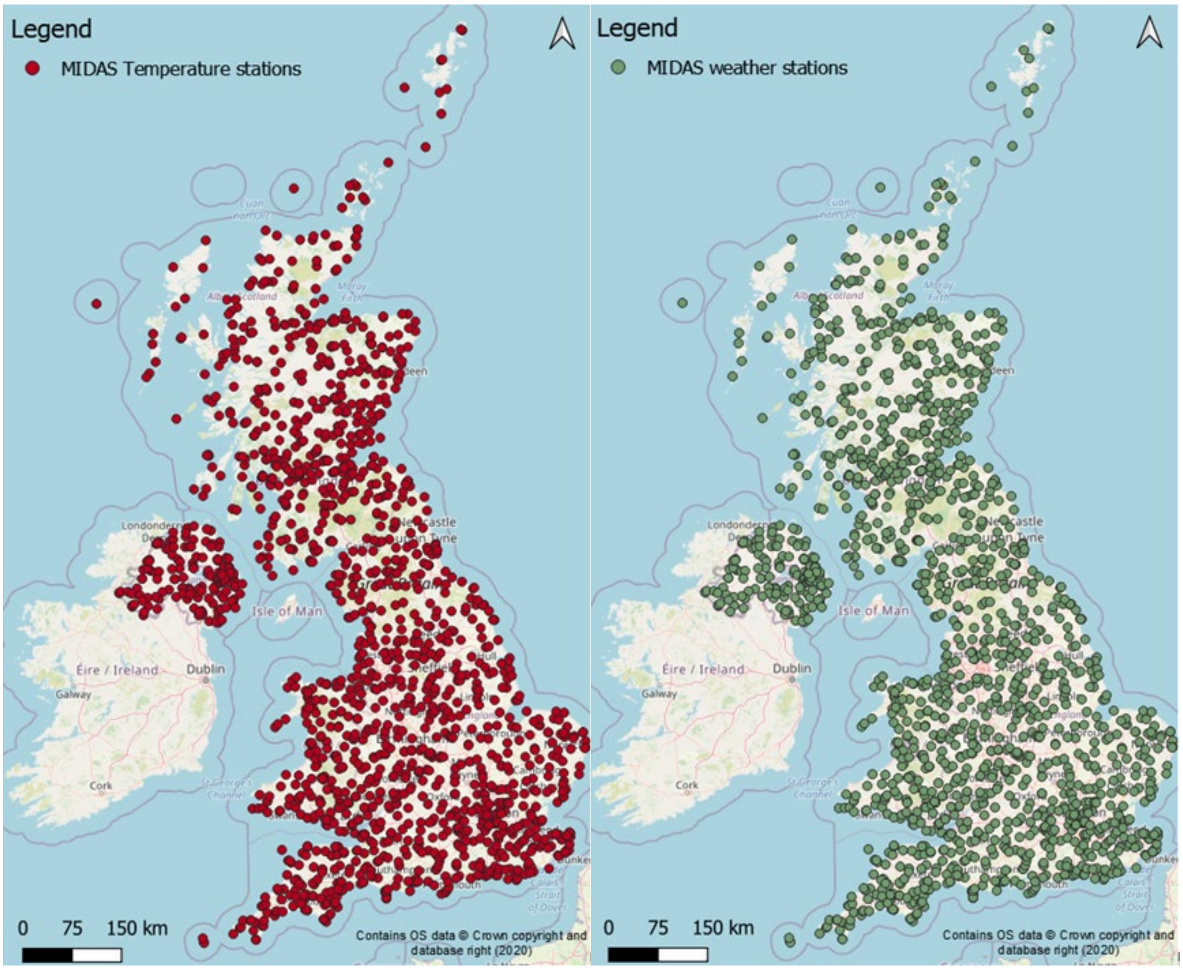

Figure 6: Location of MIDAS temperature and weather stations (contains OS data Crown copyright and database right 2020)

In Figure 6, the left map shows the locations of MIDAS temperature stations with red dots, and the right map shows the MIDAS weather stations using green dots.

For each extreme event, the nearest MIDAS station with data was selected. Where the nearest gauge did not have temperature or snow depth data available, the next nearest gauge with suitable data was selected. The distances to the nearest MIDAS station range from 0.1 km to 28.4 km. Details of the MIDAS stations used for each event are available in Table 24 in Appendix 2.

Daily maximum and minimum air temperature are recorded at the MIDAS stations. The data for each event are saved in csv files with the filename eventid_location_temp.csv. The files also contain the remaining temperature observations for the station.

A number of snow parameters are recorded as part of the daily weather observations at the stations. The station records provide the following information of interest:

- snow depth (cm, recorded at 09:00)
- fresh snow amount (cm, for the time period 09:00 to 09:00)
- lying snow flag (if more than half of the ground at the station has lying snow, then it is recorded as a lying snow day)

- an indication of lying snow height (manual assessment of the lowest height of lying snow)

The snow data for each event are saved in csv files with the filename: eventid_location_weather.csv. These files also contain the remaining daily weather observations for the station.

Further information about the measurements included in the MIDAS data is provided in the MIDAS Data User Guide (Sunter, 2020).

2.5 Contents of the event catalogue

The event catalogue file contains a number of tabs with different information. An overview of the data contained in each tab is provided below.

2.5.1 Event catalogue

The main event catalogue. This tab contains data including the event reference; date (and time if available); location (place name); brief event description (includes information on storm type where available); duration; rainfall depth and peak flow values (where available); source references; data quality flag; and an indication of whether gauge data, radar images, damage reports and additional data (soil moisture, temperature, snow and flow) are provided alongside the catalogue.

2.5.2 Location data

Easting, northing, latitude, longitude and British National Grid reference for all events.

2.5.3 UKGrsHP

Details of the events in the catalogue for which the UKGrsHP data set was reviewed. Where data from UKGrsHP provided plausible results, images showing the data are included.

2.5.4 Temporal profiles

For selected events, this tab contains the rainfall data for the event duration, at the closest gauge in the GSDR data set. Data are provided at a 15 minute resolution, or at an hourly resolution where data at a higher resolution was not available.

2.5.5 GSDR – all exceedances

Data for all exceedances of the rainfall threshold in the GSDR data.

2.5.6 GEAR – all post 2006 exceedances

Data for all exceedances of the rainfall thresholds in the CEH-GEAR data. All data are post 2006.

2.5.7 GEAR – comparisons and checks

This tab contains data comparing the rainfall totals from the CEH-GEAR data set with rain gauge data from the GSDR data set. The 2 data sets were compared as part of the quality assurance process. It also contains information on the distance of each relevant grid cell to the nearest daily gauge.

2.5.8 Data for gauged catchments

Temporal profiles for some rainfall events.

2.6 Discussion of catalogue contents

2.6.1 Overview

The catalogue contains 569 entries, representing 324 distinct events. Multiple entries for one event represent either different locations affected or rainfall depths accumulated over different durations. 474 exceedances of rainfall thresholds were found, and 50 exceedances of flow thresholds. A large number of rainfall events were added to the catalogue, in addition to those already reported in Stewart and others (2013). These events come from a range of sources – mainly the GEAR and GSDR data sets, with a number of events from the flood chronologies as well. 76 events have been added after 2006 (24% of all events in the catalogue). This is shown in Figure 7.

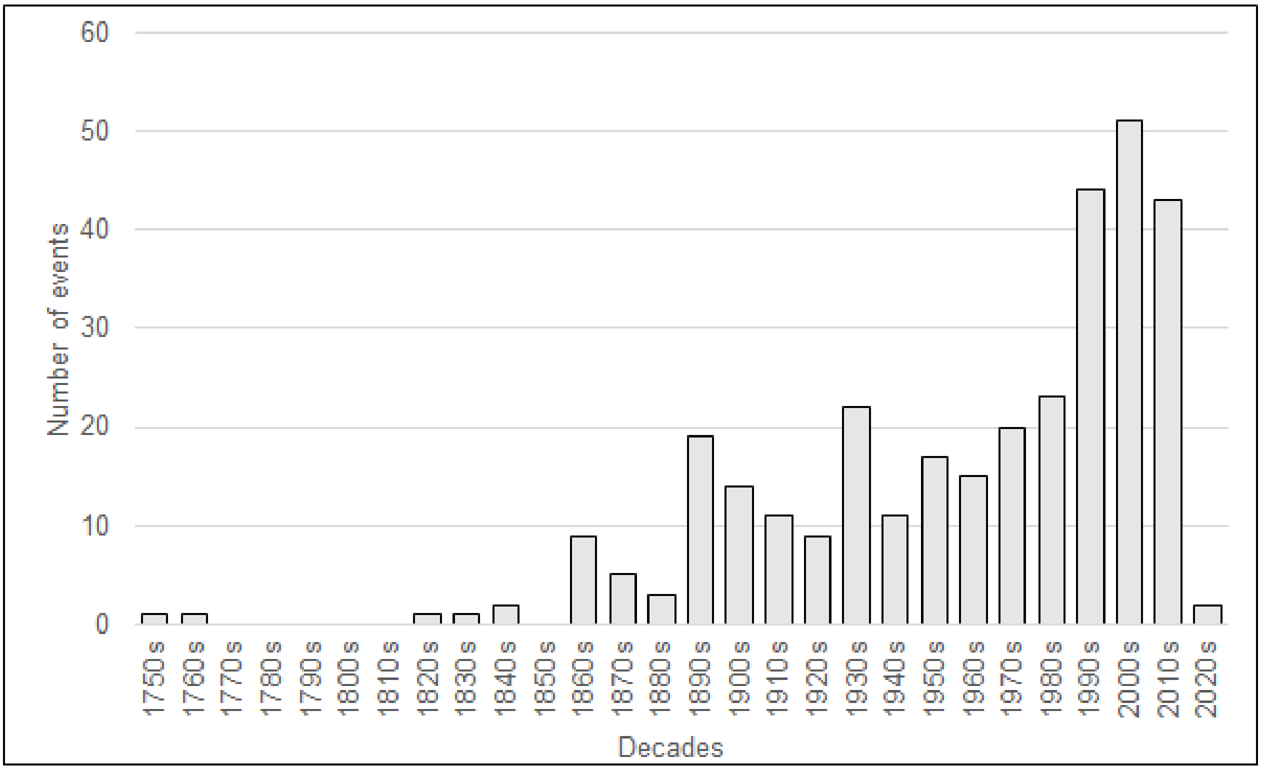

Figure 7: Distribution of catalogue in each decade from the 1750s to the 2020s

Figure 7 provides a breakdown of the number of events occurring in the centuries covered in the catalogue. The distribution, with far more events in the 20th and 21st centuries than the 18th and 19th, is likely to be because of more digital data sets being available, as opposed to a change in the occurrence of extreme events. 115 events (36% of events in the catalogue) were from new digital data sources. 96 of these events were from GSDR (1973 onwards), and a further 19 from GEAR (2006 onwards). The flood chronologies reviewed also contained a lot of additional rain gauge data and these provided a number of events, both before and after 2006. A change in the occurrence of extreme events cannot be ruled out, but it would not be detectable by the cataloguing work. The last 3 complete decades (1990s, 2000s and 2010s) each contain a similar number of catalogued events.

Events in the catalogue cover most parts of the UK (Figure 8). Most events with flow data are in the west or north of the UK. This is in part a reflection of the way the thresholds for peak flow were defined.

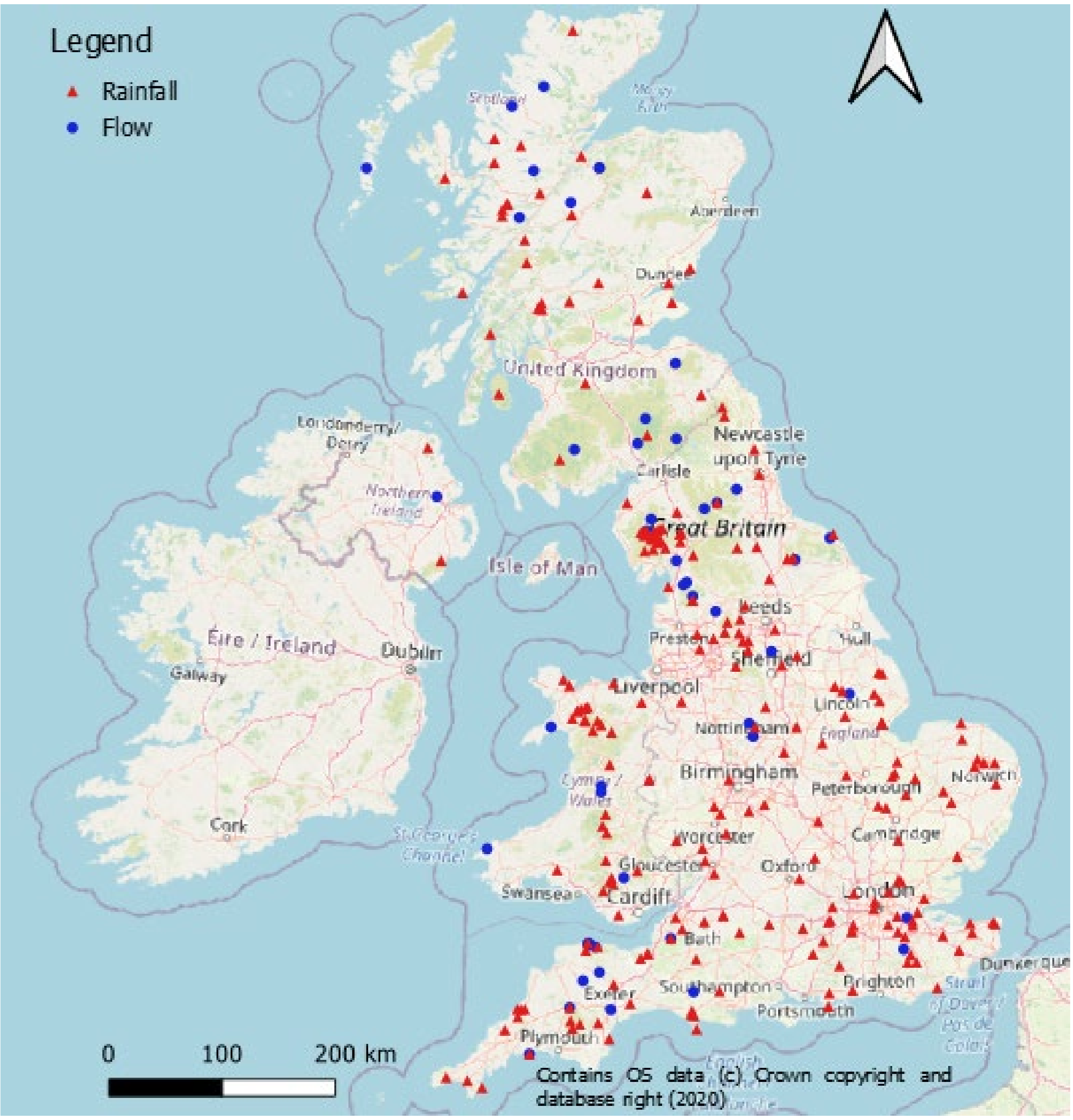

Figure 8: Locations for which rainfall and flow exceedances were extracted. Contains OS data © Crown copyright and database right (2020)

Figure 8 is a map of the UK showing locations for which both rainfall, shown by red triangles, and flow, shown by blue circles, exceedances were extracted. These cover England, Scotland, Wales and Northern Ireland.

2.6.2 Rainfall

There is a large amount of rainfall data in the catalogue. Not all sources have been subject to the same degree of quality control. Some very high rainfall totals can be seen for durations of 24 hours and greater, mostly in the GEAR and GSDR data. Some of the largest rainfall totals have been examined in more detail and, where problems were found, have already been removed from the catalogue. Additional quality assurance checks may identify more events to revise or exclude.

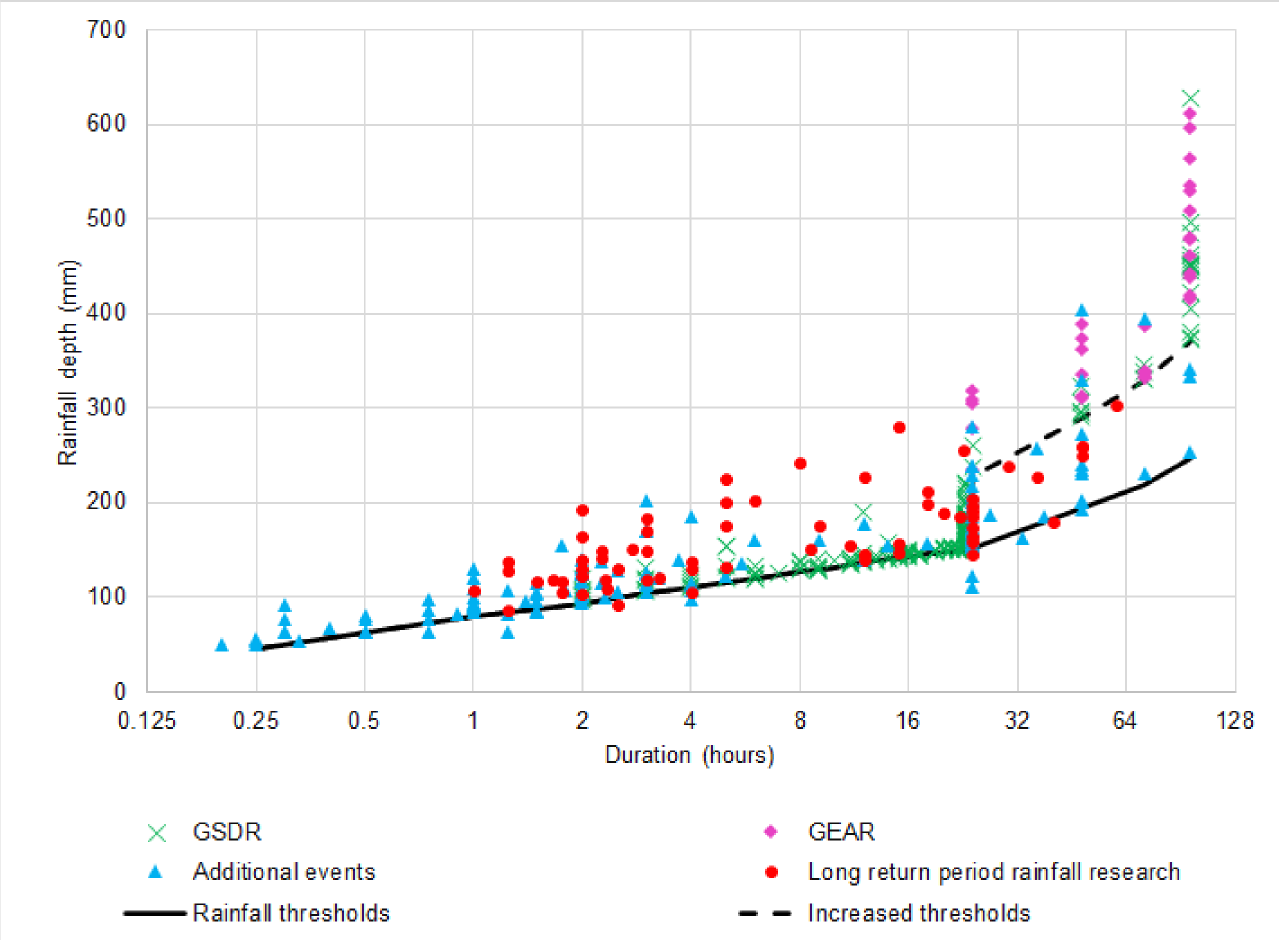

Figure 9: Plot of rainfall amount versus duration for all events in the catalogue with rainfall data

Figure 9 illustrates the events in the catalogue for which rainfall data is available. It distinguishes between the different sources of rainfall data. The vertically aligned symbols towards the right of the plot represent information from daily rain gauges or the interpolated GEAR data set. Some events in the catalogue are represented by multiple points, where they exceed thresholds at more than one duration.

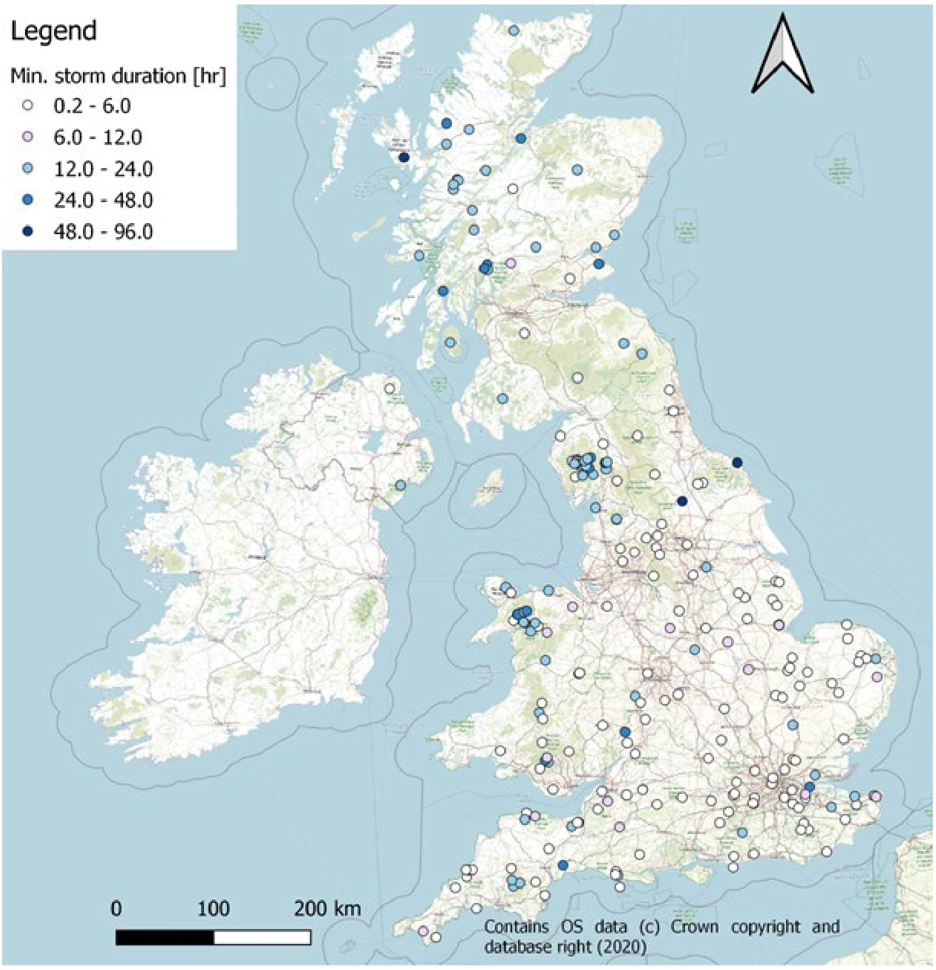

Figure 10: Shortest durations at which rainfall thresholds were exceeded at each location. Contains OS data © Crown copyright and database right (2020)

Figure 10 shows the geographical distribution of the events with rainfall data, indicating the shortest duration for which each event exceeded the threshold depth. Unsurprisingly, there is a clear tendency for the longer-duration events to be located in upland areas such as north Wales, Cumbria and western Scotland. There are a few exceptions. Outside these upland areas, the coverage of events is fairly even across England and Wales. The lower density of events in Scotland may reflect a sparser coverage of rain gauges. There are only 2 events in Northern Ireland. This is most likely due to a lack of data rather than a lack of events.

Figure 11 is an equivalent map showing the longest duration for which each event exceeded the threshold depth.

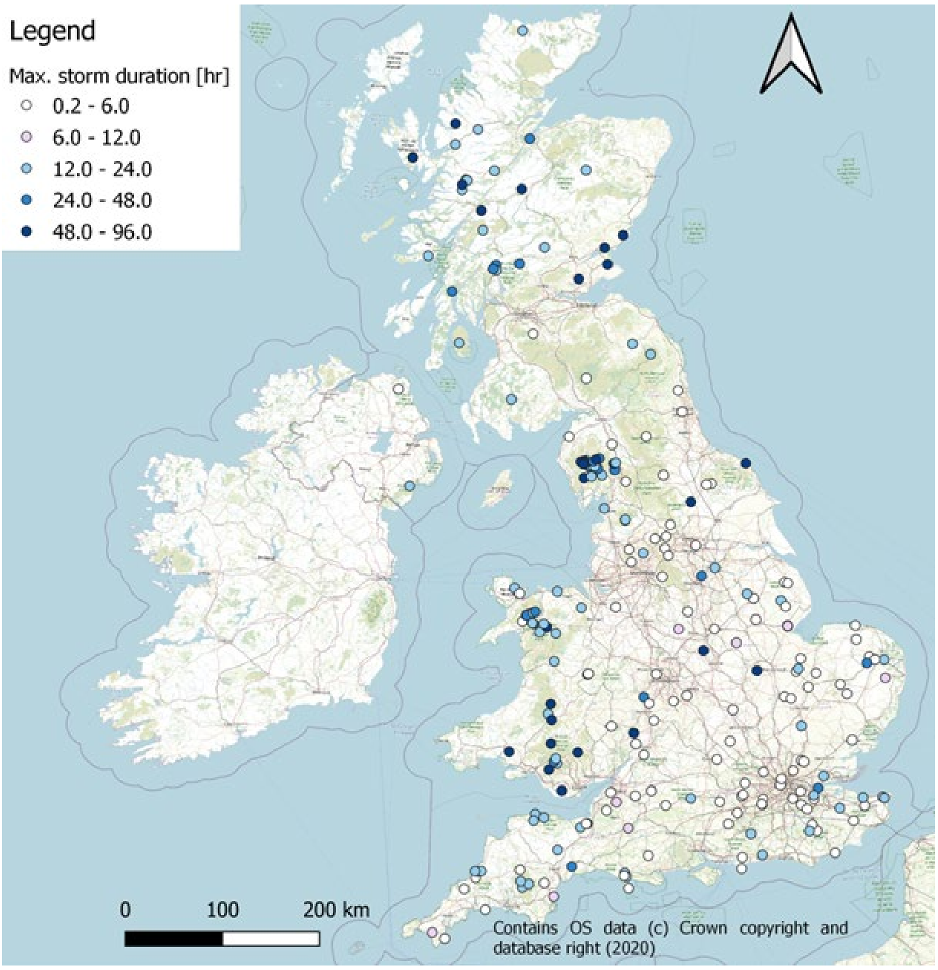

Figure 11: Longest durations at which rainfall thresholds were exceeded at each location. Contains OS data © Crown copyright and database right (2020)

Figure 11 shows a map of the UK showing different coloured circles that represent the longest durations at which rainfall thresholds were exceeded at each location in the catalogue.

For the more recent events in the catalogue, data from additional sources were sought to provide further information about the event. For events identified in the literature, GSDR and CEH-GEAR data sets, occurring from 2005 onwards, the UKGrsHP data set was reviewed. Where there was good agreement with the original source, UKGrsHP data were provided to include in the catalogue. Two events were identified in the British Chronology of Flash Floods where the gauge data from these records was in agreement with the blended UKGrsHP data set:

- Figure 12 shows the UKGrsHP data for an event in Hastings on 7 July 2009
- Figure 13 shows data for an event in Nottingham on 23 July 2013

UKGrsHP Precipitation Totals for 7th July 2009 00:00-00:00 (24 hours)

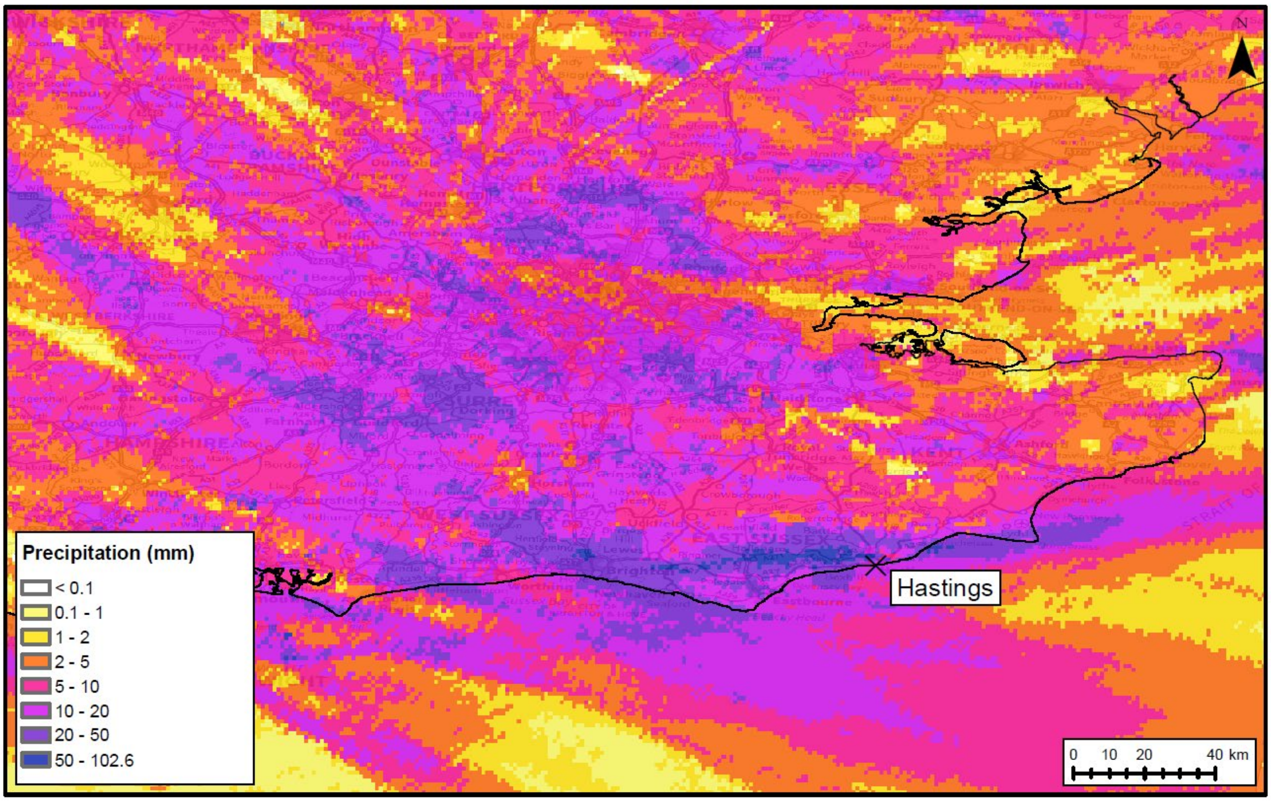

Figure 12: UKGrsHP data for event number 287 – Hastings (south-east England), 7 July 2009

Figure 12 shows the south-east of England, with Hastings marked on the map. Colouring on the map gives precipitation totals for July 7 2009 (24 hours) based on UKGrsHP data. The map shows a band of heavy rain between 50 to 102.6 mm across the south coast. This is event 287 (Hastings) in the catalogue.

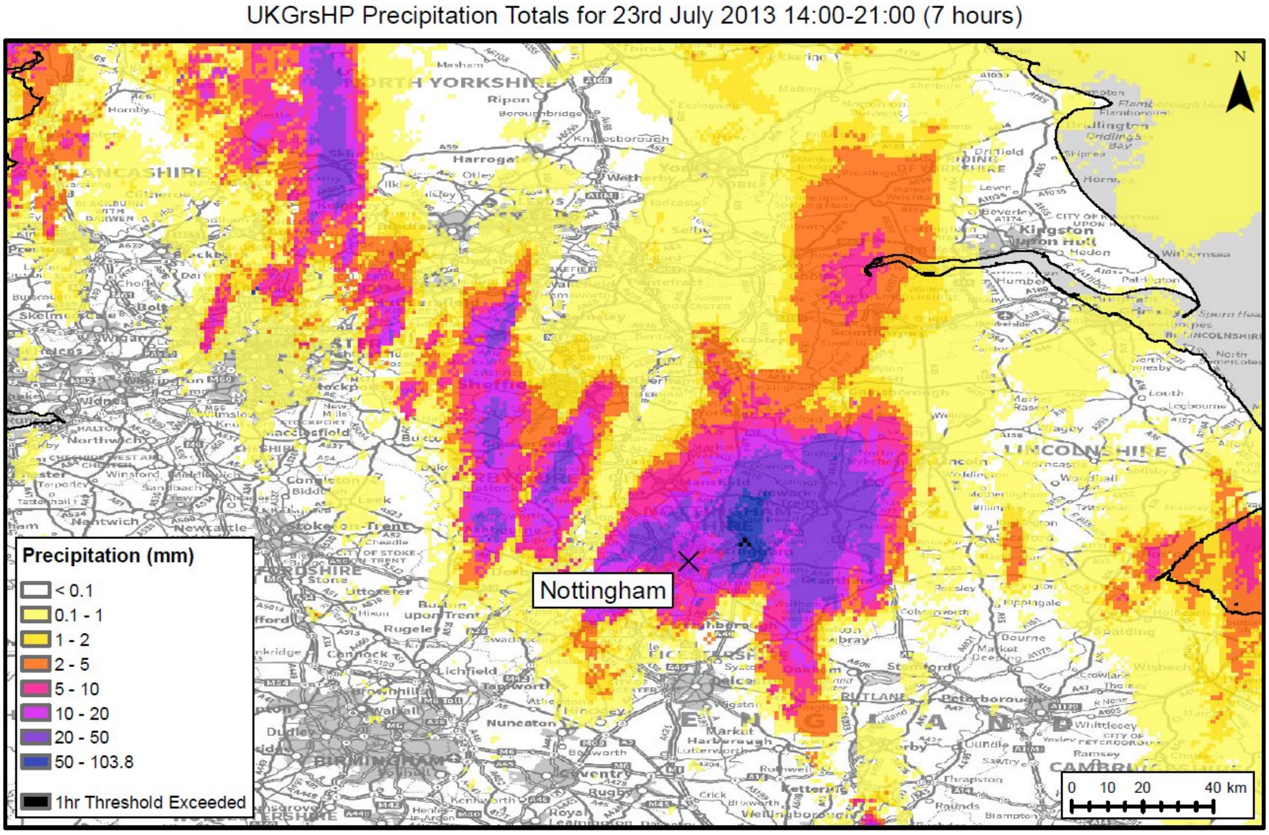

Figure 13: UKGrsHP data for event number 304 – Nottingham (East Midlands), 23 July 2013

Figure 13 shows the east Midlands, England, with Nottingham marked on the map. Colouring on the map gives precipitation totals for July 23 2013 (24 hours) based on UKGrsHP data. This is event 304 (Nottingham) in the catalogue. The map shows a patch of heavy rain across the east Midlands, with the highest totals of 50 to 103.8 mm in the centre.

2.6.3 Flow

Figure 14 illustrates the events included in the catalogue for which peak flow data are available.

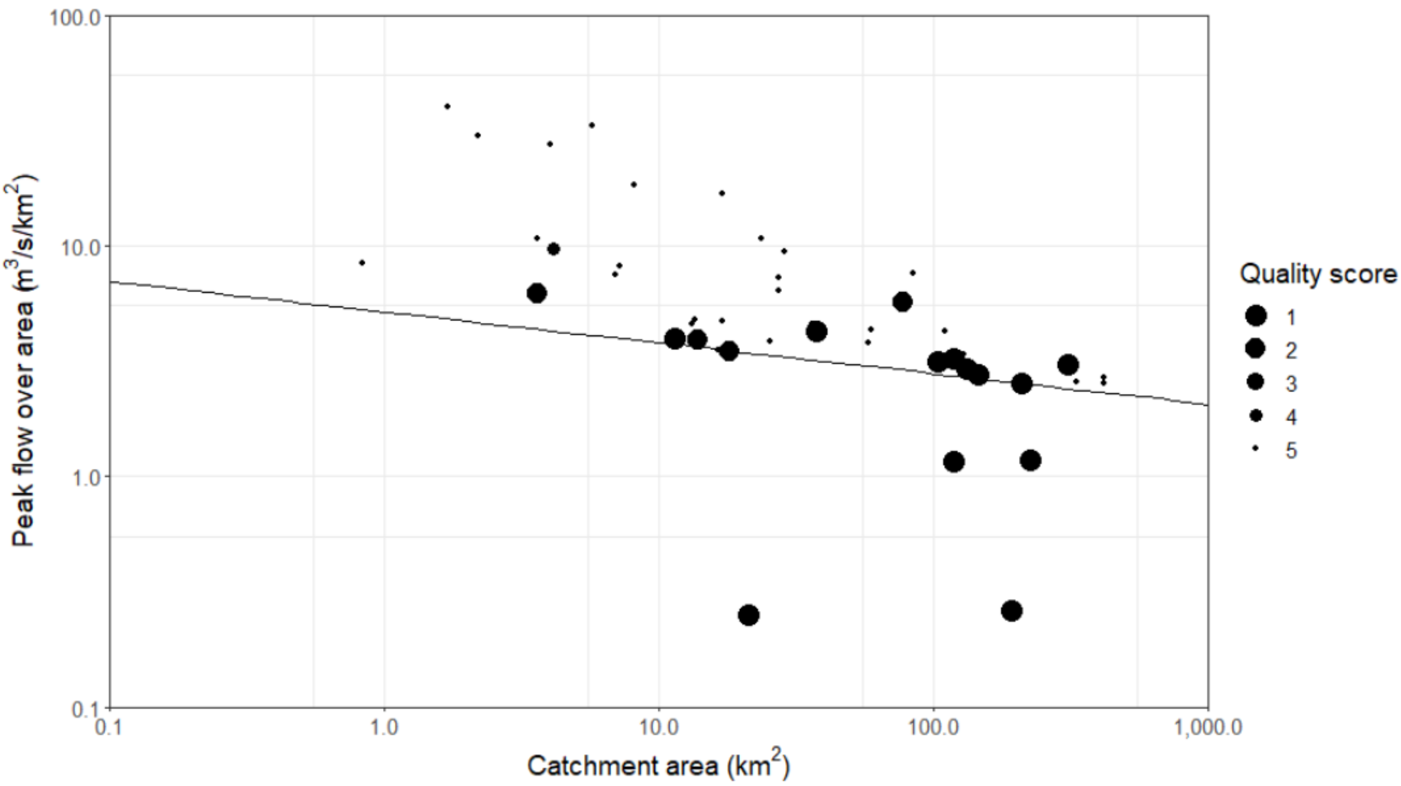

Figure 14: Plot of Q/AREA against catchment area for all events in the catalogue with peak flow data. The line is the Q/AREA threshold applied for event selection

The graph in Figure 14 shows a general negative trend that as catchment area increases the peak flow over area decreases. The larger the symbol, the more confidence we can have in the flow magnitude. Most of the events with the largest unit discharges are very low confidence estimates.

Not all events in the catalogue lie above the Q/AREA threshold line, because some were selected on the basis of the Q/QMED threshold. The reason for doing this is illustrated by the variation of annual rainfall values for the set of annual maximum flows shown on Figure 15. Nearly all events with high Q/AREA are on high rainfall catchments. Sole use of the Q/AREA threshold risks missing floods that are extreme in drier areas.

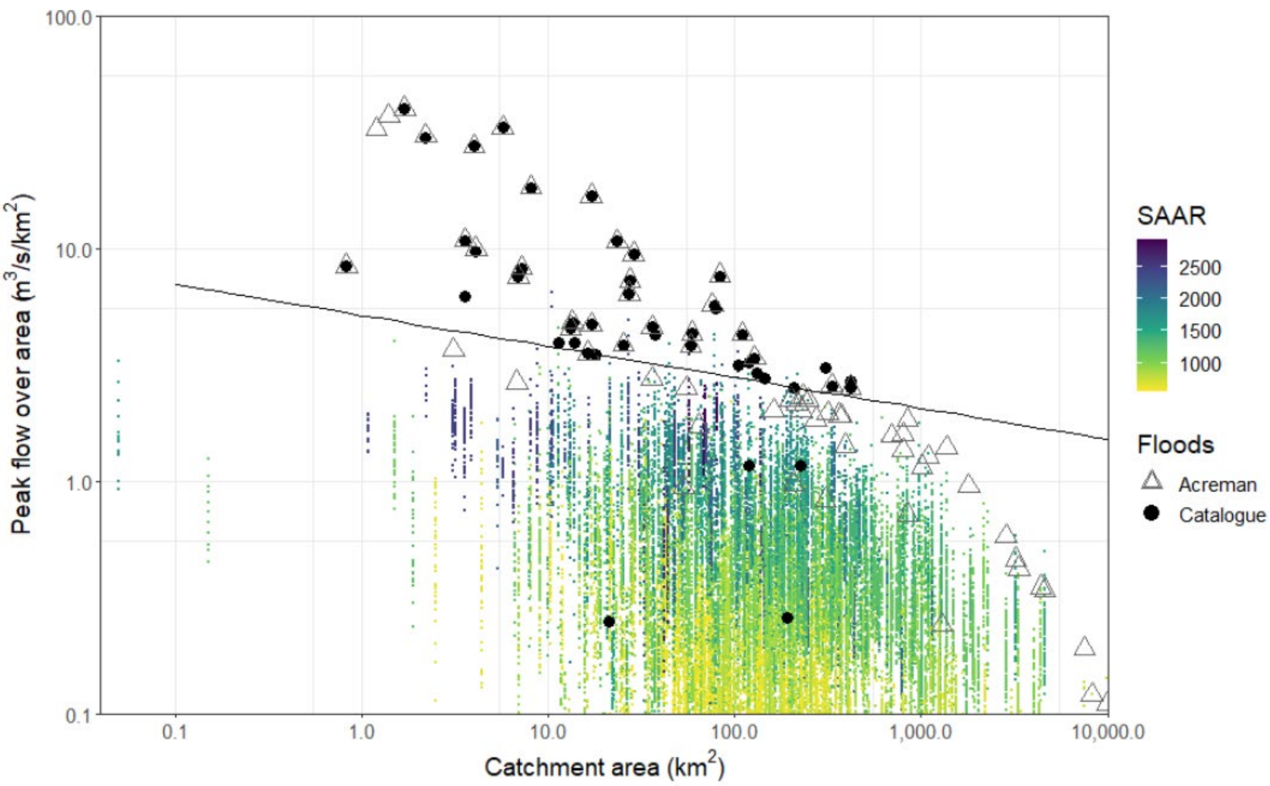

Figure 15: Plot of Q/AREA against catchment area, comparing events from Acreman (1989) with those included in the current catalogue. The small coloured points show all annual maximum flows in the NRFA data set. The line is the Q/AREA threshold applied for event selection

Figure 15 is an updated version of a plot generated by Acreman (Figure 2, 1989). Many of the events identified by Acreman are also in the catalogue. Where they are not, it is either because they fall below the Q/AREA threshold and QMED values are not available to check the Q/QMED threshold (mostly on larger catchments), because their flow has been reassessed, or because multiple entries for one event have been consolidated.

There are some annual maximum flows on the plot that lie above the Q/AREA threshold and yet were not included in the catalogue. These are mostly either on very wet catchments that have several annual maxima above the threshold, or at gauges where there is evidence of gross overestimation of flows. Further details of the exclusion criteria are given in the section 2.2.4 National River Flow Archive.

Acreman (1989) included 2 lines on his plot showing how the ‘normal maximum flood’ and ‘catastrophic flood’ vary with area. These concepts make no allowance for extreme flood magnitudes to vary with any factor other than catchment area, and so we have not included them on the plots in this report.

2.7 Comparisons with estimated PMP and PMF

2.7.1 Background and rationale

Reports of observed events that exceed current estimates of PMP or PMF can be one of the most persuasive sources of evidence that the estimation methods need to be revised.

Previous studies have already identified several such exceedances, as summarised by Faulkner and Benn (2019). Stewart and others (2013) report 5 events that exceeded estimated PMP. Three were in south-west England, one in Lincolnshire, and one in west Yorkshire, with the most recent being the Halifax storm in May 1989. In 4 of the 5 cases, the rainfall total was only marginally in excess of the estimated PMP (less than 5% exceedance). However, it is possible that larger depths of rain fell at locations away from rain gauges. For example, Clark (2005a) states that around 350 mm fell at the centre of the Martinstown storm in 1955, from detailed analysis of informal measurements and the structure of the storm. This is 17% above the FSR estimate of PMP at that location.

Six exceedances of the estimated PMF were reported by Acreman (1989) in a review of extreme historical floods. Three of the floods were in England and 3 in Scotland, with the most recent occurring in 1982. All but one were on catchments smaller than 10 km^2. None of the 6 floods were directly measured at gauging stations. Instead, they were estimated using a mixture of approximate methods, in most cases the slope-area method using flood level information surveyed from wrack marks. Accurate reconstruction of hydraulic conditions during extreme floods is very difficult, particularly where the channel bed and banks are eroded during the flood. Acreman (1989) acknowledges that the accuracy of the flow estimates is poor and that the true peaks may not have exceeded the estimated PMF. The maximum apparent exceedance was a flood in June 1980 on the Caldwell Burn in Dumfriesshire, with an estimated peak discharge 3.8 times the PMF. This is very likely to be an overestimate, and there are some comments to this effect in the catalogue.

One of the events listed by Acreman (1989) has since been downgraded and is not included in the catalogue, as discussed earlier.

2.7.2 Selecting events

The budget for this part of the project allowed for estimating point PMP at up to 30 locations and estimating PMF at up to 15 locations. Previous PMP estimates made for the 63 events reported by Stewart and others (2013) have been retained because the method for estimating PMP is unchanged. PMF estimates at the locations of the 5 exceedances reported by Acreman (1989) have been recalculated because current practice is to add a snowmelt allowance using a method which was not available at the time of Acreman's work.

The criteria for selecting locations for estimating PMP aimed to identify events that were thought most likely to exceed PMP. These included extreme short-duration rainfalls, particularly in upland or western areas, and extreme longer-duration rainfalls, particularly in lowland or eastern areas.

The criteria for selecting locations for estimating PMF, in addition to the 5 from Acreman (1989) were:

- range of locations and catchment types, showing some of the higher threshold exceedances and so more likely to exceed PMF
- reasonable confidence in the measured discharge, for example, avoiding estimates not made at flow gauges
- no major lake or reservoir influence in the catchment - this is because the method used to estimate PMF does not account for upstream storage, unless it is applied in conjunction with a routing model to represent the storage features

2.7.3 Methods of estimating PMP and PMF

At the locations of rainfalls, whether measured by rain gauges or extracted from gridded data sets, a point estimate of PMP was derived using the FSR method. The FSR maps of estimated maximum 2-hour and 24-hour rain were digitised and interpolated to a grid in order to remove the element of subjective judgement required to visually interpolate between the isohyets. For some locations, PMP depths were estimated over a range of durations, for comparison with the reported rainfall depths.

At the locations of floods, PMF was estimated using the FSR/FEH method. The estimated maximum 2-hour and 24-hour rain values were extracted at the catchment centroid. This provides an approximation of the catchment-average values. Most events were on catchments small enough for there to be no discernible spatial variation in the statistics on the FSR maps.

Both summer and winter estimates were made. For the winter PMF, snowmelt was calculated using Hough and Hollis (1997). The procedure is set out in Restatement of method currently used to estimate PMP and PMF in the UK. The higher of the summer and winter PMFs was compared with the reported peak flow from the flood event.

2.7.4 Initial comparison of rainfall events

Out of the 30 extreme rainfall totals included in the comparison with PMP, 9 were initially found to exceed the estimated PMP. These are in addition to the 5 exceedances reported by Stewart and others (2013). Table 5 lists the 9 events and the subsequent text discusses their validity.

Table 5: Extreme rainfall totals apparently exceeding PMP, and results of further quality assurance checks

Event ref	Date	Location	Duration (hours)	Rainfall depth (mm)	Primary source	Ratio of reported rain to PMP before further checks
124	11 Jul 1959	Hindolveston, Norfolk	0.3	93, reduced to 63.5	Webb and Elsom (2016)	1.13
219	9 Feb 1997	Carno Reservoir, Ebbw Vale, Blaenau, Gwent	96	491.9	GSDR	1.13
239	23 Nov 2003	King's Cliffe, Northamptonshire	96	581.4	GSDR	1.81
269	13 Aug 2007	Portmoak, Kinross-shire	96	711	GSDR	2.32
276	5-8 Sep 2008	Shepshed, Loughborough, Leicestershire	96	525.8	GEAR	1.63
289	17-19 Nov 2009	Seathwaite Fell, near Great Gable, Cumbria	72	565.4	GEAR	1.24
311	23-27 Oct 2014	Sgurr an Fhuarain, near Loch Quoich, Highland	96	564.7	GEAR	1.14
322	5 Dec 2015	Honister Pass, Cumbria	24	341.4	Chiverrell and others, 2019	1.08

Event ref	Date	Location	Duration (hours)	Rainfall depth (mm)	Primary source	Ratio of reported rain to PMP before further checks
323	4-5 Dec 2015	Thirlmere Reservoir, Cumbria	48	405	Barker and others, 2016	1.11

Event 124: Hand and others (2004**)** state a rainfall accumulation of 93 mm. However, many other sources such as Webb and Elsom (2016) mention that 63.5 mm fell in 20 minutes at Hindolveston. The catalogue entry was amended to 63.5mm, which is below the estimated PMP.

Event 219: The Met Office Daily Weather Summary does report rainfall over south Wales for the period in question. However, timeseries data for the event only shows integers. Assuming the integer values represent 0.2 mm tips, the event total is reduced to 94.4 mm. A search of the NRFA for the Ebbw River where the gauge is located, shows high but not extraordinary daily flows during this period. The catchment daily rainfall (CEH-GEAR daily derived) total for the period is 87.7 mm, which is close to the 'corrected' gauge total. Conclusion: the rainfall reported by the gauge is incorrect. The event was not extreme and should be removed from the catalogue.

Event 239: The event was added after expanding the search to the version of GSDR that uses data from hourly measurements. In the sub-hourly version of the data set, the event has been removed by quality control. Conclusion: the rainfall measurement is spurious and should be removed from the catalogue.

Event 269: The time series for the event shows almost uninterrupted rainfall for 96 hours, which seems suspicious. Newcastle University does not have quality control flags from the original rain gauge data, which was provided by SEPA. The Met Office Daily Weather Summaries indicate that the days in question had predominantly westerly airflows with dry interludes, especially in the east. Conclusion: the rainfall measurement is spurious and should be removed from the catalogue.

Event 276: This is a lowland area where orographic effects are expected to be minimal. The rain total is at a grid cell in GEAR which contains a rain gauge, and so should not be an artefact of the interpolation process. The daily data in GEAR show that over 8 days between 1 and 12 September 2008 the rainfall at this cell was very much higher than at other cells a few km away at the locations of other rain gauges. This seems highly unlikely; while a localised convective storm may affect one gauge and not its neighbours, it would not last for a period of 8 days.

At the 10 closest sub-daily gauges in GSDR, the maximum 96-hour accumulation was 71 mm. This casts great doubt on the rainfall accumulation from GEAR. Conclusion: The data for this event in GEAR is probably erroneous, most likely as a result of incorrect data at the closest rain gauge. This event should be provisionally removed from the catalogue. The daily rain gauge data could be examined for any further investigation.

Event 289: The GEAR data set shows similar rainfall accumulations at 3 x 1 km cells around the head of Borrowdale during this period. The closest daily rain gauge is at Seathwaite Farm, in the valley below Seathwaite Fell, where the maximum accumulation over 3 rainfall days was 456 mm (Stewart and others, 2012). This is very close to the PMP. At the 10 closest sub-daily gauges in GSDR, the maximum 72-hour accumulation was 442 mm.

Given the orographic influences expected in this mountainous area, the GEAR data are considered to be consistent with these rain gauge readings. Conclusion: Although there is uncertainty over the exact amount of rain that fell over the high ground, this was probably a genuine exceedance of estimated PMP.

Event 311: The GEAR data set shows high rainfall accumulations over a large area of high ground, during a period of 11 days from 17 to 27 October 2014. The closest daily rain gauge is about 5 km south of the cell showing the highest rainfall, in Glen Dessary, at a much lower elevation. At the grid cell corresponding to the rain gauge, the 4-day accumulation is 283 mm. At the 10 closest sub-daily gauges in GSDR, the maximum 96-hour accumulation is 269 mm. While these are both much lower than the rainfall total in GEAR, this does not necessarily invalidate it. The area is mountainous and orographic influences may give rise to large variations in rainfall over short distances. Conclusion: retain, although with some uncertainty over whether this was a genuine exceedance event.

Event 322: This event is the highest 24-hour total on record in the UK. It has been investigated thoroughly in a number of studies. No reason has been found to doubt the rain gauge measurement at Honister Pass. This PMP exceedance is a good example of the effect of the low-resolution of the isohyetal maps of PMP provided in the FSR. There are just 2 isohyets for 24-hour PMP covering the Lake District, one at 300 mm and one at 350 mm. Honister lies between the two. We have used an automated interpolation technique. Individual analysts may use subjective judgement and so could come up with different estimates of PMP. Conclusion: This was probably a genuine exceedance.

Event 323: This is the same event as above, but the Thirlmere rain gauge is 11 km away to the north-east of Honister Pass, and at a lower elevation. Both rain gauges recorded rainfall in excess of the estimated PMP. It is likely that rainfall over the mountains surrounding Thirlmere Reservoir was higher than recorded at the gauge. The GEAR data set gives an interpolated depth of 504 mm for 2-day rainfall around the summit of Helvellyn, 5 km south-east of Thirlmere. This would be an even larger exceedance of PMP. Conclusion: This was probably a genuine exceedance.

2.7.5 Comparisons of floods with PMF

Table 6 compares the summer and winter PMFs with the reported peak flows for the 15 events chosen for comparison. All 5 of the exceedances from Acreman (1989) remain higher than the estimated PMF. None of the other events was found to exceed the estimated PMF. The closest was the Dearne at Barnsley in June 2007, 22% smaller than the PMF.

There are some differences between the PMF values in Table 6 and those reported by Acreman (1989). There are 2 main reasons for these: the change in the method of estimating snowmelt (only applicable for the winter PMF) and the change in estimating Standard percentage runoff (SPR) from the WRAP[1] maps used in the FSR to the HOST[2] data set used in the FEH.

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[1] Winter rainfall acceptance potential

[2] Hydrology of soil types

Table 6: Results of the 15 floods selected for comparison with PMF

Event ref	Date	Location	Primary source	Quality code	Peak flow (m3/s)	Summer PMF (m3/s)	Winter PMF (m3/s)	Ratio of reported flow to PMF
66	17 Aug 1917	Red-a-ven, Dartmoor	MCA	F5	110	65	87	1.26
107	12 Aug 1948	Birns Water at Stobshiel	MCA	F4	40	32	30	1.25
136	08 Aug 1967	Claughton Beck	MCA	F5	66	33	29	1.98
137	06 Nov 1967	Esk at Sleights	NRFA	F1	945	1348	1296	0.70
139	15 Sep 1968	Eden at Penshurst	NRFA	F1	262	778	587	0.34
139	16 Sep 1968	Darent at Hawley	NRFA	F1	50	461	565	0.09
157	30 Oct 1977	Ettrick Water at Brockhoperig	NRFA	F1	160	442	558	0.29
161	14 Jun 1979	Caldwell Burn, Berryscaur	MCA	F5	189*	63	61	2.99*
169	12 Jul 1982	Ford Brook, Chulmleigh	MCA	F5	68	28	25	2.45

Event ref	Date	Location	Primary source	Quality code	Peak flow (m3/s)	Summer PMF (m3/s)	Winter PMF (m3/s)	Ratio of reported flow to PMF
237	30 Jul 2002	Trout Beck at Moor House	NRFA	F1	45	169	200	0.22
250	19 Jun 2005	Rye at Broadway Foot	NRFA	F1	384	704	677	0.55
266	25 Jun 2007	Dearne at Barnsley	NRFA	F1	383	477	489	0.78
266	25 Jun 2007	Heighington Beck at Heighington	NRFA	F1	5.3	56	81	0.07
277	06 Sep 2008	Derwent at Eddys Bridge	NRFA	F1	137	840	732	0.16
322	05 Dec 2015	Kent at Sedgwick	NRFA	F1	527*	1512	2358	0.22

Notes for Table 6:

- MCA is Acreman (1989), NRFA is National River Flow Archive
- quality codes are defined in Table 3
- * likely to be an overestimate, as discussed in the catalogue

Some of the floods in Table 6 are very much lower than the estimated PMF, the most extreme example being the 2007 flood on the Heighington Beck. Refer to the Discussion section below.

2.7.6 Summary of rainfalls and floods thought to have exceeded PMP or PMF

After checking, only 4 of the rainfall totals in Table 5 could be treated with enough confidence. Others were either not genuine (and have been removed from the final catalogue) or highly uncertain. Two of the 4 measurements were from the same event, Storm Desmond in December 2015.

Table 7 gives a combined list of rainfalls thought to have exceeded PMP. The first 5 entries in Table 7 are from Stewart and others (2013).

Table 7: Final list of extreme rainfalls that exceed estimated PMP, including 5 from Stewart and others (2013)

Date	Location	Duration (hours)	Rainfall depth (mm)	Summer PMP (mm)	Winter PMP (mm)	Ratio of reported rain to PMP
28 Jul 1917	Bruton, Somerset	8	243	238	n/a	1.02
18-19 Aug 1924	Cannington, Somerset	5	225	218	n/a	1.03
19 Jul 1955	Martinstown, Dorset	15	280(1)	278	n/a	1.01
7 Oct 1960	Horncastle, Lincs	3	184	182	n/a	1.01
19 May 1989	Halifax, W. Yorkshire	2	193	162	n/a	1.19
19-22 Nov 2009	Seathwaite Fell, near Great Gable, Cumbria	72	Approx. 565(2)	393	457	1.24
26-29 Oct 2014	Sgurr an Fhuarain, near Loch Quoich, Highland	96	Approx. 565(2)	437	497	1.14
5 Dec 2015	Honister Pass, Cumbria	24	341	291	316	1.08
4-5 Dec 2015	Thirlmere Reservoir, Cumbria	48	405	307	366	1.11

Notes for Table 7:

- (1) Clark (2005a) estimated 350 mm
- (2) from interpolated GEAR data, checked against nearby rain gauge measurements

Table 8 provides the equivalent for floods thought to have exceeded PMF. All 5 entries are events reported by Acreman (1989), although the PMF estimates have been recalculated.

Table 8: Final list of extreme floods that may have exceeded estimated PMF

Event ref	Date	Location	Quality code	Peak flow (m3/s)	Summer PMF (m3/s)	Winter PMF (m3/s)	Ratio of reported flow to PMF
66	17 Aug 1917	Red-a-ven, Dartmoor	F5	110	65	87	1.26
107	12 Aug 1948	Birns Water at Stobshiel	F4	40	32	30	1.25
136	08 Aug 1967	Claughton Beck	F5	66	33	29	1.98
161	14 Jun 1979	Caldwell Burn, Berryscaur	F5	189(1)	63	61	2.99(1)
169	12 Jul 1982	Ford Brook, Chulmleigh	F5	68	28	25	2.45

Note for Table 8:

- (1) this is likely to be an overestimate, as discussed in the catalogue - the peak flow may have been closer to half of the report amount, however, this would still exceed the estimated PMF

2.7.7 Discussion

In the relatively short period from 2006 to 2020, there are 3 rainstorms that appear to have produced depths that exceed the FSR estimate of PMP. All occurred in mountainous areas, over relatively long durations, and in late autumn to early winter. These can be added to the list of 5 earlier exceedances during the 20th century, all of which were shorter-duration storms, mostly occurring in summer conditions and in more lowland areas. It appears from this that the FSR method may be underestimating PMP over a wide range of durations, at least in some parts of the UK. The largest exceedance is by 24%, although this is based on an estimate of rainfall from interpolation. The largest exceedance found at a rain gauge remains 19% at Halifax in 1989.

The storms that affected Cumbria and other areas in 2009 and 2015 gave rise to some rainfall totals greater than PMP. This finding can be viewed in light of recent work that has re-estimated the return period of these rainfalls using a re-calibrated model of rainfall depth-duration-frequency (Vesuviano and others, 2021). The re-estimated return periods include:

- 3-day rainfall at Seathwaite Farm, November 2009: 132 years - the rainfall depth is very close to the estimated PMP
- 24-hour rainfall at Honister Pass, December 2015: 131 years - the rainfall depth exceeds the estimated PMP
- 2-day rainfall at Thirlmere Reservoir, December 2015: 7,000 years - the rainfall depth exceeds the estimated PMP

The first 2 results listed above are particularly concerning. The rainfall frequency analysis indicates that events close to or greater than current estimates of PMP can be expected to occur about once every century on average in these upland locations. This adds impetus to calls to update PMP estimation methods in the UK.

There may be more exceedances of PMP than those identified above, either in the catalogue or in other sources. Only 30 extreme rainfalls from the catalogue were compared with PMP. Although care was taken to choose events that were thought most likely to approach PMP, a more comprehensive comparison might identify more. There are examples in the literature of other events being mentioned as possibly exceeding the estimated PMP. These include the 1768 storm at Bruton, Somerset and an event in August 1770 at Lynmouth, Devon (both events mentioned in Clark, 2003). We recommend that further comparisons are carried out, using an automated method to estimate PMP.

Exceedances of the estimated PMF are harder to find. No new examples have been found; indeed, one of the 6 mentioned by Acreman (1989) has now been discounted. All of the remaining 5 are uncertain estimates of flow made using approximate methods. It is possible that a more in-depth investigation of any of them would lead to downgrading the estimated peak flow to below the PMF.

The highest confidence can probably be put in the magnitude of the 1948 flood at Stobshiel, 25% above the estimated PMF. The catchment area quoted by Acreman (1989) matches that of the dam of Stobshiel Reservoir, which is consistent with Acreman's comment about the flow being estimated by theoretical rating of a hydraulic structure - presumably the dam spillway. Acreman (1989) gives the watercourse as the [East Lothian] River Tyne, but Stobshiel Reservoir is on the Binns Water, a small tributary of the Tyne. It can be possible to make accurate estimates of peak discharges over engineered spillways, although problems can be caused by non-modular flow, bypassing or debris. The peak inflow to the reservoir would have been higher than the peak discharge. The PMF estimate does not allow for reservoir routing, so it is for the inflow to the reservoir. This further increases the likelihood that the flood exceeded the PMF.

Acreman (1989) mentions several possible reasons why floods might exceed current estimates of PMF. These are:

- the observed peak discharges are overestimated
- the peak discharges were artificially increased by surges, for example, caused by collapse of debris dams or embankments - note that more recent research has found that near-vertical rising hydrograph limbs can develop as a response to intense rainfall without any blockage and failure of a structure (Archer and Fowler, 2018)
- the PMF is underestimated

It should not be surprising that few exceedances of the PMF have been found. For a flood to exceed the estimated PMF, not only does the rainfall most likely need to exceed the PMP, but also this needs to occur over a duration and temporal profile likely to cause critical conditions for the catchment, and the antecedent catchment conditions need to be exceptionally severe. There may well have been other exceedances of the PMF within the period covered by the data search that were not recorded by any flow gauge. Any flood large enough to exceed the PMF is likely to cause damage to flow measuring equipment, along with severe channel erosion and bypassing that is likely to make measurement very difficult. Measurement of extreme rainfalls is not as fraught with difficulty.

There is a possibility that other exceedances of PMF are lurking in the catalogue, having avoided being selected in the group of 15 events for comparison. We recommend that further comparisons are carried out, using an automated method for estimating PMF. There are examples in the literature of other events being mentioned as exceeding the estimated PMF, such as a flood in Langtoft, East Yorkshire in 1892 (Clark, 2007).

Some of the floods identified in the catalogue are extreme when compared with QMED - and yet they are a long way below the estimated PMF. Examples in Table 8 are the 1968 flood on the Darent and the 2007 flood on the Heighington Beck. The peak flows are, respectively, 17.8 and 8.4 times QMED. Neither of these was more than 10% of the PMF. Both of these floods occurred on lowland catchments with low annual rainfall and chalk or limestone geology. On such catchments, it appears that the estimated PMF can be 100 or more times larger than the median annual flood. The main factor that contributes to this is the assumpion of frozen ground in estimating the winter PMF, leading to a large increase in percentage run-off on highly permeable catchments. It appears that this assumed switch in behaviour has not occurred during the period of gauged records. However, there are historical accounts of extreme floods on groundwater-dominated catchments being exacerbated by freezing conditions (Environment Agency, 2022). One question to be considered in developing any new method of estimating PMF is whether it is reasonable to combine a PMP storm with near-impermeable conditions on such catchments.

2.7.8 Recommendations for further work

We recommend that rainfalls and peak flows for more events are compared with estimates of PMP and PMF, using an automated procedure to estimate PMP and PMF. These may detect more exceedances.

It may be possible to investigate the handful of apparent PMF exceedances in more depth, reviewing the original flood reports. Sensitivity tests would help indicate the uncertainty in the estimated peak discharges. This line of investigation is recommended as a way of improving confidence in the findings of the PMF comparison.

The evidence is clear that rainfalls have exceeded current estimates of PMP. The case for replacing the FSR estimation method is unlikely to be strengthened by finding more exceedances.

The method for detecting rainfall events was considered acceptable for the needs of this study, but may need revisiting if this event catalogue is to be used for other purposes.

3 Restatement of method currently used to estimate PMP and PMF in the UK

3.1 Purpose and scope

The project specification calls for “a clear step-by-step example of PMP and PMF derivation using existing methods. This should be based on the guidance outlined in Volume 4 of the FEH, and in the ICE (2015) guidance.”

Although a worked example, for the West Lyn at Lynmouth, is already provided in the FEH (Institute of Hydrology (1999), Volume 4, chapter 4), it has one limitation in that it uses the standard 42 mm/day snowmelt rate. While this may be adequate for a coastal catchment like the West Lyn, many reservoirs are in upland areas where melt rates could be higher. For this reason, an upland catchment has been chosen for this worked example, and the melt rate is calculated from a method developed by Hough and Hollis (1997) and recommended in ICE (2015).

This example explains how to estimate the PMF at a reservoir, but the presence of a dam is incidental. The estimate is the PMF inflow for the reservoir; the example does not include flood routing or allow for the reservoir lag effect which would be necessary to estimate a PMF for the dam spillway.

It is not possible to explore all issues relevant to PMF estimation in a single case study. Two issues that do not affect the example catchment are:

1. High permeability. On catchments with very low SPRHOST, there may be a need to consider consistency between the PMF and estimates of other extreme floods such as the 10^5-year return period. The frozen ground allowance applied for the winter PMF can greatly increase the PMF in such cases.

2. Upstream flood storage. It is sometimes appropriate to explicitly represent the routing of the PMF through upstream storage in reservoirs or extensive floodplains.

The example provides references to the FEH, Floods and Reservoir Safety (ICE, 2015) and Hough and Hollis (1997) (H&H). These explain the source of the various equations and procedures that are applied. All references to the FEH are to Volume 4 unless otherwise stated. It is assumed that readers are familiar with the basics of FEH methods, including the definition of catchment descriptors.

3.2 Overview of method

The method can be broadly divided into 2 steps:

1. Estimating the PMP.

2. Estimating the PMF. This step uses the FSR/FEH rainfall-runoff model with a PMP as the design storm and suitably conservative choices for other inputs.

There is some interaction between these steps because the storm duration for the PMP depends on a parameter of the rainfall-runoff model, and so the parameters of that model are estimated before calculating the PMP.

PMF estimates are made separately for the summer and winter seasons, and the higher of these is taken as the overall PMF for design purposes.

3.3 Catchment and data available

Grimwith Reservoir near Grassington in North Yorkshire drains an area of upland moorland, with a catchment area of 25 km^2.

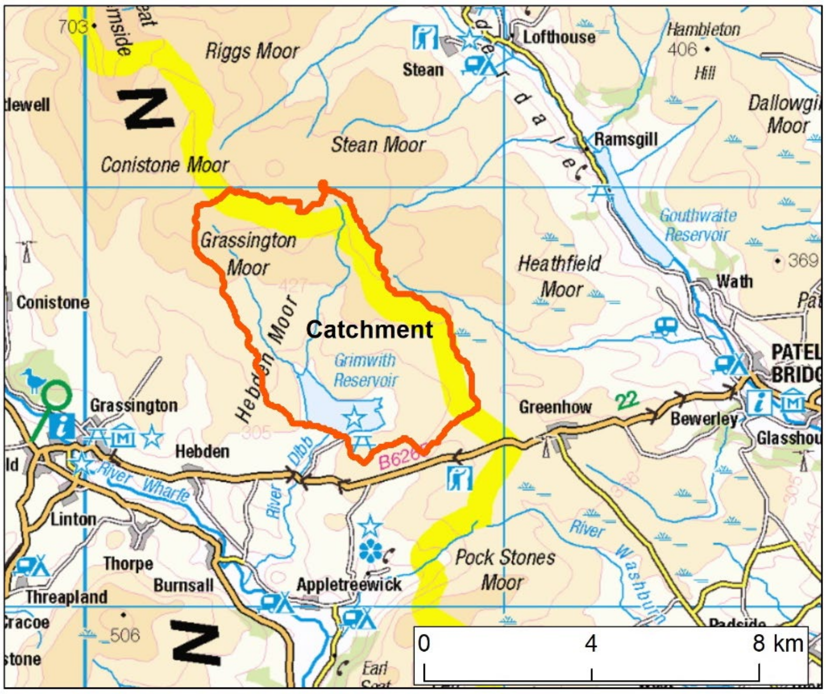


Figure 16: Location and catchment of Grimwith Reservoir. Contains OS data © Crown copyright and database right 2021

Figure 16 is a map of the catchment for Grimwith Reservoir. The dam is at an elevation of 290 m and the catchment extends up to 550 m, with a mean altitude of 400 m. The solid geology in the catchment is largely Millstone Grit, with superficial peat deposits. This example assumes that no local hydrometric data are available for deriving parameters of the rainfall-runoff model. In any real study, efforts should be made to acquire such data and use it in preference to deriving parameters from catchment descriptors.

Relevant catchment descriptors are listed in Table 9 below. These are all as given on the FEH web service. Refer to FEH Volume 5 and the Flood Estimation Guidelines for advice on how to check catchment descriptors and update urban extent where necessary. Checking catchment boundaries is particularly important when estimating the PMF and other extreme floods because of the potential for overspill between catchments, perhaps exacerbated by drainage paths being blocked by landslides. ICE (2015) stipulates site inspections to establish drainage paths during extreme floods. For further discussion of changes in catchment processes during extreme floods, refer to section 4.4.2 Change in processes with event magnitude.

Particular care is needed when the catchment includes soil HOST class 4. This HOST class has an SPR of 2% which has been observed to significantly underestimate run-off rates for some soil types. SPRHOST needs to be adjusted to allow for higher run-off rates from this soil type. Refer to the Flood Estimation Guidelines.

Table 9: Catchment descriptors for Grimwith Reservoir

Catchment descriptor	Value
AREA (km2)	25.5
Annual average rainfall, SAAR (mm)	1358
Mean drainage path length, DPLBAR (km)	3.87
Mean drainage path slope, DPSBAR (m/km)	79.3
Standard percentage run-off from hydrology of soil types data SPRHOST (%)	56.5
Proportion of time soils and wet, PROPWET (-)	0.62
Urban extent, URBEXT1990 (-)	0
Mean altitude, ALTBAR (m)	406
Easting of catchment outlet (m)	406,000
Northing of catchment outlet (m)	464,100
Easting of catchment centroid (m)	405,935
Northing of catchment centroid (m)	466,773

3.4 Rainfall-runoff model parameters

The FSR/FEH rainfall-runoff model has 3 parameters. The first 2 are estimated as follows. The third, baseflow, depends on the catchment wetness index which is estimated at a later stage in the procedure.

3.4.1 Standard percentage runoff (SPR)

SPR is set equal to the value of SPRHOST obtained from the FEH web service.

SPR = SPRHOST = 56.5% (FEH Eqn 2.17)

To estimate the summer PMF, the SPR value is applied without any adjustment.

To estimate the winter PMF, SPR is set to a minimum of 53% to allow for the possibility of frozen ground. SPR already exceeds this, so no adjustment is needed.

3.4.2 Time to peak of the instantaneous unit hydrograph (Tp(0))

Tp(0) is estimated from catchment descriptors as follows.

$Tp(0) = 4.27\ DPSBAR^{-0.35}\ PROPWET^{-0.80}\ DPLBAR^{0.54}\ (1+URBEXT)^{-5.77} = 2.8$ hours (FEH Eqn 2.10)

This is then reduced by one-third to model the PMF:

$Tp(0)_{PMF} = 0.67\ Tp(0) = 1.9$ hours (FEH Eqn 4.1)

The time interval for calculations has been set to ΔT=0.25 hours. The time to peak for a unit hydrograph with time interval 0.25 hours is found from:

$Tp(0.25)_{PMF} = Tp(0)_{PMF} + \Delta T/2 = 2.0$ hours (FEH Eqn 2.4)

A minimum time interval of 0.25 hours is recommended.

3.5 PMP

The design storm duration D is calculated from:

$D = Tp(0.25)_{PMF}\ (1+ SAAR/1000)$ (FEH Eqn 3.1)

$= 4.72$ hours

This needs to be rounded to the nearest odd multiple of ΔT=0.25 hours, so that there is an odd number of time steps in the design storm, giving:

$D = 4.75$ hours

To estimate the PMF for the outflow of Grimwith Reservoir, it would be necessary to extend D to allow for the reservoir lag time. This is explained in FEH Volume 4, section 8.2.1. Here, we are estimating the inflow.

The PMP is estimated from the estimated maximum (EM) rainfall depths over 3 durations (2 hours, 24 hours and 25 days) which are read off maps in FSR Volume 5: EM-2h, EM-24h and EM-25d. The maps are also included, at a much smaller size, in FEH Volume 4, chapter 4. EM-25d is only needed for PMP durations longer than 96 hours.

Extracts from 2 of the maps are shown below in Figure 17 and Figure 18. EM-25d is not required for this case, because the design storm duration is relatively short. It is necessary to interpolate between the rainfall isohyet (contour) lines. This can be done by eye or by digitising the maps and producing a gridded data set. The catchment average rainfall depths are required, although for small catchments such as this, there is no appreciable spatial variation given the coarse resolution of the maps.

Note that the units for the labels are in 10s of mm, so the numbers extracted from the map need to be multiplied by 10.

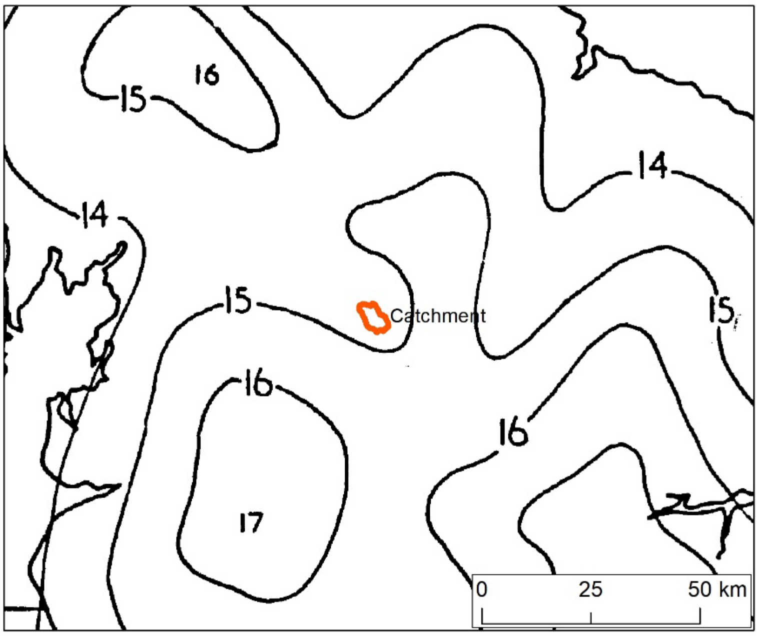


Figure 17: Extract from FSR map of 2-hour estimated maximum precipitation (EM-2h), in units of 10 mm

Figure 17 shows map of rainfall over Grimwith Reservoir catchment, indicating ~150 mm of rainfall fell within 2 hours.

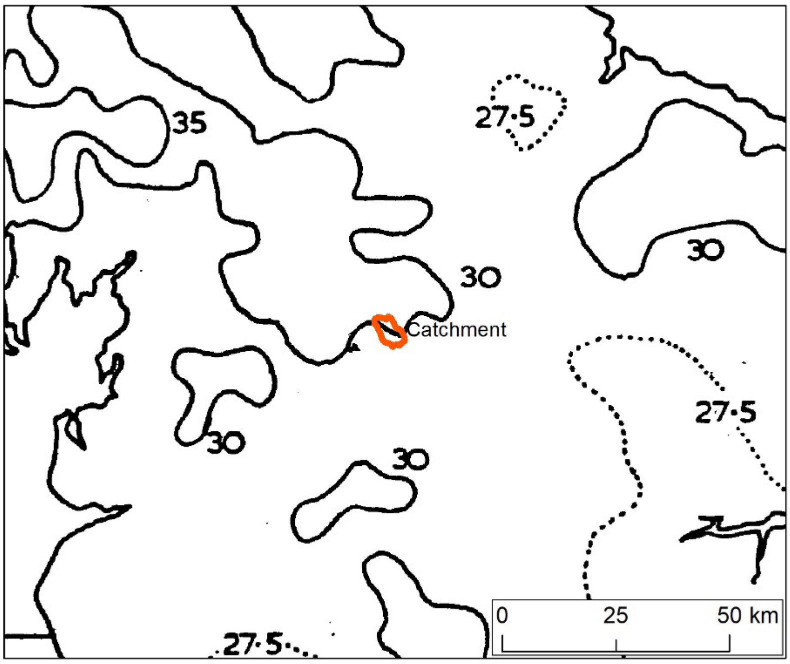


Figure 18: Extract from FSR map of 24-hour estimated maximum precipitation (EM-24h), in units of 10mm

Figure 18 shows map of rainfall over Grimwith Reservoir catchment, indicating ~300 mm of rainfall fell within 24 hours.

For the Grimwith Reservoir catchment, the quantities are:

EM-2h: 149 mm

EM-24h: 300 mm

We need to derive a PMP for a storm duration of D=4.75 hours. To construct the PMP hyetograph and to derive the antecedent rainfall, it is also necessary to calculate PMPs for shorter durations, down to ΔT (0.25 hours) and longer durations, up to 5D (24 hours).

Table 4.1 in FEH Volume 4 provides factors, depending on SAAR, which enable calculation of PMP rainfalls from EM-2h and EM-24h.

Table 4.2 in FEH Volume 4 provides factors that convert the all-year PMP into a winter or summer PMP. They vary with SAAR and rainfall duration. For SAAR up to 1,400 mm, the summer PMP is the same as the all-year PMP over the full range of durations, up to 8 days.

Factors taken from those 2 tables in the FEH are shown in green below.

Table 10: Factors used to calculate PMP for selected durations, and convert from all-year to winter PMP depths

Duration (hours)	0.25	0.5	1	2	24
% of EM-2h	47%	65%	83%	n/a	n/a
All-year PMP (and summer PMP) (mm)	70	97	124	149[a]	300[b]
Winter PMP as % of all-year	50%	57%	63%	69%	79%
Winter PMP (mm)	35	55	78	103	237

Notes for Table 10:

- (a) is the EM-2h, taken from the FSR map as described above
- (b) is the EM-24h, taken from the FSR map as described above

The FEH uses the term EMP (Estimated Maximum Precipitation) for the PMP depths over different durations that are used in the process of deriving the hyetograph. For simplicity, the term PMP is used throughout in this example.

To derive the PMP hyetograph, PMPs are needed for durations of 0.25, 0.75, 1.25 hours and so on up to 4.75 hours. PMPs for durations not shown in Table 10 above are derived by log-linear interpolation. The resulting point rainfalls are converted to catchment rainfalls using an areal reduction factor (ARF). The ARF varies with the rainfall duration, and can be found from Figure 3.1 or Equation 3.1 in FEH Volume 2.

Table 11 sets out the interpolated values of point and catchment PMPs for the summer and winter seasons. The final 2 columns are used in constructing the hyetograph, as explained below. The final row is used for deriving the antecedent rainfall. The design storm depths are given in the penultimate row:

PMP_{summer} = 187.4 mm, PMP_{winter} = 139.0 mm

Table 11: Calculation of seasonal PMPs, point and areal, for the full range of durations required to construct the PMP hyetograph and the antecedent rainfall

Duration (hours)	Point rainfalls (mm) summer PMP	Point rainfalls (mm) winter PMP	ARF	Catchment rainfalls (mm) summer PMP	Catchment rainfalls (mm) winter PMP	Half of the difference between successive durations (mm) summer PMP	Half of the difference between successive durations (mm) winter PMP
0.25	70.0	35.0	0.80	55.8	27.9	No data	No data
0.75	112.5	68.5	0.86	97.2	59.1	20.7	15.6
1.25	131.8	85.9	0.89	116.8	76.2	9.8	8.5
1.75	144.1	98.0	0.90	129.6	88.2	6.4	6.0
2.25	156.2	109.2	0.91	141.8	99.1	6.1	5.5
2.75	168.4	120.0	0.91	154.0	109.7	6.1	5.3
3.25	178.5	129.0	0.92	164.1	118.6	5.1	4.4
3.75	187.2	136.8	0.92	172.9	126.3	4.4	3.8
4.25	194.8	143.5	0.93	180.6	133.0	3.8	3.4
4.75	201.6	149.5	0.93	187.4[(a)]	139.0[(a)]	3.4	3.0
23.75	300	237	0.96	288.2	227.7	50.4[(b)]	44.3[(b)]

Notes for Table 11:

- (a) - these are the PMP totals for the design storm duration (summer and winter)
- (b) - these are the antecedent rainfall totals, used later in the procedure (summer and winter)

The PMP hyetograph is constructed by nesting PMP depths inside each other, starting with the central block in the hyetograph, which contains the 0.25-hour PMP, 55.8 mm for the summer season. The central 0.75-hour block of the storm contains the 0.75-hour PMP, 97.2 mm. Of this, 55.8 mm occurs in the central block and so the remaining 41.4 mm is shared between the 2 outer 0.25-hour periods, with 20.7 mm in each. The quantities for the remaining parts of the hyetograph are shown in the final 2 columns of the table. The resulting catchment PMP hyetographs, for the 2 seasons, are shown in Figure 19. The hyetograph is tabulated in Table 12, which is shown later because it also includes the net rainfall.

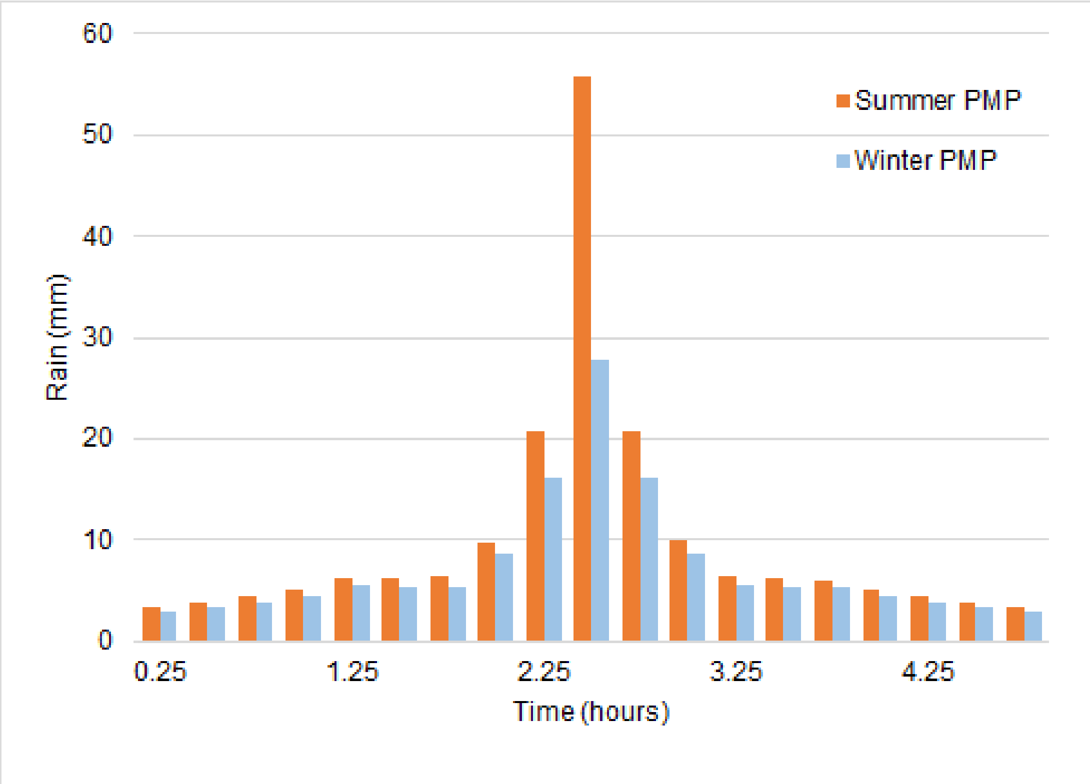


Figure 19: Hyetographs for PMP over the catchment of Grimwith Reservoir.

Figure 19 shows rain on the y-axis from 0 to 60 mm, and time on the x-axis from 0.25 to 4.25 hours. Summer (orange bars) and winter (blue bars) PMP are shown.

Note that the Figure 19 PMP hyetograph has the same intensity-duration relationship no matter what its total duration. This is fundamentally different to the way in which T-year design rainfall hyetographs are constructed in the FEH or ReFH rainfall-runoff methods. One consequence is that there is no point trying to derive a critical storm duration for the PMF by trial and error. Longer durations will not lead to any reduction in the peak rainfall intensity. Because the rainfall volume keeps on increasing with duration, the peak flow or water level is also likely to keep on increasing.

Instead, the storm duration needs to be derived using the formula given earlier. If the site of interest is at the outlet of a reservoir, it is also necessary to take account of reservoir lag times. An alternative, for complex reservoir systems, is to adopt the same critical duration as that of a non-PMF flood (for example, the 10^5-year event) derived by trial and error.

3.6 Antecedent rainfall and catchment wetness index

The catchment wetness index (CWI), which affects the percentage run-off, is calculated from antecedent rainfall and soil moisture deficit.

The antecedent rainfall, PMPa, is also assumed to be a PMP, uniformly distributed over a wetting-up period of length 2D, ending at the start of the design storm. For Grimwith Reservoir, the design storm duration D is 4.75 hours meaning 2D is 9.5 hours (Figure 20).

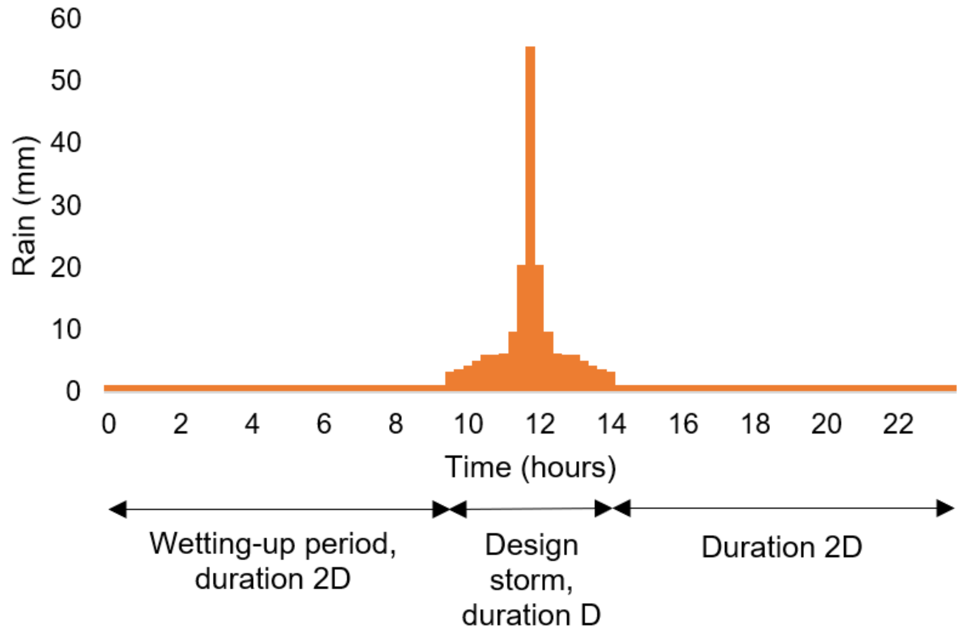


Figure 20: Illustration of antecedent wetting-up period prior to PMP design storm

Figure 20 shows rainfall recorded over a 22-hour period. Rainfall is observed between 9.5 and 14 hours. Low rainfall totals <10 mm between 9.5 and 11 hours, followed by 2 hours of rainfall >10mm between 11 and 13 hours. Peak rainfall totals of 55mm are observed between 11.5 and 12 hours. From here, rainfall totals decline in a symmetrical trend where <10mm is recorded between 12.5 and 14 hours.

PMPa is derived using the same procedure as set out above for the storm hyetograph. It is assumed to form the first 2D hours of a 5D hour-long storm, centred on the peak of the design storm. This means that PMPa is half of the difference between the PMP for duration 5D and the PMP for duration D. Both quantities need to be catchment rainfalls, for the appropriate season.

The calculation of PMPa for this example is included in Table 11. Taking the summer storm as an example, the PMP for duration 5D (23.75 hours) is 288.2 mm and the PMP for the design storm duration D is 187.4 mm. The difference between these is 100.8 mm. This constitutes the rainfall that falls before and after the design storm duration, as illustrated in Figure 20. Half of the rainfall falls before the design storm, during the wetting-up period, and so PMPa for the summer event is half of 100.8 mm = 50.4 mm.

The catchment wetness index is given by the formula in the table below, which sets out the calculations. The derivation of this formula is given in FEH Volume 4 section 4.3.3. It assumes that there is no soil moisture deficit at the start of the antecedent period. This gives:

PMPa from Table 12 (FEH Eqn 4.2). Summer: 50.4 mm. Winter: 44.3 mm.

CWI = 125 + PMPa (0.5D/24) (FEH Eqn 4.4). Summer: 168.9 mm. Winter: 163.6 mm.

CWI_{winter} is subsequently adjusted to allow for snowmelt during the antecedent period.

3.7 Snowmelt

The winter PMF is estimated by combining a 100-year snowmelt rate with the PMP. Snowmelt is added to the antecedent rainfall as well as the main storm event. It is necessary to account for the depth of snow available for melting.

As recommended in ICE (2015) for upland areas, snowmelt is calculated from procedures in Hough and Hollis (1997) (H&H). This paper is freely available from Meteorological Applications - Wiley Online Library.

There are 3 steps: estimating the 5-year return period melt rate in the absence of rainfall; scaling this up to the 100-year melt rate; and increasing the melt to allow for heat energy provided by rain falling on the snow. Some of these steps can be applied separately to the design storm and to the antecedent period.

This part of the worked example is presented in more detail because there is no existing guidance on how to apply the H&H calculations in the context of estimating PMF. There are several ways in which some aspects can be approached, as discussed below. There has been no comprehensive testing of the different approaches and so there is scope for users to apply their judgement. We introduce some additional notation to that given in the FEH, to distinguish between snowmelt calculated with and without the addition of heat energy from rainfall.

The FSR procedure assumes that the 24-hour melt rate is applicable to shorter or longer durations, with the one-hour melt simply being 1/24 of the daily melt. Using Table 4 of H&H, which gives melt rates at 17 UK locations for durations between 3 hours and 6 days, it is possible to obtain melt rates specific to different durations, which can be rather different to those obtained from the above assumption. However, it is not straightforward to apply these within the FSR procedure, because it is necessary to estimate the melt for the antecedent period as well as during the PMP storm. Different estimates would be obtained depending whether the melt rates were calculated separately for the storm and the antecedent period, or for the combined duration of those 2 periods. An added complication is introduced by a discrepancy in the results in H&H, in which melt rates can decrease with duration. This is discussed in the subsequent chapter on review of methods.

Some further investigation and tests would be needed to assess whether and how to apply melt rates derived for different durations, and so the rest of this procedure concentrates on estimating 24-hour melt rates. These are then adjusted to account for incoming heat energy from rainfall, separately for the antecedent and storm periods.

3.7.1 Estimating the 5-year melt rate

Table 7 in H&H provides a geographical regression equation for estimating the 24-hour melt rate with 5-year return period during periods when rain is not falling:

$MELTdry_{24hr,5yr} = 0.083\ ALT + 0.00187\ NORTHING - 3.80$

($R^2 = 0.82$, root mean square error = 7.3 mm)

ALT is the altitude above sea level in m, which for a catchment can be taken as the mean altitude, ALTBAR, an FEH catchment descriptor.

NORTHING is the National Grid northing expressed as a 4-figure reference, in units of 100 m.

For the Grimwith Reservoir catchment, this regression gives $MELTdry_{24hr,5yr}$ = 38.6 mm/day.

An alternative approach would be to avoid using the regression at locations close to the stations for which melt rates are listed in H&H, instead simply obtaining $MELTdry_{24hr,5yr}$ from the tables in the paper.

3.7.2 Estimating the 100-year melt rate: explanation of procedure

To scale the 5-year melt rate up to a 100-year return period, use the parameters of the Gumbel distributions of melt rate, along with the probability of no snow being present, in Table 2 of H&H. The mathematical procedure is given in sections 4.1 and 4.2 of H&H. It is set out below in a way that is clearer to follow (Dan Hollis, pers. comm., 5 December 2017).

Notation

- T Return period (years).
- x Melt (mm) over a given duration, which is 24 hours here.
- y Gumbel reduced variate.
- u,α Location and scale parameters of the Gumbel distribution.
- p Annual probability of no snow cover persisting over the relevant duration.

F(x) Annual probability that the melt is less than x, assuming snow is present. This probability applies only to annual maximum melts from years with enough snow.

F'(x) Annual probability that the melt is less than x, without that assumption. This probability applies to annual maximum melts from all years, including those without enough snow.

Steps

Carry out steps 1 to 4 twice, for T=5 years and T=100 years, to obtain a growth factor which is the ratio of the 100-year melt to the 5-year melt.

1. Convert return period T into F'(x), using F'(x) = 1 - 1/T.

2. Convert F'(x) to F(x) by allowing for the probability that there will be no snow persisting over the relevant duration, using F(x) = (F'(x)-p) / (1-p).

3. Convert the probability F(x) to the Gumbel reduced variate: y = -ln (-ln (F(x))).

4. Using the Gumbel distribution, calculate x from y: x = u + αy.

The parameters u, α and p at the sites of weather observation stations are given in Table 2 and Table 3 of H&H. Table 2 presents results for durations between 3 hours and 6 days at stations with hourly data. Use the 24-hour durations. Table 3 adds more results, just for 24-hour melt, at climate stations in upland areas.

3.7.3 Application to Grimwith example

Table 3 of H&H includes a station at Malham Tarn, which is 17 km from Grimwith Reservoir and at an elevation of 380 m, similar to the mean altitude of the Grimwith Reservoir catchment.

The parameters for Malham Tarn are:

u = 24.34, α = 15.53, p = 0.0

Steps 1 to 4 above give the following results:

1. F'(x) = 0.80 (T=5 years) and 0.99 (T=100 years).

2. F(x) = 0.80 (T=5 years) and 0.99 (T=100 years).

3. y = 1.50 (T=5 years) and 4.60 (T=100 years).

4. x = 47.6mm (T=5 years) and 95.8mm (T=100 years).

The results at step 4 give a growth factor of 2.01 for the 100-year melt divided by the 5-year melt at Malham Tarn. At Grimwith, assuming the same growth factor applies, we obtain:

$MELTdry_{24hr,100yr}$ = 2.01 x 38.6 = 77.6 mm.

Scaling this down to the design storm duration of 4.75 hours gives:

$MELTdry_{4.75hr,100yr}$ = 77.6 x 4.75/24 = 15.3 mm.

Scaling it to the duration of the antecedent period we find:

$MELTdrya_{9.5hr,100yr}$ = 77.6 x 9.5/24 = 30.7 mm.

3.7.4 Allowing for heat energy from rainfall

Finally, the melt needs to be increased to allow for the heat energy added to the snowpack by incoming rainfall. H&H section 2 suggests allowing:

0.0125 mm (of melt)/mm (of rain)/°C.

It is necessary to decide on a suitable temperature for the rainfall. This can be set using local judgement and experience. A suggested conservative value is to assume that, during the passage of a warm front in winter, the temperature might reach 10°C. This is consistent with a finding reported in the FSR (NERC, 1975) that the 100-year return period temperature at times when snow is lying was 8.6°C.

Using this in combination with the winter PMP rainfall of 139 mm, we obtain an additional:

17.4 mm of melt.

Therefore, the total melt during the design storm duration is:

$MELTwet_{4.75hr,100yr}$ = 15.3 + 17.4 = 32.7 mm.

For the antecedent period the rainfall, PMPa, is 44.3 mm, and so the additional melt during that period due to energy from rainfall is 5.5 mm.

Therefore, the total melt during the antecedent period is:

$MELTweta_{9.5hr,100yr}$ = 30.7 + 5.5 = 36.2 mm.

3.7.5 Allowing for snow depth

This melt rate does not allow for any limitation imposed by the depth of snow available for melting. There is a map of 100-year snow depth, expressed as water equivalent, in Figure 4.7 of FEH Volume 4. For the Yorkshire Dales, the depth is a little over 200 mm. This is more than the total amount of melt estimated for the antecedent period and design storm combined, so the melt is not limited by snow depth.

If there is not enough depth of snow to sustain the melt rate, the procedure to follow is:

1. First, calculate the snowmelt during the design storm duration.

2. Apply this melt during the entire storm duration or, if there is not enough snow depth, centred on the most intense part of the storm.

3. If there is any snow still available for melting, add this to the antecedent precipitation.

3.7.6 Comparison with uniform melt rate in FSR

The FSR suggests a melt rate of 42 mm/day, that is, 1.75 mm/hour. The melt rates derived above are very much higher, equivalent to 6.9 mm/hour during the design storm duration and 3.8 mm/hour during the antecedent rainfall.

3.7.7 Effect of snowmelt on the total event precipitation and CWI

The effect of adding snowmelt, in the winter season PMF, is to increase the water input to the catchment:

- from $PMPa_{winter}$ = 44 mm to $PMPa'_{winter}$ = 80 mm during the antecedent period
- from PMP_{winter} = 139 mm to PMP'_{winter} = 172 mm during the design storm

The CWI is adjusted for the snowmelt contribution using:

$CWI'_{winter} = CWI_{winter} + MELTweta_{9.5hr,100yr}\ (0.5^{D/24})$ (FEH Eqn 4.11)

$= 164 + 36\ (0.5^{4.75/24})$

$= 195$ mm

Note that this adjustment is done differently if there is not enough depth of snow to sustain melting through the whole antecedent period. In that case, use FEH Eqn 4.9 and 4.10.

3.8 PMF

3.8.1 Percentage run-off

PR is calculated in the usual way for the FSR/FEH rainfall run-off method:

$PR_{rural} = SPR + DPR_{CWI} + DPR_{RAIN}$ (FEH Eqn 2.13)

where DPR_{CWI} and DPR_{RAIN} are the dynamic components of PR due to prior catchment wetness and event rainfall (including snowmelt). Their calculation for the 2 seasons is set out below.

SPR = 56.5%

$DPR_{CWI} = 0.25\ (CWI' - 125)$ (FEH Eqn 2.14). Summer: 11.0. Winter: 17.5.

$DPR_{RAIN} = 0.45\ (PMP' - 40)^{0.7}$ (FEH Eqn 2.15). Summer: 14.8. Winter: 13.7.

$PR_{rural} = SPR + DPR_{CWI} + DPR_{RAIN}$. Summer: 82.3%. Winter: 87.7%.

The catchment is rural so there is no need to adjust PR_{rural} for urbanisation. Even if the catchment were urbanised, an adjustment would not be applied in this case because PR_{rural} exceeds 70%, which is the assumed run-off from urban areas. This will not always be the case on more permeable catchments. The urban adjustment to calculate the overall PR is carried out as follows:

$PR = PR_{rural} (1.0 – 0.615\ URBEXT_{1990}) + 70\ (0.615\ URBEXT_{1990})$ (FEH Eqn 2.12)

3.8.2 Baseflow

Baseflow (BF) is calculated using the formula below (FEH Eqn 2.19):

$BF = [33\ (CWI'-125) + 3.0\ SAAR + 5.5]\ 10^{-5}\ AREA$. Summer: 1.4 m^3/s. Winter: 1.8 m^3/s.

3.8.3 Net rainfall hyetograph

The net rainfall hyetograph is simply calculated by multiplying the total rainfall hyetograph (with the snowmelt added in the winter) by PR at each time step, as set out in Table 12. A visual representation of the resulting net rainfall hyetographs, for the 2 seasons, are shown in Figure 21.

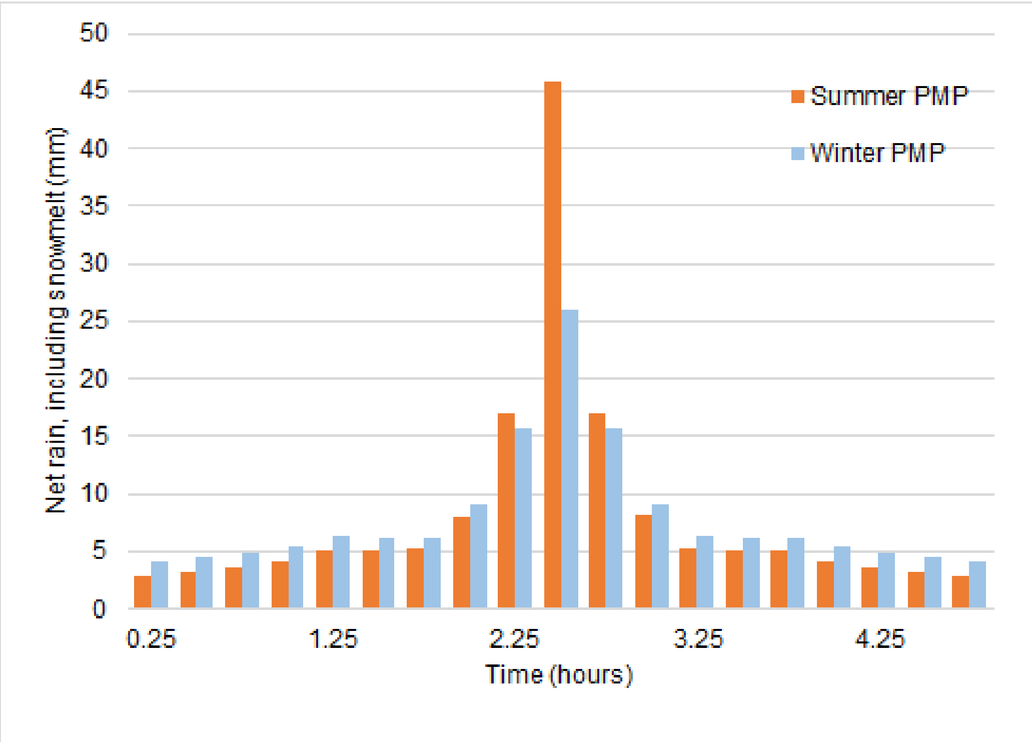


Figure 21: Hyetographs for net rainfall and snowmelt over the catchment of Grimwith Reservoir

Figure 21 shows hyetographs of net rainfall including snowmelt, during summer (orange bars) and winter (blue bars) PMP predictions - the data can be found in Table 12.

Table 12: Calculation of PMP hyetograph: total rainfall and net rainfall

Time since start of storm (hours)	Total rain summer PMP precipitation depth (mm)	Total rain winter PMP precipitation depth (mm)	Total rain + snowmelt winter PMP precipitation depth (mm)	Net rain summer PMP precipitation depth (mm)	Net rain + snowmelt winter PMP precipitation depth (mm)
0.25	3.4	3.0	4.7	2.8	4.1
0.5	3.8	3.4	5.1	3.2	4.5
0.75	4.4	3.8	5.6	3.6	4.9
1	5.1	4.4	6.2	4.2	5.4
1.25	6.1	5.6	7.3	5.0	6.4
1.5	6.1	5.3	7.1	5.0	6.2
1.75	6.4	5.3	7.0	5.3	6.2
2	9.8	8.6	10.3	8.1	9.1
2.25	20.7	16.1	17.8	17.0	15.6
2.5	55.8	27.9	29.6	45.9	26.0
2.75	20.7	16.1	17.8	17.0	15.6
3	9.8	8.6	10.3	8.1	9.1
3.25	6.4	5.6	7.3	5.3	6.4
3.5	6.1	5.3	7.1	5.0	6.2
3.75	6.1	5.3	7.0	5.0	6.2
4	5.1	4.4	6.2	4.2	5.4
4.25	4.4	3.8	5.6	3.6	4.9

Time since start of storm (hours)	Total rain summer PMP precipitation depth (mm)	Total rain winter PMP precipitation depth (mm)	Total rain + snowmelt winter PMP precipitation depth (mm)	Net rain summer PMP precipitation depth (mm)	Net rain + snowmelt winter PMP precipitation depth (mm)
4.5	3.8	3.4	5.1	3.2	4.5
4.75	3.4	3.0	4.7	2.8	4.1
Totals	187.4	139.0	171.7	154.3	150.6

3.8.4 Rapid run-off hydrograph

This is derived by convolution, running the net rainfall hyetograph through the unit hydrograph. The details of the calculations are not given here; the process is explained in section 2.2.1 of FEH Volume 4.

The resulting hydrographs are shown in Figure 22, after the addition of baseflow. They were calculated using the ISIS software (which is no longer available for sale).

3.8.5 Total run-off hydrograph

Baseflow is added to the rapid run-off hydrograph at a constant rate to give the total run-off hydrograph. The plot below shows the PMF hydrographs for the summer and winter seasons.

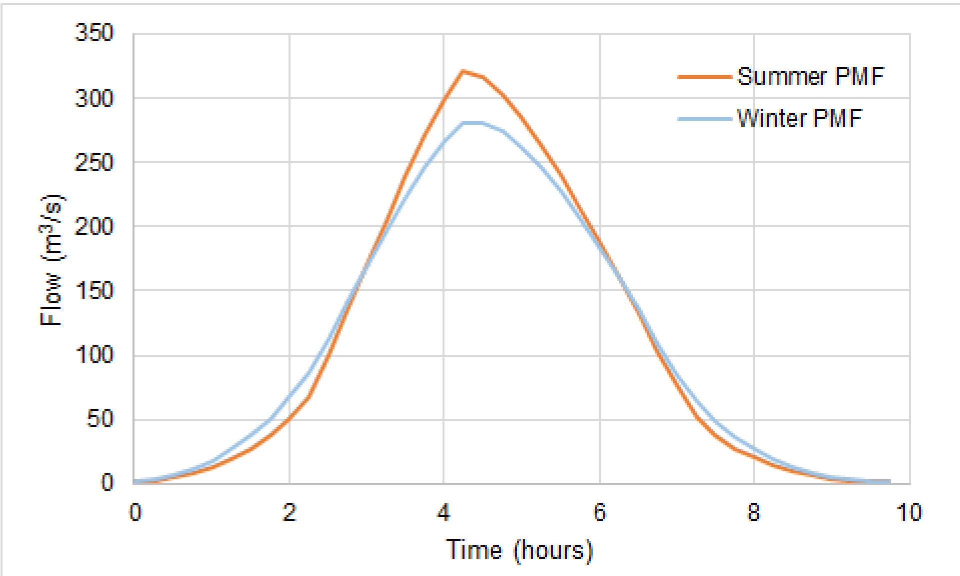


Figure 22: Hydrographs for PMF inflow to Grimwith Reservoir

Figure 22 shows the summer (orange line) and winter (blue line) PMFs are similar. The summer event has a slightly higher peak flow. The volumes of the summer and winter hydrographs are closely similar. The differences in the shapes of the hydrographs are largely due to the differences in the hyetograph shapes, which are controlled by the relationship between PMP depth and rainfall duration.

Larger differences between summer and winter PMFs are seen on some catchment types, for instance those where snowmelt is lower or where soils are highly permeable and so the allowance for frozen ground leads to a large increase in SPR.

The main reason why the summer PMF is higher in this case is that the summer PMP is 34% higher over the design storm duration and also more intense. The addition of snowmelt to the winter event, and the higher percentage run-off in the winter, are not enough to overcome this difference.

Because the summer PMF gives a higher peak flow, and slightly higher volume, it is taken as the overall PMF, with a peak flow of 320 m^3/s.

3.9 Software

It is very rare for practitioners to implement all the above steps by hand. They can be coded up in a spreadsheet or in programming languages such as R or VBA. There are also commercial software packages that can implement most aspects, although not the snowmelt calculation using the H&H procedure. These include Flood Modeller (www.floodmodeller.com).

As part of this project, a spreadsheet tool has been developed to help practitioners implement the above method.

4 Review of methods for estimating PMP and PMF

4.1 Introduction

4.1.1 Purpose and scope of review

This chapter reviews research and practice in estimating PMF, including the PMP.

Most references describe estimating PMF by rainfall-runoff modelling using the PMP as an input; a few also mention the use of data on historical or pre-historical (palaeo) flood deposits.

The review is not intended to cover policy issues, such as the types of dams for which PMF is adopted as a design standard or whether to prefer a standards-based or a risk-based approach to dam safety. However, the latter is touched on by including a review of methods for assigning a return period to the PMF and some pointers to methods of extending flood frequency curves up to very long return periods without relying on the PMF. Also excluded are methods of reservoir routing and other influences on peak water levels at dams such as wind and waves.

The review covers a range of practitioner guidance and research into both standard and novel approaches to estimating PMP and PMF. Literature was sought out from a combination of prior knowledge of project team and project board members, requests to researchers or practitioners working in other countries, academic search engines and cross-references. The review does not claim to be systematic or to achieve complete coverage of the topic. The project scope calls for inclusion of scientific and grey literature from the UK, the United States, Australia, France and Norway as a minimum. All these countries and several others have been included.

The findings of the review have been drawn together into a simple conceptual model of the processes that influence the PMF, which is explained in the next chapter, Conceptual model of PMF formation. The subsequent chapter draws on the findings of this review and the conceptual model to assess the adequacy of current UK methods. The report then goes on to make recommendations for their improvement.

4.1.2 Structure of this chapter

This chapter includes:

- issues common to estimating both PMP and PMF: definitions, probability of occurrence, uncertainty and effects of climate change
- methods for estimating PMP depths and storm profiles

- rainfall-runoff models for estimating PMF, including a discussion of changes in processes with event magnitude, also selection of storm durations and antecedent conditions
- other ingredients of the PMF estimation process: snowmelt and frozen ground
- an alternative approach to estimating PMF, using palaeoflood data
- validity of current UK methods in light of the review
- case studies to compare the results of alternative methods

4.2 Definition, probability, uncertainty of PMP and PMF and effects of climate change

4.2.1 Meaning of standards-based and risk-based

There are many mentions of a risk-based approach to reservoir safety management, as distinct from a standards-based approach. The essential difference between these is explained here.

Standards-based

This means a pass/fail approach. If the dam cannot pass the mandated design flood, its structure or its management needs to be upgraded. This approach is less subjective and provides confidence to regulators and insurers, but it might lead to over-investment in comparison to the losses being mitigated against. A standard-based approach usually involves deterministic modelling.

Risk-based

These approaches take a more nuanced view of the overall risk profile, balancing the likelihood and consequences of a breach against the costs required, for example, to upgrade a spillway. A typical aim is to reduce the probability of dam failure to as low as reasonably practicable. A risk-based approach can be more advantageous to the owner or investor because it considers all of the risks to dam safety in a holistic manner. Application of a risk-based approach requires some greater degree of professional judgement in assessing probabilities and consequences and 'grey areas' such as warning times and the value of losses. This generally requires a modelling method that can associate flood hazard with a probability.

Even so-called standards-based approaches incorporate an element of risk consideration. For example, since 1978, the UK system has been to divide reservoirs into 4 categories depending on the downstream consequences of a breach. The current edition of Floods and Reservoir Safety (ICE, 2015) retains a standards-based approach, but when an existing reservoir fails to meet the standard, the guide recommends that a risk-based assessment is carried out to help decide whether an upgrade is needed. New reservoirs are recommended for assessment using both approaches. In practice, some are likely to continue using only the standards-based approach.

An independent review of UK reservoir safety commissioned in the aftermath of the Toddbrook Reservoir incident in 2019 recommended that, in future, the assurance of reservoir safety in England should be managed on the basis of risk (Balmforth, 2021).

The methodological requirements for supporting a risk-based approach in a UK context are discussed on page 143.

4.2.2 Concept of a probable maximum

There is general agreement on what is meant by PMP and PMF, with some variation in the wording of their definitions, as discussed below. This variation is not substantial enough to cause any difficulty with including literature on methods of estimating PMP and PMF from different countries and sectors.

However, some authors question the very concept of PMF. Sellars (1991), quoted in Alberta Transportation (2004), states that “the probable maximum flood concept has been criticized by eminent hydrologists on the basis that it violates scientific principles, and has been questioned from a philosophical viewpoint particularly with regard to the implications of a no-risk criterion.”

New Zealand guidelines on the PMF (McKerchar, 2010) point out that the validity of the PMP/PMF concepts has been debated vigorously since the 1950s. They quote Benson (1973) who regarded PMF as a flawed concept “... because it provides a solution that removes responsibility for making important decisions as to degree of risk or protection.” The same guidelines also state that there has been a history of PMF estimates increasing as improved meteorological understanding has emerged and as more observations of extremes have accumulated.

Other authors question the usefulness of the probable maximum concept, such as Brown and Root (2002): “In principle the concept of a ‘maximum physically possible’ value is attractive, but there remains considerable uncertainty over:

- how it can be integrated with the probability distribution for T year events
- how the concept of confidence limits can be integrated
- how this estimate may change over a few decades (a relatively short period in the life of a dam)”

Likewise, FEMA (2013) notes that “some engineers, owners and state regulators supported the PMF standard, while others felt that although the PMF was easily calculated, it was not risk-based and ultimately diverted critical resources away from other potential failure modes that could be more likely to cause dam failure and life loss.” In general, the USA is moving away from the deterministic concept of PMF towards a risk-based analysis of all aspects of dam safety, including flood hazards (USBR, 2013; FERC, 2014).

Nathan and others (2011) summarise the Australian system in which, rather like the UK, PMF is considered alongside a risk-based system for dam safety: “Under the ANCOLD deterministic fallback provisions, a detailed risk assessment can be avoided if it can be shown that a dam… can safely pass the PMF. In addition, the PMF may still be a useful upper limit if it is found that risk reductions beyond the acceptable level can be justified on the basis of small incremental costs under the ALARP principle."

Some of the criticisms of the concept of PMF do not appear to address the issue of how otherwise to estimate floods for very low exceedance probabilities. McKerchar (2010) provides a justification for continued use of PMF: its hydrometeorological basis complements the extrapolation of extreme value analysis which tends to form the foundation of flood frequency methods.

4.2.3 Definition of PMP

Definitions from the literature include the following:

- WMO (2009), introduction: "the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends"
- WMO (2009) main text: "the theoretical maximum precipitation for a given duration under modern meteorological conditions"
- WMO (1986) earlier version of above, as quoted in the Flood Estimation Handbook (FEH: Houghton-Carr, 1999): "theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year (with no allowance for long-term climatic trends)"
- ICOLD (2015): "the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year"
- ICE (2015): "the (theoretical) greatest depth of precipitation for a given duration that is meteorologically possible for a given basin at a particular time of year - includes rain, sleet, snow and hail as it occurs, but not snow cover left from previous storms"

There are few substantial differences in these definitions. Debating whether the PMP is physically or meteorologically possible seems to be splitting hairs.

Some definitions focus more on the area of the storm and others on the area of a watershed, which is more relevant for estimating PMP for the purposes of PMF.

The phrase "With no allowance for long-term climatic trends" is not all that clear. It does not preclude the possibility of such trends occurring and affecting the PMP. If they do, a PMP needs to be associated with a particular point in time, or an epoch during which the climate can be regarded as approximately stationary. The alternative phrasing used in some definitions, "under modern [or perhaps current] meteorological conditions" is more helpful, although for the design of dams there will also be a need to consider future conditions.

We propose this working definition of the present day PMP: “The greatest depth of precipitation for a given duration that is meteorologically possible under contemporary climatic conditions for a catchment at a particular time of year.”

4.2.4 Definition of PMF

Definitions include the following:

- WMO (2009): “the theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed. Such a flood could plausibly occur in a locality at a particular time of year under current meteorological conditions”
- ICOLD (2015): “the largest flood that may occur at a given point on a drainage area from the most severe combination of critical meteorological and hydrological conditions reasonably possible on a particular watershed”
- USACE (1975), quoted in FEH: “the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in a region”
- USBR (1989): “the maximum runoff condition resulting from the most severe combination of hydrologic and meteorologic conditions that are considered reasonably possible for the drainage basin under study”
- ICE (2015): “the flood hydrograph resulting from PMP and, where applicable, snowmelt, coupled with the worst flood-producing catchment conditions that can be realistically expected in the prevailing meteorological conditions”
- ARR: Ball and others (2019): “the limiting value of flood that could reasonably be expected to occur”

We propose this working definition of the present day PMF: “The greatest fluvial discharge that is realistically possible under contemporary climatic conditions for a catchment.”

This is more consistent with the PMP definition in that both refer to the greatest value of a measurable parameter (precipitation depth and river discharge). ‘Largest flood’ is less precise than ‘greatest fluvial discharge’ and could be taken as referring to depth or extent of water rather than discharge; also, it does not specify that the flood is from a river. It is important to specify the location in the river system where the PMF is being evaluated. For a reservoir, the flood that gives the largest outflow over the spillway(s) will generally not be the same as the flood that gives the highest peak inflow. For some types of spillway, the duration of the outflow over the spillway may be an important factor in design, but the PMF is not normally defined in terms of a maximum duration.

Some other definitions add a mention of the most severe combination of critical meteorological and hydrological conditions. This could perhaps be added as a helpful illustration of the definition, but it seems a tautology because the definition already includes ‘largest’ or ‘greatest’.

The above definition is compatible with all the others listed above. The ICE (2015) definition is the only one of the above to mention the PMP. Although it is common to estimate PMF from PMP, it is worth acknowledging that there are other approaches, such as using evidence from recorded floods and sedimentary deposits.

4.2.5 Seasonality

Time of year is mentioned in PMP definitions but not in most PMF definitions. This is because for design purposes, dams and other structures need to be able to safely pass a PMF irrespective of the season in which it occurs, whereas the PMP needs to be associated with a particular season so that it can be combined with seasonally appropriate catchment conditions to estimate the PMF.

4.2.6 Meaning of ‘probable’

We interpret ‘probable’ as referring to the fact that PMP and PMF are estimates with uncertainty. An alternative approach might be to rename the concepts as the maximum precipitation and maximum flood, and then estimates of those quantities could be termed the EMP and EMF. The Flood Studies Report used ‘estimated maximum’ rather than ‘probable maximum’ for rainfalls. However, ‘probable maximum’ is now widely used.

4.2.7 Return period of PMP or PMF

4.2.7.1 Background

The requirement for cost-benefit analysis, as part of a risk-based framework for dam safety, leads to a requirement to associate a probability, or return period, with the PMF. This aspect has been reviewed in some detail in the light of concerns expressed by some dam engineers about continued reliance on PMF as a standard for designing and assessing dams. For a broader discussion on this topic, refer to section 5.3 The wider context: flood estimation for risk-based reservoir safety management.

Debate over the association of the return period with the PMF or PMP has a long history. The Flood Studies Report (FSR) (NERC, 1975) noted that the concept “has attracted much controversy in the past”, with opinion at that time being divided between those who can visualise an upper limit to flow rates which can be estimated on physical grounds and those who prefer to retain statistical terminology and refer to an exceedance probability approaching zero.

Although strictly speaking the definition of PMP implies a zero probability of exceedance and so an infinite return period, we only need to tweak the definition of return period to the mean interval between occasions when a rainfall depth is equalled or exceeded and we could in theory end up with a finite return period associated with the PMP.

PMFs should be expected to occur less often than PMPs; perhaps very much less often. This is because for a PMF to occur, not only must a PMP occur but also the other contributory factors (storm duration, catchment wetness, snow and frozen ground, if relevant) must be at their worst. If the rainfall is less than the maximum, then the ensuing flood is not the PMF. This implies that PMF might have a return period much longer than that of PMP. This point is made by Brown and Root (2002) among others.

4.2.7.2 UK methodology

In current UK practice for risk assessment, the PMF is associated with a provisional return period of 4×10^5 years (ICE, 2015), equivalent to an annual probability of 2.5×10^{-6}. This originates from an analysis described in Bowles and others (2013) (Environment Agency Guide to Risk Assessment for Reservoir Safety Management). The return period was obtained from extrapolating a frequency curve fitted to points such as the 1,000-year and 10^5-year floods expressed as fractions of the PMF. These fractions were taken from the 'rapid method' for estimating reservoir flood inflows, included in the ICE Floods and Reservoir Safety guide (ICE, 2015). Their source dates back to the first edition of the same guide, published in 1978. The rapid method was intended only for preliminary screening, developed at a time when software was not widely available. The 1,000-year flood is taken as 0.3 PMF and the 10^4-year flood as 0.5 PMF.

Therefore, the estimate of 4×10^5 years relies on an extremely crude analysis. In reality, the return period of the PMF estimated using the current procedure probably varies between catchments and seasons (Archer, 1984). Some more convincing approaches to estimating return periods in the context of UK methods are described in the 3 references mentioned below.

Cluckie and Pessoa (1990) discuss several approaches to associate a return period with the PMF. The authors claim that these methods assume that the return period of PMP closely matches that of PMF in areas where floods are not caused by snow. The basis of this claim is not entirely clear.

Houghton-Carr (1999) (FEH Volume 4) suggests 2 approaches to assigning a return period to the PMF:

- methodology-based
- geometry-based

The methodology-based method gives a return period of 10^6 years on catchments up to 100 km^2, longer on bigger catchments or if the snowmelt rate is increased. The implication that PMF might be approached more often on small catchments makes intuitive sense, visualising a small catchment entirely covered by an exceptionally intense rain cell, although catchment size is allowed for in calculating PMF via the areal reduction factor.

The geometry-based method gives a return period of 10^6 to 10^9 years depending on the ratios of PMF, Q1000 and Q100. This method is from an earlier edition of Australian Rainfall and Runoff (ARR); refer to the review comments on the current ARR below.

It is suggested that the lower of the return periods from these 2 methods is adopted. The FEH also gives a method for linking a flood frequency curve to the PMF.

Stewart and others (2013), Appendix M, mention 2 approaches to estimating return period of the PMP: rainfall frequency analysis (FEH99, FEH 2013) and the stochastic storm transposition (SST) method, the latter applied in conjunction with the storm model approach for conceptualising major thunderstorms. This work was separately published by Collier and others (2011). The analysis concludes that the return period of rainfall around 10 hours duration approaching PMP in England and Wales is about 10^4 years at a point, rising to 2×10^5 years for rainfall over a catchment of 200 km^2. These results are highly sensitive to a rather large number of assumptions that are made in the analysis. The approach would result in a return period of infinity if applied to the PMP itself.

Both of the approaches presented by Stewart and others (2013) are applied operationally in the USA. For example, Applied Weather Associates (2020) estimated the return period of PMP estimates for dams in 5 catchments in New York State, finding that rainfall frequency analysis and stochastic storm transposition gave consistent results. Return periods were in the range 10^5 to 10^8 years, with most estimates being 10^6 to 10^7 years, for durations of 6 hours and 24 hours.

4.2.7.3 Australian approaches

The most in-depth literature on PMF and PMP return periods (expressed in terms of annual exceedance probabilities (AEP)) appears to originate from Australia. Relevant references are summarised below.

Nathan and others (2001) express the difficulties: “While it is possible to estimate an upper limiting value of flood magnitude, it is not possible to assign an AEP to this event. Conservatively estimated (reasonably possible) values of the factors involved in the transformation of the PMP to the PMF introduce a shift in probability but, because the phrase ‘reasonably possible’ is a qualitative description of probability, the AEP of the resulting flood defies quantification.” The paper acknowledges this as a limitation to the acceptance of risk analysis for dam safety. As an alternative, it introduces the concept of the PMP Design Flood, which is the flood derived from the PMP under ‘AEP-neutral’ assumptions, that aim to ensure that the AEP of the flood is the same as the rainfall. This concept is retained in the current version of ARR.

Nathan and Weinmann (2004) recommend looking at the shift in AEP between PMP and PMF, but caution over attempting to estimate the absolute AEP of the PMF.

Nathan and others (2016) make the point that while the definition of PMP infers a physical upper limit with a zero probability of exceedance, in practice such estimates are based on a set of simplifying assumptions. It is, therefore, useful to differentiate between the concept of a theoretical PMP and its ‘’operational estimate’. Therefore, while the theoretical definition of the PMP implies an event that cannot be exceeded, there is a small, but finite probability that the operational estimate may be. As well as SST, the paper also applies a method termed SSR (stochastic storm regression) as an alternative way of estimating the return period of PMP. The 2 methods give similar results.

The current edition of ARR (Ball and others, 2019) continues along these lines. PMF cannot be readily assigned an AEP, but the PMP Design Flood can. ANCOLD guidelines for dam safety specify return periods up to 10^7 years rather than PMF. There is a useful review on estimating the AEP of PMP, including definition of confidence limits. The AEP varies only with catchment area.

4.2.7.4 Other international literature

Other literature relevant to the return period of PMP and PMF includes the 2 references below.

WMO (2020): “PMP and PMF events are considered to be at least two degrees of magnitude greater (10^4–10^6) than those events that may be considered as extreme events, as estimated by statistical methods…. As the probability function extends to low levels of probability, magnitude becomes asymptotic to the probability axis. In this way, PMP cannot be considered as having a specific return period, which can be related to results from an extreme probability analysis of an annual maximum dataset.”

Alberta Transportation (2004): "The PMF does not have an assigned probability, nor is it intended to be a maximum possible value. If every separate factor involved in its computation were truly maximized, PMF values would often be considerably larger than they are".

This comment may be referring, in part, to the need to account for interactions between the factors that influence PMF, avoiding physically unrealistic combinations of inputs.

4.2.8 Effects of climate change

4.2.8.1 Introduction

The suggested working definitions given above allow for the possibility of PMP and PMF changing over time. Faulkner and Benn (2019) provide a recent review of research and practice related to the impact of climate change on PMP and PMF. This section draws on their findings, as well as additional literature.

Current UK guidance on flood estimation for reservoir safety (ICE, 2015) avoids giving a definitive statement on whether and how to allow for the potential effects of climate change. It refers to change factors for extreme rainfall and river flood flows published by the Environment Agency, while noting that ‘extreme’ in the context of fluvial flooding refers to much more frequent events than those often considered for reservoir safety.

A similar picture was found in overseas guidance, with no specific advice offered on climate change impacts on the PMF in guidance from the WMO (2020), the USA (FEMA, 2013), Canada (Alberta Transportation, 2004), Australia (Ball and others, 2019), New Zealand (McKerchar, 2010) or Norway (NVE, 2011). Several of these documents mention that climate change is expected to have an impact, but none attempt to quantify that impact.

The picture may change in the future as a result of recent or current research initiatives, some of which are mentioned in the sections below, which cover first the impacts of climate change on PMP and then other ways in which climate change may affect PMF.

Climate change can no longer be regarded as purely a future phenomenon. It is increasingly recognised that the period spanned by meteorological and hydrological observations may have been subject to trends influenced by the changing climate. Non-stationary methods are widespread in academic literature on statistical estimation of rainfall and flood frequencies, and are starting to be applied by practitioners, including in the UK. Non-stationarity should be a relevant consideration in estimating PMP using methods that may incorporate data from storms that occurred several decades ago.

Balmforth (2021) made a specific recommendation on the topic of climate change and non-stationarity, directed at the present project: “The current research project commissioned by the Environment Agency into PMP and PMF should allow for the non-stationarity of climate. It should give guidance on estimating the frequency of present day and future extreme flood events suitable for use in reservoir risk assessment. This should be based on data from multiple scenarios of computer-generated weather using the best available tools and incorporating the latest rainfall climatologies.”

4.2.8.2 Meteorological considerations on climate change

There has been limited UK research on the impacts of climate change on PMP or other extreme rainfalls (Babtie, 2002; Atkins, 2013). Collier (2009) noted that theoretical considerations suggest that air can hold more moisture in a warmer climate. This is due to a relationship known as Clausius-Clapeyron that describes the relationship between saturation vapour pressure and temperature or, more simply, the moisture holding capacity of an airmass relative to its temperature. According to this relationship, specific humidity increases at approximately 6 to 7% per degree of warming (K^{-1}) near to the Earth’s surface (O’Gorman and Muller, 2010): a rate used as a first approximation to indicate how rainfall extremes may change with a warming climate.

Fowler and others (2021) state that evidence suggests that the intensity of long-duration (one day+) heavy precipitation increases with climate warming close to the Clausius-Clapeyron (C-C) rate (6 to 7% K^{-1}), although large-scale circulation changes affect this response regionally and rare events can scale at higher rates, while localised heavy short-duration (hourly and sub-hourly) intensities can respond more strongly (for example, 2xC-C instead of C-C).

Globally, the current day warming of the climate is already reported to be causing observable changes in extreme precipitation. The widespread increasing trend in observed annual maximum one-day precipitation increases confidence and follows physical and climate model expectations (C-C), with about 18% of moderate daily precipitation extreme events over land now attributable to warming (Fischer and Knutti, 2015). For the UK, it is not yet possible to discern if, or how, trends in extreme precipitation are being influenced by climate change (Kendon and others, 2018).

Changes in moisture availability are only one of the ways in which climate change may affect PMP. The state of scientific knowledge of the various impacts of climate change on processes that drive PMP is summarised below, based on a figure from McCormick and others (2020). It is:

- very likely to increase, high confidence: moisture availability and convective intensity
- future trends less clear: storm efficiency (horizontal convergence and ascent), storm durations, storm tracks and precipitation type

Storm efficiency is an important concept in some methods of estimating PMP. It is defined as the ratio of rainfall to the amount of precipitable water in the representative air column during the storm. The storm efficiency can be several times greater than one due to atmospheric moisture being brought in from outside the air column and recycling of precipitated water which subsequently evaporates.

Research in the USA has indicated increases in peak moisture content of 10% every few decades that would correspond to 10% increases in PMP (Easterling and Kunkel, 2011). Using simulations from 7 climate models, Kunkel and others (2013) concluded that changes in air movement associated with a warming atmosphere were too small to offset the increase in moisture, and, therefore, climate change will increase PMP globally.

Studies in various parts of North America have projected increases in PMP; for example, Rastogi and others (2017) gave an increase of +20% for the period 2021 to 2050 and +44% for later in the 21th century, in south-eastern USA. These findings are starting to be captured in legislation, such as in Colorado where in 2020 the Rules and Regulations for Dam Safety and Dam Construction were modified to include an adaptive strategy rule. This stated that “all rainfall depth estimates calculated by means acceptable to the State Engineer, shall be multiplied by a factor of 1.07 prior to calculating runoff to account for expected increases in temperature and associated increases in atmospheric moisture availability over the 50-year period 2020 to 2070” (McCormick and others, 2020).

One approach that is emerging for estimating PMP is the so-called ‘hybrid method’ in which moisture maximisation (a process where moisture factors of storms are adjusted to maximum appropriate values) is applied to outputs of climate models. One stated advantage of this approach is that it allows for explicit consideration of the impacts of climate change on PMP (Chen and Hossain, 2019).

Research by the Australian Bureau of Meteorology (Jakob and others, 2009) noted that while it is likely that rainfall extremes will increase thanks to increased moisture availability, it was not possible at the time to confirm that PMP estimates will definitely increase under a changing climate.

4.2.8.3 Hydrological considerations on climate change

Some research has taken this analysis a step further to model impacts of climate change on extreme floods, accounting for changes in catchment wetness and snowmelt as well as in rainfall. Research in France (Brigode, 2013) and Norway (Midttømme, 2004) has examined these issues, although neither focuses particularly on PMF.

One of the most advanced published investigations of the impacts of climate change on PMF is that of Clavet-Gaumont and others (2017). The authors used an ensemble of regional climate models to compute PMP under current and future climates, considering storm durations from one to 5 days. They combined changes in PMP with those in snow water equivalent and temperature, although the latter did not give meaningful results. Changes in PMF for 5 hydroelectric dams in Canada ranged between -1.5% and +20%.

Another study in the south-eastern USA extended the work of Rastogi and others (2017), mentioned above, to include the effects of changes in soil moisture, reservoir storage, land use and land cover on the magnitude of PMF, using the WRF weather model in conjunction with a distributed hydrological model, DHVSM. Results showed significant increases in PMF.

4.2.9 Uncertainty of PMP and PMF

Although the guidance documents included in the review widely acknowledge the (large) uncertainty in estimating PMF and PMP, they do not provide methods for quantifying that uncertainty. WMO (1986), quoted in Brown and Root (2002), summarises the situation like this: “There is no objective way of assessing the accuracy of PMP estimates derived using the recommended procedure. Judgement is involved in the various steps in the estimation procedure. Since alternative decisions could be made it would be possible to estimate upper and lower limits although in practice this is not done. The development of confidence limits is not possible as the derivation does not follow a statistical procedure.”

Three decades on, ARR (Ball and others, 2019) has a similar message for practitioners, stating that estimating PMF is confounded by:

- the lack of established criteria to determine the ‘reasonableness’ with which to combine the various flood producing factors
- the level of subjectivity inherent in assigning limiting maxima
- limited understanding of physical factors that constrain extrapolation of flood producing processes and their representation in models
- differential availability of relevant design information across the country
- poor selection of model structure and calibration of model parameters

It suggests that the main strategy available for reducing the impact of this form of uncertainty is to ensure that practitioners are appropriately qualified and supervised. It also stresses the importance of involving the wider dam safety engineering team in decisions on the appropriate level of conservatism. One route that ARR provides for testing the impact of the subjective judgements made in estimating PMF is to compare the estimate with that of the PMP Design Flood, described earlier.

Current practice in the USA is to express uncertainty in PMF using a range between the upper and lower estimate. This is expected to transition towards full quantification of uncertainty.

Research into estimating PMP has started to develop methods to quantify uncertainty. Micovic and others (2015) present what may be the first uncertainty analysis for a PMP. Their method combines the probability distributions of the various parameters used in the moisture maximisation and storm transposition method for estimating PMP. They include 5 sources of uncertainty, with their likelihood functions derived based on judgement. The PMP estimate for an example catchment was found to be most sensitive to 2 of these sources: storm efficiency and moisture maximisation. The approach not only quantified the distribution of PMP estimates, but also led to a change in the best estimate of PMP, since the mean of the distribution was 18% higher than the original deterministic estimate. We agree with the references cited above that it would be very difficult to give a convincing estimate of the resulting uncertainty in a PMF estimate. Our incomplete understanding of hydrological processes makes this task challenging. The method developed by Micovic and others (2015) has been applied by Kappel and others (2020), who considered 7 sources of uncertainty in PMP.

An alternative way of towards quantifying uncertainty in PMP is the climate modelling approach, in which ensembles of climate model runs provide an indication of the spread in PMP estimates (Chen and Hossain, 2019).

A practical implication of the uncertainty in PMF is suggested by ARR: Ball and others (2019): “Estimation of floods like the PMF borders on the 'unknowable', where even a high level of expertise cannot reduce the level of uncertainty substantially. Any extensions beyond the credible limit of extrapolation should employ a consensus approach that provides consistent and reasonable values for pragmatic design. The procedures relating to this range of estimates should be regarded as inherently prescriptive, as without empirical evidence or scientific justification there can be no rational basis for departing from the consensus approach.”

The promotion of a prescriptive approach, although it differs from the typical advice given to hydrologists, is worth considering when planning improvements to the UK method of PMF estimation.

In practice, many projects do not attempt to quantify uncertainty in PMF estimates. Where it is quantified, this is typically via sensitivity analysis. For example, a study for Whittier Narrows Dam in California tested sensitivity of the PMF hydrograph to factors including PMP, loss rate, lag time between the antecedent storm and the PMP storm and initial reservoir level (USACE, 2017b). Outputs from the sensitivity test were expressed in terms of uncertainty bounds for the time series of inflow and reservoir water level.

4.2.10 Alternative methods of estimating extreme floods for dam safety

The desire for a risk-based framework for managing dam safety has led some organisations and researchers to recommend methods of flood frequency estimation that can be extended to very long return periods without recourse to the concept of a probable maximum. This section mentions some such approaches that are applied internationally.

In UK practice, the FEH 2013 rainfall frequency model can output ‘indicative’ results for return periods up to 10^5 years. However, there has been little or no work looking at the implications of running rainfall-runoff models such as FEH or ReFH for such extreme return periods.

In the USA, USBR (2013) describes the use of flood frequency curves (one type of ‘hydrologic hazard curve’ (HHC)) for return periods up to 10^5 years. They are derived from a combination of at-site and regional discharge and rainfall data and palaeoflood data, sometimes including Monte-Carlo simulations or continuous stochastic simulations within rainfall-runoff models. Further details on these approaches are given by FERC (2014) (draft). These guidelines from the USA allow a great deal of discretion for practitioners rather than setting out a prescribed methodology. For example, a wide range of rainfall-runoff model types is considered. The most detailed modelling approach advocated, for estimating the highest return periods or on large complex catchments, involves in-depth modelling which would appear to require a lengthy and expensive hydrology study for each dam considered.

While USBR (2013) states that the HHC should be bounded so that they do not exceed the PMF, FERC (2014) (draft) indicates that an upper bound will not be imposed: “The FERC is not going to truncate the HHC at the PMF. The primary reason is that using a non-frequency based extreme-flood estimate is inconsistent with a risk-informed process.” However, even in this document, the PMF retains a role in dam safety assessment: “As part of the risk informed decision, the PMF should however be compared with the proposed probabilistic design flood.” Different approaches are used at different levels in the hierarchy of risk-informed decision-making.

In Australia, guidelines on dam safety specify return periods up to 10^7 years rather than PMF (Ball and others, 2019). Event-based methods of rainfall-runoff are recommended, using either an ensemble of events or a Monte-Carlo simulation in preference to a deterministic selection of a single set of design inputs. It is recommended that these approaches sample a variety of rainfall temporal patterns, as a minimum, and also consider sampling distributions of losses, rainfall spatial patterns and initial reservoir levels. ARR notes that “the estimation of extreme events can involve more significant degrees of non-linearity than present in the estimation of more frequent floods” (Ball and others, 2019). ARR also recommends reconciliation with the results of flood frequency analysis.

Reservoir safety procedures in France do not use PMF. For the highest category of dams, the design flood has a return period of 10^4 years, as in the UK (République Française, 2018). Earlier documents mentioned another requirement for a safety check flood with a return period of 10^5 years (ICOLD, 2009). Flood frequency information for return periods up to 10^4 years is provided by the SCHADEX method (Paquet and others, 2012), which simulates events stochastically. Rather than assuming that a flood of return period T years arises from a rainfall of the same return period, SCHADEX generates a wide set of combinations of precipitation and soil moisture states.

4.3 Methods for estimating PMP

4.3.1 Overview of methods

Over the years, there have been many approaches for estimating PMP. In a broad sense, the approaches can be seen as falling into 2 categories: those that use historic observations of rainfall and other variables with extrapolation techniques to estimate PMP from the observations; and those that use meteorological parameters to estimate PMP. In this analysis, we have termed these categories:

- statistical extrapolation approaches
- meteorological approaches (traditional and new)

In its manual on PMP, the WMO (2009) states that “procedures for estimating PMP cannot be standardized. They vary with the amount and quality of data available, basin size and location, basin and regional topography, storm types producing extreme precipitation, and climate.” Choosing which approach should be used for the UK needs to bear in mind the UK context, such as the longitude and latitude of the UK, its maritime temperature zone climate, and the size of the catchments over which PMP events could occur.

A statistical extrapolation method was put forward by Hershfield in 1965 and is still used in some countries today. The Hershfield method is considered as a convenient and effective statistical method of estimating PMP, provided long enough precipitation records are available (Sarkar and Maity, 2020). This method has the advantage of taking account of the actual data, expressing it in terms of statistical parameters, and being easy to use. The disadvantages are that the local influences on the storm, or its peculiarities, are not assessed and these may be significant (Collier and Hardaker, 1996).

Meteorological approaches have existed for many decades and their origins are well documented in the WMO (2009) manual. Three ‘traditional’ methods are usually used in estimating PMP in non-orographic regions. The first is local storm maximisation. Methods of maximisation include moisture maximisation and wind maximisation. The second is the storm transposition method that is an extension to the moisture maximisation method. Elevation adjustment, barrier adjustment and horizontal displacement adjustment need to be performed in the transposition. The third method is spatial and temporal maximisation, where the spatial and temporal distributions of one or more storms are adjusted deliberately using certain principles, thereby forming a new storm sequence to enhance the effect of flood creation.

The first method, maximisation, has been widely used, usually focusing on maximising moisture rather than other meteorological parameters. Understanding this method requires an understanding of various basic meteorological concepts. The method increases observed storm rainfall to reflect the maximum possible moisture availability. It is assumed that the rainfall amount is proportional to the atmospheric moisture availability. Therefore, observed rainfall amounts are scaled by the ratio of the climatological maximum moisture to the observed moisture condition (represented as the precipitable water ratio) (Chen and Bradley, 2006).

Chen and Hossain (2019) highlight 3 deficiencies with the more traditional PMP estimation approaches. Firstly, that traditional PMP estimation makes no allowance for a long-term climatic trend that is expected to continue in the future. So, by applying the PMP derived from historical observation to planned dams in the future, a stationary climate is assumed. Secondly, conventional PMP is a deterministic value, which does not provide any uncertainty information, making it less appealing for risk assessment scenarios. Thirdly, the idea of moisture maximisation is hard to justify from a scientific standpoint. Moisture maximisation implicitly assumes a constant precipitation efficiency, which is not the case in the extreme storms and within the framework of a changing base state climate.

Chen and Hossain (2019) present results showing that the occurrence of extreme precipitation in many parts of the world, including the UK, is more often accompanied by extreme vertical wind speeds than by extreme precipitable water. These results are based on a global atmospheric reanalysis of 3-day precipitation totals which is not of high enough resolution to explicitly represent the processes of convection (the processes frequently resulting in intense rainfall). The results do suggest, however, that simply maximising the moisture available to a storm may not always be the most appropriate way to achieve a PMP storm.

The concept of precipitation efficiency is also used in an alternative approach to moisture maximisation, referred to as the ‘storm model method’ (Collier and Hardaker, 1996). This method attempts to parametrise the physical processes occurring in convective systems, such as the strong vertical ascent due to surface heating, the low-level moisture and convergent inflow, and also orographically forced ascent, to derive a precipitable water amount representative of a convective system. The storm model approach has had limited application internationally, currently only applied in the UK and Czech Republic (Rezacova and others, 2005). The method also only applies to PMP estimates on the timescales of convective weather systems (less than one day).

In recent years, interest has focused on numerical weather prediction (NWP) modelling as a potential source to better understand PMP. An important development in NWP modelling has been the application of ‘convection-permitting’ modelling, in which convective rainfall (Trapp, 2013) that is responsible for the highest rainfall intensities can be modelled explicitly at scales of 2 km resolution or less (Clark and others, 2016). The NWP approach to estimating PMP follows the idea of moisture maximisation, but provides increased physical representation by allowing the NWP model to react to the enhanced moist environment in a dynamically consistent way. There are also drawbacks associated with this approach, including how to enhance the moisture field in a realistic way, and the representation of weather events that have not been observed (most NWP PMP approaches seek to model historical events with enhanced moisture). Addressing the latter issue has been the subject of studies using ensemble NWP simulations, where multiple slightly different simulations of the same event are run. This approach could also be used with the latest high resolution convection permitting climate models, such as those used to generate the UKCP local climate projections (Kendon and others, 2021).

Climate projection simulations using global and regional climate models cover time periods from 10 to around 100 years into the future. It is computationally very expensive to run global and regional climate models at grid scales required for explicit representation of extreme precipitation (at the scales used for NWP simulations). Therefore, such models typically have coarser grid sizes requiring convective and microphysical parameterisation schemes to be used. These schemes do not explicitly represent convection and, therefore, usually, climate models are not suited to providing robust estimates on future changes in extreme precipitation (Mahoney and others, 2018). However, the advancement of running NWP-scale climate simulations opens up the possibility of having a long enough modelled record to directly estimate PMP.

4.3.2 UK methodology

In the FSR (and re-stated in the FEH), PMP is based on an analysis of the storm efficiency of observed events combined with the theoretical maximum precipitable water in a vertical column above the catchment. The FSR describes the process of determining the storm efficiency (a function of storm duration) and lists a few of the largest 2-hour events recorded in the UK in the previous 60 years. Typical values of storm efficiency were between 3 and 4.

Maps of estimated maximum precipitation (known as EMPs) for durations of 2 hours, 24 hours and 25 days were generated for the UK and Ireland, enabling extreme rainfall to be estimated for any location and any duration. Catchment specific values of the specified durations are obtained by calculating the area-weighted average over the catchment. PMPs of durations not mapped are obtained by interpolation on a graph of PMP rainfall depth versus the logarithm of PMP duration, or from tables of values giving the PMP as a function of estimated maxima of known duration.

This ability to derive pre-calculated PMP values for any catchment of interest is a significant help to practitioners, meaning complex meteorological considerations are not necessary.

Design rainfalls below the PMP are estimated using the FEH13 rainfall frequency model (Stewart and others, 2013), which does not take any account of PMP as an upper limit.

4.3.3 Approach taken to review PMP estimation methods

The project team decided to separate the review of present day PMP estimation methods from methods to derive climate change amplification of PMP estimates. This allows assessment of the relative merits of each individually for the UK context. This approach assumes that PMP is calculated (estimated) for suitability to the present day, and that the effect of climate change is added on as a separate step in the process. Benefits of this concept are that the PMP estimation process is more transparent and that the climate change impact for the future can be understood separately, increasing confidence in the way the final PMP estimate is derived. It also allows for more varied use of PMPs, whereby some users may not need to consider future climate change effects.

Separation of present day PMP estimation from the impact of future climate change is consistent with the views of Chen and Hossain (2019) who favour a hybrid between the traditional and physics-based approaches to estimating PMP. The hybrid approach uses moisture maximisation methods with information from climate models in place of observed data to inform future PMP. In this way, non-stationarity can be addressed by estimating PMP for different historical/future periods.

4.3.4 International approaches for estimating PMP

The project team carried out the review of methods for estimating PMP by assessing available and potential methods used across the world. The outcome of this analysis produced a table of international approaches (Appendix 5). A distinction has also been made between studies or material representing official guidance from a government or national agency and that from research literature where the methods may have been applied over a limited area only.

Appendix 5 highlights many approaches taken worldwide across 22 countries, with relatively few countries providing official guidance for estimating PMP. Analysis of Appendix 5 shows that in terms of official guidance in 8 countries, storm maximisation and transposition are most commonly used, with the statistical approaches joint second. Several countries have used multiple different methods to derive their PMP estimates.

Factors that could influence a country’s preferred PMP estimation approach include its available historic data, its level of advancement in NWP modelling, its climatology (for example, continental, maritime, temperate, tropical) and its relative exposure to risk (number of dams, size of dams, age of dams).

4.3.4.1 Summary of international approaches for estimating PMP

Below is a summary of international approaches for estimating PMP.

Few countries provide official guidance on estimating PMP, but those that do most frequently use the storm maximation and transposition approaches

Multiple methods are often used in the same country, either sequentially through update studies or new guidance, or to directly calculate PMP estimates from different methods.

Preferred PMP approaches used in a given country depend primarily on available historic data and the climate zone. However, the nature of the character of the country’s dams and their contributing catchments also plays a significant role, for example, flood studies for very large dams on major rivers may be more likely to adopt bespoke estimation methods.

4.3.5 PMP hyetograph shape

4.3.5.1 UK methodology

The rainfall profile of the PMP event used in the UK has not changed since the 1975 FSR approach. This approach develops a symmetrical hyetograph with a central peak. The ratios of each part of the profile either side of the peak are calculated using predefined maps of PMPs for specific durations. This is illustrated in Figure 19 in which the symmetrical profiles for the 'summer' and 'winter' conditions are shown – the summer profile being considerably more peaked than the winter. The question is whether such a storm profile is representative of rainfall profiles in extreme (or PMP scale) rainfall events; both now and in the future.

It should be noted that the FSR PMP hyetograph approach differs from the profile shapes specified in the FSR, and is still used today, for T-year rainfalls.

While the shape of the hyetograph might seem of less importance than the total depth of the rainfall used, and the duration of the event, the shape can affect PMFs and flow characteristics markedly. A very peaky hyetograph will result in higher flows, while a flatter less peaked hyetograph, or one with multiple peaks, could result in substantially reduced peak flows.

The storm model developed by Collier and Hardaker (1996) produced a hyetograph profile that "greatly differs from [the symmetrical profile] proposed in the FSR." The 2 differences are that the Collier and Hardaker profile is multi-peaked, with its biggest peak coming early in the profile, more common in a typical meso-scale convective system (front with embedded convection) and that it is positively skewed. "Very rarely it is likely to take the form of the FSR hyetograph," they say. The Boscastle flood event of August 2004 is another example of a multi-peaked hyetograph.

A recent study has objectively extracted thousands of individual storm profiles using UK rain gauge data, based on the observed event duration rather than the profile within a defined duration (Villalobos Herrera and others, 2022a). By grouping these objective profiles by event duration and using a normalised time axis, composite storm profiles can be produced. Results support the postulation of Collier and Hardaker (1996), with all duration groups (from 2 hours up to 24 hours) exhibiting less symmetrical, flatter profiles than those of the FSR (Villalobos Herrera and others, 2022b). Profile shapes do not vary greatly with location in the UK, or with return period.

4.3.5.2 International approaches

Some international methods for estimating PMP and PMF continue to use fairly simplistic approaches for defining the storm profile shape. In Australia, PMPs for durations up to 6 hours are derived from the Generalised Short Duration Method (GSDM), which applies a single temporal distribution derived from data recorded during major storms (Bureau of Meteorology, 2003). For longer durations, the Generalised Southeast Australia Method (GSAM) provides a set of storm profiles that vary with storm duration and geographical zone (Bureau of Meteorology, 2006). They were derived using the average variability method, which analyses observed storms, plus some smoothing.

In the USA, the Hydrometeorological Report 52 (HMR52) approach to storm profile has some commonality with the FSR method, using ‘nested’ PMP depths over a range of durations from 3 to 72 hours (Hansen and others, 1982). This gives a unimodal hyetograph shape. The user has some flexibility over where to place the most intense part of the storm within the sequence. The HMR method remains in use within some states of the USA and it is also recommended for nuclear power plant design (Prasad and others, 2011).

An example of a state-of-the-art approach to deriving hyetograph shapes is given by Felder and Weingartner (2016). The paper presents an approach for randomly generating spatio-temporal patterns for a PMP. It recommends that at least 10^4 physically plausible patterns are generated and run through a rainfall-runoff model, the worst case being selected for deriving the PMF. An example application of this method for the 3,000 km^2 Aare catchment in the Swiss Alps is given by Felder and others (2017). The peaks of the 100 hydrographs with highest peak discharges vary over a range of 30%.

4.4 Rainfall-runoff models used for estimating PMF

This section reviews rainfall-runoff models used for estimating PMF and approaches to setting inputs to those models. The second aspect is arguably at least as important as the first: in principle, it is possible to estimate the PMF using a wide variety of rainfall-runoff model types. Some of the biggest challenges lie in how to define a realistic combination of inputs to apply to the model in conjunction with the PMP. Inputs specific to winter conditions are discussed in the subsequent section 4.5 Snow, frozen ground and joint probability issues.

The review starts with an introduction to rainfall-runoff models in general, which is then expanded to summarise rainfall-runoff models used within PMF estimation. Sub sections then discuss the issues relating to PMF estimation and the incorporation of these within the PMF estimation method. All sections include a summary of UK research and application followed by a wider summary of relevant international literature.

The following sections are presented in turn:

- rainfall-runoff models
- change in processes with event magnitude
- storm duration
- antecedent conditions

In application in the UK, it is necessary to complete PMF estimation at both gauged and ungauged sites, with the latter being more likely. Where gauged data exists, parameters for rainfall-runoff models can be calibrated using the gauged data, therefore, a wide range of rainfall-runoff models may be applicable. However, to apply PMF estimation at ungauged sites parameters needs to be estimated without recourse to observed data.

Regionalised rainfall-runoff models, where parameters can be estimated from catchment descriptors (physical features which are described by spatial data sets, for example, average slope), are, therefore, required for ungauged sites. Both the existing FSR/FEH model and ReFH2 are examples of regionalised event rainfall-runoff models.

It should be noted that the very act of completing a literature search will introduce an intrinsic bias into the process of gathering information relating to application of PMF both in the UK and internationally. To be considered for publication, papers need to present new ideas, concepts or particularly complex or comprehensive studies which may be of interest to others (either researchers or practitioners). While guidance from recognised institutes or governing bodies may provide a more balanced presentation of methods, it is still necessary to consider that case studies within these are also likely to focus on 'best practice' studies with greater complexity. Recommended methods within guidance may also include those that, in practice, are unlikely to be used in all but the most complex or high-risk situations in an attempt to encourage users to move towards using these methods. Within the review process it can, therefore, be difficult to identify the 'typical' methods that are routinely used. It is wise to consider this inherent bias when developing conclusions relating to application within the UK as part of a risk-based framework.

4.4.1 Rainfall-runoff models

4.4.1.1 Model classification

The objective of rainfall-runoff modelling, in its broadest sense, is to simulate the translation of a precipitation incident upon the surface of a catchment to stream flow at the catchment outlet, accounting for evaporative losses from the system. Todini (2007), Singh (1995) and Beven (2012) present useful reviews of the development of the science of rainfall-runoff modelling and modelling philosophies, starting with the development of the rational method, the introduction of the unit hydrograph and moving through to the development of more physically based models, as well as artificial neural network (ANN) models. Many classifications for hydrological models have been proposed, for example, the classifications by Singh and others (1995) and Wheater and others (1993), a general classification by Chow and others (1988) and a process classification by Refsgard (1996). Figure 23 presents a general classification, whereby models are classified based on process description, spatial representation and randomness. A model can be described depending on how each of these aspects are incorporated.

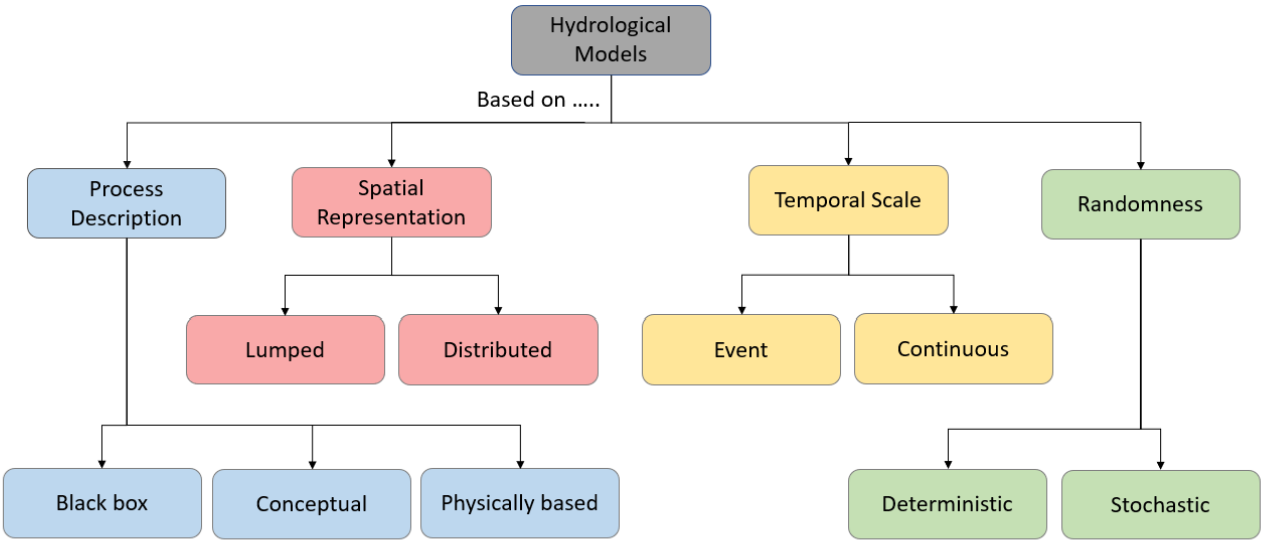


Figure 23: General hydrological model classification

Process description models can lead to black box, conceptual or physically-based hydrological models. Spatial representation models can be lumped or distributed. Temporal scale models can be event or continuous and randomness models can be deterministic or stochastic. In reality, the boundaries between classifications and between the individual boxes within a classification are not as clearly defined. Many models are essentially hybrid, with constituent parts drawing from stochastic and deterministic components. The deterministic components may seek to describe the physics of the process, using differential equations and are commonly called 'physically-based', or may use a conceptual representation of the physical processes, in which integral equations are commonly used to represent the processes. Physically-based models are distributed in that the model equations include space co-ordinates.

One class of model with a physically-based component is 2D models of overland flow based on the shallow water flow equations, sometimes known as 'direct rainfall' or 'rain-on-grid' models. These are sometimes used across a whole catchment in place of rainfall-runoff models. Although such application has been criticised (for example, by the Environment Agency, 2020) because of the weakness of the assumption that all run-off is conveyed overland, it may be that the assumption is more valid for some catchment types during a PMF.

Another example of blurring of boundaries between model classes is that stochastic techniques are commonly used when formulating the catchment implementation of deterministic model components; for example, the semi-distributed soil moisture module of the Probability Distributed Model (PDM) (Moore, 1985). The PDM has been widely used in the UK within flood forecasting models, individual catchment modelling studies and generalised continuous simulation models. In the context of event models, the ReFH model employs the probability distributed soil moisture concept.

Singh (1995) states: “A vast majority of the (available) models are deterministic, and virtually no model is fully stochastic. In some cases, only some parts of the model are described by the laws of probability, and other parts are fully deterministic. It is then fair to characterise them as quasi-deterministic or quasi-stochastic.”

In summary, models grade in their complexity (both with respect to the model structure and spatial resolution) from ‘black box’ models through to differential physically-based distributed models. Conceptual models, whether lumped or with some degree of spatial discretisation, lie between these extremes.

In the context of this review, a model is considered as ‘lumped’ if the input data, output data and model equations do not include a spatial description. This definition does not make a distinction between stochastic or deterministic formulations.

Physically-based models are typically associated with considerably higher demands on data availability and parameter estimation, as well as requiring more expert knowledge of computational hydrology from the user. Research has demonstrated that the predictive ability of this class of models may be only marginally or no better than that achieved by lumped models (for example, Bell and Moore, 1998; Reed and others, 2004).

An argument can be constructed that no model components are truly physically-based. Any mathematical description of a process is an approximation of that process and, therefore, is always a conceptualisation. The preservation of the physicality of physically-based deterministic model components is called into question in the application of the model. While the process descriptions may model the transport of water under well-defined laboratory conditions, they may not when applied to the complexities of a real catchment. The scale of the spatial and temporal discretisation of the model is extremely important. In practice, it is necessary to limit the resolution of distributed models to a grid scale that is commensurate with the input data describing catchment properties, the climatological/precipitation event variations and computing power available. This spatial averaging and the uncertainty in the input climatic data and field measurement of catchment properties (and, therefore, parameter values) will generally mean that the model will require calibration to compensate for these uncertainties (Beven, 2006). Therefore, the true physicality of the model is compromised.

Of specific interest when estimating PMF is whether a rainfall-runoff model is applied as an event model or as a continuous simulation model. In the former, the initial conditions for the model are specified, based on rules or sampled from a distribution, and the model is then applied in conjunction with precipitation over a defined duration, specifying an extreme event (commonly a unimodal event or a multimodal event). These precipitation data may be a series of data describing an observed event, or more commonly (and specifically in the case of UK PMF estimation), a design event in which a design depth of rainfall is distributed across a specified duration using a pre-determined hyetograph profile.

The input rainfall may also be the outputs from a stochastic event model; in the context of PMF this includes the SCHADEX model used in France (Paquet and others, 2012) and the application of the TREX model within the US (England and others, 2014).

Continuous simulation approaches, as the name suggests, model longer periods of rainfall. A continuous simulation model can be used directly as part of a flood study or be a part of an event modelling approach; to enable antecedent conditions for an event of interest to be adequately captured. Input data may either be observed or stochastically produced in a synthetic long time-series; the latter producing a long series of run-off that can be used as part of flood frequency analysis (Lamb and others, 2016). This approach was the subject of much research in the UK in the 1990s (Calver and others, 1999), but has not gained the traction that it might. This is partly due to the limitations of stochastic weather generators and partly due to the observation that flood frequency analyses generated using generalised rainfall-runoff models do not seem to offer significant advantages over the current FEH statistical methods. In the context of PMF, continuous simulation could provide a realistic representation of antecedent conditions and estimates of PMF could be approached through analysis of the largest event in a long stochastically generated record, or through extension of a flood frequency analysis.

4.4.1.2 Models in UK practice for dam safety

Figure 24 provides an illustrative timeline showing the evolution of rainfall-runoff models used in UK flood management and dam safety from 1975 to 2022.

The predominant rainfall-runoff model used in the UK for estimating PMF is the FSR/FEH method. First presented in the FSR (NERC, 1975), the FSR is an empirical, lumped, event model comprising 3 components: an empirical percentage runoff-based loss component, a unit hydrograph routing component, and a fixed baseflow model. The loss model comprises a standard percentage run-off component – a function of catchment soils – and a dynamic percentage run-off component which is dependent upon an empirical assessment of antecedent catchment wetness, along with the storm rainfall depth – for more details on the application of the PMF method, see section 3.8 PMF. For design application within an ungauged catchment, the initial conditions and model parameters are estimated via equations relating these to mapped climatic and physical catchment descriptors. Where gauged data is available, the parameters can be estimated from observed data. A depth-duration frequency (DDF) model was used to create equivalent T-year rainfall hyetographs. The PMP hyetograph is derived using a separate empirical method using data provided in the FSR.

The FSR rainfall-runoff method was restated in the FEH (Houghton-Carr, 1999) introducing digital catchment descriptors and a new Depth-Duration-Frequency (DDF) rainfall model. The derivation of the PMP and PMF remained largely unchanged.

In comparison with estimation of a T-year flood, there are some important changes to the rainfall-runoff modelling process made when estimating a PMF, all of which are discussed in later sections. In summary, the changes are that:

- the time to peak of the unit hydrograph, Tp(0) is reduced by one-third to represent the potential for more rapid routing during the PMF
- the catchment wetness index is evaluated differently
- snowmelt is added when modelling a winter PMF

- an allowance for frozen ground is added for a winter PMF

The current UK procedure for estimating both PMP and PMF has been set out in full in section 3 Restatement of method currently used to estimate PMP and PMF in the UK.

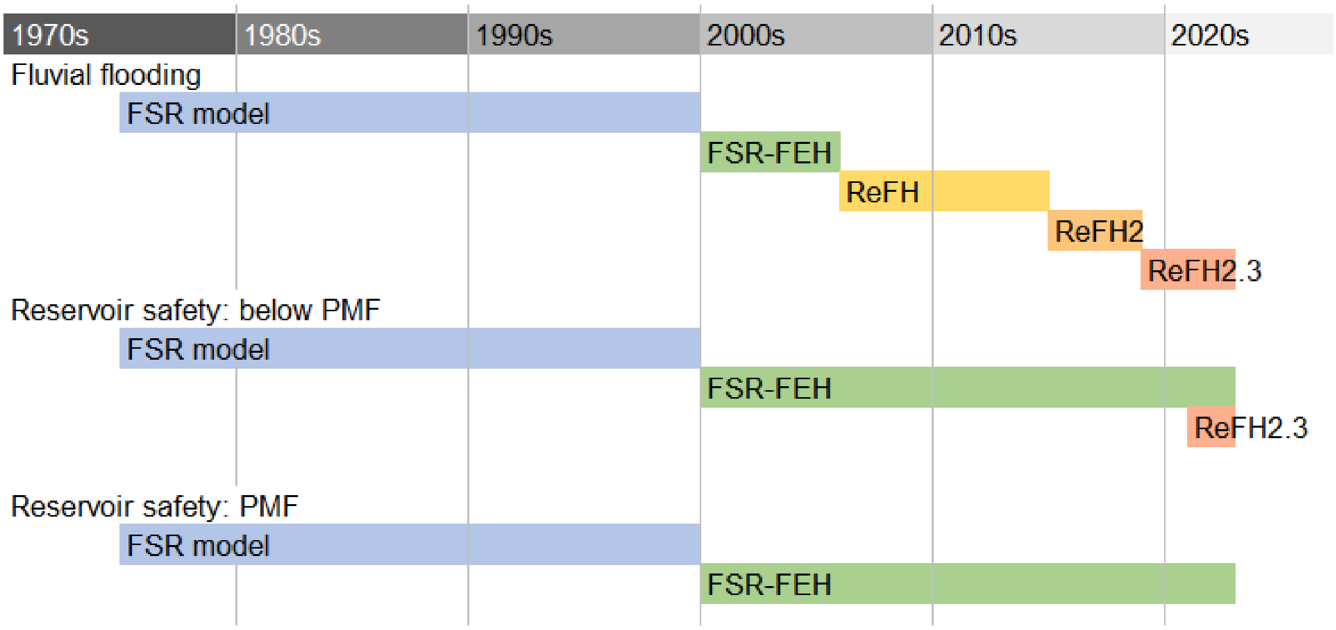


Figure 24: Timeline of rainfall-runoff methods used in the UK for estimating design floods and PMF

Figure 24 shows a timeline or rainfall-runoff methods used in the UK for estimating design floods for fluvial flooding, reservoir safety: below PMF and reservoir safety: PMF, respectively. From 1970 to 2000s, all flooding types used the FSR model. In 2000s, fluvial flooding used FSR-FEH up to 2005, ReFH from mid-2005 to 2015, ReFH2 from 2015 to 2018, and ReFH2.3 from 2018 onwards. Reservoir safety: below PMF used FSR-FEH from 2000 to 2021 and ReFH2.3 from 2021. Reservoir safety: PMF is shown to use FSR-FEH from 2000 onwards.

For estimating design floods smaller than the PMF, the restated FSR model has been superseded by the Revitalised Flood Hydrograph model (ReFH), first published in 2005 (Kjeldsen and others, 2005). ReFH addressed several important limitations in the FSR model, including the:

- lack of consideration of seasonality - FSR allowed mixing of summer rainfalls and winter soil moisture deficits
- weakness of the CWI concept, which can double-count recent rainfall
- limitations of the way in which the FSR model allows percentage run-off to vary with flood magnitude
- tendency of the model to overestimate peak flows, when compared with the results of flood frequency analysis

Not all the above limitations apply equally to the use of the FSR/FEH model for estimating PMF.

Using ReFH identified many areas for further model improvement. These have been addressed in the subsequent research, leading to the development of the ReFH2 method, which is implemented though the proprietary ReFH2 software (WHS, 2019).

Providing a link to the early FSR model, the structure of ReFH retains the 3 core model components. However, the empirical fixed percentage run-off component of the FSR was replaced by Moore’s (1985) simplified form of the probability distributed deterministic soil moisture accounting procedure. The evolution of soil moisture status, therefore, the rate of run-off production during an event, addresses a primary weakness of the FSR model. The routing model for simulating direct run-off was updated to use a ‘kinked’ unit hydrograph. Baseflow also evolves during the event; a more realistic representation of catchment process than the fixed baseflow of the FSR. The baseflow is a function of the simulated direct run-off, thereby enabling the baseflow parameters of the model to be identified from the recession characteristics of a relatively small set of observed events. As for the FSR, the parameters and initial conditions for ReFH and ReFH2 can be estimated from catchment descriptors.

Without a dynamic updating of soil moisture status to represent drainage to baseflow from the store, the original ReFH model could overestimate run-off when applied to events of durations outside of the normal range for a catchment (Faulkner and others, 2009). The latest version of ReFH, ReFH2.3 addresses this through a dynamic updating of soil moisture status at intervals equivalent to the recommended duration for a catchment.

Using the FEH99 DDF model, the original ‘design package’ release of ReFH (ReFH1) was only recommended for short return period design events (less than 150 years). The methods are subject to continuous improvement. The most recent ReFH2 updates to the design package include the use of the FEH 2013 DDF model, the improved estimation of initial conditions and model parameters, the introduction of a deterministic representation of the influence of urbanisation (and the urban water balance), and the baseflow update to the soil moisture accounting procedure and close of a water balance in impermeable catchments.

Both FSR/FEH and ReFH rainfall-runoff methods are now used in tandem; ICE (2015), published prior to the release of ReFH2 recommends the ReFH rainfall-runoff model up to 150 years, citing “until ReFH is extended” for greater return periods. Following the release of ReFH2, in which model performance was assessed for the 1,000-year return period, Pether and Fraser (2019) recommended the use of FSR/FEH and/or ReFH rainfall-runoff models up to the 1,000-year return period and FSR/FEH above this. UKCEH currently recommends (E. Stewart, pers. comms, 2020) that for the 10^5-year event, the FEH 2013 rainfall model should be used, and suggests that both the FSR/FEH and ReFH2 should be used for comparison purposes at this return period until further work is completed.

A study by Pucknell and others (2020) proposed a framework for using ReFH to obtain PMF estimates based on an adaptation of the FSR method, applying adjustments to parameters and initial conditions equivalent to those assumed in the FSR method. A relationship between the initial soil conditions based on 15 study catchments used by Reed and Field (1992) and those under PMF conditions was derived and appropriately transferred to the ReFH2 rainfall-runoff model. Together with the incorporation of the Tp adjustment, the PMF estimates of peak flow were found to be comparable with those obtained by applying the FSR/FEH PMF method. Stewart and others (2019) presented a broad scale comparison of ReFH2 and the FSR/FEH methods for extreme events (10^5-year and PMP). The study did not consider the changes in antecedent conditions that Pucknell and others considered, but did incorporate the reduced Tp and set a minimum value of 53% for percentage run-off when emulating PMF adjustments. This is directly comparable with setting a minimum PR in the FSR/FEH methods to reflect the enhanced run-off from frozen ground. The study was focused on comparisons of the 10^5-year event using both the FSR and ReFH model. It found that, for winter events, peak flows arising from the PMP and the 10^5-year rainfall (using FEH 2013 DDF) were comparable in some catchments once the reduction in Tp and the lower limit to percentage run-off were applied.

IH Report 114 (Reed and Field, 1992) presents a useful review of reservoir flood estimation in the UK at the time. The report summarises the PMF methodology as well as exploring issues relating to storm duration, relationships between PMF and lower return period events, snowmelt and the use of local data.

An exception to the usual UK practice of lumped rainfall-runoff modelling is sometimes made when estimating a PMF on catchments with upstream storage, whether this is in formal reservoirs, defacto storage in floodplains, or behind road or rail embankments. In such cases, the FSR/FEH rainfall-runoff model can be applied in a semi-distributed fashion, splitting the catchment into 2 or more sub-catchments and routing the modelled hydrographs to the outlet using a suitable channel routing model. ICE (2015) suggests that where engineered features in the catchment of a reservoir would temporarily impound significant quantities of water during a flood, and where they are assessed as being stable, they may be treated as additional reservoirs to be incorporated in the routing.

In practice, the switch from lumped to semi-distributed modelling has been seen to lead to large reductions in the estimated peak flow during a PMF. Reasons for this may include the explicit representation of timing differences for adjacent tributaries.

4.4.1.3 Models in international practice for dam safety

Outside the UK, guidance and established methods are often less prescriptive when advising on specific rainfall-runoff models to be used within high return period or PMF studies. As will be discussed, a general recommendation is made to use models with deterministic representations of the underpinning hydrological process. These include both conceptual deterministic representations and physically-based models with perceived benefits from applying models in a semi-distributed or fully distributed modelling framework. There are obvious trade-offs here between model complexity, data requirements and costs of application. A more subtle point is that the more complex the modelling framework, the higher the overhead in terms of modelling skill and audit for both the originating modeller and those who might be called upon to audit the model application. Of course, these overheads can be mitigated through training, experience and by adopting formal model audit frameworks to ensure accountability of the modelling decision-making process.

One of the exceptions to this less prescriptive approach is France, where Paquet and others (2012) state that the semi-continuous simulation SCHADEX has been the standard method used by Électricité de France (EDF) since 2008 (replacing GRADEX) for reservoir flood safety. Combining both the rainfall and rainfall-runoff elements required for peak flow estimation, SCHADEX combines a weather pattern-based rainfall probabilistic model (MEWP) and a lumped, conceptual rainfall-runoff model (MORDOR) within a stochastic event simulation framework. The emphasis is very much on extreme events (up to 10^5 years) rather than specifically PMF. The method is data intensive, requiring a minimum of 20 years of climatological data (rainfall and temperature) to be collated for MEWP. The MORDOR hydrological model includes processes such as evapotranspiration, direct and indirect run-off, ground water, snow accumulation and melt, but also requires calibration to observed run-off.

The HBV (Hydrologiska Byråns Vattenbalansavdelning) model, which is summarised by Bergström and others (2015) was developed by the Swedish Meteorological and Hydrological Institute. Whilst applied worldwide, it has been most extensively used within Scandinavia. It is a lumped conceptual model and includes functions to account for snow accumulation and melt as well as a soil moisture routine, response function and routing routine.

In the USA, hydrological methods used for estimating PMF are based on models and methods published by the US Army Corps of Engineers (USACE) and the US Bureau for Reclamation in its Flood Hydrology Manual (USBR, 1989). These provide guidance on producing PMF based on PMP, with infiltration rates based on Horton’s infiltration theory and the development of unit hydrographs based on observed data where available. The Federal Energy Regulatory Commission (FERC) is responsible for more than 1,700 non-federal dams, whereas the USACE is responsible for federal dams. Guidance by the FERC (2001) is similar to the USBR, relating estimating PMF to estimating PMP and developing a suitable rainfall-runoff model. However, later guidance (FERC, 2014) moves towards a more risk-based approach, as opposed to a single ‘PMF’ event approach, and mentions the option of physically-based watershed modelling. The latter guidance allows a high level of user discretion, with a wide range of rainfall-runoff models being acceptable, although in practice these are mainly drawn from the range of models published by the USACE, a variety of which are implemented in the HEC-HMS software package.

Guidance in the USA advocates the most detailed modelling approach for estimating the highest return periods or for large complex catchments. This involves in-depth modelling and requires a lengthy and expensive hydrology study for each dam considered. One comprehensive study is that presented by England (2007, 2014), which combines a stochastic storm transposition event model with the TREX rainfall-runoff model, a physically based 2D and 1D model structure within the 12,000 km^2 Arkansas river basin. The TREX model accounts for (1) extreme storm rainfall (duration, spatial pattern, location, areal extent); (2) partial-area rainfall and run-off; (3) hillslope run-on, run-off and routing; and (4) channel network and routing. The authors also provide examples of other models being used for high-return period floods, including TOPMODEL, another distributed model, although with a less explicit physical basis.

Both continuous and event models are presented within US literature. There is a preference for models that have been calibrated to observed data (either continuous or individual events). It is also accepted that where multiple runs are being completed, event models can be far more efficient. Simpler hydrological methods are reserved for risk screening evaluations only.

In Canada, Alberta Transportation (2004) also does not mandate any one particular rainfall-runoff model, although it mentions HEC-HMS (which provides a range of model formulations) and cites that both event and continuous type models have been used for PMF studies. The stated preference is for an event-based model with physically-based parameters (that can be determined from direct measurements of the physical properties of a catchment) where possible. The complexities of extrapolating from point measurements to a catchment scale are not explored exhaustively. Where this is not the case, regional relationships between parameter values and measurable physical characteristics can be used.

The above tendency to prefer deterministic, distributed models driven by observed data is also a common theme within the southern hemisphere. The Australian Rainfall and Runoff guidance (ARR: Ball and others, 2019) recommends using semi-distributed representation in larger catchments, with models representing the routing of all elements in the catchment like hillslopes, river channels and storage. A number of models are discussed, including RORB (described as a node-link type model), XPRAFTS (a simple semi-distributed model) and URBS (a simple semi-distributed model). The perceived importance of distributed run-off routing means that unit hydrograph methods are now rarely used in Australia. Specific guidance on rain-on-grid models is not provided for extreme events, although the guidance notes "the use of hydraulic models to simulate extreme floods does have some theoretical merit." McKerchar (2010) in New Zealand focuses more on appropriate conceptualisation of the modelling challenge (catchment features, scale, discretisation, realistic antecedent conditions) rather than the specific modelling code to be used, or indeed the concept of a design modelling procedure. Explicit in this approach is the use of recorded event data to calibrate/verify rainfall-runoff models before use with the PMP estimate and conceptualised initial conditions. The paper includes a PMF case study using the Australian developed RORB distributed rainfall-runoff model where loss rates and model parameters were determined from observed events. Other rainfall-runoff models appear implicit within the list of case studies.

4.4.1.4 Models applied in other fields and research

A very large number of rainfall-runoff models have been applied in research settings. This section reviews a small selection of such models, focusing on those that have either been applied or suggested for estimating extreme floods, or have featured prominently in recent application.

Addor and Melsen (2019) provided interesting insight into the model selection process. They compared information provided in the abstracts from 1,529 studies and found that the choice of models can be predicted based on the first author in 74% of studies, indicating that model selection is typically based on familiarity as opposed to necessarily the most adequate model. This finding is worth bearing in mind when assessing the range of models that are applied in different countries and fields of study.

Cluckie and Pessoa (1990) describe various methods used to estimate high return period and PMF event at Stocks Reservoir in Lancashire. While they include the use of statistical methods, they also use radar data to derive a spatially distributed PMP event. This was subsequently used within 2 distributed models (RADEN and GDBM) and the FSR/FEH lumped rainfall-runoff model. The results indicate similar PMF events from the differing models, and the authors note these are also similar to other existing techniques.

The use of a one-parameter unit hydrograph as used within both FSR/FEH and ReFH has been criticised by Littlewood (2019). The author argues that there has been resistance to substantial changes to UK flood hydrology lumped model approaches, citing the 3 parameter IHACRES (Littlewood and Jakeman, 1994) unit hydrograph approach as an alternative. Sefton and Howarth (1998) and Sriwongsitanon and Wisuwat (2011) have investigated the possibility of regionalised applications of IHACRES in the UK (60 catchments) and Thailand (9 catchments), respectively. The former was at a daily resolution and focused on the fit across the flow duration curve. Littlewood (2002) notes that “to maximise its utility for that purpose [regionalisation], it needs to be applied with more care and attention than hitherto to individual catchments to ensure the quality of model-fit over a wide range of the flow regime.” These comments reflect many of the issues associated with regionalisation studies in general. IHACRES would require a new regionalisation scheme, at a sub-daily resolution, if it were to be adopted for estimating PMF in the UK.

It could be argued that it is the simplicity of the FSR/FEH and ReFH unit hydrograph models that have allowed these methods to be regionalised for use in ungauged catchments. Although only one study, the results of Cluckie and Pessoa might suggest that a more complex run-off routing framework may not yield significant improvements in estimating very extreme events.

Another simple type of conceptual model that has seen wide application in recent years is the GR family, developed at INRAE-HYCAR in France (Perrin and others, 2003). This includes GR4J (4 parameters, daily), and GR4H (hourly). These models have been applied for flood forecasting, water resource assessment and climate change studies. They have been found to outperform several other models, and their parsimonious nature (few parameters) helps with calibration.

The review has found little evidence of physically-based models being used operationally for PMF. One example of a physically-based model is SHETRAN. There is a version known as SHETRAN-GB (Lewis and others, 2018), which can be set up rapidly for British catchments. The standard setup of SHETRAN-GB runs on a 1 km grid, so is probably not suitable for the very small catchments typical of many UK reservoir contributing areas. Any application of SHETRAN to estimate PMF would need to address questions over how to define suitable initial conditions.

Another class of model that is seeing current application in a range of settings is machine learning or deep learning approaches, a type of purely empirical model. An example is long short-term memory models, LSTMs. They have been found to outperform lumped conceptual models and a process-based model (Lees and others, 2021, Nearing and others, 2021). LSTMs showed a large performance improvement in upland areas, thought to be due to their ability to capture snowmelt processes (Lees and others, 2021). They are reportedly particularly good at transferring into ungauged catchments without degrading performance (Beven, 2020). An approach to estimating PMF using LSTMs could offer an opportunity to benefit from current and expected future developments in so-called deep learning (Nearing and others, 2021). A challenge would be how to convincingly demonstrate that such models could simulate extreme events much larger than those included in their training data set.

4.4.1.5 Summary and discussion

In an international context the focus for modelling of PMF, or more generally extreme floods, is on using deterministic models, either in a continuous simulation or event mode, making maximum use of hydrometric measurements to either directly identify model parameters, or constrain parameter uncertainty.

There is a mixture of lumped, semi and fully distributed run-off routing frameworks, although it should be borne in mind that such routing frameworks may not yield the same benefits in the temperate maritime UK context where reservoir catchments tend to be small.

In contrast, in the UK the modelling framework is more prescribed and dates back to the original FSR empirical, unit-hydrograph lumped catchment rainfall-runoff model of the 1970s. The UK has a strong track record of using generalised hydrological models in the absence of local monitoring data, or to augment sparse monitoring data. In the context of dam safety, a contributing factor may be the typically small size of UK dams: many of the published studies from overseas that involve locally-specific calibration work are for much larger dams.

In the UK, the ReFH model has largely replaced the FSR for estimating lower return period events. The latest version of ReFH, ReFH2 has been found to provide broadly comparable estimates of PMF to those obtained using the FSR when the same modelling assumptions reflecting antecedent conditions and enhanced run-off routing are applied.

There is a very large number of alternative rainfall-runoff models available. Researchers and practitioners often select models mainly because of their familiarity. Recent research indicates that empirical ‘deep learning’ models can outperform conceptual or process-based models. Any application of these to estimating PMF would need to convincingly demonstrate that such models could simulate extreme events much larger than those included in their training data set.

4.4.2 Change in processes with event magnitude

4.4.2.1 Processes and their representation in models

As floods become larger the dominant hydrological processes that control the catchment response to the event can change. As summarised within the Australian ARR guidance (Ball and others, 2019), some of these processes, such as greater connectivity of flow paths, stripping of vegetation and deeper flow, will increase the rate of response within a catchment. Other processes however, for example, more turbulence, energy required for sediment transport, and more flow within the floodplain (plus storage effects) may decrease the response rate. The overall impact will, therefore, depend on the balance of these processes within the catchment of interest. Another example of a change in processes that may affect some catchments during extreme floods is alteration to the contributing area via transfer of water across catchment boundaries. A more detailed summary of some of these processes is discussed below.

Water chemistry studies show that much of the water in the rising limb of the hydrograph has been in the catchment for a while. There is the concept of the ‘hydraulic piston’ pushing water through the catchment though a range of spatially complex mechanisms, including true interflow, exfiltration, overland flow, re-infiltration, and so on. As the event progresses, precipitation from the event starts to enter the stream network and is routed quickly through the catchment. Most rainfall-runoff models wrap this complexity up as a second order reservoir-based routing model (quick and slow flow), and model parameterisation reflects this (both calibration at site and generalised parameter equations).

In an extreme event, infiltration excess run-off may dominate over saturation excess, with rapid routing of overland flow (as sheet flow, or more commonly through topographic drainage paths). These processes can result in a reduction in run-off accumulation times, and greater proportion of effective run-off, resulting in a more peaked hydrograph with greater volumes of run-off. This can be a gradual transition, but in some catchments the change is thought to occur more suddenly, as a tipping point.

Once the flood water has entered channels, the rapidity of the routing may be strongly influenced by features within the channel network, including bridges, woody/debris dams, as well as the failure of structures such as dams, bridges or landslides. There will also be instream sediment transport within the network reducing available energy, as well as additional storage, in the form of the natural flood plain, or more formal storage features.

These processes can be modelled within an appropriate physically-based model where any changes will manifest implicitly within the model outputs. Physically-based models, therefore, have the advantage that is not necessary to predict the balance between the processes that increase or slow catchment response. Ideally, the structure and parameterisation of a true physics-based model would be based entirely on catchment observations of physical properties. However, while this is a potentially realistic proposition at the scale of the hillslope, it becomes increasingly generalised at any sort of catchment scale in the face of paucity of measurement and the ability to measure the actual physical properties that the model might require. As discussed previously, most ‘physically-based’ models are hybrid models. Calibration to observed events, preferably large ones in the context of PMF estimation to ensure that the dominant processes are captured adequately, is inevitably required. Some processes are more straightforward to represent than others. For example, storage and routing of overland flow may be better represented than sub-surface flow processes. However, even overland flow routing can depend critically on factors such as the resolution of the model grid. Therefore, although more theoretically ‘transparent’ than the simpler modelling frameworks, the predictive power of physically-based models at a meaningful catchment scale may not necessarily be better.

All the within and out-of-channel temporary or chronic hydraulic restrictions to flow (debris dams) and the consequences of collapse of some of those features can be modelled to a greater or lesser extent by hydraulic models, for example, the catastrophic event at Boscastle (Bettes and others, 2006). However, the ability of models to capture these impacts can vary significantly depending on data availability and the specific model used.

The class of conceptually deterministic models that underpin generalised model schemes and indeed models for catchment level calibrations cannot capture the aforementioned processes in a meaningful way. Similarly, the sample of extreme events in any one catchment that would be required to adequately calibrate this class of model is rarely available. Literature suggests that the impacts of these process changes result in a higher proportion of rainfall becoming run-off and shorter run-off accumulation times, resulting in a more peaked hydrograph. This has led to ad-hoc contractions of unit hydrograph time to peak, the reduction of time-constants for routing reservoirs, as well as an increase in the proportions used to derive effective rainfall.

Generally, parameters, whether of complex physically-based models or simpler lumped models, wherever possible, are calibrated using observed data associated with large historical events to provide confidence that the model is capturing the processes that dominate during large events adequately.

In practice, we need to have methods that are tractable for practitioners to apply with a reasonable skills base, and within a reasonable time and budget. Reservoir safety is a niche area of hydrological application. While the estimation challenges might appear to be simpler than those facing hydrologists grappling with more frequent events, until we start to see true physics-based models gaining traction both in studies looking at more frequent floods and daily flow regimes (for water resources), it could be argued that they should not be considered seriously for reservoir safety.

The following section reviews how these process changes are represented in current methods across the world and considers the supporting evidence for these changes.

4.4.2.2 UK methodology

The increase in percentage run-off with rainfall depth is modelled in the FSR method using a dynamic term, DPR_{RAIN}, in the percentage run-off equation. This term is only applied above a threshold of 40 mm and is formulated as:

$DPR_{RAIN} = 0.45 (P - 40)^{0.7}$

where P is the precipitation within an event, including snowmelt.

This is a very simple, entirely empirical, approach to simulating the evolution of soil moisture saturation within the event. It could be argued that this is no substitute for a deterministic soil moisture accounting procedure applied with a catchment specific parameterisation.

The unit hydrograph theory, on which the FSR/FEH method is based, assumes that catchments respond as linear systems. Two of the main principles are:

- proportionality - effective rainfall intensities (volumes) of different magnitude produce hydrological responses that are scaled accordingly
- superposition - responses of several different storms can be superimposed to obtain the composite response of the catchment

In practice, this assumption does not always hold and the FSR discusses the evidence for a non-linear model and potential solutions.

At present, for estimating PMF within the UK, one of the main parameters that is adjusted to incorporate these perceived process changes, and the potential for non-linearity, is a reduction in the time to peak parameter of the unit hydrograph, Tp. While the FSR (NERC, 1975) notes that no consistent relationship was found between the intensity of an event and the Tp in the data set as a whole, it puts forward several arguments to indicate why there might be either a shortening or lengthening of the unit hydrograph. It states that, based on hydraulic theory, greater depths of water move faster, therefore, high depths of rainfall will impact the distribution through time of the run-off, resulting in a quicker catchment response. This led to the recommendation that the unit hydrograph should be adjusted according to the size of the design storm. The FSR also cites the work of USACE in the US which suggests a slimmer and taller unit hydrograph for large events. However, a converse argument is also presented within the FSR that, as the catchment gets wetter the size of the ‘contributing area’ extends back from the channels and up into the higher areas. Therefore, the wetter the catchment, the longer the average travel time within the catchment.

Despite a lack of evidence within the wider data set, the FSR found that individual UK ‘extreme’ events (the report cites the Louth event from 1920, the Lynmouth disaster from 1952 and the Dunsop Bridge event of 1967) show response run-offs for very large events which are quicker than the corresponding average response times. For the chalk-dominated Louth catchment, this was attributed to rapid response run-off being generated from the chalk outcrops.

A more in-depth analysis was completed on a small number of catchments from the UK and overseas where underestimation of the peak was attributed to overestimation of Tp in at least 3 cases: Louth (1920), Dunsop Bridge (1967) and New Zealand (1967). Within further discussion of discontinuities in run-off processes, it was proposed that it might be possible in the future to change to a non-linear model form, with Tp being dependent on CWI, that is, the antecedent soil moisture conditions. The FSR, and subsequently the FEH (Houghton-Carr, 1999), on balance recommend a reduction of one-third in Tp when modelling the PMF, based on the few extreme events analysed. Another reason for this reduction was an attempt to represent the worst-case scenario of a storm moving downstream.

Later studies have also attempted to produce more clarification on whether the Tp adjustment is sufficient or justified. Acreman (1989) theorised that the design estimate of PMF was exceeded within 6 historical floods (now reduced to 5 after reassessment in the current project) due to not reducing Tp enough. It should be noted that the peak flows were estimated using approximate hydraulic methods rather than measured at gauging stations. Kjeldsen and others (2005) found that 15 of the largest events collated as part of the ReFH development research showed a faster than average response. Faulkner and Benn (2019) present results from a small number of catchments, showing evidence of a trend towards a shorter Tp for more intense rainfall, including data from work by Wass and all, (2008) where the lag time (related to Tp) reduced dramatically as the maximum 15-minute intensity increases for 3 catchments on the North York Moors as well as one lowland catchment (Cherry Tree Brook). It is reported that the phenomenon has been observed on other lowland catchments in the south-east of England. In addition, analysis of the June 2005 flood on the River Rye indicated a Tp one-third of its average value. A postulated physical explanation was that the extreme rainfall intensity led to overland flow, concentrated into erosion gullies that extended the channel network, making the delivery of rainfall to the river more efficient, as discussed above.

Bettes and Bain (2006), investigating the extreme flood in Boscastle in 2004, modified the FSR method, when applied as part of a composite hydrological and hydraulic model of the catchment to fit the observed flood inundation depths by both reducing the Tp by 50% and incorporating an empirical time-variant percentage run-off. The latter mimics the evolution of saturation excess that is modelled deterministically by ReFH and other deterministic rainfall-runoff models.

A reduction in run-off time has been observed both in the UK (for example, Faulkner and Wass 2008; McIntyre, 2013) and elsewhere (for example, Grimaldi and others, 2012; Kjeldsen and others, 2016; Meyersohn, 2016). On some watercourses hydrographs have been measured with near-vertical rising limbs as a response to intense rainfall without any blockage and failure of a structure (Archer and Fowler, 2018).

As part of a Royal Society fellowship with WHS, Kjeldsen (2020) analysed peak flow events from a number of the experimental catchments within the Plynlimon paired catchment experiment, finding some evidence of a reduction in Tp with event magnitude. However, further analysis from 19 medium to large Scottish catchments was less conclusive, and it was recommended that further work was necessary to see if the results are more widely applicable within the UK.

4.4.2.3 International practice and research

While international guidance also discusses non-linear routing, this is often not supported by clear recommended methods. In the USA, the USBR (1989) Flood Hydrology Manual says, for PMF, that infiltration rates should be "more conservative" than average and advises that the use of the unit hydrograph should be representative of extreme conditions. It notes that, depending on whether there is a decrease or increase in the hydraulic efficiency of the catchment's network, the impact on the 'lag' could be increased or decreased. This approach is reflected within the FERC Engineering Guidelines (2014), which note that the predicted peak flow of the PMF may be too low (or too high) as a result of non-linear effects in the run-off and the channel flow process that violate the unit hydrograph assumption of linearity between streamflow and excess rainfall. The guidelines cite Pilgrim (1988) and state that studies relating to such effects have been inconclusive.

Alberta Transportation (2004) in Canada similarly does not give firm recommendations beyond considering an adjustment by reducing the lag or increasing the peak flow and refers to the UK FSR approach of reducing Tp by a third and similar. It also states that the percentage run-off within a PMF event can be higher than 75%, whereas run-off in historical events is usually 20% or less, particularly in drier areas of Alberta, indicating that they consider that percentage losses can also change significantly. The example percentage run-off values are presented as a precaution against distrust of PMF values which may, initially, seem too high.

In Australia, ARR (Ball and others, 2019) recommends that the non-linearity of routing should be analysed on a per catchment basis by plotting parameter variation with flood magnitude or, for ungauged catchments, by assessing evidence from very rare floods on similar catchments. As within the UK and US guidance, ARR accepts that there are factors that may result in either a decrease or increase in the response rate within a catchment.

ARR notes that different loss models (mentioning the initial loss – continuing loss and initial loss – proportional loss) may yield similar flood peaks for the 100-year design event, but if the same parameterisation is retained for the 10^6-year event each model would produce very different design flood hydrographs. These types of loss models are widely used worldwide. Initial loss is specified as a depth that is subtracted from the rainfall to account for effects such as interception and depression storage. Continuing loss is where a mm/hr rate is subtracted from rainfall at all time steps. Proportional loss is specified as a fixed proportion of the rainfall in each time step, once the initial loss has been satisfied.

ARR considers the proportional loss model less appropriate than the continuing loss model for estimating extreme events. For the PMF, it recommends that losses should be equal, or possibly a little less, than the minimum value in large floods observed on the catchment. The guidance suggests a 1 mm/hr loss rate across most of Australia. ARR also notes that longer events are likely to be associated with lower losses as more of the catchment becomes saturated. However, within short duration events losses are lower relative to the total depth of precipitation than longer duration events, therefore, the resulting hydrographs (particularly volumes) may be more sensitive to the parameterisation within short duration events. This latter point may not be so applicable to the temperate maritime climate of the UK where generally soil moisture deficits are comparably low. For baseflow, ARR recommends adopting a constant value 20% to 50% higher than maximum observed, but note that baseflow is only significant when simulating long duration events relating to volume-dependent problems.

Within South Korea, analysis by Kjeldsen (2016) using the ReFH model showed no link between the parameter controlling run-off volume and any of the event characteristics, but established a dynamic link between the unit hydrograph (Tp) and rainfall depth. The authors demonstrated that a PMP event could reduce the Tp by 75%, resulting in an 80% increase in the magnitude of a PMF event when compared to simulations based on an average Tp value. Other relevant international research on the reduction in response time with event magnitudes includes Grimaldi and others (2012) and Meyersohn (2016).

One approach sometimes taken to represent changes in storage and routing processes is to couple a conceptual rainfall-runoff model (or models) with a hydrodynamic model which typically represents the lower parts of a catchment. This may help to represent processes that are not evident in smaller floods to which a hydrological model may be calibrated. The hydrodynamic model is physically based and should be more robust when the discharge exceeds the range of the observed data. Felder and others (2017) give an example of this application in Switzerland. This type of approach is occasionally applied in UK practice where there is a need to represent upstream storage, for example, when estimating PMF for a reservoir in a cascade.

4.4.2.4 Summary on changes in process with magnitude

- UK and international guidance recognises that, as floods become larger, some processes may slow the response within a catchment, while others will increase the response rate.
- Within the UK, this response change is currently captured by reducing Tp by a third, which increases the modelled peak flow. There is evidence to show that, within some small catchments at least, extreme rainfall events tend to have a more rapid response than lower return events.
- It is recognised within international literature that loss processes may also change within extreme events. The ARR guidance recommends that, for this reason, proportional loss models should not be used. Within the FSR/FEH model a dynamic term DPR_{RAIN} in the percentage run-off equation reflects an increase in the proportion of run-off as events become larger.
- Although not widely reported in the international literature, the Australian experience expressed in the ARR guidance is that baseflow may be enhanced in long duration events.
- Although physically-based models may have the ability to represent changes in process more explicitly, their predictive power at a meaningful catchment scale may not necessarily be better.
- Physically-based models do offer the prospect of representing processes such as storage and routing of out-of-bank flow which may not be present in events to which rainfall-runoff models are calibrated.

4.4.3 Storm duration

The storm duration of the PMP event will impact on both the volume of input precipitation (rainfall and/or snowmelt) within a catchment and the temporal distribution of the rainfall (intensity), and, therefore, will have an impact on the resulting PMF calculated.

The critical duration is defined as the duration for which a unit depth of rainfall will give rise to the maximum peak flow or water level at a particular point in a hydrological system. This is clearly related to the run-off accumulation times within a catchment. However, the attenuating influence of the storage of a reservoir can mean that the critical duration at the outlet is longer than that at the inlet, sometimes several times longer.

For some aspects of reservoir design and assessment, it is important to assess the maximum period of time for which discharge is expected to continue over a spillway. This may mean selecting a different critical duration from that which gives the maximum peak discharge over the spillway. Some reservoirs, especially in upland areas, can be affected by sequences of wet weather lasting for days or weeks, leading to prolonged periods of spilling. In such cases, there is a risk that the water level is already above the spillway crest when a major flood arrives. It is important to allow for that when modelling design floods and safety check floods. This is not further addressed within the present study, which focuses on the PMF rather than reservoir flood estimation in general.

4.4.3.1 UK methodology

In current UK flood estimation, the recommended design storm duration is based on an equation relating duration to Tp and SAAR (annual rainfall). Originally defined in the FSR, this equation has been retained for both the FEH restatement of the FSR rainfall-runoff method and ReFH. The equation was originally intended to find the critical duration, that is, the duration that provides the highest peak flow. The derivation of the equation is glossed over in the FSR, but the reason for including SAAR was because of the dependence of the critical duration on a ‘continentality factor’ included in the FSR rainfall frequency model. The equation assumed a triangular unit hydrograph. Since neither of these considerations applies to contemporary approaches to design event modelling in the UK, there should be no expectation that the equation still generates the critical duration.

IH Report 114 (Reed and Field, 1992) provides a method for estimating the RLAG, the increase of the critical duration, to account for the impact of reservoirs. Reed and Field (1992) also evaluated the sensitivity of the critical duration and found that for the FSR DDF rainfall model, the critical duration decreases with return period. They also compared the critical duration with the FSR/FEH recommended storm duration, noting that while the former can occasionally be much longer, usually the peak flows are very comparable for the 2 durations. The report also recommends that bespoke, iterative analyses are carried out to determine the critical duration of a reservoir system where practicable to do so.

Similarly, the ICE guidance recommends the use of the critical duration for a given reservoir, relying on practitioners to complete sensitivity studies to determine that ‘critical’ duration. Storm duration in other UK studies such as Pucknell and others (2020) and

Stewart and others (2019) use the FSR/FEH recommended duration, to allow consistency of results between catchments, therefore, it does not directly assess the influence of duration on peak flows.

It should be noted that the concept of a ‘critical’ duration is immaterial when considering the PMF within the current UK method. This is due to the ‘nested’ nature of the PMP profile, such that the central rainfall intensity for both a 4-hour duration or 8-hour duration of timestep one hour, will be that associated with the one-hour event; there is no decrease in central intensity as duration increases, as is found with the T-year rainfall profiles. However, it is still necessary to select a duration for the design PMP event.

The impact of using different durations of PMP events on peak flows, and importantly volumes, appears not to have been fully assessed in the UK.

4.4.3.2 International practice and research

In Australia, ARR (2019) guidance for the design of a dam spillway or a detention basin recommends that floods should be calculated from a range of design rainfall durations and should be routed through the storage for a variety of combinations of spillway and gate configurations, operating procedures and dam crest heights to determine the optimum design. The guidance recommends that, for very large storage volumes or large catchments, very long durations may be necessary (over 7 days), and in this case, sequences of storms may need to be considered. This may be less of an issue within the UK, although there are examples of sequences of storms, for example, the sequence containing Storm Desmond in 2015.

In the USA, FERC (2001) recommends considering both short (local) and long duration storms in determining the critical duration.

In New Zealand, McKerchar (2010) focuses on what is appropriate for a catchment. An interesting topic that is discussed is the modelling of a sequence of wet weather (number of storms) that may result in catchment conditions giving rise to large floods. However, no prescriptive guidance is provided.

4.4.3.3 Summary on storm duration

At present in the UK, the FSR/FEH recommended design duration is often used.

Research by Reed and Field (1992) showed that the critical duration may be far longer than the recommended duration for T-year events. Due to the development of the PMP using a ‘nested’ approach, the concept of a critical duration for the PMF event becomes less relevant.

In most literature, the identification of a catchment-specific critical duration is recommended through sensitivity testing.

Operational practice in the UK for complex reservoired systems will often consider the conjunctive modelling of the catchment run-off and reservoir storage to identify the critical storm duration.

4.4.4 Antecedent conditions

While antecedent conditions can include a number of factors, this section is largely concerned with estimating antecedent soil moisture conditions. It does not explicitly consider snowmelt (see section 4.5.1 Snowmelt) or reservoir levels, because the study is not concerned with methods of reservoir routing.

4.4.4.1 UK methodology

In the FSR, there is an assumption that a PMF event will follow a period of extremely wet weather. This is represented by adjusting the catchment wetness index (CWI) using an antecedent event. First, the PMP event for a storm 5 times the design duration, centred on the design event is determined. The CWI is then calculated using only the part before the PMP event.

The guidance was modified in the ICE 1978 guide to avoid mixing summer and winter rainfalls. For winter events, snowmelt can also contribute to the antecedent conditions, affecting CWI. While unclear in the original guidance, the method is clarified within the FEH (Houghton-Carr, 1999); first the snowmelt during the design storm duration is subtracted from the 100-year snow depth, then the remainder is added to the antecedent precipitation at the melt rate.

A review of the role of antecedent conditions relative to that of event rainfall in historical dam safety incidents in the UK is given by Reed (1992). Antecedent rainfall was found to be more influential in relatively permeable and low rainfall catchments, in which significant soil moisture deficits can develop. Reed (1992) focuses on the issue of joint probability. While this may be less of a concern in estimating PMF than the T-year flood, it is worth considering whether the assumptions made about antecedent rainfall in the FSR method of PMF estimation are appropriate.

ReFH uses different loss model parameters, therefore, the wetting up and frozen ground adjustments are not directly transferable. Pucknell and others (2020) devised an adjustment to C_{ini} (initial soil moisture in ReFH) to represent the changes in antecedent conditions and the impact of frozen ground within the FSR/FEH PMF method based on the absolute difference in percentage run-off. Using this adjustment, but over a relatively small catchment data set, this study demonstrated that, by using this adjustment in conjunction with a contraction of Tp, ReFH can provide comparable estimates of the PMF to the FSR based procedure.

4.4.4.2 International practice and research

International antecedent condition guidance is also based on applying antecedent rainfall, but can vary considerably. The USBR (1989) assumes antecedent rainfall has satisfied any soil moisture deficit (SMD), so that there are no initial losses for the PMF. There is also some guidance on adding an antecedent storm which varies with location in the country. FERC (2001) recommends analysis of historical extreme floods and antecedent storms (a method is presented) for the region and to add this to the beginning of the PMP event. The guidance also notes that for PMF run-off computations the soil should be assumed to be saturated, with infiltration occurring at the minimum rate applicable to the area-weighted average soil type. USACE (2017a), in application at Whittier Narrows dam, includes an antecedent rainfall (60% of the PMP) with a one-day lag between this and the PMP, based on an analysis of historical events. The FERC guidance also states that allowances should be made for antecedent rainfall in choosing the initial reservoir level for routing. One suggested approach is to assume that a 24-hour storm of return period 100 years ends 3 days before the PMP. England and others (2014) tested the sensitivity of antecedent soil moisture conditions as part of their detailed modelling of the Arkansas basin and found that it had a ‘moderate’ effect on the peak flows and volumes; for soil moisture changes from 0.5 to 0.8 (50% saturation and near saturation) peak flow discharges and volumes were found to increase by a factor of 1.2 to 1.75. However, for the largest events, most relevant in the cases of estimating PMF, the differences were less; the factorial increase for a soil moisture change from 0.05 (dry) to 0.8 (near saturation) was 1.59.

The Alberta Transportation guidance (2004) in Canada also has a useful review of various guidelines. While it discusses the use of antecedent storms, for example, BC Hydro guidelines recommend a 100-year snowmelt or 100-year rainfall before the PMP, it generally favours the approach of combining PMP with severe but not maximised antecedent conditions. The guidance states that back-to back events are relatively uncommon in Alberta, therefore, it is recommended that, for both general and local storm PMPs, initial soil moisture levels at the start of the PMP can be determined by assuming that a 10-year 48-hour general rainfall event finishes 5 days before the start of the PMP. Recovery of soil moisture deficit between the end of the antecedent event and the start of the PMP should be estimated as appropriate for the time of year, soil conditions and vegetation cover. This recommendation was based on analysis of Alberta storm data.

Other countries do not have clear guidance but are distinct, based on the climate and their location in the world. In Norway’s Guidelines for flood calculation (2011), it is assumed that coastal catchments are saturated. For other catchments, the soil moisture deficit (SMD) is assumed to be approximately 20 to 50 mm for calculations of floods with T<1,000 years. For PMF, it is advised to consider a lower SMD. In Australia, while it is stated that there is no evidence that initial losses are any different for extreme storms in SE Australia for PMF, the initial loss is recommended to be set to around the minimum observed initial loss value for the catchment, or zero (Ball and others, 2019).

4.4.4.3 Summary on antecedent conditions

At present in the UK, antecedent rainfall is used to adjust the antecedent soil conditions. This uses an event of 5 times the PMP duration centred on the PMP event, of which it is assumed that only 2 times the design duration occurs before the PMP event.

Pucknell and others (2020) have demonstrated an approach for applying the current PMF modelling guidance within the ReFH2 model.

International guidance offers varied approaches in applying antecedent rainfall, with methods being distinct for varying climate.

4.5 Snow, frozen ground and joint probability issues

4.5.1 Snowmelt

4.5.1.1 UK guidance: overview

In the current UK procedure, when estimating a PMF for the winter season, snowmelt is added to the design storm. The sections below start by considering the relative importance of the 2 components to estimate snowmelt: the melt rate and the depth of snow. The evolution of the UK procedure for estimating snowmelt is then described, followed by a review of related research.

4.5.1.2 UK guidance: melt rate versus snow depth

As well as providing the rate of snowmelt, it is also necessary to provide the expected depth of snow, in case the melt rate is large enough to melt all the available snow before the end of the design rainfall event. It may be possible to avoid this second step, depending on how the melt rate has been estimated, as discussed below.

The FSR provides a map of snow depth across the UK with a return period of 2 years, estimated from 18 years of data between 1946 and 1964. It estimates that the 100-year snow depth is about 7.5 times the 2-year depth. It suggests that the depths on the map can be interpreted as the snow water equivalent with return period 100 years, because the density of liquid water is about 7.5 times that of snow, with snow having a density of about 0.13 g/cm^3 and liquid water 1.00 g/cm^3 (at 4^{o}C). This assumption was criticised by Archer (1984) who suggested that the density of a snowpack after a prolonged period of cover could be about twice as high. If so, the depth of snow water equivalent would need to be increased.

In the UK context, melt rate is thought to be more important than snow depth on most catchments, because response times are usually short enough that the melting does not exhaust the available snowpack (Reed and Field, 1992). This may be the reason why the reviews and improvements to the FSR procedure described below have concentrated more on melt rate than snow depth. However, it is important to remember that the snow depth map in the FSR is based on limited data and may become increasingly out of date as the climate warms. By the 2070s, most lowland areas of the UK are predicted to be almost snow-free in winter, and decreases in snow cover are also expected in mountainous areas (Kendon and others, 2021).

The findings of Reed and Field (1992) assume a 42 mm/day melt rate and so would not necessarily apply using much higher melt rates, as can be found from the Hough and Hollis (1997) procedure described below.

Taken together, these observations indicate that snow depth may be a more limiting factor than previously thought, and increasingly so in the future.

4.5.1.3 UK guidance: FSR and FEH procedure for snowmelt

The FSR (NERC, 1975) recommends that a winter PMP is combined with the 100-year return period snow depth in conjunction with a melt rate of 42 mm/day, also intended to represent a return period of 100 years. The melt rate was derived from an estimate of the 100-year temperature at times when snow was lying, which was 8.6°C.

Snowmelt is to be added to the design rainfall at a uniform rate, as long as the snow depth lasts. Melt should also be added to the antecedent rainfall, from which the catchment wetness index is evaluated. The same procedure is repeated in the FEH (Houghton-Carr, 1999), which makes clearer how snowmelt should be apportioned between the antecedent rainfall and the storm rainfall. First, the snowmelt during the design storm duration should be calculated. This should be applied during the entire storm duration or, if there is not enough snow depth, centred on the most intense part of the storm. If there is any snow still available for melting, this should be added to the antecedent precipitation, at the same melt rate.

The FEH provides a map of the rate of snowmelt over 24 hours, based on analysis by Hough and Hollis (1997), discussed below. The map is for a return period of 5 years and so the melt rates need to be scaled up to a 100-year return period, although this is not stated in the FEH. The map shows one contour, for a melt rate of 42 mm per day (1.75 mm/hour) and also demarcates large upland regions where a higher, but unspecified, value might apply (Houghton-Carr, 1999).

ICE (2015) continues to recommend the FSR procedure, using the 100-year return period melt rate, with an important addition for upland areas. It recommends that in the upland areas, practitioners should make their own estimate of the melt rate, for example, using information from Hough and Hollis (1997).

4.5.1.4 UK snowmelt research from the FSR to the present day

Faulkner and Benn (2019) provide a recent review of UK research and practice related to the calculation of snowmelt for estimating PMF. This section draws on their findings, as well as additional literature.

There were 2 components to the FSR snowmelt analysis, one based on meteorological data, carried out at the Met Office, and the other on snowmelt run-off, based at Newcastle University. The results from these studies were widely divergent. The work at Newcastle University found melt rates in excess of 5 mm/hour and these findings were supported by observations of snowmelt run-off in the northern Pennines (Archer, 1981) and theoretical studies (Mawdsley and others, 1991). The disparate views are resolved to some extent by Hough and Hollis (1997), discussed below.

Reed and Field (1992) provide an in-depth review of estimating snowmelt for reservoir flood studies. They conclude that radiation balance and turbulent exchange processes play a major role; the contributions of heat from precipitation or heat at the ground surface are thought to be small or negligible. High windspeeds are found to be a big influence on heat transfer for snowmelt. In 14 out of 15 case study catchments, the summer PMF was found to be higher than the winter, suggesting perhaps that estimating snowmelt is not a widespread issue of practical importance in estimating PMF for the UK. There are 3 important caveats to this finding. These are that:

1. the calculations use a 42 mm/hour melt rate - higher rates would tend to increase the dominance of the winter season
2. the calculations were for inflows to reservoirs - summer dominance was found to reduce when calculating outflows, with an increased storm duration to allow for the reservoir lag effect
3. summer dominance was reduced in high rainfall areas, where many reservoirs tend to be located

Hough and Hollis (1997) is an important milestone in estimating snowmelt in the UK. Using an energy budget formula, the authors calculate snowmelt from hourly and daily windspeed, air temperature and vapour pressure data. Incoming solar radiative energy is ignored, as is energy from rainfall. The study uses data from 25 weather stations around the UK. Information on snow cover is included so that the melt rates are calculated only at times when snow covers more than half of the ground at the station.

Extreme snowmelt rates are extracted over durations between 3 hours and 7 days, and a Gumbel distribution fitted to the annual maximum melt rates. The paper provides a map of the 5-year melt rate with 3 contours, an improvement on the FSR map. It also gives regression equations that predict the 5-year melt rate for a 24-hour duration from either geographical variables (altitude and Northing) or meteorological variables. The geographical regression is recommended by ICE (2015).

Hough and Hollis (1997) tabulate melt rates for a range of return periods and durations at 17 UK locations. This information allows conversion from the 24-hour melt rate estimated by regression to a D-hour melt rate, also for the 5-year return period. Melt amounts in the table scale approximately with the logarithm of duration. This differs from the approach taken in the FSR/FEH, in which the melt varies linearly with duration. One consequence can be a large increase in snowmelt depths if the results in Hough and Hollis (1997) are used to estimate the melt for design durations of a few hours. This could significantly increase PMF estimates in some cases.

The publication also allows scaling up to longer return periods. Although it only provides melt rates for return periods up to 50 years, for the same locations it also provides parameters of an extreme value distribution fitted to annual maximum melts, along with the annual probability, p, of there being no snow on the ground for the duration in question.

From this information, it is possible to estimate the 100-year return period melt rate in a way that accounts for any limitation on the availability of snow for melting. However, this is only applicable for melt rates when rain is not falling, as discussed below.

There is a discrepancy in the results of Hough and Hollis (1997) in that the snowmelt depths can decrease with increasing duration at some stations. This is thought to be due to an oversight in the way the data were selected, with melt sequences lasting under D hours not included in the analysis of D-hour melts, even though they may have had the highest depths of melt (D. Hollis, pers. comm., 5 Dec 2017). Another possible implication of this is that the rate of increase of melt with duration is underestimated at some stations.

Another important factor is the need to increase the melt rate to allow for the energy added to the snowpack by incoming rainfall. The formulae in Hough and Hollis (1997) do not initially account for this increase in rate. It can be large during a PMP. Hough and Hollis (1997) recommend adding 0.0125 mm (of melt) per mm (of rain) per °C. The derivation of this allowance is not given, but the same expression can be found in Pena and Nazarala (1984). This addition could greatly increase the melt rate during a winter PMP in which a warm front moves over an upland area with snow cover. This does not agree with the findings of Reed and Field (1992). The influential role of energy added by rainfall is stressed in guidance for the USA (FERC, 2011). This additional factor does not account for any limitations on the depth of snow available for melting, so the resulting melt rate needs to be applied in conjunction with a map of snow depths, for example, that provided in the FSR.

Since 1997, there has been limited research on estimating extreme snowmelt in the UK. Two studies described below have focused on Scotland.

Gosling and others (2002) carried out an experimental evaluation of 6-hour and daily snowmelt rates in the Cairngorm mountains. The melt rates were found to exceed the values from the FSR but not those from Hough and Hollis (1997). There is also a discussion of the melt rates in the context of the contribution to flows. The authors note that the melt rates were limited by the water volume available in the snowpack.

For a PhD on mountain snow conditions in Scotland, Spencer (2016) used a model to derive snow cover and melt on a grid over a 50-year period, then carried out extreme value analysis, comparing his 5-year estimates with those of Hough and Hollis (1997). Reasonable agreement was found at low elevations, but the newer melt rates were much lower at higher elevations. Spencer (2016) suggests this might be due to an underestimate of higher elevation precipitation in the gridded rainfall data used by the model and a lack of sub-cell parameterisation, rather than querying the results of Hough and Hollis.

4.5.1.5 International practice and research

Some international literature has been included in this review. The amount of attention paid to snowmelt varies greatly in accordance with the climate, with Canadian guidance providing much more detail than Australian, for example. Methods used to calculate snowmelt include:

- a degree-day model in Canada (Alberta Transportation, 2004) and Norway (NVE, 2011)
- an energy budget method in the USA (FERC, 2011) - this is recommended in preference to the degree-day method which is applicable only to dry periods and the energy budget method allows for the heat added to the snowpack by rain, which can be an important, even dominant melt factor
- the SCHADEX method in France which simulates both rainfall, snow accumulation and snowmelt (Paquet and others, 2012)

Zhirkevich and Asarin (2010) describe snowmelt in the context of estimating PMF for Russia. The paper states that for snow-rain run-off events, rain contributes 30% to 40% of the volume. The peak flow is caused by rain, and no infiltration is assumed, due to complete saturation of soils.

Fassnacht and Records (2015) aim to quantify precipitation, rainfall and snowmelt at higher elevation locations across the Southern Rocky Mountain region for 10 and 100-year return periods.

Yan and others (2020) describe recently developed next-generation intensity-duration-frequency (IDF) curves for the USA that explicitly account for the mechanisms of extreme water available for run-off, including rainfall, snowmelt, and rain-on-snow, under nonstationary climate. This novel approach dispenses with the need to combine snowmelt with rainfall. When comparing the new IDF curves with previous rain-only analysis using rainfall-runoff modelling, the authors found that 70% of sites were subject to under-design, with the old method underestimating peak design floods by as much as 300% [it is not clear how underestimation by more than 100% is possible]. It is doubtful whether snowmelt is an important enough influence on UK floods for such an analysis to be worthwhile.

4.5.1.6 Effect of climate change on the role of snowmelt in flooding

Madsen and others (2014) reviewed observed and projected trends in climate across Europe, including impacts of climate change on snowmelt-contributed floods. The paper reports that several studies from regions dominated by snowmelt-induced peak flows have found decreases in extreme streamflow and earlier spring snowmelt peak flows, likely caused by increasing temperature. The authors project a general decrease in flood magnitude and earlier spring floods for catchments with snowmelt-dominated peak flows, consistent with the observed trends.

A picture more focused on the UK is given by Brown (2019) who, using an empirical model linking snow cover to temperature and precipitation, found a long-term decline in average UK snow cover. The decline was strongest in some mountainous areas, notably northern England. Further declines in snow cover are projected in the future: a climate projection showed average yearly snow cover predominantly confined to mountain areas of Great Britain by the 2050s.

Other references, not reviewed for this phase of the project but worth consulting in future research, include Kay (2016) and Bell and others (2016), which examine the impact of projected changes in snow on peak river flows.

One conclusion that could be drawn from these observations and projections is that further research into snowmelt in the context of estimating PMF in the UK should be allocated a lower priority than some other aspects of the estimation procedure.

4.5.2 Effect of freezing or snowmelt on run-off or infiltration

The FSR suggests allowing for the possibility of frozen ground by setting the standard percentage run-off (SPR) parameter to a minimum of 53% when estimating the PMF for the winter season. This is in line with the ‘worst possible scenario’ philosophy of the PMF concept, although the need for this adjustment is acknowledged to be a matter for judgement given the conservatism of other components of the design event (NERC, 1975). Frozen ground was thought to have been an exacerbating factor in the severe floods of 1947. Reed and Field (1992) add 1809 as another example of a flood in which frozen ground and rapid snowmelt were thought to have been influential.

In the UK context, the possibility of extreme rainfall on frozen ground is a particular concern on groundwater-dominated catchments which normally show a subdued run-off response. The great flood of 1841 on the River Till in Wiltshire is sometimes quoted as a classic example of this effect (Acreman, 1989). The Till drains a chalk catchment on the southern edge of Salisbury Plain. However, the role of frozen ground in this flood is disputed by Clark (2004) who concluded that the subsurface was probably not frozen. Another extreme flood on an (unnamed) chalk catchment is mentioned in NERC (1975), Volume I, section 7.2.5: a small chalk catchment in southern England produced a flood 10 times its mean annual flood in 1947.

Relatively few references to the effect of ground temperature on run-off were found in the international guidance documents on PMF estimation included in this review. USBR (1989) envisages that, since the melting snowpack tends to satisfy infiltration losses, losses will be minimal during rain-on-snow events. FERC (2011) has a more detailed review of the effect of infiltration characteristics of soils in freezing conditions. It distinguishes between granular frost, which leads to little reduction in infiltration and tends to occur in coarse-grained sandy soils or in dry conditions, for example, in woodland, and concrete frost, which is largely impervious and is more likely in clay soils or wet conditions.

FERC (2011) also makes an important point that thawing and refreezing can result in the formation of an impervious ice layer on the soil surface. This seems relevant to the UK context, where winter temperatures during some cold spells oscillate around the freezing point.

Academic references on the effect of frozen ground on run-off are more widespread. Literature from Canada was found particularly informative. Gray and others (2001) state that, in most situations, the infiltration rate of a frozen soil is low. However, limited infiltration might be expected, and percolation and refreezing into the snowpack may also occur. A model of snowmelt infiltration to frozen ground was developed by Grey and others (2001), and measurements of infiltration rates are reported by Pomeroy and others (2005). In both cases, infiltration rates to frozen soils in the boreal forest were found to be lower than rates found in a prairie environment, for equivalent conditions of soil moisture and snow depth. In the southern boreal forest, little or no infiltration was found, regardless of soil moisture conditions. Despite this, there may be some absorption of rain by deep snowpacks, and/or some infiltration even into frozen ground in situations where the soil moisture content is low before freezing (Watt, 1989).

Research in Vermont found that frozen ground increased the run-off response in a small experimental basin but not in a larger catchment nearby. The paper states that “the enhancement of runoff due to soil frost is evident on small plots and in extreme events, such as rain on frozen snow-free soil. In the north-eastern USA and eastern Canada, the effect is often masked in larger catchments by several confounding factors, including storage of meltwater in the snowpack, variability in snowmelt timing due to elevational and aspect differences, interspersed forested land where frost may be absent, and the timing of soil thawing relative to the runoff peak.”

In summary, understanding and modelling the effect of frozen ground on run-off response is not straightforward. It is often complicated by the presence of snow and by the heterogeneity of catchment conditions, as well as depending on soil properties and moisture. However, it could be that in a UK context the magnitude of the frozen ground effect is less important than the question of its likelihood: is frozen ground likely to coincide with extreme rainfall and snowmelt? The next section examines the question of joint probability. It is relevant not only to estimating inflows, but also to questions of the hydraulic capacity of dam spillways, which might be reduced by ice blockage.

4.5.3 Joint probability of rain, snowmelt and frozen ground

4.5.3.1 UK guidance and related research

Although guidance on estimating PMF is not always concerned with attaching probability to the estimate, there is still a desire to produce an estimate that is reasonable rather than impossibly high. For this reason, joint probability is a relevant consideration (ICOLD, 2015). It becomes a more important issue when there is a need to associate PMF with a probability.

Relevant considerations include the joint probability of storm rainfall with antecedent rainfall (discussed earlier), snowmelt and frozen ground. The latter 2 phenomena are considered in this section. Also relevant to reservoir safety is the occurrence of extreme wind speeds, although this is not considered in the present project.

The guidance to combine the PMF with a 100-year return period snowmelt (and 100-year snow depth), still applicable today in the UK, originated in the FSR (NERC, 1975). The FSR acknowledges that, assuming independence, the chance of the 10^5-year rain and the 100-year snowmelt occurring in the same year is one in a million, and even lower for occurrence in the same day. However, it was thought "wise not to regard even the occurrence of an extreme thunderstorm over a frozen catchment with deep snow lying as physically impossible." The 100-year return period does not appear to have been based on any explicit consideration of joint probability.

The FEH notes in passing that conditions for extreme rain and snowmelt may not be fully independent. An obvious case in point is the energy provided to the snowpack by incoming rainfall.

In the early 1990s, the Department of the Environment (DOE) commissioned research on joint probability for reservoir flood safety. The findings are not all easily accessible: some were published as journal or conference papers and others as a PhD thesis. Relevant references include Reed (1992), Reed and Anderson (1992) and Brown and Root (2002). Reed and Field (1992) also provide a critique of joint probability issues in UK reservoir flood estimation, although the outputs of the DOE project were not yet available. Reed and Anderson (1992) discuss joint probability of variables, including wind speed, catchment wetness and initial reservoir level as well as rain and snow. Frozen ground is not considered. The focus is more on T-year flood estimation than on the PMF despite its prominence in the abstract. The project was part way through at the time of writing the paper and, therefore, no results or relevant conclusions are presented.

More recently, Collier (2017) investigated the joint probability of various meteorological influences on dam failure. The paper sets out the statistical concepts for analysis of concurrent risks when considering failure modes for dams. It includes a brief example of the joint occurrence of PMP and snowmelt, using snowmelt probabilities from Hough and Hollis (1997). The paper does not suggest any alternatives to current guidance on combinations of rainfall and snowmelt for estimating PMF.

4.5.3.2 International practice

The combination of a 100-year snowmelt with PMP is also recommended for the USA by USBR (1989) and FERC (2011), for parts of the catchment where a snowpack is likely to exist.

In Canada, Alberta Transportation (2004) suggests various combinations of rain and snowmelt inputs to a PMF such as a 100-year temperature sequence with mean maximum snowpack, or the average temperature sequence applied to a 100-year snowpack.

Clavet-Gaumont and others (2017) refer to the Canadian Dam Association Dam Safety Guidelines, in which 3 main scenarios are identified as potentially generating the PMF: (i) a summer PMP event; (ii) a spring PMP event combined with the melt of a 100-year snowpack; and (iii) a 100-year spring rainstorm combined with the melt of a probable maximum snow accumulation.

Both USA and Canadian recommendations on joint probability of rainfall and snowmelt are compatible with the current approach advocated in the UK.

4.5.4 Summary on snow, frozen ground and joint probability

The method for estimating snowmelt is more up to date than most other aspects of the PMF estimation procedure in the UK.

The allowance for additional melt due to the heat energy provided by rainfall on the snowpack can lead to large increases in the melt rate.

There may be value in carrying out some sensitivity tests of the influence of snowmelt on the estimated PMF and checking whether the Hough and Hollis (1997) method gives realistic results in all cases.

Climate change is expected to reduce the role played by snowmelt in UK floods.

Understanding and modelling the effect of frozen ground on run-off response is not straightforward. It is often complicated by the presence of snow and by the heterogeneity of catchment conditions, as well as depending on soil properties and moisture.

The rule of thumb that combines a 100-year snowmelt with a PMP is arbitrary, but compatible with the approach applied internationally.

4.6 Palaeofloods

4.6.1 Introduction and UK examples

Palaeoflood investigations offer an alternative or complementary approach to estimating PMF or a wider range of extreme floods required in reservoir safety work. This approach has the potentially major advantage of looking at floods that have actually happened, avoiding complete reliance on uncertain estimates of PMP and rainfall-runoff models. Palaeoflood studies may locate evidence of ancient or recent floods that were missed by river gauges or rain gauges (Foulds and others, 2014). Another claimed benefit for dam safety assessments is that palaeoflood techniques avoid reliance on gauged records which may not include flood-rich episodes (Foulds and others, 2014). This is less of a convincing advantage when it comes to estimating PMF, since PMP is usually estimated from physically-based methods rather than extrapolated from gauged records.

Palaeoflood techniques are widely used in dam safety studies in some parts of the world, in particular the USA (see the next section). Palaeoflood information can also be found on UK rivers and there are examples of it being incorporated into flood frequency analysis (Longfield and others, 2018; Chiverrell and others, 2019). An in-depth review of the applicability of palaeoflood data to UK flood frequency estimation can be found in the report on the FEH Local project (Dixon and others, 2017). It refers to the availability of 556 palaeoflood records in upland areas of the UK, dating back to 1750.

This review has not come across any examples of reservoir flood studies in the UK incorporating palaeoflood data. This is despite the fact that UK guidance has long advocated that such palaeoflood data are considered in studies of extreme hazards such as reservoir floods (Bayliss and Reed, 2001).

Longfield and others (2018) provide an example of an upland stream in west Wales which demonstrates the potential for estimating past flood flows from boulder berms. Figure 25 is an example of a boulder berm where large boulders have been deposited next to the current river channel from previously experienced high flows. The highest estimate of the largest palaeoflood was nearly 20 m^3/s, but the preferred discharge estimation method gave a much lower estimate of 7 m^3/s. The PMF estimated by Longfield and others (2018) using FSR methods was 16.5 m^3/s. This used the standard 42 mm/day snowmelt allowance, and so may increase using a locally-derived estimate of snowmelt. In this example, the palaeoflood data did not justify any increase in PMF.

Figure 25: Boulders deposited by an exceptionally severe flash flood on Cogden Gill, Swaledale, in July 2019, photographed in 2020

Figure 25 shows small boulders and coarse sediment deposited in a river channel with the river running through the centre. The banks are well vegetated in a rural, woodland setting.

The large variation in the estimates of discharge associated with one flood deposit (7 to 20 m^3/s) highlights a major uncertainty which affects many palaeoflood investigations: it can be very difficult to come up with robust estimates of discharge on the basis of evidence such as boulder size or analysis of flood plain sediments alone. For example, the method used by Longfield and others (2018) to estimate flows from boulder sizes includes an empirical relationship developed on just one catchment in Teesdale and tested against one other flood elsewhere. It is possible to use sensitivity analysis to investigate uncertainty, but this can hide the ‘unknown unknowns’ which may lurk when deriving the methods. Further research is required to quantify the uncertainty propagation when translating geomorphological data into peak flow estimates.

It is possible that some of these limitations will be overcome or reduced. Methods for estimating discharge on the basis of geomorphological evidence continue to be developed (Benito and others, 2022). Alexander and Cooker (2016) present a new method for estimating flow from boulder deposits, accounting for short-term fluctuations in velocity. This can greatly reduce the estimated discharge rate associated with boulder deposits.

A different approach to evaluating palaeoflood discharges in a UK setting is given by Chiverrell and others (2019), who present the first quantitative reconstruction of palaeofloods using lake sediments for the UK, and incorporate the results in a flood frequency analysis. The findings, for a site in the English Lake District, would not have any impact on PMF estimation because the lake sediment data indicated that the gauged flood of 2009 had no precedent in 600 years.

4.6.2 Palaeofloods and dam safety in the USA and Australia

Recent examples of palaeoflood investigations at several dams have been published by the US Army Corps of Engineers (USACE) Risk Management Center. Palaeoflood data are also used extensively in dam risk analysis by the US Bureau of Reclamation (USBR), which manages water resources in the western USA. They have been included in the development of hydrological hazard curves which have led to increases in spillway capacity at Folsom Dam (California) and Glendo Dam (Wyoming). Typically, palaeoflood data are used in conjunction with other information or techniques. England and others (2014) describe how palaeoflood and gauged flow data were used as a test of the predictions of a rainfall-runoff model for a dam on the Arkansas River in Colorado, within a hydrological hazard framework that integrates temporal, spatial and causal information.

USGS (2020) provides 5 case studies using historical or palaeoflood data, concluding that "...inclusion of historical and palaeoflood data can refine the tails of the frequency distribution; potentially assist with the detection of nonstationarities; and validate any proposed PMF, envelope curve, or existing extrapolations of the systematic flood record." On the Colorado River, palaeoflood data revealed there were 2 extreme floods that exceeded the original estimate of PMF. One example showed that adding palaeoflood data might increase uncertainty for very low probability floods.

Jarrett (2000) is an example of how palaeoflood data can be used across an entire catchment. An envelope curve encompassing maximum contemporary floods (19 sites) and palaeofloods (99 sites) was developed for streams in the Cherry Creek catchment, Colorado. Despite finding evidence from floods up to many thousands of years in the past, the study found that PMF estimates were all much higher than the maximum palaeoflood discharges.

USACE (2017a) provides an example from Vermont in the eastern USA. A frequency analysis of palaeoflood data spanning several thousand years demonstrated that the skew of the inflow-frequency curve was much less than previous estimates and so the risk of overtopping of the Ball Mountain Dam was less than previously thought. The geology and geomorphology of the West River as described in the report are strikingly different to that of many UK reservoir catchments, with a bedrock channel resistant to erosion that is thought to have retained the same shape for millennia, and the presence of crevices and alcoves along the valley walls that are easily distinguished from overlying glacial and alluvial deposits. Encouragingly, the report concludes that “all components of paleoflood analyses, from identifying and delineating palaeostage indicators and non-exceedance bounds, to quantitative discharge estimation, to flow frequency analysis, to incorporating results into risk assessments, are all scalable according to time and resources.”

Palaeohydrological methods have received less attention in Australia, but ARR: Ball and others (2019) refers to recent examples that have demonstrated potential for estimating very rare floods in both desert and sub-tropical parts of the country.

4.6.3 Implications for UK practice

The popularity of palaeoflood studies in the western USA may partly be because the geological and geomorphological setting of dams in those areas is favourable for the preservation of flood deposits over very long periods. There are probably other reasons why palaeoflood methods are more widely used in the USA than elsewhere, including the typical budgets available for flood studies at major dams and the degree of familiarity that practitioners and regulators have with the methods.

In the UK context it is difficult to envisage palaeoflood investigations playing more than a subsidiary role in dam safety. While evidence from past floods may justify an increase in an estimated PMF, it seems very unlikely that such evidence from UK rivers could be treated with enough confidence to justify decreasing a PMF estimated in the conventional way from PMP. For a start, it would be necessary to demonstrate that no floods approaching the original PMF had occurred over a period of several millennia. Climate change would add a complicating factor.

Palaeoflood investigations in lowland areas can require large budgets and specialist equipment for core sampling and X-ray fluorescence spectrometry and carbon-14 dating to analyse the core’s elemental composition (a proxy for grain size) and date. In contrast, in upland areas (where many reservoirs are sited), sedimentary evidence of past floods may be readily accessible on the ground surface in the form of boulder deposits. Reconstructing discharges of upland floods requires measurements of boulder size, which does not rely on specialist equipment. In addition, if the focus were to be solely on PMF estimation, as opposed to risk-based flood frequency, there may be no need to date the deposits; all that matters is that the floods have occurred. In light of this, it seems wise to recommend palaeoflood investigations as a complement to PMF estimation in upland catchments. Although that would require an increased budget for the flood study, the amount of money is likely to pale into insignificance compared with the cost of upgrading a spillway. If evidence from palaeofloods can be taken into account either for the initial spillway design or for an upgrade, it could potentially help avoid the need for a future upgrade if the spillway is found to be inadequate in practice, therefore, providing good value for money.

Similar comments apply to the use of information on historical floods obtained from documentary or epigraphic evidence.

4.7 Validity of current UK methods

The current method for estimating PMF in the UK has been set out in the earlier section, Restatement of method currently used to estimate PMP and PMF in the UK. Here, we evaluate the method in light of the findings of the literature review.

4.7.1 PMP estimation method

The method used for estimating PMP has not changed since it was published in 1975. Our conclusion is that it now needs to be replaced. PMP estimation using the 1975 FSR methodology may be poorly representative of current and future PMP because:

- it is based on now very old historic data, excluding all rainstorms since 1972, and does not make use of rainfall radar data
- it does not allow for climate change in the future or non-stationarity of climate in the past
- it does not quantify uncertainty in the estimates
- there is no use of meteorological modelling or extreme rainfall science that has been developed significantly in the past 2 decades
- it uses challenged hyetograph shapes
- there are questions over the validity of some of the assumptions in the FSR analysis, for example, reducing the Hewenden storm rainfall in 1956 by 50% on the assumption that the reported depth would not have been possible
- the estimate of the winter PMP relies on the untested assumption that the seasonal maxima have the same ratio as the 100-year values (Archer, 1984)
- there is evidence that PMP estimates have been exceeded in the UK, as shown in the Catalogue of extreme events
- 10^5-year estimates from FEH 2013 exceed PMP estimates over much of England and Wales for the one-hour duration
- PMP estimates from storm models are higher than FSR for durations longer than 12 hours
- moisture maximisation methods applied using more recent estimates of storm efficiency can show higher PMP estimates than FSR for some locations
- the results are mapped at a coarse resolution which does not fully account for local orographic influences on rainfall

The above reasons mean that PMP estimates might under- or overestimate PMP and that the profiles used might not be representative. Particularly because of climate change, PMP estimates may be too low.

4.7.2 PMF estimation method

The method used, in conjunction with PMP, for estimating PMF, has had some updates, but much of it remains unchanged since 1975. The main updates have been:

- the development of the FEH version of the rainfall-runoff model, which allows estimation of model parameters from digital catchment descriptors
- the publication of a new snowmelt estimation method by Hough and Hollis (1997)

In addition to the above limitations of the PMP methodology, the limitations of PMF estimation using the current methodology are that:

- FSR/FEH rainfall-runoff model uses the concept of catchment wetness index (CWI) which has been criticised as it can double-count recent rainfall (Kjeldsen and others, 2005)
- the model relies on some limited assumptions that control how percentage run-off varies with rainfall magnitude and catchment wetness index
- the model has been found to overestimate peak flows, when compared with the results of flood frequency analysis (although this limitation is not necessarily applicable to PMF)
- percentage run-off is estimated from the catchment descriptor SPRHOST which is less accurately estimated from soil type than BFIHOST or its replacement BFIHOST19, both of which are based on a significantly larger data set (Kjeldsen and others, 2005)
- the assumption that the PMP of duration D hours occurs in the middle of a 5D-hour long PMP is arbitrary - the antecedent rainfall affects the percentage run-off but not the initial inflow to the reservoir or the initial level of the reservoir, unlike some methods used in the USA (Archer, 1984)
- the procedure gives percentage run-offs with a rarity that can vary greatly between catchments (Archer, 1984), resulting in PMF estimates of unequal return period
- a one-third reduction in time to peak for estimating the PMF is arbitrary
- frozen ground allowance is arbitrary and optional, with little guidance available on whether it is realistic to combine it with an extreme rainfall - this can lead to large discontinuities with estimates of the 10^5-year flood on more permeable catchments (Faulkner and Benn, 2019)
- the recommendation to combine a 100-year snowmelt rate with a winter PMP is arbitrary, although consistent with approaches used internationally
- Hough and Hollis's (1997) procedure for snowmelt estimation has not yet been fully tested in its application across the full range of UK conditions - there is more than one way that the procedure can be applied and taken together; these lead to a possibility that its results will not always be realistic
- there is no guidance on how to allow for the potential impacts of climate change in estimating PMF
- there is no procedure to quantify uncertainty in PMF, even indicatively
- it is difficult to confidently link the estimated PMF with flood frequency estimates - current practice relies on a crude estimate of the return period associated with PMF

An additional limitation in practice is that at the start of this project there was no readily-available free software for applying the current method. This has been addressed in the current project by the development of a spreadsheet to provide an interim tool for practitioners to use until a replacement method is available.

4.8 Case study comparisons of alternative PMP and PMF methods

The project included a limited number of case studies trialling alternative methods for comparison with the current UK approach. The purpose was to explore alternative methods and provide an indication of the extent to which their results might differ.

4.8.1 PMP methods

4.8.1.1 Purpose of comparison

This case study compares PMP estimates derived using different estimation methods. A comparison of PMP estimates across multiple known historical heavy rainfall and/or flood events provides an indication of the scale of uncertainty in PMP for individual events, but also the level of variability in PMP between events.

Note, the case study is not intended to provide an exhaustive comparison of PMP estimation methods or to provide PMP estimates for any specific class or set of historical events. Additionally, the PMP estimates provided for the methods and cases selected are mostly indicative only; many have not been exposed to rigorous scrutiny such as may occur when published in peer-reviewed literature.

4.8.1.2 Choice of locations

Notable historical events were selected for which information on rainfall amount, duration and spatial extent was readily available. Additionally, where possible, locations of events with PMP estimates provided in published literature were also used. The selected events are detailed in Table 13, identified by the location and date of the event, along with estimated rainfall depth and duration.

Table 13: Locations of selected storm events for estimating PMP

Storm location	Date	Estimated rainfall depth (mm)	Estimated storm duration (mins)
Hewenden	11/06/1956	155[a]	105[b]
Hampstead	14/08/1975	169[a]	155[a]
Halifax (Walshaw Dean)	19/05/1989	193.2[b]	120[a]
Boscastle	16/08/2004	183[c]	300[c]
Boltby	19/06/2005	126.2[b]	120[b]
Ulley	24/06/2020	92.4[b]	1,440[b]
Great Hockham	16/08/2020	197[d]	150[d]

Notes for Table 13 - the sources of the rainfall depth and duration information provided in the table is given as follows:

- (a) Met Office UK climate extremes (https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-extremes)
- (b) C. Collier (personal communication)
- (c) Golding and others (2005)
- (d) Dent and others (2020)

4.8.1.3 Choice of PMP methods

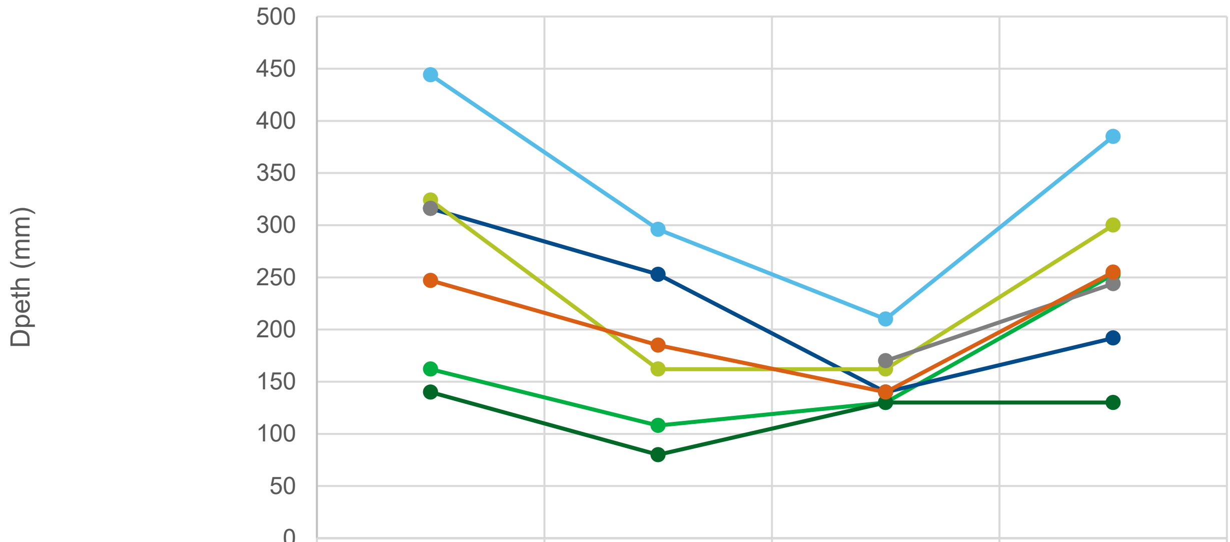
The PMP estimation methods explored in this case study include the FSR, moisture maximisation and storm model approaches (described in 4.3 Methods for estimating PMP) A fourth PMP estimate is also derived for the storm model method using adjusted precipitable water and/or height values (C. Collier, personal communication).

These approaches were identified as the most easily applicable methods for deriving PMP for historical storm events and have often already been applied for events described in published literature.

For the selected storm events, where a PMP value was available in published literature using these estimation methods, that value is given here; see Table 13 for the data sources. Where PMP estimates for these methods were not already available, the values have been estimated here using appropriate and available data. Such values should be considered as indicative, rather than definitive, estimates of PMP.

4.8.1.4 Summary of results

The PMP estimates derived using the 4 estimation methods for the 7 selected historical heavy rainfall and/or flood events are given in Figure 26.



	Storm model	Storm model (modified)	FSR	Moisture maximisation
Hewenden 1956	162	108	130	252.8
Hampstead 1975	316	252.8	140	191.8
Halifax 1989	324	162	162	300
Boscastle 2004	444	296	210	385
Boltby 2005	140	80	130	130
Ulley 2020	316		170	243.9
Great Hockham 2020	247	185	140	255

Figure 26: PMP rainfall depths (mm) estimates for the selected storm events

Comparing the PMP estimates across all events, those using the FSR method show much smaller variability between the cases than for all other methods, and are often the lowest estimate out of all methods. There is also little consistency in the ranking of events by their PMP estimates using the various methods, excluding the most and least extreme cases (Hewenden and Boltby, respectively). This highlights how the varying characteristics of each storm event can have differing responses in the estimated PMP due to the varying implicit properties of each PMP estimation method.

This case study has reaffirmed several conclusions regarding the estimation of PMP. The conclusions are that:

- the FSR approach frequently yields PMP estimates lower than those from other methods

- it is worth considering several methods of PMP estimation as they may all yield different answers
- the spread or uncertainty in PMP estimates for any case can be large

4.8.2 PMF methods

4.8.2.1 Purpose of comparison

A comprehensive comparison of PMF estimates made from different methods on different catchments would not have been feasible within the project because it would have been necessary to first develop the methods in a UK context and then to calibrate the various rainfall-runoff models. Instead, a very limited illustrative comparison was carried out, running a small number of alternative rainfall-runoff models on a single catchment, using the FSR estimate of the summer PMP as an input, along with conservative settings for antecedent wetness. The summer season was chosen to avoid complications with representing snow and frozen ground.

The resulting peak flows are not claimed to be estimates of PMF. They are indications of a flood that could arise from a PMP occurring in the summer season.

4.8.2.2 Choice of models

The only models considered were those for which parameters had already been calibrated for the study catchment, or could be readily estimated from physical catchment properties. The following models were chosen:

1. FSR rainfall-runoff model: the current method for estimating PMF.
2. ReFH2 model, the current method for modelling floods up to the 10^5-year return period.
3. ReFH2 model, modified as proposed by Pucknell and others (2020) for applying the framework of the existing FSR-based PMF estimation method within the structure of the ReFH rainfall-runoff model.
4. IHACRES, an alternative conceptual rainfall-runoff model.
5. HEC-RAS 2D, a 2D model of overland flow based on the shallow water flow equations, with rainfall applied to the whole of the 2D terrain grid (the ‘direct rainfall’ approach). This was applied both with and without infiltration losses.

Appendix 4 gives information on how the models were set up and parameterised. Note that only one model (IHACRES) was calibrated to local hydrometric data, simply because that calibration had already been carried out before the project. Calibration of the other models would have been possible but was not feasible within the project scope.

4.8.2.3 Choice of catchment

The models were compared for the Wye at Cefn Brwyn catchment (NRFA number 55008). This catchment is one of the Plynlimon experimental catchments in central Wales. It was chosen because the IHACRES model had already been calibrated using hourly data for this catchment (Littlewood and Croke, 2013).

The catchment descriptors, derived from the NRFA Peak Flow dataset version 10, together with the observed baseflow index (BFI) are summarised in Table 14.

Table 14: Catchment descriptors for the Wye at Cefn Brwyn

Catchment descriptor	Value
Area (km2)	10.50
SAAR (mm)	2457
URBEXT2000	0
DPLBAR (km)	3.24
DPSBAR (m per km)	192.4
PROPWET	0.66
BFIHOST	0.38
BFIHOST19	0.30
BFI (from NRFA daily flows)	0.32

The catchment is small, very wet, steep and impermeable, therefore, in normal conditions it will have a relatively high percentage run-off and fairly rapid routing. The changes in differences between processes within PMF events, as understood and applied within the current FSR method, are, therefore, likely to be smaller than within permeable, drier, larger and less steep catchments.

4.8.2.4 Summary of results

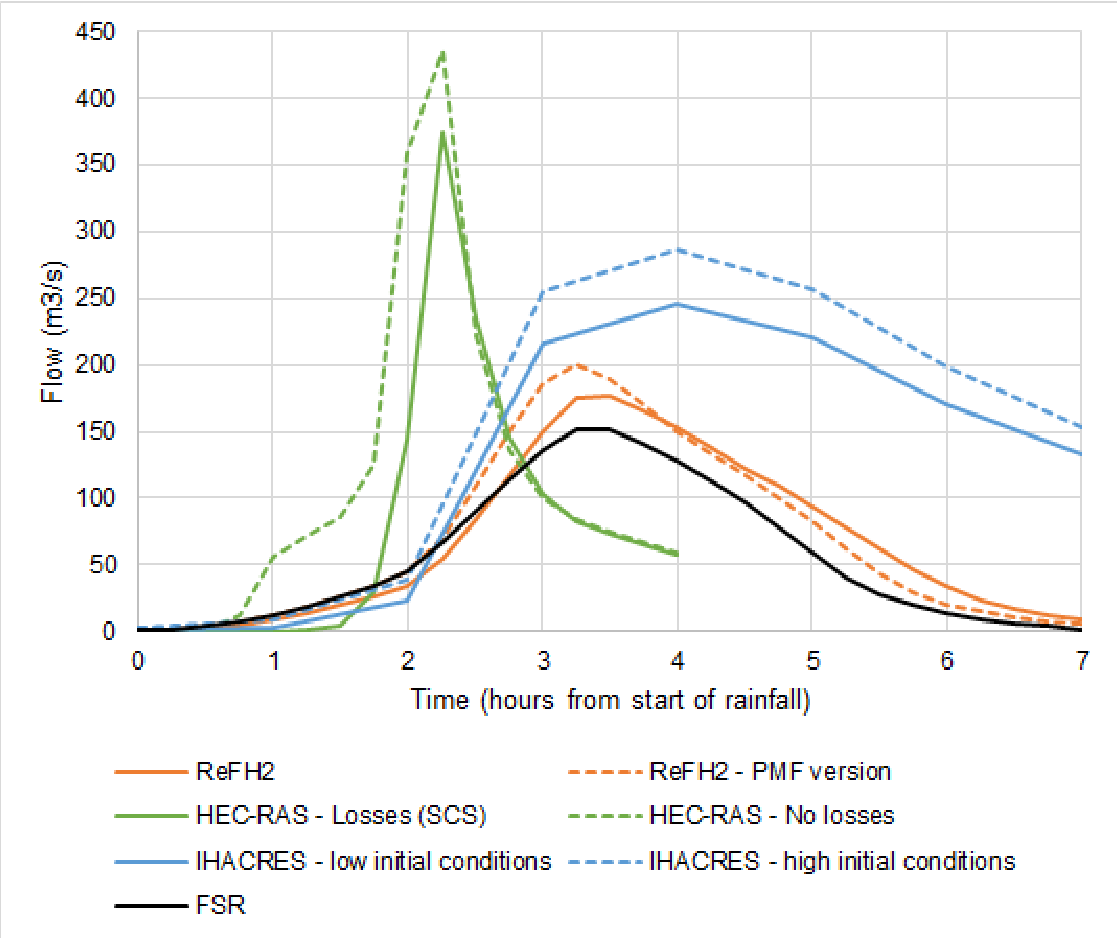


Figure 27: Comparison of hydrographs estimated by different models for a summer PMP over the Wye at Cefn Brwyn

The modelled hydrographs are shown in Figure 27. Every alternative model gives a higher peak flow than the FSR model. HEC-RAS gives a much higher and earlier peak flow than the other models, whether it is applied with or without losses. IHACRES gives a larger volume of run-off than any of the other models. As discussed in Appendix 4, its results are unrealistic because it produces a larger volume of run-off than the volume of rainfall. The results from ReFH2 are closest to those from the FSR model, as expected as these are both regionalised, lumped, unit hydrograph-based models with the PMF assumptions replicated in the ReFH2 PMF model.

As described within Appendix 4, the modification to ReFH that applies the framework of the existing FSR PMF estimation method has a relatively low impact within this catchment as it is a small, wet, upland catchment. The differences are further limited due to the existing lower Tp limit of one hour, as discussed in Appendix 4, applied within ReFH2 but not within the FSR rainfall-runoff method.

It is important to stress that these results are for one catchment only, in summer conditions, and should not be taken as representative of other catchments. They show some large differences between models and also some smaller differences caused by variations in settings such as initial conditions, calculation of losses and parameter values. In winter conditions there is more scope for variation due to the need to make decisions about snow depth, snowmelt rate and the impact of frozen ground.

4.8.2.5 Conclusions

It is difficult to draw any firm conclusions from this case study due to the limitations previously discussed, which were that:

- the case study was completed on one catchment, for a summer event only, therefore, any conclusions are specific to this catchment and season
- only one model was calibrated to observed data, therefore, it is difficult to compare the validity of the models - IHACRES, the only one that was calibrated, has an internal water balance error and produces unrealistic results

While limited in scope, the outputs of the case study indicate that:

- the existing method for estimating PMF, FSR, produces the lowest peak flows and volumes in this catchment
- all 4 models provide different, in some cases significantly different, peak flows and volumes from the same PMP event (using varying assumptions relating to antecedent conditions and routing)
- due to the different structures of the various models the differences between the models are likely to be different for other catchment types, although this assumption could not be tested within this project
- ReFH2 and FSR, both regionalised, lumped, unit hydrograph rainfall-runoff models which, for the PMF scenario, use similar assumptions, are the most similar
- the lower limit of one hour for the time to peak in the ReFH2 method may restrict the ability of the model to represent accelerated flood response during a PMF in catchments that have a rapid response, although with careful consideration this restriction could be amended in future applications
- accelerated response and higher peak flow results from the ‘direct rainfall’ model are characteristic of the run-off response sometimes observed during intense rainfall, perhaps reflecting a transition from sub-surface flow to overland flow
- the fact that these results are an outlier compared with those of other models should not be used to dismiss them

These findings underline the need for careful consideration and development of rainfall-runoff models that can be considered suitable for estimating extreme floods such as PMF.

5 Requirements and opportunities of an improved method of estimating PMP and PMF

The cataloguing work and review have confirmed that there are weaknesses in the FSR method of estimating PMP and PMF. The remaining parts of this report look ahead to future research requirements. This chapter discusses the requirements of an improved method and how it should fit into the wider context of flood estimation for risk-based management of reservoir safety. It starts by considering the physical processes that a method should represent.

5.1 Conceptual model of PMF formation

The literature review has shown that there are many components that need to be included when estimating a PMF.

Figure 28 illustrates a conceptual model of the components that are thought to be important for estimating PMF in the UK. When these are maximised in a way that respects their interdependence, they can be expected to give rise to a maximum flood for the catchment in question. The estimate of this is the PMF.

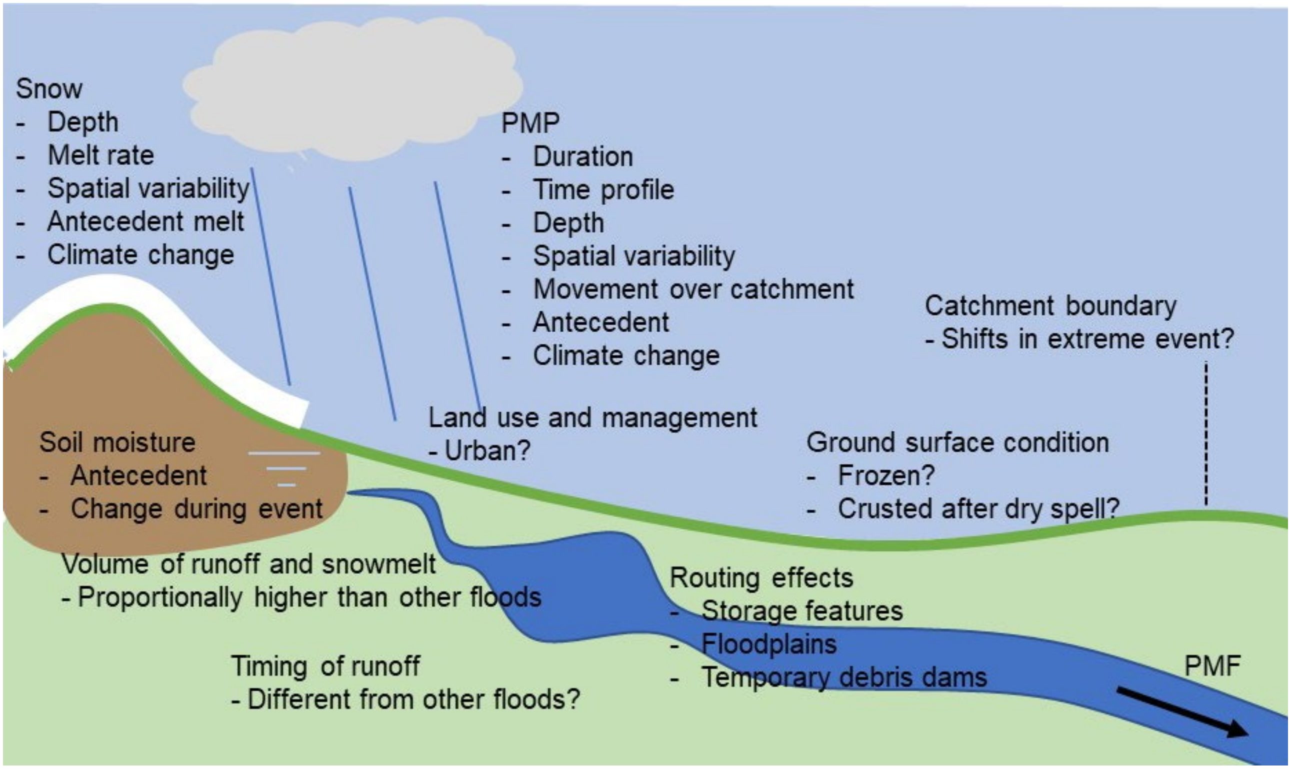


Figure 28: Sketch of conceptual model of PMF formation

Figure 28 depicts a typical river catchment and the considerations for PMF formation. Highlands with snow present require consideration of the depth, melt rate, spatial variability, antecedent melt and climate change. A cloud depicting rain on the catchment and the resulting PMP require duration, time profile, depth, spatial variability, movement over catchment, antecedent and climate change considerations. The ground surface needs considering if its frozen or crusted after a dry spell and the land use and management that is present throughout the catchment. Similarly, the sub-surface soil moisture properties need considering if they are impacted by antecedent or change during an event. The river following downstream from the highlands highlights the following areas that need considering: the volume of run-off and snowmelt is proportionally higher than other floods; the timing of run-off and potential differences from other floods and routing effects that may impact storage features, floodplains and temporary debris dams.

There is partial dependence between many of the components. For example, frozen ground is more likely during cold conditions, when snow accumulations and high soil moisture are also likely. Also, the amount of snowmelt is affected by the depth of rainfall. Most methods applied in practice appear to make some rather arbitrary assumptions about these issues of joint probability, although there are some more objective approaches in existence.

Some of the processes shown in Figure 28 affect floods of any magnitude. Others are much more relevant for extreme floods. These include:

- meteorological conditions favouring the maximisation of rainfall at a point location or across a catchment, including the spatial extent and motion of the weather system; dynamical forcing from mesoscale systems; enhanced local convergence (for example, forced by surface conditions); orographic upslope motion; maximum storm efficiency (how effective and efficient a given storm is at converting atmospheric moisture into rainfall); cloud water content (the amount of atmospheric moisture that is available to be converted into rainfall); strength and depth of the convection (extent and vigorousness of ascending motion); seeder-feeder mechanism
- combination of rainfall and snowmelt
- influence of unusual conditions at the ground surface which may reduce the infiltration rate, leading to infiltration excess run-off
- higher than normal proportional run-off volumes, as a result of the above or high antecedent soil moisture
- reduction in run-off accumulation times, for example, due to more overland flow in areas where run-off is normally sub-surface - this may include concentration of overland flow into new channels which are eroded during the event, leading to even quicker concentration of run-off - this sort of dynamic landscape effect is not represented in most hydrological models, although computational fluid dynamics models are able to represent the shear stress forces that cause erosion - landscape evolution models, for example, Caesar Lis flood, in which the Caeser morphodynamic model is linked to the Lis flood 2D hydrodynamic model, can allow these changes to be modelled explicitly (Coulthard and others, 2013)
- shifts in catchment boundaries, which may occur due to overspill from neighbouring watercourses, perhaps exacerbated by geomorphological changes associated with extreme events such as landslides and debris dams

- changes in routing processes such as activation of additional floodplain areas - the impact of these could be to either increase or decrease the peak of the flood hydrograph

Some components of the conceptual model are sensitive to the impacts of change in the climate or in land use and land management.

It should be clear from the above that estimating a PMF is rather more than a matter of applying a PMP to a rainfall-runoff model.

Not all components are influential in all circumstances; for example, on catchments when the PMF is expected to occur in the summer season, snow and frozen ground are not relevant ingredients in the UK. However, it is often difficult to identify such catchments without first testing a winter PMF as well as a summer event. In choosing the season that gives the highest PMF, it may be important to compare volumes or peak discharges from dams rather than only peak inflows to dams.

Different methods of estimating PMF represent these components more or less explicitly. It is not likely that further research will be able to develop a single procedure that can account for all the factors that are relevant in all circumstances. Practitioners will need to make their own judgement about the relevant components for their study, bearing in mind the nature of the catchment and also the types of information available. In some cases, they will need to apply additional tools, such as a hydraulic model to represent routing of the flood through storage features in the catchment.

5.2 Requirements of an improved method of estimating PMF

As discussed in the review, the very concept of the PMF has been questioned for a long time. There are some fundamental difficulties with it, both from a scientific viewpoint and in terms of its application in risk management. These include a lack of empirical evidence, which creates difficulties with any method for estimating PMF. There are no measurements of floods that are known to be at their upper physical limit against which estimates of the probable maximum can be compared. This makes it very difficult to judge what a successful method of PMF estimation looks like. In addition, there does not appear to be any satisfactory way of integrating PMF with a probability distribution of flood magnitudes.

At the same time, PMF continues to have a value in assessing the safety of high-risk assets. Alternative probability-based methods suffer from drawbacks such as major extrapolation of limited sample sizes, whether the data in question are rainfall or river flow; observed or simulated. This is discussed further in the section on flood estimation for risk-based reservoir safety management on page 143.

The following are suggested as requirements and/or desirable attributes for a method (or a set of methods) for estimating PMF in UK practice. It is important that the outcome has the confidence of the user community, which in practice will overlap very closely with those involved in managing reservoir safety. It should also stand up to scientific scrutiny. To achieve these aspirations, any new method should incorporate important scientific advances and data sets, while being practical to apply and giving credible results that are useful in flood risk management.

Some requirements will be more realistic to achieve than others. While some can be satisfied using scientific approaches that have already been developed, others will need research and development. In some cases, there are approaches that have been developed overseas that could be transferred into a UK context. Each requirement has been scored to indicate the degree of effort that would be needed to achieve it in a UK context. The scores range from 1 to 4, with decreasing difficulty:

1. Fundamental difficulties with achieving this requirement: may be possible with research, but otherwise may need shift in foundational concepts or acceptance of compromise.
2. In-depth research and development needed.
3. Some research and development needed.
4. Off-the-shelf solution already available, although may need some testing or checks before rolling out. Note that there may be drawbacks to applying some off-the-shelf approaches, so these scores should be regarded as minimum estimates.

The requirements are split into Table 15 and Table 16 below, which distinguish between components and attributes (characteristics) of the method. While all the components are believed to be essential for any method of estimating PMF to be applied in the UK, the indispensability of some of the attributes is open for debate.

Table 15: Required components of the method

No.	Requirement	Score: 1 (hardest) to 4 (easiest)
1	Method of estimating PMP that accounts for all important meteorological processes, including both convective and frontal rainfall, local dynamical forcing and seasonal variation.	2
2	PMP generalised to provide national coverage at a spatial resolution that reflects topographic influences on rainfall, covering a range of storm durations from one hour up to 8 days.	2
3	Realistic time profiles for PMP storms, including option to test sensitivity to multiple profiles.	2
4	Guidance on whether and how to allow for spatial variation in rainfall and/or storm movement across catchments. This could potentially extend to representation of spatial coherence across wider areas, for example, to test scenarios of PMFs occurring at multiple nearby reservoirs from a single extensive PMP.	2/3
5	Realistic representation of antecedent soil moisture conditions expected in combination with PMP, with seasonal variation, including impact of snowmelt on antecedent conditions.	3
6	Guidance on joint occurrence of snowmelt in conjunction with winter PMP.	3
7	Snow depth and melt rate for required exceedance probability.	3/4
8	Model component to transform volume of rainfall and snowmelt to volume of run-off, reflecting influence of processes expected to operate during extreme floods, including frozen ground.	3/4
9	Model component to represent routing of run-off, reflecting influence of processes expected to operate during extreme floods.	3

Table 16: Required or desirable attributes of the method

No.	Requirement	Score: 1 (hardest) to 4 (easiest)
1	Ability to contribute to a risk-based evaluation of reservoir safety, for example, by assigning an exceedance probability to the PMF or by taking a stochastic approach to estimating design floods, including the PMF.	1
2	Consistency between approaches used to estimate PMF and those for lesser floods, for example, guidance on whether adjustments such as frozen ground or reduction in flood response time should also be applied for events such as the 105-year flood.	2/3
3	Consistency across catchment types, so that PMF estimates are not unduly conservative or otherwise in some locations.	3
4	Ability to define confidence limits for PMF along with guidance on how to understand, reduce and communicate uncertainty in design flood estimates for extreme conditions.	1
5	Ability to represent potential impacts of climate change on PMP, snow and other components; both impacts that have already occurred and those expected to impact the future resilience of infrastructure.	2
6	Ability to allow the practitioner to make changes in catchment boundary compared with less extreme floods.	4
7	Ability to incorporate local hydrometric records via calibration.	4
8	Ability to incorporate other types of information where available such as palaeoflood evidence.	4
9	Ability to apply on ungauged catchments from readily available data.	4

No.	Requirement	Score: 1 (hardest) to 4 (easiest)
10	Range of approaches from a rapid screening estimate that can be applied with minimal input or knowledge up to a more in-depth analysis where warranted.	3
11	Flexibility, for example, with modules that can work with other methods where required to represent extra processes, such as upstream flood storage.	4
12	Capable of being updated, for example, if additional data becomes available.	3
13	Openly available for practitioners to apply using either standard or bespoke software.	3
14	Capable of being applied and audited after appropriate training, using skills already typically available across practitioner community.	3

5.3 The wider context: flood estimation for risk-based reservoir safety management

PMF is only one of many aspects that contribute to management of the safety of high-risk infrastructure. It is important that estimating PMF is not seen as an end in itself. An awareness of the wider decision context is important. Options have been sought that are better able to contribute to a risk-based evaluation of reservoir safety. This section discusses some of the issues that are relevant to that aspiration.

5.3.1 Risk-based approach and relevance of return period

Following the current guidance in Floods and Reservoir Safety (ICE, 2015), a risk-based approach should be carried out when an existing flood safety provision falls short of that required by the deterministic standards approach. As the methods for evaluating PMP and PMF improve, it is expected that the number of dams reappraised for flood safety using a risk-based approach in the future will increase, not least because it is known that PMP values have been exceeded and new estimates of PMP/PMF are likely to be generally higher than those used over the last few decades. Without the application of a risk-based approach, many more spillway improvement projects could be undertaken in future, and may be more expensive than can be justified in terms of the benefits. The government's independent reservoir safety review report (Balmforth, 2021), which has been accepted by the government, recommends adopting risk-based methodologies in managing reservoir risk. Recommendation 13a of the report states:

“The current research project commissioned by the Environment Agency into PMP and PMF should … give guidance on estimating the frequency of present day and future extreme flood events suitable for use in reservoir risk assessment.”

Risk-based reappraisals have been carried out in accordance with the Environment Agency’s guide on reservoir risk assessment (Bowles and others, 2013) for several years. The relevance of the frequency of the PMF is most acute when considering very high consequence dams, that is, those that pose the greatest risk to downstream communities. The challenges in applying risk-based methods to such reservoirs are described by Brown and Hewitt (2014).

To help decision-making on whether to intervene on dam safety matters to reduce the probability of failure in light of the consequences of dam breach, a frequency-fatalities (F-N) chart can be used to express societal acceptability of the risk posed by any individual dam. **Figure 29** is an example.

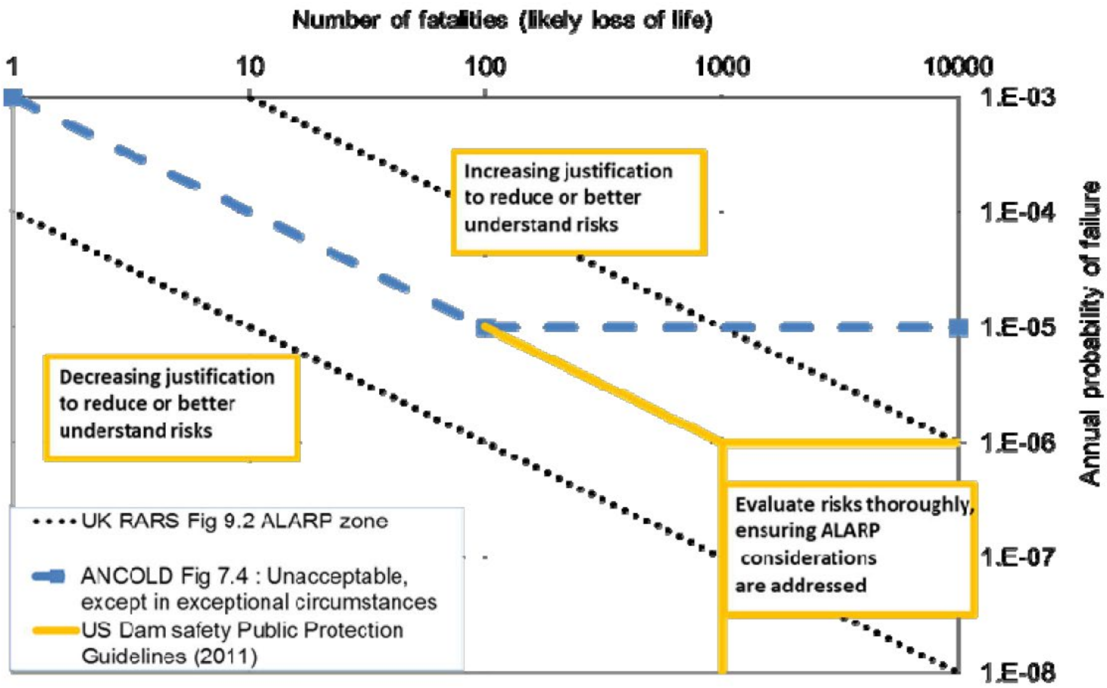


Figure 29: Comparison of international tolerable risk guidelines for existing dams (from Brown and Hewitt, 2014)

Figure 29 shows a graph with number of fatalities (likely loss of life) across the x-axis and annual probability of failure on the y-axis. The graph has 2 black dotted lines and a blue line in the middle running parallel, showing a positive trend that as the number of fatalities increases so does the annual probability of failure. More fatalities predicted the increasing justification to reduce or better understand the risks associated.

UK practice considers 3 risk bands. Those dams falling above the upper dotted line are considered unacceptable and in need of improvement. Their risk must be reduced to as low as reasonably practicable (ALARP), that is, within the zone between the 2 dotted lines, or to the ‘broadly acceptable’ zone below the ALARP zone.

Australian practice (defined by the Australian National Committee of the International Commission of Dams (ANCOLD)) provides for a horizontal truncation on the F-N chart at $1x10^{-5}$ where the likely loss of life is estimated as greater than 100. For dams plotting above this dashed line, the risk of failure would be considered unacceptable and interventions would be needed to reduce the risk of failure.

US practice follows the Australian practice for a likely loss of life <100 but adapts the zoning for higher loss of life. It is important to note that both UK and US practice considers very low aggregate annual probabilities of failure in evaluating acceptability. Flood safety is relevant to impounding reservoirs which constitute the great majority of UK reservoirs. For these reservoirs the computation of the aggregate annual probability of failure will include for failure modes associated with flood safety. Therefore, the return period of the PMF is important in determining whether the overall probability of failure of the subject reservoir is judged to be acceptable or not in light of the consequential risk.

Some example cost-benefit applications of risk assessment for reservoir safety (RARS) in assessing flood safety improvements are provided in Brown and others (2014). The cost for preventing a fatality (CPF) is calculated as the capital cost of the measure less the present value reduction in damage divided by the present value reduction in loss of life. The aim is to determine at what value of CPF ALARP is satisfied. The calculation requires an estimate of the annual probability of failure due to floods before and after completion of proposed improvement works. If it can be shown that the scale of the improvement for a lesser flood than the PMF is appropriate to meet the risk criteria (that is, larger scale works would be disproportionate to the benefit) then cost savings can be made in comparison to an upgrade to the PMF standard. Equally, if the frequency of the PMF is such that the analysis indicates that a notional flood of even lower probability should be adopted, the PMF standard can be used on the basis that it represents the worst credible condition.

Balmforth (2021) proposed that reservoirs be classified into 3 consequential risk bands. The highest consequential risk band (Class 1) is where the number of fatalities is in the 100s to 1000s, for which it is recommended that the reservoir be shown as within the ALARP/broadly acceptable zone as part of routine periodic inspections. It follows that all high consequence reservoirs are likely to be subjected to risk-based flood safety reviews regardless of changes in PMP/PMF estimates.

If the PMF concept is retained in UK practice, there is some prospect of improving on the current crude estimate of 4×10^5 years as its return period, as discussed in the review section. The consequences of not improving the return period estimate for the PMF are that:

- one of the recommendations by Balmforth accepted by government would not be fulfilled
- risk-based assessments to determine whether upgrades are cost-effective would be compromised by the current crude evaluation, potentially leading to poor investment

choices where money might better be spent in mitigating mechanisms of failure unrelated to flood inflow
- future routine risk-based safety evaluations of the UK's highest consequence dams would in particular be impacted by the current crudely determined evaluation of the PMF return period

5.3.2 Current UK practice for reservoir flood estimation (below the PMF)

It would be desirable for any new methods of estimating PMP and PMF to be compatible with the approach used for estimating lesser design rainfalls and floods for reservoirs. UK practice in this field has evolved in recent years and is expected to continue to evolve.

Dams are divided into 4 categories, A to D, based on the consequences of a breach (ICE, 2015). The dam category is determined by the inspecting engineer. Within a standards-based approach, the standards for the design flood and the safety check flood depend on the category. The relevant return periods range from 150 years, through 1,000 and 10^5 years, to the PMF. When a risk-based approach is applied, it is necessary to evaluate consequences over a fuller range of probabilities.

Rainfall-runoff methods are nearly always used in preference to statistical estimation of flood frequency curves. This puts most of the burden of the frequency estimation on the rainfall depth-duration-frequency statistics, which is generally appropriate given the relative degrees of confidence in rainfall frequency estimation and flood frequency estimation at long return periods. Another reason for preferring rainfall-runoff approaches is that they explicitly generate a hydrograph which can be routed through a reservoir. However, in some situations, it may be appropriate to compare and perhaps adjust the results against those from flood frequency analysis, particularly when it is based on a long peak flow record, perhaps augmented using longer-term historical information and/or palaeoflood data. If the flow record is downstream of the reservoir, it may be necessary to make adjustments to avoid double-counting the routing effect.

The FEH 2013 rainfall frequency statistics are recommended for return periods up to 10^5 years. This was replaced by an updated version in December 2022. Currently, there is no guarantee of compatibility between rainfall frequency curves and PMP. Indeed, there are large areas of the UK in which the FEH 2013 statistics give estimates of the 10^5-year rainfall (for some durations) that exceed the estimated PMP (Stewart and others, 2019). A more joined-up approach would be desirable in the future, although in practice it may be difficult to know whether PMP should yield to the rainfall frequency curve at extreme return periods or vice versa. Both are subject to large uncertainty that is difficult to quantify.

The choice of rainfall-runoff model for reservoir safety work is not entirely clear-cut at the moment. Environment Agency (2020) states:

> "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 1,000-year return period. The reason why the FEH run-off 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 4th edition of the Floods and Reservoir Safety guide was published before the release of the ReFH2 method and so does not mention it. Recommended rainfall-runoff models are summarised in a table published by Pether and Fraser (2019), repeated in Environment Agency (2020). The recommendations depend on the return period as follows:

- 150 years: FEH, ReFH or ReFH2
- 1,000 years: FEH or ReFH2
- 10^5 years and PMF: FEH

The choice of modelling approach can make quite a difference to the results. Apart from the difference in the structure and parameterisation of the models, there are also contrasts in the way the FEH, ReFH and ReFH2 methods specify inputs, such as seasonal adjustments for rainfall. Stewart and others (2019) present a graphical comparison of peak flows for a return period of 10^5 years estimated using the FEH and ReFH2 models. Even on a log scale, some large differences are evident. More commonly, ReFH2 gives lower peak flows.

Even if the same modelling approach (typically FSR) is used for the full range of return periods, it is liable to lead to discontinuities between the PMF and lesser floods (Faulkner and Benn, 2019). There are questions over whether some of the adjustments made for modelling PMF, such as the assumption of frozen ground or the reduction in Tp, should also be made for other extreme floods such as the 10^5-year.

It would be desirable for practitioners to have access to a single rainfall-runoff modelling approach that they could use with confidence across the full risk profile, up to the PMF.

5.3.3 Towards a probabilistic approach to reservoir flood risk

Probabilistic approaches to decision-making have the potential to offer a more comprehensive approach to the design and assessment of structures such as reservoir spillways. They can highlight the uncertainties that tend to be obscured in a deterministic framework (Mahoney and others, 2018). They are better suited for incorporating information about climate change impacts, since this tends to be highly uncertain. However, they can place larger demands for time, resources, and technical capacity on regulators and other decision-makers, as they require a greater number of subjective, site-specific judgments that must then be justified to stakeholders (Mahoney and others, 2018).

As found in the literature review, there are fundamental difficulties with associating a probability, and therefore a level of risk, with PMP and, even more so, PMF. The Australian approach is to focus more on the flood with the same return period as the PMP.

One approach that may avoid this difficulty is to reduce the deterministic concept of PMF to a limited role, in favour of a fully probabilistic approach to reservoir flood estimation. This may involve thinking outside the ‘design event’ box. The desire for a risk-based framework for managing dam safety has led some organisations and researchers to recommend methods of flood frequency estimation that can be extended to very low probabilities without recourse to the concept of a probable maximum. Some ideas on how this is tackled internationally are given in the section in the literature review on 4.2.10 Alternative methods of estimating extreme floods for dam safety. All 3 examples; USA, Australia and France, make some use of stochastic simulations or ensembles in an effort to sample a wider range of events than that contained in the observed record. This type of approach has been advocated for the UK by Balmforth (2021), recommending that present-day and future estimates of extreme floods “should be based on data from multiple scenarios of computer-generated weather.”

A drawback of relying on conventional frequency analysis of rainfall or river flow at extremely low probabilities is that the amount of extrapolation will be enormous, and it may not be known whether the estimate falls far short of or exceeds the maximum flow that is physically possible. An example of the former can be found in England and others (2007, 2014).

Alternative ways of developing probabilistic information on flood hazards suitable for risk assessment of high-risk assets such as reservoirs include:

Continuous simulation

Continuous simulation of the catchment and reservoir system, using hydrological or (more commonly) meteorological inputs generated from a stochastic model which reproduces the statistical properties of observed precipitation. This does not necessarily circumvent the extrapolation problem noted above because a stochastic model could generate occasional rainfalls that are beyond what is physically possible. Beven (2021) suggests that the effect of this could be supressed by using a model run much longer than the return period of interest, to allow any occasional outliers not to have an effect on the return period of interest.

Physics-based model

The same as above but with inputs from a physics-based model of the atmosphere. This might involve coupling a regional climate model with a hydrological model and running a very long-term simulation, perhaps spanning tens of thousands of years. Current work of this nature tends to use much shorter simulations, such as in the UNSEEN method applied by the UK Met Office (UNprecedented Simulated Extremes using Ensembles), which runs the Hadley Centre global climate model at relatively high resolution (60 km for the atmosphere; Thompson and others, 2017)

Monte-Carlo simulations

Monte-Carlo simulations that generate large numbers of samples from distributions of storm depth, duration, profile, snow conditions, antecedent moisture and any other relevant variables.

It is desirable that any hydrological approach selected for future reservoir safety management is compatible with the approaches that will be used in future for fluvial flood risk management. These will be defined through the Environment Agency's Flood Hydrology Improvements Programme. At the time of writing, this is in its early stages.

5.3.4 The way ahead

If the current 'design event' approach and the role of PMF are to be retained for the foreseeable future, it would be beneficial to have a:

1. rainfall frequency estimation method compatible with estimating PMP
2. rainfall-runoff model structure and parameterisation that can be applied across the full range of event probabilities needed in reservoir safety
3. system for specifying combinations of input to the model (or models) that will simulate consistent design floods of the intended return period or PMF

In developing the options set out in the following section, we have assumed that PMF will continue to play an important role in reservoir flood management. We have sought options that help to fulfil points one to 3 above, as far as is possible. The challenge of incorporating the probable maximum concept into risk-based management of reservoir safety is a big one because of the difficulty of assigning a probability to the PMF.

In the longer run, it may be that integrated models of meteorological and hydrological systems permit an approach to estimating extreme floods that combines a physical basis with explicit analysis of probability.

5.4 Data available for developing and applying a new method

5.4.1 Meteorological data

An essential component of most methods for determining PMP is the observed hourly or sub-hourly rainfall depth records over long periods (preferably 50 years or more), and for specific storm events. These data typically come from rainfall gauges, but increasingly, radar data is being used to provide inferred rainfall depths with near seamless, high spatial and temporal resolution across the entire country. Radar estimates of rainfall allow the gaps between conventional rain gauges to be filled, allowing for larger rainfall depths, which might otherwise have occurred between rainfall gauges, to be identified. However, rainfall depths from both rainfall gauges and from radar have limitations.

Rainfall depth measurements from radar are typically less accurate than those from rainfall gauges, particularly when associated with heavy rain or hail. There can be large differences between radar measurements over a 1 km square and rain gauge measurements within that square. Caveats with radar rainfall data include the relatively short record length, changes in radar technology resulting in step changes in spatial and temporal resolution, the validity of assumptions in the reflectivity-precipitation rate relationship, and the impact of varying precipitation phase, beam attenuation, ground clutter and beam-blocking. In particular, for the case of extreme rainfall, radar rainfall depths tend to be underestimated due to enhanced attenuation, conversely the presence of hail can result in overestimates of rainfall depths. Following the introduction of dual polarisation radars across the UK (completed in 2016), mitigation of the latter aspect has been an active area of research.

Rainfall gauge estimates of depth can also be subject to uncertainty, particular for extreme rainfall depths. When rainfall intensity is particularly large, rain falling beside a rain gauge can splash into the gauge, resulting in an overestimate of the overall rainfall depth[3]. The opposite effect can occur during windy conditions, with gauges not recording all rainfall that reaches the ground (undercatch) (Muchan and Dixon, 2019).

Gridded data sets of rainfall depths, constructed using rainfall radar estimates merged with gauge observations, can provide useful information on the spatial variation of rainfall corrected with the more accurate point estimates from rainfall gauges.

The majority of the meteorological methods for determining PMP require, in addition to rainfall depth observations, other observations describing the state of the lowest levels of the atmosphere. Typically, the methods have been derived to use observations that are generally readily available at surface and upper air observing stations, such as surface air temperature, and wind speed and direction and variables which describe the moisture content of the air (usually dewpoint temperature), both at the surface and at height within the lower atmosphere. As with rainfall records, PMP methods frequently require long records of the other meteorological variables to allow extreme values or empirical relationships to be determined. While point observations (for example, from surface or upper air stations) close to or across the region of individual storms are used in many PMP methods, gridded data sets can provide more useful and complete coverage, particularly when assessing the climatological environment across which PMP estimate might be generalised. The data could include gridded data derived from the spatial interpolation of point observations, or numerical weather prediction model representations which assimilate these and other (for example, satellite derived) observations.

If the numerical weather prediction (NWP) approach to PMP estimation is used, considerably more data will be required to allow the NWP models to represent the storm and surrounding environment. Such data would include gridded meteorological data describing the whole atmosphere on pressure levels up to, for example, 50 or 10 hPa

[3] As discussed in the context of the disputed record for 2-hour rainfall at Walshaw Dean Lodge, West Yorkshire in 1989 (Collinge, and others, 1990).

(several 10s of km above the surface of the earth), covering a sufficient area beyond the model domain and for the entire durations of the event to be modelled. Ongoing research is indicating that PMP estimates resulting from the NWP estimates can be sensitive to the size and resolution of the domain used for the modelling (Tarouilly and others, 2022).

5.4.2 Hydrometric data

5.4.2.1 Opportunities for using hydrometric measurements

There are 2 opportunities for which hydrometric data (together with rainfall data) could be drawn on for estimating PMF:

1. By researchers during the development of a method for PMF estimation, for example, to generalise a rainfall-runoff model, so that its parameters can be estimated for ungauged catchments.
2. By practitioners carrying out flood studies, for example, to estimate the parameters of a rainfall-runoff model for a site where hydrometric data is available. This can be expected to provide a more confident estimate of PMF than reliance on generalised formulae that estimate model parameters from catchment descriptors.

Opportunity 1 can benefit from data on all sorts of catchments, not just those containing reservoirs. Data on small upland catchments may be particularly valuable, because many dams are in such locations, but PMF estimates are also needed for large catchments and in lowland regions, for example, at flood storage areas. For example, there are offline flood storage areas classed as Category A reservoirs beside the lower River Dee near Wrexham, where the catchment area is 1,600 km^2.

Opportunity 2 would require data at or near to sites where an estimate of the PMF is needed, which will mainly be dams. Rainfall-runoff models generally need to be developed for the inflow to a reservoir, so measurements of inflow are particularly useful for model calibration.

While opportunity 1 will require data sets that are already available at the start of the method development and of suitable length, opportunity 2 could draw on measurements from gauges that are recently installed or may be installed in the future. For major reservoir flood studies, it may be worth installing instrumentation in advance, because some rainfall-runoff models can benefit from calibration using short records, perhaps even only a few months of data recorded during a period with some wet spells.

For both opportunities 1 and 2, records from closed gauges could be as relevant as those that extend to the present day.

The UK benefits from a relatively dense network of flow gauges, including many that are capable of measuring flood flows. Most, but not all, of the long-established formal flow gauging stations are included in the National River Flow Archive. It includes 1,598 stations. Of these, 188 have catchments that are smaller than 100 km^2 and with a mean altitude of at least 300 m. This indicates that the data set has the potential to provide a good sample of flow measurements for smaller upland catchments.

As part of this project, a sample of reservoir owners was contacted to enquire about the availability of additional sources of hydrometric data. The following types of data could be useful for reservoir flood studies:

- flow gauging stations on inflows to a reservoir, where they capture the majority of the inflow
- flow gauging stations downstream of a dam, measuring the combined spillway release, compensation flow and other releases - together with measurements of water level, it may be possible to use downstream discharge data to estimate an inflow series using the technique of reverse routing, discussed on page 150.
- loggers measuring the stored water level at a sufficiently fine time resolution (at least hourly).

For some types of dam, a water level series is all that is needed to allow calculation of the discharge and, therefore, estimation of the inflow. This can be achieved where there is a unique stage-discharge relationships that governs the discharge from the dam. The presence of movable gates can complicate matters.

5.4.2.2 Data held by reservoir owners

Information on hydrometric data holdings relevant to reservoir flood studies was obtained from 5 organisations, each of which is responsible for a large portfolio of reservoirs: the Environment Agency, the Canal and River Trust, United Utilities, Yorkshire Water and Dŵr Cymru Welsh Water (DCWW).

Although many water supply reservoirs have regular measurements of level taken for statutory purposes or water resource assessments, these are often manual measurements taken once every few days, or once a week. Most of the supply reservoirs, from the organisations sampled, do not have reliable records of sub-daily water level measurements. Where sub-daily level measurements do exist (for example, at many dams operated by DCWW and Yorkshire Water), they are mostly from loggers installed for operational purposes rather than for the creation of a hydrometric archive. These data sets are not always usable, although in some cases they can be rescued by cleaning and gap-filling techniques. DCWW has level data sets at 15-minute resolution dating back to 2004 at many dams, which are thought to provide potentially useful information.

In the near future, much more hydrometric data is expected to become available at supply reservoirs. For example, the Canal and River Trust is currently installing remote monitoring of water level (and rain gauges) at many of its dams. Yorkshire Water is currently installing about 40 new level loggers.

Flood storage reservoirs are more likely to have instrumentation installed than supply reservoirs, because flood management can be helped by real-time monitoring of the filling and emptying of storage areas. The Environment Agency operates a large network of water level gauges, at least 86 of which have been identified as being located at reservoirs, flood storage areas or washlands. These have a median record length of 18 years, which is long enough to provide a potentially valuable data set for calibration of rainfall-runoff models.

5.4.2.3 Reverse routing

Reverse routing allows estimation of an inflow series from knowledge of the outflow and the rate of change in water level. It relies on the level pool assumption, that is, a horizontal water surface across the water body. This can be violated by wind effects for some larger reservoirs. Reverse routing can be a helpful way of evaluating the inflow to a reservoir, which can be difficult to measure, particularly if there are multiple watercourses that contribute flow. The process involves solving the differential equation:

$$I(t) - Q\big(S(t)\big) = \frac{dS}{dt}$$

where:

I(t) is the unknown inflow, which is a function of time (t)

S(t) is storage volume, a function of water level

Q(S(t)) is discharge, which varies with storage volume

Zoppou (1999) sets out 2 ways of solving this equation; an implicit and an explicit scheme. In an implicit scheme, there are multiple unknowns at each time step. In an explicit scheme there is only one. Implicit solutions are normally solved by iteration. Traditionally hydrologists have used an implicit solution, but this can produce severe oscillations in the calculated inflow hydrograph. These can be avoided by using an explicit solution. Zoppou (1999) recommends a centred finite-difference solution:

$$I(t) = Q\big(S(t)\big) + \frac{S(t+\Delta t) - S(t-\Delta t)}{2\Delta t}$$

where Δt is the time step for the calculations.

The inflow hydrograph is straightforward to calculate using this solution: the inflow at time t depends on the discharge at time t and the change in storage centred on time t.

It is often necessary to apply some smoothing to the calculated inflow hydrograph.

Reverse routing works well for many reservoirs although it can be affected by factors such as wind and waves affecting the water level, and is sensitive to any imprecision in the water level measurement. For small reservoirs, including some flood storage areas, it does not always give meaningful results. It requires knowledge of the relationship between water level and storage volume, although for flood periods the only relevant part is the portion of the reservoir above the water surface at the start of the flood.

5.4.2.4 Summary

In summary, there are already many flow records at sites representative of the wide range of catchment types for which PMF estimates are needed. Sub-daily records of inflows to reservoirs are relatively few, but there is potential to add to their number by a combination of reverse routing, developing ratings for level gauges, and installing either permanent or project-specific temporary gauges. Rainfall-runoff models also need catchment rainfall data, and usually data on potential evaporation or soil moisture, for calibration. This project has not investigated availability of sub-daily rainfall data, but in general it can be expected that such data is more readily available now than it was in the past thanks to the installation of recording rain gauges in many catchments in recent decades.

6 Options for an improved method

6.1 Approach to developing options

There is more than one way in which many of the requirements listed above can be met. The options set out below provide a range of approaches. At the simplest end is ‘do nothing’: continue to use the current approach to estimating PMP and PMF. This would mean continuing to use a method that was developed about 50 years ago and has been found to be inadequate in some ways and limited in others. Refer to the earlier section on 4.7 Validity of current UK methods.

Options that improve on current UK practice tend to lie somewhere on a spectrum from easier (such as following current good international practice) to more difficult (such as leading the way internationally with a state-of-the-art approach that capitalises on emerging scientific advances). For some aspects the ‘easier’ option is already available as an off-the-shelf solution, or can be adapted from something already available, perhaps with some checks and tests. Approaches that lie further along the spectrum will be more costly to develop and will introduce a greater degree of risk and unpredictability to any future research on this topic. On the other hand, it will be desirable to have a method that stands up to scrutiny and will not be regarded as outdated within a few years of its launch. It will be necessary to strike a balance between cost, practicality and rigour. The degree of effort that is appropriate for developing each component should be guided by the expected level of sensitivity of the estimated PMF to that component, as discussed in the following section.

The selection of options has drawn heavily on the review of international research and practice described earlier. It has also considered some additional types of methods that do not currently appear to be applied for estimating PMF. It is important to consider that not all overseas practice and research necessarily offers a template that can be directly transferred into the UK context. For example, some of the publications from the USA describe in-depth dam safety studies on very large dams with correspondingly large catchments. The owners of these major facilities may have substantial budgets available for flood studies. They also tend to have flow records available to enable calibration of models. In contrast, many dams in the UK are on small catchments with no suitable hydrometric records available. As an illustration of the difference in scale, the US Geological Survey defines a major dam as being at least 15 m tall, with a storage capacity of at least 6.2 million m^3, or of any height with a capacity of 31 million m^3. The various thresholds used to define large raised reservoirs in UK countries are 3 orders of magnitude smaller.

Some options that have been considered take a more holistic approach than others. For example, physics-based models may explicitly represent processes such as snowmelt along with rainfall-runoff. Other approaches develop the components separately, for example, adding a pre-calculated snowmelt rate to rainfall, along the lines of the current UK method.

There is a decision to be made about how prescriptive to make the new approach. International practice varies greatly in this regard, as shown in the literature review. At one end of the range, guidance from the USA allows practitioners freedom to choose between a wide range of rainfall-runoff types. In contrast, ARR (Ball and others, 2019) advocates a prescriptive approach based on the idea that since the PMF is essentially unknowable, a pragmatic, consistent, consensus approach is desirable. This thinking aligns with research showing that experts who make predictions in uncertain and unpredictable cases tend to be over-confident in their abilities and can be outperformed by algorithms, in fields ranging from medicine to social sciences, finance and engineering (for example, Kahneman, 2011; MacRobert, 2018).

6.2 Sensitivity testing

Some components of a new method of estimating PMF are clearly required. The most obvious of these is the need for a replacement method for estimating PMP. PMP is a vital factor to estimating PMF in most circumstances, and the current method for estimating PMP clearly needs replacing.

For some other components, it may be difficult to judge how much effort is justified in developing improvements. These include:

- PMP temporal profile
- snowpack depth
- snowmelt rate
- antecedent soil moisture

It would help to know how much influence they are likely to have on the estimated PMF. This will not be known until a new method is well under development. There are method-specific factors, for example, depending on which method is used to estimate PMP or depending how antecedent conditions influence run-off volumes in a rainfall-runoff model. Relative sensitivities are expected to vary widely with catchment type and location.

The sensitivity is complicated by the fact that many components are altering under climate change. For example, the importance of snowmelt rate may be declining as snow depths decrease and rainfall intensities increase. Snow depths may start to become more of a limiting factor.

Some preliminary indication of sensitivity can be gleaned from the following figures, calculated from the current PMF method using representative values of PMP durations (2 hours and 24 hours), depths, SPR values and snowmelt rates from the Hough and Hollis (1997) procedure.

The proportion of total water input during a winter PMP represented by snowmelt varies from 10 to 15% in lowland areas in the south of the UK to 30 to 40% for long-duration events in upland areas of the north of England or Scotland.

The ratio of snowmelt during a winter PMP to the snowpack depth varies from below 20% for short-duration events to 50 to 80% for 24-hour events in upland areas of England or Scotland. These ratios are based on data mostly collected several decades ago and are expected to have increased and to continue increasing as climate change increases melt rates and decreases maximum snowpack depths.

The contribution made by antecedent catchment wetness to the percentage run-off in the FSR rainfall-runoff method during a PMF varies from well below a fifth of the total percentage run-off for long-duration events in upland or lowland areas with low-permeability soils to nearly two-fifths of the total for short-duration events for upland areas in the north of Scotland. This finding is highly sensitive to the way in which the current method calculates the antecedent wetness.

These indicative findings show that the relative importance of different components of estimating PMF can be expected to vary a lot with geographical location, catchment response time and soil characteristics. In some upland catchments, accurate estimation of snowmelt amount may be important because it can be expected to form a substantial component of the water input during a PMF. Snowpack depths, while they tend not to be a limiting factor on current estimates of melt amounts, may become more important once past and future climate change is accounted for. Assumptions over antecedent catchment wetness are relatively unimportant in some circumstances, such as long-duration events, but could become a significant influence for catchments with short response times in upland areas.

It is important to stress again that the sensitivity of elements in a new method could differ from the above results, derived from the current method. The scope for future research will be developed under the assumption that PMF is sensitive to all components listed above in some circumstances. Sensitivity to the spatial profile of PMF is a different question that cannot be addressed using a lumped rainfall-runoff model. This is further considered in one of the options described in section 6.5 Options for other aspects of estimating PMF.

6.3 Summary of all options

Figure 30 gives a visual summary of the options described in the following sections. It shows how options for the different components of the procedure can be combined. Many options for one component can be applied together with most options from the other components. There are some that are more stand alone, in particular those that involve continuous simulation. Note that some options are radical departures from the current approach to reservoir safety. The bottom row indicates the type of outputs that can be expected: single PMF hydrograph, sample of extreme event hydrographs and continuous flow series.

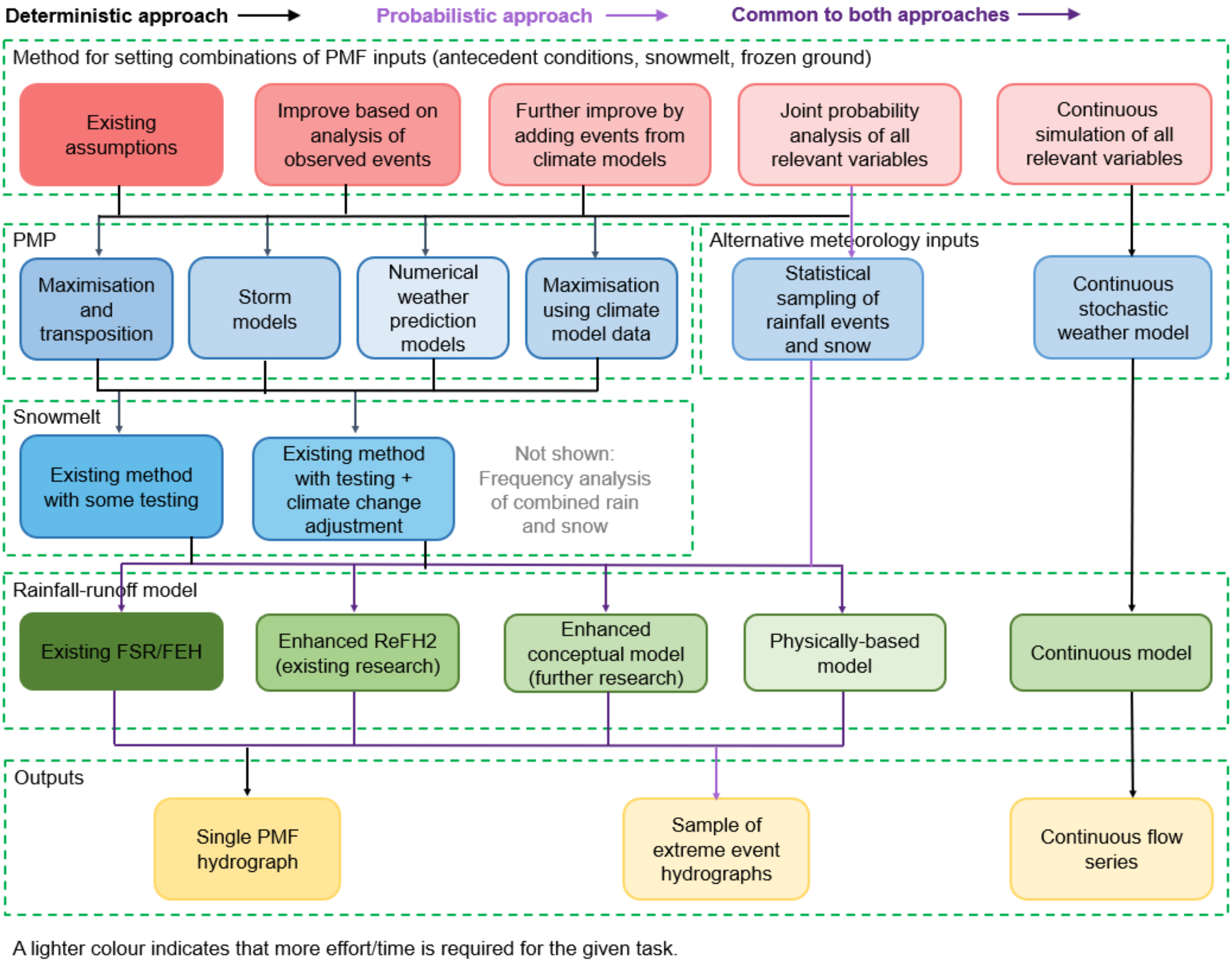


Figure 30: Summary of how the various options might fit together – this is described in the following sections

6.4 Options for estimating PMP

We first present a long-list of 5 types of method for estimating present-day PMP. We give a brief description of each and list their potential benefits for the UK context, followed by their drawbacks or challenges to overcome. This is followed by an equivalent discussion of methods for adjusting PMP to account for climate change. Following this, the methods are scored. Finally, a shortlist of the highest-scoring methods is presented.

6.4.1 PMP estimation approaches

A long-list of 5 potential options for a new method of estimating PMP has been drawn up by grouping and categorising approaches that are either used or being developed internationally, based on the review across 22 countries described earlier in section 4.3 Methods for estimating PMP.

The options are grouped into the 2 categories introduced in the review:

- statistical extrapolation approaches
- meteorological approaches (traditional and new)

The list of options below includes commentary on the benefits of each approach for the UK context, as well as potential negative aspects. It also considers whether the approach allows for non-stationarity in the historical climate. The following section assigns scores to each option.

It is worth pointing out that most of the PMP methods described below would typically be applied by a research team as part of a national or regional project, with practitioners being presented with generalised results from the meteorological or statistical analysis.

Statistical extrapolation approaches

1. Statistical analysis of extreme rainfalls

   Statistical approaches are generally applied in one of two situations:

   - to give a quick estimate of PMP in situations where data for applying meteorological techniques is not readily available
   - as an alternative way of estimating extreme rainfall in situations where the concept of an upper limit is not held to be credible or where probabilities need to be associated with the estimates

   The Hershfield approach (WMO, 2009) is a simple statistical technique for estimating PMP that is widely used in data-sparse countries. It dates back to the 1960s and is based on analysis of annual maximum rainfalls. The essence of the method is storm transposition, but instead of transposing the rainfall amount of individual storms, an abstracted statistic is transposed. It is typically regarded as giving preliminary estimates which are not as reliable as those obtained from meteorological analysis.

   A stochastic storm transposition (SST) technique (Foufoula-Georgiou, 1989) has been used in several countries, including the USA and Australia. The multifractal approach of Douglas and Barros (2003) has been developed in the USA with some success.

   The potential benefits are that:

   - statistical approaches offer a route towards associating PMP with a return period; an important component of a risk-based approach to dam safety
   - the Hershfield method can be applied rapidly, using only annual maximum rainfalls as input
   - results of these approaches can be fairly readily generalised

   Negative aspects or challenges to overcome include:

   - statistical approaches are limited by the observed rainfall data that is available - since they do not consider meteorological processes, it can be difficult to be confident that they are estimating the probable maximum

- they do not explicitly account for local factors such as topography that may influence extreme storms
- the Hershfield method provides only point values of PMP
- the more advanced statistical procedures have not generally been tested in the UK
- wide range of uncertainty at very rare recurrence intervals
- regional L moments and SST methods require extensive work to be completed at the site/region to develop the background database for use in probability estimation

Meteorological approaches (simpler)

2. Maximisation of observed extreme precipitation amounts, and transposition to the location of interest of actual storms, including generalised procedures based on this approach.

   Estimation and maximisation of atmospheric moisture, wind maximisation and storm transposition are necessary. Envelopment of the maximised transposed depth-duration and depth-area amounts of the extreme storm is carried out (a depth-area-duration analysis). This traditional meteorological approach remains the most common method of operational PMP estimation and can now benefit from the widespread availability of high-resolution data sources such as weather radar, re-analysis products and other outputs from numerical models.

   The potential benefits of the approach are that:

   - it is long-established, so that its capabilities and limitations are well understood
   - it has been and continues to be used in many countries, including South Africa, Spain, USA, Australia, China and India
   - it can be applied to storms of any size and duration, which makes it an attractive option for a seamless and consistent application
   - storm transposition provides a method for deriving PMP at any location
   - there is a considerable amount of both rain gauge and radar data for the UK - radar coverage is good, and with increasing model resolution and data assimilation, there is potential for further improvements in the UK
   - in the UK, there has been some use of moisture maximisation in south-west England and as part of storm models; this approach could be used more extensively in the UK

   Negative aspects or challenges to overcome include the following:

   - it is difficult to allow for past or future climate change within this approach - PMP is treated as a static value
   - typically, uncertainty information is not provided
   - moisture maximisation is insufficiently grounded in physics (Abbs, 2009)

- moisture maximisation implicitly assumes a constant precipitation efficiency, which is not the case in extreme storms
- typically, it is moisture that is maximised, but there is evidence that other meteorological parameters may be more appropriate to maximise such as vertical windspeed or convective available potential energy (WMO, 2009; Chen and Hossain, 2018)
- rainfall has been found not to scale linearly with precipitable water over smaller spatial scales (Chen and Bradley, 2003)
- moisture is typically maximised using a relationship between precipitable water and surface dewpoint temperature, but this can be an oversimplification; the result may not be representative of the moisture content being fed into the storm aloft (Chen and Bradley, 2006)
- moisture maximisation typically relies on some other assumptions, such as that the maximum persisting 12-hour dewpoint can be approximated by the 100-year return period estimate (WMO, 2009)
- since the method is data-driven, it can be difficult to know when enough storms have been included to confidently estimate PMP
- it is only in the last few years that radar data has been of good enough quality to help reliable analyses
- rain gauges and radar often underestimate maximum precipitation events

3. Storm models

These models represent the precipitation process in terms of physical parameters such as surface dew point, height of cell, inflow and outflow, surface heating, mechanical lifting by orography, convergence and solar heating. Each process has a particular parametrisation. However, with the development of high-resolution numerical models, these processes need not necessarily be individually specified, although they can be used as diagnostic tools to understand which processes may dominate in individual cases. A storm model requires as input the maximum storm efficiency for the duration of the event required. Storm efficiency is the capability of the storm to convert precipitable water to precipitation. Storm models are particularly useful in looking at specific events and results of these can help estimate precipitation efficiency, where available.

The potential benefits of these models include the following:

- a method of generalising the 3D structure of a storm weather system based on principles of synoptic meteorology can be used to create a simplified physical equation that represents a storm which can be maximised to estimate the PMP; this is known as the ‘inferential model method’
- storm models avoid the need to estimate the maximum surface dewpoint temperature, as required in the moisture maximisation method - instead, the model objectively calculates this quantity; this is useful because surface dewpoint temperatures are often not available for many upland areas of the UK

- there is some experience of applying these models in the UK - the model of Collier and Hardaker (1996) has provided a method of estimating PMP for specific storm durations up to around 20 hours - this has given values which improve on those produced by the FSR for mesoscale convective storms
- they have potential to represent the impacts of climate change, using modifications to parameterisations - the processes represented by these parameterisations are probably unlikely to be different in a warmer world, however parameters within the parameterisations may be modified to vary, for example, how efficiently, effectively or quickly the parameterised process takes place

Negative aspects or challenges to overcome include:

- the storm model approach provides good results for convective precipitation, but not for frontal systems producing long-term rainfall totals
- the approach requires specific parameterisations of convective processes and not complex large scale and mesoscale dynamic processes such as the structure and behaviour of fronts
- there is little or no experience of using storm models outside research settings to provide generalised operational estimates of PMP

Meteorological approaches (more complex)

4. Numerical weather prediction (NWP) models

These are increasingly being used in research settings for estimating PMP, taking advantage of improvements in model resolution. PMP is typically estimated by modifying the model's initial conditions or boundary conditions to represent extreme events. One such approach is the relative humidity moisture maximisation method in which the relative humidity at the model boundaries is increased to 100% for each extreme storm that is modelled (for example, Rastogi and others, 2017 and Toride and others, 2019). As for the traditional meteorological method, it may then be necessary to carry out a depth-area-duration analysis of each modelled storm to generalise the results across a range of temporal and spatial scales.

The potential benefits include:

- current state-of-the-art tool for explicit simulation of extreme precipitation governed by main physical equations of atmospheric motion and thermodynamics
- potential to overcome some of the assumptions and limitations of the maximisation and transposition approach
- not directly limited by sparse resolution of ground observations
- may be more readily generalised than most other methods
- represents the spatial structure of PMP storms, providing relevant information for estimating PMP on larger catchments

- in combination with downscaled results from global and regional climate models, NWP models can provide a process-based understanding of the impacts of climate change (Kendon and others, 2021)
- potential to evaluate uncertainty in PMP through use of ensembles

Negative aspects or challenges to overcome include:

- worldwide, this method remains largely a research tool, mainly applied in individual catchments
- it may be challenging to maintain a physically realistic basis for the model, and will be important to consider whether such models adequately represent the relevant micro and macro physical processes: see, for example, Gadian and others (2018)
- there is an issue of adequately parameterising the models to represent a PMP environment when there is no/limited observational data
- there remain some assumptions about which aspects of the model should be maximised, and how
- the degree to which maximised boundary conditions affect precipitation over the catchment of interest depends on the model domain size, in other words, how far the model boundary is from the catchment
- as with the traditional meteorological method, the NWP approach is usually applied to maximise observed historical events and, therefore, can be limited by the historical record and location of the storms - applying transposition processes to move storms to other areas can be more complicated for this approach to correctly handle the full 3D view of the atmosphere and the impact of local geography
- there are challenges with representing climate change effects: regional climate models run at convective-permitting resolutions rely on large-scale conditions inherited from coarser resolution global or regional climate models - large ensembles of model runs would likely be needed to provide robust samples of long return period extremes; these are very computationally expensive and not likely to be feasible at convection-permitting scales for the foreseeable future

5. Moisture maximisation method combined with reanalysis or climate model data

This is a variant of method 2 in which the inputs to the maximisation are gridded data sets, either output from meteorological models (for example, reanalysis data sets) or from more comprehensive climate models, rather than being directly observed point meteorological data. Note that this differs from method 4, which uses much higher-resolution weather models to directly simulate PMP-type storms. Model outputs that are relevant include 3D fields of horizontal and vertical wind, temperature, geopotential height and relative humidity.

Chen and others (2017) applied a traditional moisture maximisation PMP approach to 5 statistically downscaled CMIP model outputs producing an ensemble of PMP estimate in the US Pacific Northwest for a current and future climate. For each catchment, about 100 severe storms were identified. Their origins were identified using the HYSPLIT model for back-calculation of storm trajectories. At the end point of the back trajectory, a maximum sea-surface temperature was used to maximise the moisture availability of the storm. The maximum ratio between the maximum moisture availability and the actual atmospheric moisture along the trajectory was used to calculate the PMP.

Chen and Hossain (2018) used the NCEP North America Regional Reanalysis (NARR) and ECMWF Interim Reanalysis (ERA-Interim) data to investigate a statistical analysis of the relationship between extreme 3-day precipitation and atmospheric instability, moisture availability and large-scale convergence over the continental USA. The result provided an evidence-based guideline for modernising PMP estimation using numerical models.

An alternative temporal and spatial combination method uses hydrometeorological methods to combine 2 or more storms using synoptic climatology and weather forecast experience to produce a new sequence of an extraordinary storm which is used as a typical storm to determine the PMP (WMO, 2009). This is achieved through maximisation and transposition using storm combination techniques and common correlation methods.

The potential benefits of this method are that:

- it allows application of the traditional maximisation method in a framework that permits consideration of non-stationarity and uncertainty
- climate model outputs can be used to derive both present-day and future projections of PMP
- depending how it is applied, it can avoid some of the typical assumptions and limitations of the traditional method, by allowing air parcels to move vertically in the back trajectory procedure, and searching for the maximum moisture maximisation ratio along the whole trajectory of the parcel
- it can draw on existing long output series from reanalysis and climate models without the need for computationally-demanding modelling resources
- it can avoid some steps in the traditional procedure such as orographic adjustments and creation of depth-area relationships - if sufficient storms are available, it may also obviate the need for storm transposition
- statistically downscaled numerical climate model outputs could generate an ensemble of PMP estimates for the UK
- it provides a bridge towards fully model-based methods of estimating PMP which may become feasible in future

Negative aspects or challenges to overcome include:

- it remains limited by some of the drawbacks and assumptions of the maximisation approach, including the question over whether to maximise moisture or some other parameter and the assumption of linearity between precipitable water and rainfall

- it is limited by the coarse resolution of reanalysis and climate models in comparison with NWP models
- it is a novel technique which has seen only experimental application to date, with no experience of applying this in the UK
- published examples are for multi-day PMP over catchments subject to atmospheric rivers; it may be less skilful at estimating PMP in catchments where extreme precipitation over the relevant duration is caused by small-scale convective processes (Mahoney and others, 2018)
- the physical processes leading to large rainfall depths at short, sub daily durations are fundamentally different to those at even 12 hour+ durations
- it perhaps has more value in data-sparse areas where meteorological observations are less widely available than in the UK

6.4.2 Methods for assessing the impact of climate change on PMP

The effects of climate change on PMP have been discussed in the section 4.2.8 Effects of climate change.

Approaches available for amplifying the PMP estimate due to the projected impacts of climate change range in complexity from applying percentage increases to present day PMP estimates (sometimes termed an ‘uplift’) based on empirical formulae or calculations derived from other projects[4], to using high-resolution weather models.

Approaches that have been considered are:

- applying the Clausius-Clapeyron relationship directly to projected temperature increases - this assumes that changes in precipitable water translate directly to changes in PMP, which is consistent with the moisture maximising approach to PMP estimation but ignores other effects - it also assumes that Clausius-Clapeyron scaling continues for extreme rainfall; this could easily be applied using the existing UKCP18 land projections
- applying rainfall uplifts derived from other projects, not specifically derived for the PMP - this could make use of existing uplifts, for example, those from the FUTURE DRAINAGE project, however there may be some difficulty extending the uplifts to extreme events beyond the highest return period (limited to 100 years in the FUTURE DRAINAGE data set)
- use of storm models, based on known storm events but with specific parameters amplified

[4] For example, the on-going NERC FUTURE-DRAINAGE project (http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FS017348%2F1&cookieConsent=A)

- use of large quantities of climate model data from convection-permitting climate models to identify changes in precipitation extremes directly (for example, Rastogi and others, 2017) - this may be less feasible due to the limited amounts of such model data currently available; a very long time series or a very large ensemble would be needed - however, a hybrid approach could be adopted that uses statistical relationships between large scale conditions and local extremes, derived from available global model – convection permitting model pairs could then be used to create a long synthetic timeseries
- use of analogue data from other countries representative of future UK climates to provide estimates of uplifts for PMP - global hourly data records across the world are available, however this approach would rely on the assumption that uplifts were similar to those for observed events
- adjusting inputs to PMP estimation using scaling factors from climate model outputs of thermodynamic properties. Examples include:
    - using projected changes in mean sea surface temperature as a proxy for changes in storm inflow moisture that would directly affect PMP values (Mahoney and others, 2018)
    - a precipitable water adjustment factor that is easily computed from many climate project data sets, a relatively accessible option for quantifying ratio of future to past maximum moisture (Mahoney and others, 2018; Chen and others, 2017; Kunkel and Easterling, 2017)

  The UKCP18 data set provides suitable data for this approach, however, identifying suitable events and extracting relevant environmental data in future projections would require additional effort.

The value of simple methods is limited since the dynamics of extreme precipitation can be highly non-linear, so that precipitation does not always scale directly with changes in the ingredients commonly used in PMP estimation.

6.4.3 Scoring options for estimating PMP

In order to assess the relative strengths of each option, a scoring method was developed that assessed each method against a set of criteria. These criteria are listed below, grouped into 3 categories.

The criteria aim to identify what technical improvement a method might provide in the UK context (quality criteria) – how much more scientifically robust a PMP estimate might be – as well as how practical the method might be to develop and use to create a nationally consistent PMP data set. A further criterion of data availability is also significant as it can affect both the quality of the PMP estimate as well as issues of practicality of application and method development.

6.4.3.1 Quality

Integral in evaluating the ‘quality score’ are the following questions:

1. What level of scientific improvement does this method bring?

2. How much scientific uncertainty is there about the method? - for example, is it used by practitioners elsewhere, or it something untested that is emerging from academia?
3. Is the spatial and temporal resolution of the outputs suitable for UK reservoir catchments?
4. Does it account for all important meteorological processes expected to affect PMP across UK catchments, including both convective, meso-scale convective and frontal rainfall, with seasonal variation?
5. Can it produce PMPs over a range of storm durations from one hour up to 8 days? Eight days has been chosen as a likely upper limit for the storm duration that gives rise to the highest peak discharge over reservoir spillways in the UK?
6. How well/how readily can it represent spatial variation in storm depths across a catchment during a PMP event and spatial coherence over larger areas?
7. How readily can confidence limits be quantified for PMP?
8. Has the method been evaluated in comparison to other methods?

6.4.3.2 Data

An important consideration for the development and application of the PMP estimation options concerns the data requirements. The value of the ‘data availability score’ considers the following questions:

1. Are the data required to develop the method easily available?
2. Is the spatial coverage of the required data sets appropriate for future national generalisation of the method?
3. Are there potential quality issues with the data which may need considering during application of the method?
4. Are the data records long enough to ensure the resulting PMP estimates are suitably robust?

6.4.3.3 Ease of development and application

The practical implementation of the PMP estimation options is also important, particularly for the creation of a nationally consistent set of PMP estimates that are accessible and understandable by practitioners. There are 4 separate scores in this category.

Maturity of understanding of method - How mature is the understanding of the method in terms of a process for practical application?

Ease of development - This considers the degree of research and development effort needed to implement the method in the UK, including the need for specialised hydrometeorological knowledge.

Computational effort -The amount of computational resources and power required to perform tasks and reach conclusions in a computer system.

Ability to create nationally consistent data set - How easily can the results be generalised to provide accessible

PMP estimates for practitioners? Another important aspect of consistency, as noted earlier, is with rainfall frequency statistics.

Other factors that were considered in the scoring of methods were:

- how readily can the method be updated to incorporate new data?
- how readily can it produce realistic temporal profiles for PMP storms, including the ability to generate an ensemble of profiles?
- does it provide any outputs that would be useful in setting appropriate antecedent soil moisture conditions expected in combination with a PMP?
- does it provide any outputs that would be useful in setting appropriate snowmelt conditions expected in combination with a PMP?
- is it capable of also generating rainfall frequency estimates using a consistent approach?

6.4.3.4 Scoring tables

Scores were assigned to each of the available methods using a scale of 1 to 5, in which 5 is the most favourable and 1 the least. The scoring process has an inevitable element of subjectivity, reducing the many differences between the methods to a small set of numbers. We strongly recommend that scores are considered alongside the above discussion of pros and cons of each method.

Table 17 and Table 18 show the scores agreed following this exercise. Options for estimating present-day PMP are scored separately from options for assessing the impacts of climate change. We have resisted the temptation to add a column showing combined scores across all the criteria. To do so would need careful consideration of how to weight the various criteria. Different readers of this report might assign different weights according to their priorities. It may be appropriate to set a minimum score for the quality element before considering the ease of development of application. In addition to the scores against the criteria, information is also provided on the anticipated future improvement horizon in the various methods for estimating PMP in the current climate (Table 17). This information is provided as a subjective best estimate to give an indication of methods where improvements are likely to happen in the near future, either due to scientific or technological and computing advancement.

Table 17: Scoring options for estimating PMP in the UK

Method of estimating PMP	Future improvement horizon	Quality/ scientific improvement	Data availability	Maturity of understanding of method	Ease of development	Computational effort	Ability to create nationally consistent data set
Statistical analysis of extreme rainfalls	Not anticipated	1-2	4	3	3	4	4
Maximisation and transposition	Not anticipated	3	4	5	5	4	3
Storm models	5 years	3-4	2	3	2-3	3	3
Numerical weather prediction models	10 years	5	3	3	3	1*	5
Moisture maximisation method combined with reanalysis or climate model data	5-10 years	3-4	4	3-4	4	4	5

Notes for Table 17:

- score 1 to 5 (1 = worst /hardest, 5 = best/easiest)
- scores for maturity of understanding the method, ease of development, computational effort and ability to create nationally consistent dataset are scored for ease of development and application
- * score at current status - score anticipated to increase 1 to 2 points on the timescale of the future improvement horizon

Table 18: Scoring options for assessing the impact of climate change on PMP in the UK

Method of assessing impact of climate change on PMP	Quality/ scientific improvement	Data availability	Maturity of understanding of method	Ease of development	Computational effort	Ability to create nationally consistent data set
Application of Clausius-Clapeyron relationship to PMP estimate	2	3	4	4	4	4
Use output from convective-permitting weather model to estimate uplifts in extreme rainfall and apply to PMP	4	2	3	3	5	4
Amplification of storm models to be representative of future climates	3	4	4	4	3	3
Calculate present and future PMP using a convective-permitting weather model directly	4	2	3	3	1	5
Use of international analogue data to estimate PMP/PMP uplifts	4	2	2	3	2	3

Method of assessing impact of climate change on PMP	Quality/ scientific improvement	Data availability	Maturity of understanding of method	Ease of development	Computational effort	Ability to create nationally consistent data set
Scaling factors from climate model outputs of thermodynamic properties (precipitable water content/sea surface temperature)	2	3	4	4	3	4

Notes for Table 18:

- score 1 to 5 (1 = worst /hardest, 5 = best/easiest)
- scores for maturity of understanding the method, ease of development, computational effort and ability to create nationally consistent dataset are scored for ease of development and application

6.4.4 Outcomes of the evaluation of PMP estimation methods

6.4.4.1 Present day PMP estimation

The approaches scoring highest in this category for the quality criteria are use of numerical weather prediction (NWP) models and storm models, with the 2 moisture maximisation approaches following jointly.

Adopting the NWP approaches within the project will require high volumes of data, significant computational resources and close participation of the Met Office. Considerations of data availability and practicality of application will also need to be taken into account when assessing options for testing in this project. The 2 moisture maximation methods score highly across other criteria, particularly associated with the availability of data and maturity of the methods.

Based on these scores, the moisture maximation approaches likely offer the most tangible route to deriving nationally consistent PMP data sets for all event durations, using a method comparable to that used in many other countries. Whether enough long record point observation data exists to generate such data sets requires further investigation. Since the 2 moisture maximisation approaches have much in common, it is suggested that parallel investigations could be performed into deriving PMP using observed data and using gridded model data sets. Depending on the results from direct comparisons between these 2 methods for specific storm events, there may be a route to generalise the PMP estimates nationally and also provide estimates in the uncertainty around PMP values.

The storm models approach scores highly in the quality criteria, but this method is not designed for PMP estimates of one day or greater. The method might, however, provide more realistic PMP estimates for shorter durations due to the stronger grounding in describing physical processes.

The NWP approach is also recommended for further investigation to provide a potential route to address some of the limitations noted with the moisture maximisation and transposition approach. Cooperation with NWP centres of excellence such as the Met Office would be essential to provide the significant computational resources required to adequately investigate convection-permitting simulations of rare PMP events.

6.4.4.2 PMP amplification due to climate change

Similarly, the approaches for PMP amplification with climate change scoring highest in quality criteria have substantial data requirements. While they are likely to provide the most scientifically robust estimates, they may not be practical for application. Significantly easier approaches will be reusing the uplifts developed in the FUTURE-DRAINAGE research project (released in July 2021) and using observed Clausius-Clapeyron relationships between relative humidity and temperature, derived from UKCP18 climate projections.

The approach selected for incorporating the impacts of climate change into PMP estimates will also depend on the PMP estimation method chosen for the present day. Some of the shortlisted present-day methods (for example, the hybrid maximisation method) offer a relatively straightforward approach for estimating future changes in PMP using existing climate change projection data sets (for example, UKCP Local). While this method may require significant effort to identify extreme events in the data set, it would offer a consistent approach between the present day and future climates.

Given the uncertainty in estimating PMP in the present day, with different methods yielding different results, together with the uncertainties in estimating climate change impacts in general, it may be prudent to use several methods to estimate future PMP changes, allowing more of the uncertainty to be captured and characterised.

6.4.5 Evaluating PMP hyetographs

Implicit in many methods of estimating PMP is the derivation of a temporal storm rainfall profile. For methods where a storm rainfall profile for the PMP storm is derived, a comparison to the existing FSR PMP profiles and FSR T-year storm profiles is recommended. Additionally, comparison with the objectively-derived composite observed storm profiles currently under development (Villalobos Herrera, 2022b) is also recommended.

Through such comparisons, limitations associated with the PMP-method derived storm profiles can be identified, and the impact of these limitations on the PMP estimates themselves, assessed.

6.5 Options for other aspects of estimating PMF

This section is structured similarity to the above section on PMP. Each sub-section presents a long-list of options. The options are then scored, and the final sub-section presents a recommended way ahead.

6.5.1 Method for setting probabilities of inputs required in combination with a PMP to model a PMF

It is apparent from the conceptual model illustrated in Figure 28 that there are other elements needed to estimate a PMF in addition to a PMP storm depth. It will be necessary to choose a duration for the PMP, which will probably depend on the nature of the catchment (including the lag effects created by any reservoirs through which the PMF is routed). It may also be necessary to select a temporal profile, perhaps testing several alternatives produced by the PMP method. Depending on the type of rainfall-runoff model used, it may also be necessary to select a spatial profile and to allow for storm movement over the catchment. Along with these various aspects of the PMP, it will be necessary to specify reasonably conservative inputs for:

- snow depth and snowmelt rate, if modelling a winter PMF the following section (Snowmelt estimation method) discusses methods of estimating snowmelt; here our (focus is on what exceedance probability of snowmelt should be combined with a PMP

- antecedent catchment wetness conditions, including the impact of recent rainfall and, if modelling a winter event, snowmelt
- ground surface conditions, such as freezing or crusted after a hot dry spell
- initial water levels in any catchment storage features such as lakes, reservoirs or floodplains

It is not necessarily appropriate to set each of the above to its most severe possible value, because this could result in an over-conservative combination of conditions. Instead, a realistic combination of probabilities is needed for the inputs.

There is a range of approaches that could be considered, from rather arbitrary assumptions made using engineering judgement to a systematic approach that models the joint occurrence of all relevant variables. The former is more typical of current international practice as discussed in the review sections 4.4.4 Antecedent conditions and 4.5.3 Joint probability of rain, snowmelt and frozen ground.

One possible starting point would be to carry out a sensitivity analysis, which may reveal that some of the aspects are more important than others. A difficulty with this is that the sensitivity to antecedent conditions would depend on how they are represented in a rainfall-runoff model rather than being model-independent. It is possible that sensitivity tests would reveal something similar to the preliminary tests using the current method (see 6.2 Sensitivity testing), that is, each of the elements can substantially influence the estimated PMF in some circumstances.

We have considered the following options:

1. Do nothing
2. Improve the assumptions by analysis of meteorological and hydrological data
3. Use climate models to extend option 2
4. Carry out a joint probability analysis of all relevant variables
5. Continuous simulation

The following paragraphs expand on each option.

1. Do nothing

This would continue with the rather arbitrary assumptions made in the current method.

2. Improve the assumptions by analysis of meteorological and hydrological data

Option 2 would aim to improve some of the current assumptions made in setting inputs by analysing typical conditions (catchment wetness, snow, frozen ground) that are seen in conjunction with observed extreme events. The focus should probably be on extreme floods rather than extreme rainfall amounts, because the requirement is to identify combinations of conditions that result in major floods. This might include:

- analysis of temperature and discharge information for a range of events to determine whether there is evidence of how frozen ground impacts the percentage run-off, and whether there are any patterns that might allow an approach to be regionalised
- analysis of temperature data to review how snowmelt has contributed to extreme floods
- analysis of antecedent conditions to investigate the extent to which extreme floods occur at times when soil moisture is unusually high

Findings from the above would need to be treated with some caution because there is a possibility that events approaching the PMP might include different processes from those observed during lesser, but still exceptional, floods. For example, the analysis might show that few extreme floods recorded in the UK occur during periods when the ground might be frozen, but that does not rule out the possibility of frozen ground increasing the run-off response during a PMP.

3. Use climate models to extend option 2

Models could examine feasible combinations of circumstances that have not yet been observed. For instance, they may be able to indicate the likelihood of extreme rain occurring in the immediate aftermath of a spell of freezing conditions, or when there is significant snow accumulation, or at the end of a long, hot, dry spell.

4. Carry out a joint probability analysis of all relevant variables

Joint probability analysis could apply a more formal statistical approach than options 2 and 3, analysing the combined probability of variables such as rainfall depth, duration, measures of storm profile, antecedent moisture and storm conditions. One potential benefit might be that the analysis could provide benefits for estimating the entire flood frequency curve rather than merely the probable maximum. It could also consider other environmental variables relevant to reservoir safety, such as wind. The literature review mentioned UK research on joint probability for reservoir flood safety in the early 1990s, which made a start on examining some of these issues.

The results of a multivariate statistical analysis could be used to guide a single selection of variables to combine with the PMP to develop a deterministic estimate of the PMF. A more powerful way to exploit the results would be to feed into a Monto-Carlo sampling of input variables, as discussed under Option 5 for rainfall-runoff modelling, on page 175.

5. Continuous simulation

This option would replace the current design event approach with a continuous simulation of all relevant variables, including rainfall, temperature and snow accumulation and melt. This could only be done in combination with a continuous rainfall-runoff model. It would be a radical departure from the current approach to reservoir safety because it would not invoke the traditional concept of the PMP.

Refer to the sub-section below 6.5.4 Scoring options for other aspects of estimating PMF for a comparison of the above options for setting combinations of inputs.

6.5.2 Snowmelt estimation method

For the background to this section, refer to section 4.5.4 Summary on snow, frozen ground and joint probability that reviewed UK and international approaches to snow, frozen ground and joint probability issues in the context of estimating PMF.

Three options have been identified for methods of calculating snowmelt to be applied during a winter PMF:

1. The current method, Hough and Hollis (1997), with some testing, in conjunction with the FSR map of snow depths.
2. As (1) but with adjustments to represent impacts of climate change on current and future snow conditions and an update to the snow depth map.
3. A frequency analysis of combined rainfall, snowmelt and rain-on-snow.

Option 1 is the simplest. It is an existing generalised procedure that can give an estimate of snowmelt for any site in Great Britain. It would benefit from thorough testing to check its applicability in the full range of UK conditions, and explore different ways in which the procedure can be applied.

Although the FSR map of snow depths is based on a very limited record length (18 years) and is very dated, it could continue to be used within option 1 under the assumption that the available snow depth is rarely the controlling factor that influences the amount of melt during a PMP.

Option 2 is an attempt to make option 1 more representative of present-day and (potentially) future snow conditions. In addition to the testing of the Hough and Hollis (1997) procedure in option 1, option 2 would include an update to the mapping of snow depths.

Option 3 is a complete replacement that would avoid the need for arbitrary assumptions over the joint probability of rainfall and snow. This new analysis could draw on up-to-date records and, if necessary, allow for non-stationarity in the records. It may be difficult to justify the cost of this extensive data gathering and analysis task given that snowmelt is not as large a component of UK floods as it is in some parts of the world. Another drawback is it may be difficult to interpret the results in a form that would be useful for estimating PMP.

Refer to section 6.5.4 Scoring options for other aspects of estimating PMF below for a comparison of the above options for estimating snowmelt.

6.5.3 Rainfall-runoff model

6.5.3.1 Introduction to options

This section outlines 6 options that could be pursued to develop a rainfall-runoff modelling system for the purpose of reservoir safety in the UK.

For the background to the options being considered, refer to the section 4.3.4 International approaches for estimating PMP that reviewed UK and international approaches to rainfall-runoff models in the context of estimating PMF. Not all model types mentioned in the review have been included in the options that are suggested for consideration. For example, machine learning or deep learning models, while they have been shown to outperform some other model types, are not thought to be currently mature enough for operational PMF estimation. Likewise, rain-on-grid models at their current state of evolution are not thought to have a robust enough theoretical basis, although their assumptions may be more valid for extreme events than for smaller floods.

The 6 options can be broadly categorised into 2 different strategies:

a) Assuming that the industry standard approach to fluvial flood frequency estimation using rainfall-runoff modelling in the UK will remain a design event approach within the ReFH2 model.
b) Looking at a wider range of models, such as alternative conceptual models, physically-based models or continuous models. There would be benefits in selecting a model that is compatible with whatever emerges from the Flood Hydrology Roadmap as replacements for current flood frequency methods. However, it will probably be several years before these replacement approaches are settled.

Option 1 is to do nothing, continuing to use the FSR rainfall-runoff model for estimating PMF. Option 2 falls into strategy (a). Option 3 can also be placed into strategy (a), although it could also, in principle, be implemented using other conceptual rainfall-runoff models than ReFH2. Options 4 to 6 fall largely within strategy (b), although it would be possible to implement option 5 using the ReFH2 model.

The options are:

1. Do nothing
2. Enhance ReFH2 based on Pucknell and others (2020)
3. Enhance event-based conceptual modelling based on Pucknell and others (2020) and further research
4. Develop new physically-based spatially distributed rainfall-runoff model
5. Develop new design package for a conceptual rainfall-runoff model with Monte Carlo simulation approach (this could be a variant of options 2 to 4)
6. Develop a new continuous simulation system

Options 1 to 4 are compatible with the conventional approach to estimating PMP in which a single estimate is produced for a particular location and duration. For option 5, substantial additional research would be required to develop a new statistical model that can resample rainfall depth-duration-frequency and temporal profile of events across all catchments. For option 6, substantial additional research would be required to enable the stochastic generation of continuous rainfall for use in modelling of very extreme events.

The options are not necessarily mutually exclusive. One way forward might be to set up a flexible framework for estimating PMF, enabling practitioners to select from a range of rainfall-runoff modelling approaches. The selection of approach could depend on aspects such as degree of risk associated with the study, availability of calibration data, availability of existing models and importance of aspects such as quantifying uncertainty. As mentioned earlier, there will be a need to decide how prescriptive to make a new method of estimating PMF.

Each option is considered against a range of criteria, set out below.

6.5.3.2 Criteria for evaluating rainfall-runoff models

A new method for supporting the hydrological aspect of reservoir safety should ideally be able to address a number of requirements as defined in the following 5 criteria. The first 4 criteria are selected from the lists presented in section 5.2 Requirements of an improved method of estimating PMF.

i. Ability to contribute to a risk-based evaluation of reservoir safety

Options 1, 2, 3 and 4 all maintain aspects of the current method for estimating PMF where a PMP rainfall event of a selected duration is obtained separately and then converted into a PMF flood event by using an appropriate rainfall-runoff model. If the user community requires a return period to be associated with the PMF, additional research would be needed to align the 2 concepts.

Options 5 and 6 both constitute a break with current design philosophy as the rainfall input is no longer a single specified PMP event, but rather an ensemble of stochastically generated rainfall events. This type of approach is recommended by Balmforth (2021). Combined with an appropriate method for post-processing, the output from these stochastic systems will be a full flood frequency curve for a range of return periods rather than a single estimate of a PMF event. Further liaison with the reservoir safety community would be needed to discuss how this output should be used as part of the reservoir safety consideration either alongside a deterministic estimate of the PMF or instead of it.

ii. Ability to apply on ungauged catchments

Options 2, 3 and potentially 5 could make use of an existing set of equations that enable estimation of the parameters of the ReFH2 rainfall-runoff model to FEH catchment descriptors. The equations are currently subject to some commercial restrictions because they were developed commercially by Wallingford HydroSolutions (WHS). WHS has confirmed that the parameter equations may be used in future research without charge. This is on the understanding that they would be used in either furthering the science or in creating a tool that is freely available to users for estimating PMF. Any implementation of the new PMF method in commercial software, or use of the related rainfall-runoff model for applications other than estimating PMF, may need to be negotiated with WHS.

The FEH catchment descriptors are not freely available, instead needing to be purchased from the FEH web service operated by UKCEH.

Alternatively, a new regionalised procedure for estimating parameters could be developed using public funding, with no commercial restrictions on its application. This could be for ReFH or for an alternative conceptual rainfall-runoff model. The procedure could be based on catchment descriptor regressions (as at present), spatial proximity or a combination of the two. These 3 approaches are compared by Oudin and others (2008), who found that spatial proximity performed best for a large set of catchments in France. If catchment descriptors were required, they could either be the FEH descriptors or a new set of descriptors derived from open data sets, perhaps at higher resolution than the FEH digital terrain model.

The parameter estimation would require a data set of catchment rainfall and river flow for flood events. The calibration data set used in the original ReFH development is published in Kjeldsen and others (2005). UKCEH and WHS hold some additional data, for example, from more recent floods.

The cost of options 2 and 3 (and potentially 5) could be very much higher if it was decided not to rely on the existing parameter estimation equations for ReFH2.

Option 4 would require additional research to determine how a physically-based spatially distributed model should be applied in an ungauged catchment and how to ensure that the additional data requirements are available for routine use.

Option 5 could be based on the framework of the ReFH2 model, thereby allowing model parameter to be estimated based on the existing system as per options 2 and 3. Alternatively, it could be applied using an alternative event-based model.

Option 6 could build on the output from Defra/Environment Agency project FD2106 (Calver and others, 2005) where links between the model parameters and catchment properties were presented (some not included in the FEH catchment descriptor data set).

iii. Ability to consider climate change

Options 1 to 4 rely on a single estimate of a design rainfall event; the PMP combined with a pre-defined level of antecedent soil moisture. To assess the potential impacts of climate change on PMF, it would be necessary to quantify the effect of climate change on these design events. Methods for altering PMP and snow cover to allow for climate change have already been discussed. It would be necessary to combine those changes with the effects of climate change on aspects such as soil moisture and land cover.

Options 5 and 6 both rely on stochastic representations of rainfall and, again, it would be necessary to investigate how climate change is likely to impact extreme rainfall and how this might be represented in the parametric representation of the stochastic rainfall properties in the 2 types of models.

iv. Openly available for practitioners to apply using either standard or bespoke software

There is a strong desire to ensure that the new method for estimating PMF is made openly available, free from any commercial restrictions. This would enable it to be implemented in any software package and used for any purpose. It would create freedom for innovation, for example, allowing more general improvements to estimating flood frequency beyond the PMF. The level of freedom that users are granted to amend the model should be carefully considered, as there is the potential for a large increase in regulatory burden if all users, irrespective of hydrological competence, were able to amend the model without restriction.

Refer to the comments in point (ii) above about commercial restrictions on options 2 and 3 and possible ways of overcoming them. If one of these options were preferred, it would be necessary to decide whether the additional costs of developing and maintaining a fully open implementation of the ReFH model could justify the benefits of having a method with no commercial constraints.

If option 2 or 3 were to be based on the current commercial version of ReFH2, it would necessitate an update to the current software implementation of the ReFH2 model, or development of alternative systems. However, it is possible that the outcome of both options could be presented such that users could implement these changes directly in existing software without the need for additional investments.

Options 4, 5 and 6 would require new software developments to ensure that the methods are available and applicable for the user community.

v. Ease of development, including requirements for additional data analysis

Ease of development varies greatly between the options.

Option 1 requires no development work. The effort required for options 2 and 3 depends greatly on whether it is decided to retain the current commercially available approach for estimating the parameters of the ReFH2 model. In either case, some further validation would be needed for option 2. Option 3 would require analysis of flood event and meteorological data for a range of catchments across the UK.

Options 4 to 6 would require extensive research effort on a suitable number of catchments across the UK.

Demonstration across a range of test catchments will be necessary to ensure credibility among the user community.

6.5.3.3 Discussion of options for rainfall-runoff modelling

Each of the 6 options is discussed here, including highlighting research and development needs, as well as a summary of strengths and weaknesses of each method when considered against the 5 criteria outlined above.

1. Do nothing

This option would retain the existing FSR/FEH rainfall-runoff method as the basis for estimating PMF. The drawbacks of this method are reviewed in section 4.7 Validity of current UK methods.

2. Update ReFH2 based on Pucknell and others (2020)

The ReFH2 rainfall-runoff model is the current industry standard across the UK for deriving design flood events with a return period up to 1,000 years. The upper return period limit is arbitrarily determined, and there are no fundamental or methodological reasons why this could not be extended to higher return periods. Pucknell and others (2020) presented a framework for using the ReFH2 model for estimating PMF based on PMP combined with adjustments to time to peak, initial soil moisture, snowmelt and frozen ground effects. The proposed adjustments were developed by translating the existing guidelines for applying the FEH/FSR rainfall-runoff model to estimating PMF into a set of equivalent guidelines allowing the ReFH2 model to be applied in a mode similar to the existing FSR/FEH method.

The Pucknell and others (2020) method was tested on 15 catchments where estimates of summer and winter PMF, using the FSR method, were already available. Pucknell and others (2020) demonstrated that the proposed ReFH2 method was capable of producing credible and comparable estimates of PMF when compared to estimates obtained in the previous study (IH Report 114). However, further validation of the method across a larger range of catchment types is needed to ensure that the method can provide credible results for all catchment types of relevance to reservoir safety. Additional validation steps include:

- identify additional catchments representative of locations where estimates of PMF are generally required by the UK water industry
- calculate the PMF flood events (summer and winter) for each catchment using the FSR/FEH method
- calculate the PMF flood events (summer and winter) for each catchment using the ReFH2 method
- compare results of the 2 sets of estimates and investigate if there is evidence of systematic inconsistencies between the 2 methods that warrant adjustments to the method

Potential benefits include:

- off the shelf peer-reviewed method ready to use with little or no additional data analysis required
- easy to implement in existing ReFH2 software
- familiarity with ReFH likely to ensure acceptability across UK hydrology community
- ReFH2 method and software are supported and regularly updated
- consistent with method used in estimating flood frequency for reservoir safety below the PMF
- relatively simple model structure allows for transparent and rapid auditing of results

Negative aspects or challenges to overcome include:

- retains arbitrariness of adjustment to Tp and antecedent soil moisture as proposed in the original FSR study
- no explicit consideration of the effects of frozen ground on percentage run-off
- no explicit assignment of a return period to estimates of PMF
- commercial restrictions of ReFH2 calibration, although refer to the earlier comment about relaxation of these restrictions

3. Enhance event-based conceptual modelling based on Pucknell and others (2020) and further research

The framework proposed by Pucknell and others (2020) accepted the adjustments to model parameters and initial conditions that the FSR methodology introduced for modelling PMF. These adjustments were developed based on little or no analysis of observed data to quantify the hydrological processes and catchment response during extreme rainfall events. There is, therefore, an opportunity to improve the capability to model catchment flood response both to PMP events and also more broadly to extreme rainfall, including design events relevant to reservoir safety such as 10^5-year and 1,000-year floods. The issues have been introduced in section 4.4.2 Change in processes with event magnitude.

Further research is needed across a range of UK catchments to quantify the importance of the reduction in response time across rainfall event magnitudes and catchment types. This investigation could be carried out using any of a variety of conceptual rainfall-runoff models.

The effect of frozen ground on the hydrological properties controlling storm run-off is discussed in the review on h 121. This has not previously been studied in much detail in British catchments. Further research would be beneficial, alongside analysis of the likelihood of frozen ground coinciding with extreme rainfall, considered earlier in section 6.5.1 Method for setting probabilities of inputs required in combination with a PMP to model a PMF.

Potential benefits include:

- likely to capture dynamic changes to main hydrological processes (response time and percentage run-off) during extreme events
- likely to capture effects of frozen ground on run-off generation
- relatively simple structure of most conceptual models allows for transparent and rapid auditing of results

Additional benefits, if ReFH2 is chosen as the model include:

- familiarity with ReFH2 likely to ensure acceptability across UK hydrology community
- ReFH2 method and software are supported and regularly updated
- consistent with method used in estimating flood frequency for reservoir safety below the PMF

Negative aspects or challenges to overcome include:

- no explicit assignment of a return period to estimates of PMF
- commercial restrictions of ReFH2 calibration, although refer to the earlier comment about relaxation of these restrictions, or need to generalise parameters if a model other than ReFH2 is chosen

4. Physically distributed hydrological model

Using a physically-based and spatially distributed hydrological model has the potential to account for the hydrological processes based on explicit consideration through the governing equations controlling both infiltration and routing of the flood wave through the river channels. Some of the challenges and drawbacks of physically-based models have been introduced and discussed in the review in section 4.4.1 Rainfall-runoff models. Despite these challenges, using more advanced rainfall-runoff models could potentially increase the perceived credibility of model simulations.

A large number of physically-based and spatially distributed hydrological modelling system already exist, including both open-source as well as commercial modelling systems. The first task would be to choose a system considered suitable for the task of converting PMP to PMF.

The second, to calibrate and validate the modelling system using sub-hourly rainfall and run-off data from selected test catchments representative of catchments relevant for reservoir safety considerations would require identification of suitable spatially distributed data set of soil properties, land-use, and channel geometry on a national scale. Thirdly, depending on the chosen model system, a set of spatially distributed boundary conditions (for example, initial soil moisture and baseflow) based on analysis of the marginal distributions of these quantities obtained from simulation of observed events would need to be developed. Fourthly, develop of guidelines allowing model set-up, parameter specification and simulation on ungauged catchments. Finally, testing of the comprehensive methodology on test catchments where previous estimates of PMF exist.

This option is likely to require substantial investment in making a new modelling system and supporting data sets easily available on a national scale and in a format readily applicable by the chosen modelling system.

Potential benefits include:

- potential to provide more explicit and spatially distributed description of hydrological processes on a catchment scale
- will be able to make effective use of a spatially distributed estimate of PMP

Negative aspects or challenges to overcome include:

- substantial effort required to collect, quality control data for use in model calibration and validation on individual catchments as part of the development process
- new efforts likely to be required to ensure that the underlying data requirements (soil, land-use, channel dimensions) are available
- potential lack of transparency in modelling process (including potentially a large number of free parameters), making auditing time consuming and difficult for non-experts
- if used with PMP event as in current method, there is no explicit consideration of the return period of the PMF event (similar to ReFH2)
- little experience of using physically-based models among practitioners, which would create a potential barrier to acceptance and implementation

5. Monte Carlo based method

This follows on from option 4 listed earlier in section 6.5.1 Method for setting probabilities of inputs required in combination with a PMP to model a PMF.

Development of a Monte Carlo approach to estimating the magnitude of the PMF event and the corresponding flood event requires specification of the marginal and joint distribution of the boundary conditions, in particular rainfall (duration, intensity, and temporal profile), antecedent soil moisture, snow and frozen ground. The literature review discussed some international examples of this type of approach for reservoir safety such as ARR: Ball and others (2019) and sampling of rainfall profiles for PMF estimation by Felder and Weingartner (2016).

By sampling a large number of stochastic rainfall events and antecedent soil moisture conditions simultaneously, and using these properties as input into a rainfall-runoff model, a sample of extreme flood event hydrographs can be simulated. Finally, extreme event analysis of selected properties of the simulated hydrographs can be carried out, for example, peak flow, to estimate the corresponding flood frequency curve. Therefore, this method will not provide a single estimate of PMF, but rather a range of peak flow magnitudes and their associated exceedance probability.

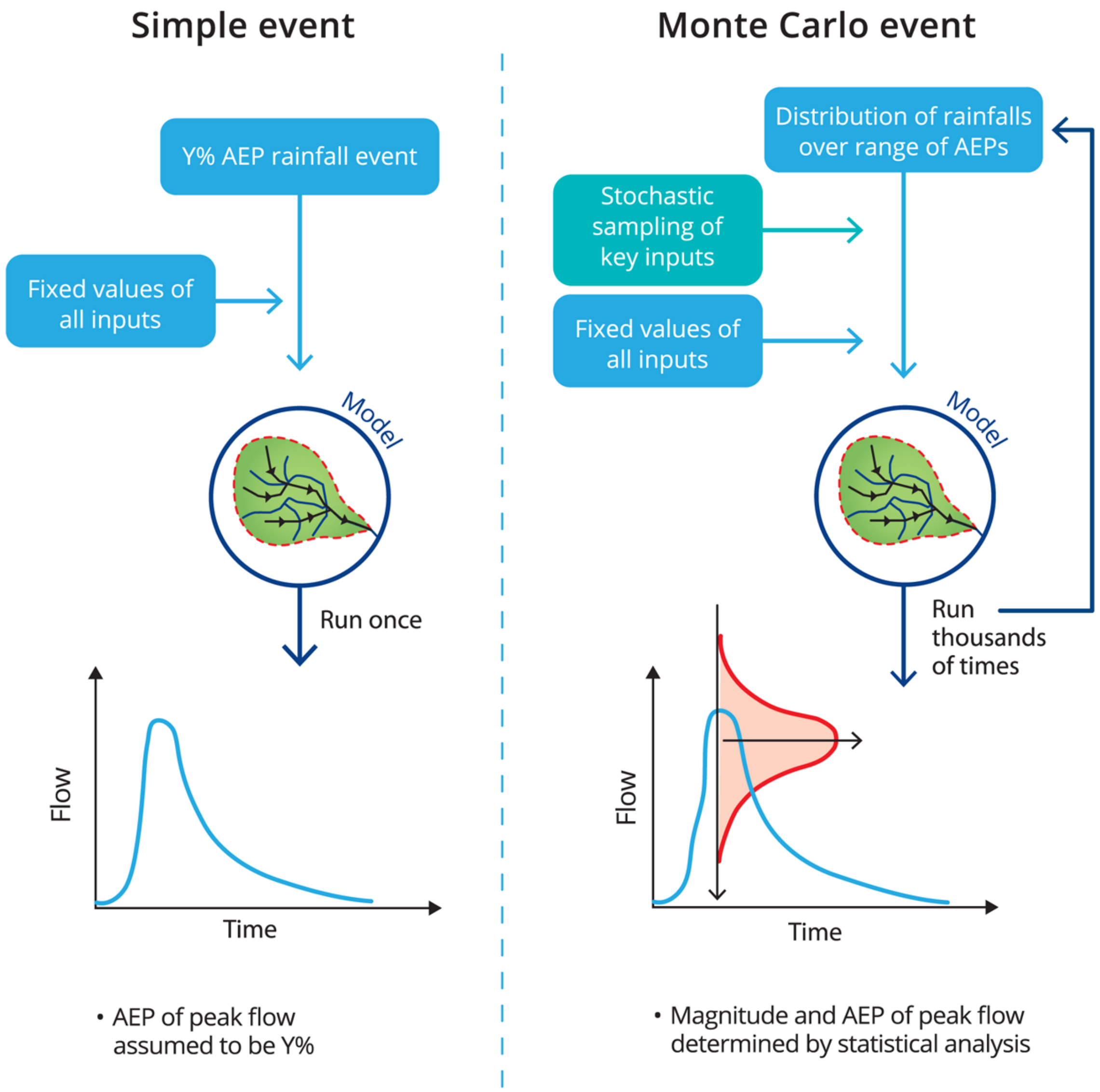


Figure 31: Schematic representation of design event and Monte Carlo methods for flood estimation using an event-based rainfall-runoff model, from Australian Rainfall and Runoff. © Commonwealth of Australia (Geoscience Australia) 2019

Figure 31 illustrates how this Monte-Carlo approach differs from design event methods for estimating flood frequency. A simple event method takes the Y% AEP rainfall event and adds fixed values of all inputs to run the model once resulting in a hydrograph of the AEP of peak flow assumed to be the Y%. However, the Monte Carlo event uses a distribution of rainfalls over range of AEPs and adds stochastic sampling of main inputs and fixed values of all inputs to run the model thousands of times resulting in magnitude and AEP of peak flow determined by statistical analysis.

Some research has previously been carried out to develop a prototype of this type of approach for use in the UK, for example, Svensson and others (2013).

A fully operational system applicable across UK catchments will require new fundamental developments to develop credible distributions that can be applied with confidence across all UK catchments.

Potential benefits include:

- method has the potential to move beyond the concept of PMF in favour of a frequency-magnitude based assessment across a range of return periods – although its results may still need to be reconciled with a physically-derived deterministic PMF
- method could be developed in conjunction with option 3, thereby preserving the operational benefits of the ReFH2 method and its easy of application across UK catchments
- the uncertainty of design floods can be deduced directly from the output of the modelling system

Negative aspects or challenges to overcome include:

- substantial new developments required to develop a statistical model of rainfall event and soil moisture characteristics applicable across catchments across scales, geographical locations and local climate characteristics
- may be difficult to convincingly demonstrate that a statistical sampling approach results in physically realistic estimates of extreme floods
- potential lack of transparency in modelling process, making auditing time consuming and difficult for non-experts

Additional work will be required if the stochastic aspects of snowmelt and frozen ground are to be included into the Monte Carlo framework. To preserve the joint distribution between all the relevant meteorological variables (rainfall, snow, temperature), it may be necessary to consider a more comprehensive weather simulation method that still maintains a focus on the simulation of extreme flood-generating rainfall events.

6. Continuous simulation modelling

This option follows on from option 5 listed earlier in section 6.5.1 Method for setting probabilities of inputs required in combination with a PMP to model a PMF.

Efforts to develop national systems for flood frequency analysis using continuous simulation models have been reported in previous Defra/Environment Agency research projects. FD2015 (Wheater and others, 2006) and FD2016 (Calver and others, 2005), and Lamb others (2016) provided an overview of opportunities and challenges in the use of continuous simulation in the context of UK catchments. The 2 Defra/Environment Agency funded projects enabled a 4-parameter version of the lumped continuous PDM model to be estimated at ungauged catchments, where it can be combined with stochastically generated rainfall.

As highlighted by Lamb and others (2016), continuous modelling has not been adopted widely for design flood estimation across the UK. A leading challenge in using continuous simulation for reservoir safety considerations is the need to simulate credible very large rainfall events as part of the continuous time series of precipitation inputs. Noticeably, project FD2105 only considered events up to a return period of 1,000 years and reported difficulties with simulating unrealistic events. Further research into the structure, parameterisation and use of stochastic rainfall models is likely to be required to enable credible estimation of very large events such as those required for reservoir risk assessment.

Potential benefits include:

- the method has the potential to move beyond the concept of PMF in favour of a frequency-magnitude based assessment across a range of return periods
- a comprehensive approach to allow for the effect of antecedent conditions on catchment and reservoir conditions, avoiding assumptions about elements of the design flood event
- uncertainty of design floods can be deducted directly from the output of the modelling system

Negative aspects or challenges to overcome include:

- substantial new developments are required to further develop and test continuous stochastic rainfall models so that they are able to provide credible representation of very extreme rainfall events across catchments across scales (size), geographical locations and local climate characteristics
- previous developments of continuous simulation modelling have not become part of standard hydrology practice in the UK despite substantial investments from Defra/Environment Agency (for example, FD2105 and FD2016)
- it may be difficult to convincingly demonstrate that a stochastic modelling approach results in physically realistic estimates of extreme rainfalls
- a potential lack of transparency in modelling process, making auditing time consuming and difficult for non-experts

6.5.4 Scoring options for other aspects of estimating PMF

Separate scores are presented for the options considered for the 3 aspects discussed above:

- setting probabilities of inputs to PMF modelling
- snowmelt estimation
- rainfall-runoff modelling

The scoring system attempts to assess how well each option might meet the requirements and attributes set out on page 139. For each option, the following aspects are scored, where relevant:

Quality

Quality is:

- ability to represent change in processes with event magnitude (only relevant to rainfall-runoff modelling)
- ability to contribute to a risk-based evaluation of reservoir safety
- ability to define confidence limits for PMF
- other scientific improvement over current method

Ease of development and application

Ease of:

- developing, testing and implementing method
- work to enable application on ungauged catchments
- application, including training and audit requirements

In interpreting the scores, please refer to the guidance on scoring PMP methods on page 166.

Table 19: Scoring options for setting probabilities of inputs to PMF modelling

Method for setting probabilities of PMF inputs required in combination with a PMP	Ability to contribute to a risk-based evaluation of reservoir safety	Ability to define confidence limits for PMF	Other scientific improvement over current method	Ease of developing, testing and implementing method	Ease of work to enable application on ungauged catchments	Ease of application, including training and audit requirements
1. Do nothing	1	1	1	5	5	5
2. Improve the assumption by analysis of meteorological and hydrological data	2	2	3	4	4	5
3. Use climate models to extend option 2	2	2	4	3	4	5
4. Carry out a joint probability analysis of all relevant variables	5	5	5	2	3	3
5. Continuous simulation	5	2-4	2-4	2	1-2	1

Notes for Table 19:

- score 1 to 5 (1 = worst/hardest, 5 = best/easiest)
- the first 3 data columns scoring refer to the quality of data and the second 3 data columns refer to ease of development and application

Table 20: Scoring options for estimating snowmelt in conjunction with PMP

Snowmelt estimation method	Scientific improvement over current method	Ease of developing, testing and implementing method	Ease of work to enable application on ungauged catchments	Ease of application, including training and audit requirements
1. Current method, Hough and Hollis (1997), with some testing, in conjunction with the FSR map of snow depths.	2	5	5	5
2. As (1) but with adjustments to represent impacts of climate change on current and future snow conditions and an update to the snow depth map.	4	3	4	5
3. Frequency analysis of combined rainfall, snowmelt and rain-on-snow.	5	1	1	3

Notes for Table 20:

- score 1 to 5 (1 = worst /hardest, 5 = best/easiest)
- the first data column refers to the quality of data
- the last 3 data columns ease of development and application

Table 21: Scoring options for rainfall-runoff model to represent the PMF

Rainfall-runoff model	Ability to represent change in processes with event magnitude	Ability to contribute to a risk-based evaluation of reservoir safety	Ability to define confidence limits for PMF	Other scientific improvement over current method	Ease of developing, testing and implementing method	Ease of work to enable application on ungauged catchments	Ease of application, including training and audit requirements
1. Do nothing.	1	1	1	1	5	5	5
2. Update ReFH2 based on Pucknell and others (2020).	1	2	2	3	5	5	4
3. Enhance event-based conceptual modelling based on Pucknell and others (2020) and further research.	4	2	2	3	4	2-5 depending on model	3-4 depending on model
4. Develop new physically-based spatially distributed rainfall-runoff model.	5	2	1-2	2-5	1	2-3	1
5. Develop new design package for a conceptual rainfall-runoff model with Monte Carlo simulation approach.	1-4	5	5	3-5	2	2-5 depending on model	1-2
6. Develop new continuous simulation system.	2-3	5	2-4	2-4	2	2-3	1

Notes

- score 1 to 5 (1 = worst /hardest, 5 = best/easiest)
- the first 4 data columns refer to the quality of data
- the last 3 data columns refer to ease of development and application

6.5.5 Outcomes of the evaluation of other aspects of estimating PMF

The following options are recommended. All of these achieve a reasonable balance between scores for quality and for ease of development and application.

Method for setting probabilities of PMF inputs required in combination with a PMP

A sensible starting point would be option 2: Improve the assumptions by analysis of meteorological and hydrological data. This is a relatively small amount of work which can exploit data holdings that are much larger and more accessible now than they were when the current PMF estimation method was developed.

If there is a strong appetite to depart from the current approach to reservoir safety and adopt a fully risk-based approach, as advocated by Balmforth (2021), it would be advisable to move on to option 4: Carry out a joint probability analysis of all relevant variables. This could provide information to allow risk-informed decision-making.

Snowmelt estimation method

Either option 1 (current method with some testing) or option 2 (adjustments to represent impacts of climate change and an update to the snow depth map) would be appropriate ways forward. Since many reservoirs have upland catchments, it seems wise to improve the representation of snowmelt rates and depths, so on balance option 2 may be preferable.

Rainfall-runoff model

Ideally the choice of rainfall-runoff modelling approach would be influenced by the outcome of the Flood Hydrology Roadmap which may lead to replacements for current flood frequency methods. However, it may be some years before these replacement approaches are selected. As an interim solution for estimating PMF, option 3 is recommended (Enhance event-based conceptual modelling based on Pucknell and others (2020) and further research). This could be implemented using any of a range of conceptual models. ReFH2 has some important advantages, as long as commercial constraints can be overcome.

To provide hydrological information to support a fully risk-based approach to reservoir safety, a comprehensive solution is offered by option 5: Develop new design package for a conceptual rainfall-runoff model with Monte Carlo simulation approach. This option scores highest on quality. While it would need a major research effort to develop and implement, it would probably be rather easier than options 4 or 6. It could be commissioned as a follow-on piece of work to option 3, since an enhanced conceptual model is a pre-requisite for option 5.

It is important to add that, whatever the preferred modelling approach for estimating PMF, it will also be important to consider the role of sources of information, including local flow data, historical floods and evidence of palaeofloods.

6.6 Providing a rapid screening method

Floods and Reservoir Safety (ICE, 2015 and previous editions) includes a rapid method of estimating PMF, as part of a screening procedure to assess the ability of a dam to withstand design floods. The rapid method was developed to provide a quick and easy to use alternative at a time when software for flood estimation was not generally available. It continues to be widely used.

For screening studies, for example on a large portfolio of dams, it can be helpful to have a method that can generate approximate estimates quickly. Some reservoir panel engineers appreciate having access to a method that can be applied as a quick check or an initial estimate without needing specialist hydrological software.

It may well be possible to meet this aspiration without any need to develop a separate procedure, or an approximation to the new PMF estimation method. As long as the new method meets the attributes listed earlier, it will be capable of being implemented by software that could give a rapid answer if applied with default values for parameters and no consideration of catchment-specific conditions or local data sources. It will be an open method that gives users the freedom to develop any software implementation that meets their needs, including automated application for a portfolio of dams. While the resulting estimates of PMF will not be as reliable as those developed through a more careful application of the procedure, incorporating local information, they should be suitable for replacing the current rapid method.

If, despite the above discussion, there is demand for a separate shortcut method, it should be straightforward to carry out a statistical analysis to estimate the peak flow of the PMF via linear regression, linking estimates of PMF peak flow with a set of FEH catchment descriptors. This could be incorporated into a simple set of formulae applicable by reservoir panel engineers.

6.7 Discussion of recommended options for estimating PMP and PMF

In considering the way ahead for further research, it is helpful to return to section 5.1 Conceptual model of PMF formation. There are many components of the model, and it is clear that estimating a PMF is more than a matter of applying a PMP to a rainfall-runoff model. Interactions and dependencies between the components can be important to consider.

There are many options available for representing individual components, as well as a need to choose an overarching framework. The question of which option is appropriate needs to be addressed in the context of the decision-making and regulatory framework in which the method is to be used (Mahoney and others, 2018). It also needs to be guided by the practicalities of time and budget available to develop and implement a new method.

There are several options that the scoring system identifies as capable of achieving a substantial improvement over the current method for estimating PMP and PMF. All will involve significant effort to develop, test and implement into a method that meets the attributes listed in Table 16. However, the recommended options appear capable of achieving these outcomes more efficiently and with a greater degree of confidence. Some of them are already applied operationally overseas. Some of the alternative options would need more in-depth research, which would not be guaranteed to lead to a favourable outcome. These methods may need more exploration and testing in academic settings before being ready to incorporate into a comprehensive national method accessible to UK practitioners.

In addition, the recommended options form a family of modules which can be built on each other (Figure 32). This will allow an element of future enhancement if budget or time restrict what can be achieved initially. It may help achieve some alignment with future methods of UK flood frequency estimation. An important decision will be whether to choose a purely deterministic approach to estimating PMF, as at present, or to add a probabilistic approach. These can use similar building blocks (Figure 32). They need not be mutually exclusive options. A deterministic estimate of PMF may provide a useful check against the outcome of a statistical sampling exercise that is not necessarily constrained by physical limits. Guidance in the USA advocates this sort of approach (see page 88).

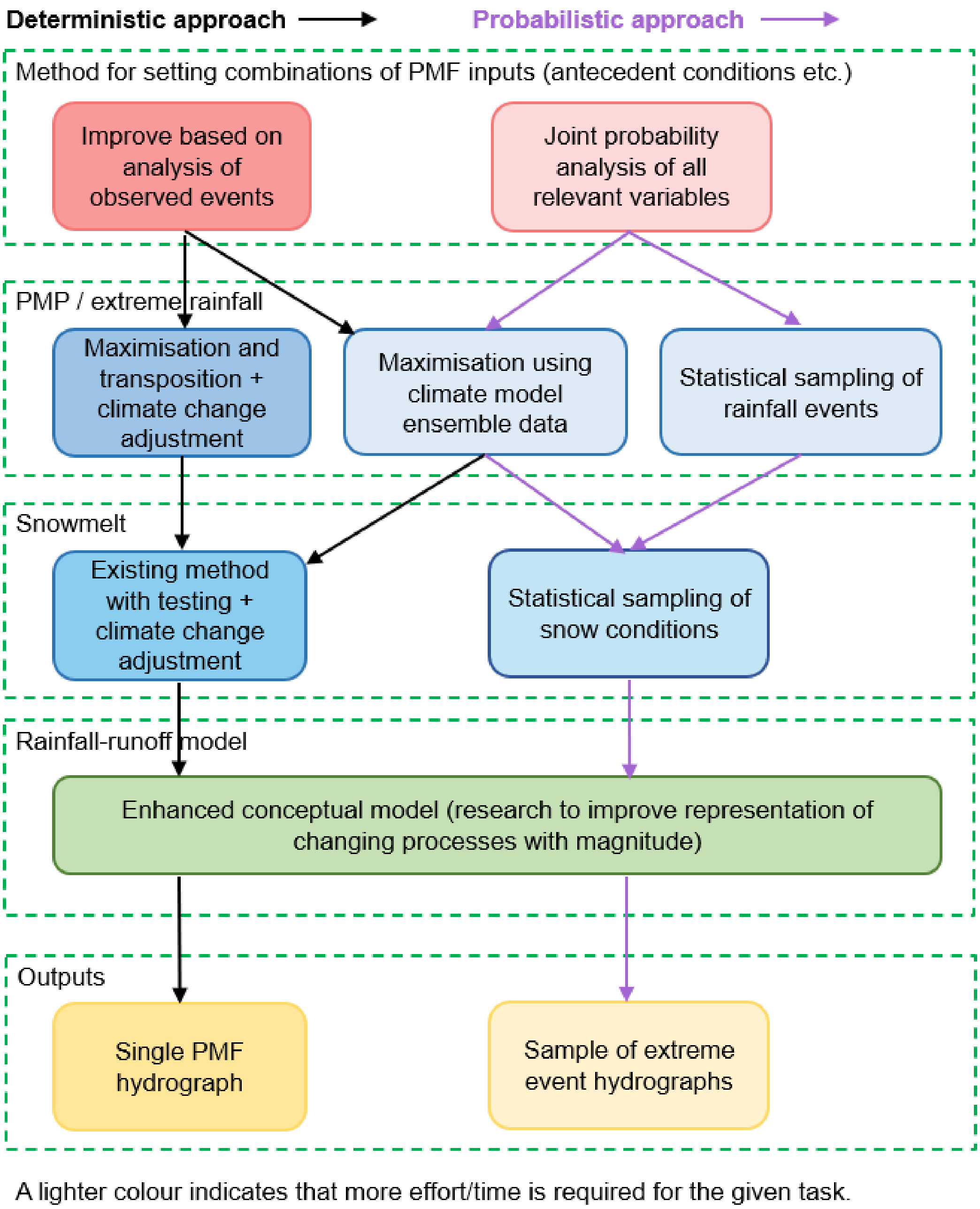


Figure 32: Summary of recommended options, showing how a probabilistic approach could use the same building blocks as a deterministic approach – a lighter colour indicates that more effort/time if required for the given task

Figure 32 shows a flow chart for deterministic and probabilistic approaches. The deterministic approach would use a method for setting combinations of PMF inputs based on analysis of observed events and use PMP/ extreme rainfall predictions using maximisation and transportation, plus climate change adjustments as well as maximisation using climate model ensemble data. Combining with snowmelt's existing method, climate change adjustment and an enhanced conceptual rainfall-runoff model to create a single PMF hydrograph output. The probabilistic approach would use a method for setting combinations of PMF inputs based on joint probability analysis of all relevant variables. It would use PMP/extreme rainfall predictions based on maximisation using climate model ensemble data and statistical sampling of rainfall events and a statistical sampling of snow conditions and an enhanced conceptual rainfall-runoff model to create a sample of extreme event hydrographs.

The scoring system is not able to neatly encapsulate every aspect of the required and desirable attributes of a method of estimating PMP and PMF. Some other issues and recommendations have been raised through the course of this report. The points below provide some summary comments on them in relation to the recommended methods, and links to where they are discussed in more detail.

Return period of PMF and risk quantification

There are fundamental difficulties with associating a return period, and, therefore, a level of risk, with the PMF. The Monte Carlo simulation approach offers a route to quantifying risk of extreme floods without recourse to the concept of a probable maximum (page 184). Alternatively, there is some prospect of improving on the current very crude estimate of the PMF return period in common UK practice (page 81).

Consistency with methods for estimating flood frequency

It would be desirable for practitioners to have access to a single rainfall-runoff modelling approach that they could use with confidence across the full risk profile, up to the PMF. Progress towards this can be made by analysis of catchment conditions during a range of event magnitudes (rather than only the most severe events) and by enhancing a conceptual rainfall-runoff model to allow for variation in flood response with event magnitude (pages 104,182). These developments will be beneficial for fluvial flood risk management as well as for dam safety.

A more joined-up approach to estimating rainfall frequency would also be desirable. As a minimum, new estimates of PMP should be compared with current best estimates of rainfall quantiles for extremely low probabilities. In practice, it may be difficult to know whether the PMP should yield to the rainfall frequency curve or vice versa. Both are subject to large uncertainty that is difficult to quantify.

Climate change impacts

The recommended options include methods for assessing the potential impact of climate change on PMP (pages 165, 172). This will form an important component of further research. Translating the results into a change in PMF will need some additional work, particularly on catchments where snowmelt is currently a significant component. The recommended approach to snowmelt estimation includes an assessment of future conditions (page 176).

Non-stationarity of observations

Non-stationarity is a relevant consideration in estimating PMP using methods that may incorporate data from storms that occurred several decades ago. Statistical tests should be used to identify any non-stationarity in input data sets. Any frequency analysis that is required, for instance of maximum persisting dewpoint data in the moisture maximisation method (page 160), can use non-stationary methods if necessary.

Uncertainty

There is some prospect of quantifying uncertainty in PMP (page 86). Associating confidence limits with a deterministic estimate of the PMF is beyond the state of the art and something of a contradiction in terms. The recommended Monto-Carlo sampling approach to estimating the frequency of extreme floods would allow full integration of uncertainty.

Spatial variation/coherence

The recommended method for estimating PMP traditionally includes a depth-area analysis of the storms which are maximised. This provides the information needed to allow for the areal reduction effect, in which catchment-average rainfall depth decreases with the size of the catchment. The more advanced variant of this method, based on climate model outputs, can avoid this step if it analyses rainfall over entire catchments.

A more explicit representation of spatial variation in storm depths, either within a catchment or between several catchments, could be provided by the Monte-Carlo sampling method. Page 93 gives an example of random sampling of spatio-temporal patterns to generate PMP storms. Although the recommended lumped conceptual approach for rainfall-runoff modelling does not consider spatial variations, it would be possible to do so by modelling sub-catchments separately. This could be relevant for analysing the safety of dams in cascade. There may also be a requirement to test scenarios of extreme floods occurring simultaneously at multiple dams from a single extensive PMP.

Palaeofloods

Palaeoflood investigations should be promoted as a complement to estimating PMF in upland catchments (page 127). The cost of them is likely to be tiny compared with the cost and benefits of upgrading a spillway.

7 Future considerations

7.1 Need for further research

Our principal recommendation is to continue research on estimating PMP and PMF. It is necessary to replace the current methods of estimating PMP and PMF used in the UK urgently because:

- estimates of PMP are too low in some places, having been exceeded by at least 8 rain storms during the 20th to the 21st century
- estimates of PMF may also be too low in some places, since there is (uncertain) evidence of 5 floods that may have exceeded the PMF
- estimates of PMP are inconsistent with the upper end of the FEH 2013 rainfall statistics
- the PMP method is based on old data, excluding all storms from the past 50 years
- aspects of the methods have been challenged in the scientific literature
- the PMF method includes arbitrary adjustments with limited scientific justification
- alternative methods give higher estimates of PMP for some locations
- there is no procedure for adjusting PMP or PMF for the ongoing or projected future effects of climate change
- there is no quantification of uncertainty in the estimates
- it is difficult to confidently link the estimated PMF with flood frequency estimates
- the government’s review of reservoir safety, commissioned in the aftermath of the Toddbrook Reservoir incident, recommended new approaches to estimating extreme floods, including generating multiple scenarios of extreme weather and allowing for non-stationarity of the climate (Balmforth, 2021)

7.2 Event cataloguing

We recommend that rainfalls and peak flows for more of the catalogued events are compared with estimates of PMP and PMF, using an automated procedure to estimate PMP and PMF. These may detect more exceedances.

It may be possible to investigate the handful of apparent PMF exceedances in more depth, reviewing the original flood reports. Sensitivity tests would help indicate the uncertainty in the estimated peak discharges. This line of investigation is recommended as a way of improving confidence in the findings of the PMF comparison.

The catalogue contains events up to 2020. It would be desirable to keep the catalogue up to date, adding exceptional rainfalls or floods soon after they occur.

7.3 Allowing for climate change

In light of the most recent research captured in Fowler and others (2021), we recommend that appropriate methods for PMP amplification due to anthropogenic climate change are included in future PMP estimation methods, since dam infrastructure needs to be resilient in the future as well as at the present day.

Guidance for reservoir safety should be amended to require the projected impacts of climate change to be considered. It may be possible to develop an interim suggested adjustment for peak flows, pending the findings of further research into the impact of climate change on extreme floods.

7.4 Flood estimation across the whole risk spectrum

To implement a fully risk-based approach to managing flooding from reservoirs, or other high-risk infrastructure, practitioners will need a single approach to estimating extreme floods that they can apply with confidence across the full risk profile, up to the PMF where required. Our recommended approach to achieving this is to develop:

- new estimates of PMP
- a rainfall frequency estimation method whose results are consistent with new estimates of PMP (outside the current project)
- a rainfall-runoff model structure and parameterisation that can be applied across the full range of event probabilities, including for the PMF
- a system for specifying combinations of input to the model (or models) that will simulate consistent design floods of the intended probability, using Monte-Carlo simulation across all relevant input variables

In the longer run it may be that integrated models of meteorological and hydrological systems permit an approach to estimating extreme floods that combine a physical basis with explicit analysis of probability.

It is desirable that any hydrological approach selected for future reservoir safety management is compatible with the rainfall-runoff modelling approaches that will be used in future for fluvial and surface water flood risk management. These will be defined through the Environment Agency's Flood Hydrology Roadmap. Although it may be several years before these future approaches are defined, this need not delay the commissioning of further work, because most of the analysis can be carried out irrespective of the choice of rainfall-runoff model formulation.

7.5 Focus on the needs of practitioners

It is vital that new methods of flood estimation for reservoir safety meet the needs of dam engineers and hydrologists. They should be:

- openly available for practitioners to apply using either standard or bespoke software, including automated application across a portfolio of sites
- capable of being applied and audited after appropriate training, using skills already typically available across the practitioner community
- able to incorporate local information, including calibration data

- capable of giving rapid results for screening studies where needed

Appendix 1: Description of soil moisture models used in event cataloguing

Continuous Estimation of River Flows (CERF)

CERF (Continuous Estimation of River Flows, Griffiths and others, 2008) is a daily, regionalised, semi-deterministic hydrological model which explicitly recognises soil properties and land cover using a scheme based upon the FA056 procedure (Allen and others, 1998). It also incorporates canopy interception losses using a generalised scheme of Young (2006). CERF has been widely used in UK hydrology, for example for Defra under the UKCP09 river flow climate change scenarios (Prudhomme and others, 2012).

The model uses the generic concept of hydrological response units (HRUs) to define a flexible model structure in which catchment descriptors of vegetation, soil type, topography and geology are used to define relatively complex, unique model structures in each catchment. The number of HRUs depends on the complexity of the catchment. So, for example, small catchments with relatively similar soils, geology and vegetation will have relatively few, while large diverse catchments may have many.

The model structure for CERF is presented in Figure 33.

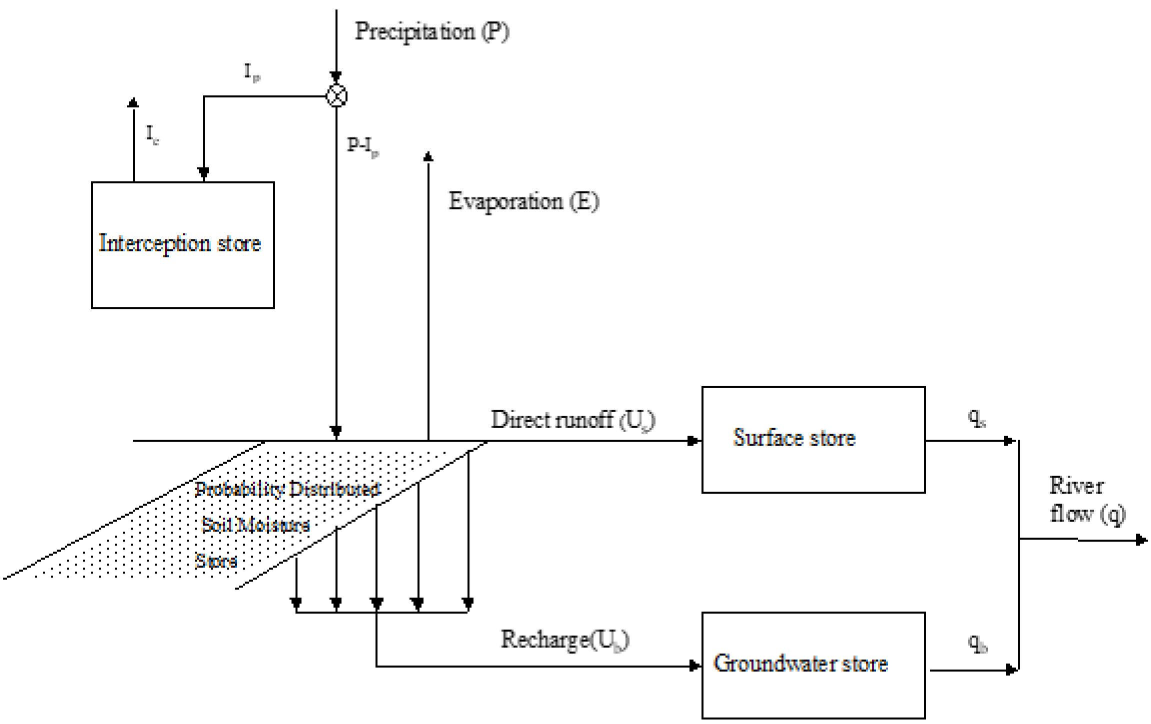


Figure 33: Conceptual structure of run-off model

Figure 33 shows a conceptual structure of run-off model, based around 2 sub model components; the loss module that generates hydrologically effective precipitation (EP) and the routing module that subsequently routes the EP to the catchment outlet. The basic model structure for the loss module is a hydrological response unit consisting of an interception sub-module and a treatment of transpiration losses based on the FAO56 soil moisture accounting procedures for determining crop water requirements. The model developed describes soil moisture as a function of maximum root depth (Zr), and ‘moisture depletion fraction’ (dp) for a range of vegetation and soil types. The amount of water available to plants after a soil has drained to its field capacity is described as the total available water (TAW). TAW is defined as a function of field capacity (FC), wilting point (WP) and maximum root depth (Zr) such that:

$$TAW = Zt(FC-WP)$$

As moisture content within the soil column decreases, vegetation will find it more difficult to extract moisture from the soil matrix. The fraction of TAW that can easily be extracted before this point, is reached is described as readily available water (RAW). The value of RAW is related to TAW by a land-cover defined depletion factor (dp), which is comparable to the ‘rooting constant’ described by Penman (1948), therefore:

$$RAW = p\ TAW$$

Figure 34 presents a schematic of the soil moisture store.

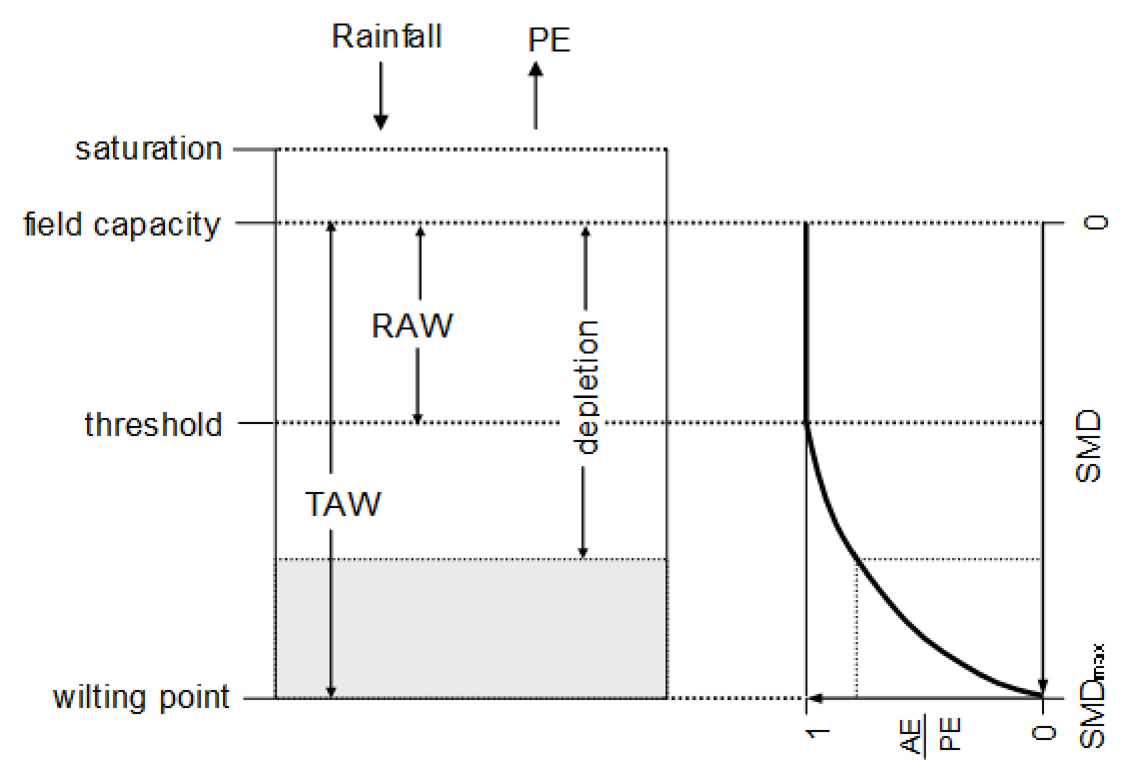


Figure 34: Schematic representation of soil moisture store, with TAW and RAW presented in relation to field capacity and wilting point (left), and the relationship

between soil moisture deficit and the ratio of actual evaporation to potential evaporation (right).

In the routing structure, the effective precipitation (EP) enters a probability distributed soil store (PDM soil store), based upon a uniform distribution, that conceptually represents the catchment variation in soil storage capacity between field capacity and saturation. Run-off from the store is passed through a surface flow reservoir with a time constant Kl, while drainage, is proportional to the storage content of the store. The sum of the resultant surface and base flow from the routing reservoirs is the simulated streamflow (q). The functioning of the store is controlled by 2 parameters; the maximum storage capacity and the drainage coefficient of proportionality, Kg.

The total soil moisture within the CERF model is a combination of both the soil moisture store and the PDM soil store.

DAYMOD

DAYMOD is a daily soil moisture accounting procedure which is also a variation on the well-known FAO56 soil moisture accounting procedure. The full mathematical formulation is present in Appendix A of the FEH Supplementary report (Kjeldsen, 2007) and is an integral part of the calibration process (setting initial conditions) for observed events using the ReFH hydrological event model. The procedure conceptualises the soil column as retaining a maximum mean moisture depth equal to the field capacity (FC)(mm). Evaporation can take place from the soil column, depleting the soil column and moisture depth, m(t) over a timestep in the absence of rainfall. Evaporation takes place at the potential rate until a lower threshold is reached, the rooting depth (RD), beyond which the evaporation takes place at a reduced rate. The magnitude of the reduction is proportionate to the difference between the soil moisture depth, m(t) and RD.

If the soil water depth exceeds FC, this water is available to fund evaporation, but also a proportion of the depth of water in excess of field capacity will drain. The drainage rate is proportional to the depth of water above FC. If the rainfall is incident when m(t) is <=FC within a time step, then m(t) will increase or decrease depending on whether the rainfall is larger than the evaporation demand or not. Above FC, m(t) will increase if the rainfall is larger than the sum of the evaporation and drainage.

The maximum mean soil moisture depth is SM. ReFH conceptualises the distribution of soil moisture depths across a catchment as a uniform distribution across the range (0, CMAX), therefore, C(t) can be calculated based on the M(t).

Default parameters for FC and RD can be obtained based on the CMAX value (which is itself calculated from the BFIHOST and PROPWET).

Data requirements

Both models require meteorological data in the form of daily rainfall and potential evaporation (PE) data. Two national data sets were used to process the catchments in a consistent and efficient way. The daily 1 km GEAR data set (described in previous sections) was used as a source of rainfall data. PE data was obtained from the 1 km daily CHESS PET data (Robinson and others, 2020). This is closely related to the Moses data set. Both rainfall and PE data sets are available to download from the UKCEH website, from which daily data for each 1 km cell can be obtained for the periods 1961 to 2017 (the GEAR data set can be extracted for earlier periods as well).

Both models require catchment boundaries to calculate average catchment rainfall and PE data from the 1 km gridded meteorological data sets. Catchment boundaries were obtained from Qube (WHS, 2021); a water resource online modelling tool.

CERF also requires a catchment boundary to obtain information on land use (using LCM2000) and geology (based on HOST). In addition, the boundary is used alongside a digital terrain model as part of the routing procedure.

The parameters of CERF are estimated using a regionalisation process, based on more than 200 gauging stations within the UK.

The default parameterisation of DAYMOD was used, based on the CMAX (maximum soil depth), which is estimated from the catchment average BFIHOST and PROPWET. The FEH Web Service was used to obtain BFIHOST and PROPWET values for each catchment.

In total, 30 catchments were identified from the event catalogue, however due to missing data the following catchments were excluded:

- Six Mile Water, Ballyclare: the location of this site is in Northern Ireland and it was not possible within the time constraints of the project to extract the relevant meteorological data or spatial data sets required for CERF
- Gauge 106003: this gauging station is in the Outer Hebrides and land use and HOST data were not available for CERF analysis - results are only available for DAYMOD
- Gauge 57015: the event identified is from 2020, therefore, meteorological data was not readily available for this event

In summary, 27 catchments were run for both models, with one additional catchment (106003) modelled using DAYMOD.

General discussion of soil moisture models and results

The time series statistics from the 2 model outputs were compared with the long-term average annual rainfall and run-off outputs from Qube. Both models adequately represented the annual water balances within the catchments. No inter-annual comparisons of water balance were completed.

The CERF and DAYMOD soil moistures values are both based on 'generalised' forms of the models, that is, they were not calibrated specifically for the study catchments.

CERF is a regionalised model which has been calibrated, using the output daily flows, to a large number of catchments. While the soil moisture, a model variable, has not been compared with observed values, the soil moisture has a direct impact on the effective run-off and consequently flow. The effectiveness of the model to capture the soil moisture conditions can, therefore, be indirectly determined by how well daily flows are captured. The performance of the model is presented in Griffiths and others, 2008.

As previously described, for DAYMOD the default parameterisation is that described by Kjeldsen, 2007.

The more complex structure of the CERF hydrological model, which allows it to better represent the relevant soil processes, combined with the calibration of the output flow data to a large number of catchments means that there is greater confidence in the CERF results. While the simplicity of the model structure, and related limited data requirements, allows DAYMOD to be run quickly and easily, the lack of a formal calibration data set does mean that care needs to be taken when interpreting results.

Despite the differences between the 2 models, results are, generally, in agreement, that is, both models represent, approximately, the same level of saturation prior to the events. There were a few exceptions where CERF soil moisture proportions were low (saturated), and DAYMOD soil moisture proportions were also relatively low (note this represents unsaturated) - although note that the converse does not occur.

Appendix 2: MIDAS stations for selected events

Table 22: MIDAS station names for selected events, with distance from event location (to the nearest meter)

Date	Location	MIDAS Station (temperature)	Distance (m)	MIDAS Station (weather)	Distance (m)
30/09/1960	Alphin Brook, Exeter	EXETER SOUTHAM	2,825	EXETER SOUTHAM	2,825
08/08/1967	Dunsop Water	SLAIDBURN	6,334	SLAIDBURN	6,334
06/11/1967	Esk at Sleights	WHITBY COASTGUARD	5,408	WHITBY COASTGUARD	5,408
15/09/1968	Eden at Penhurst	HADLOW COLLEGE	12,391	HADLOW COLLEGE	12,391
15/07/1973	Wye, Pant Mawr	MOEL CYNNEDD	5,069	MOEL CYNNEDD	5,069
24/09/1976	Polperro	FOWEY	8,834	FOWEY	8,834
15/08/1977	Severn at Hafren Flume	MOEL CYNNEDD	92	MOEL CYNNEDD	92
30/10/1977	Ettrick Water at Brockhoperig	ESKDALEMUIR	1,0449	ESKDALEMUIR	1,0449
04/08/1978	Allt Moor	FORT AUGUSTUS	19,887	FORT AUGUSTUS	19,887

Date	Location	MIDAS Station (temperature)	Distance (m)	MIDAS Station (weather)	Distance (m)
05/10/1978	Oykel	KNOCKANROCK	15,005	KNOCKANROCK	15,005
28/12/1978	Six Mile Water, Ballyclare	HYDE PARK, MALLUSK	7,015	HYDE PARK, MALLUSK	7,015
14/06/1979	Caldwell Burn, Berryscaur	ESKDALEMUIR	13,505	ESKDALEMUIR	13,504
25/09/1981	Ardessie	POOLEWE	20,676	POOLEWE	20,676
12/07/1982	Chulmleigh	CHAWLEIGH	5,620	CHAWLEIGH	5,620
17/07/1983	Ireshopeburn Farm	WIDDYBANK FELL	10,161	WIDDYBANK FELL	10,161
17/07/1983	Honister Pass	GRIZEDALE	21,800	GRIZEDALE	21,800
26/08/1983	Hermitage	KIELDER CASTLE	12,578	KIELDER CASTLE	12,578
20/05/1986	West Stream, Lyons Gate	YEOVILTON	20,496	YEOVILTON	20,496
11/08/1986	Crooked Oak, Knowstone	HAWKRIDGE	10,909	HAWKRIDGE	10,909
18/10/1987	Sawdde at Felin-y-cwm	BRAWDY	7,858	BRAWDY	7,858
02/10/1981	Muick, Invermuick	ONICH	28,428	ONICH	28,428

Date	Location	MIDAS Station (temperature)	Distance (m)	MIDAS Station (weather)	Distance (m)
21/08/2000	Erch at Pencaenewydd	PORTHMADOG	15,260	PORTHMADOG	15,260
30/07/2002	Trout Beck a Moor House	HUNT HALL FARM	15,195	HUNT HALL FARM	15,194
19/06/2005	Rye at Broadway Foot	PATELEY BRIDGE, RAVENS NEST	4,501	PATELEY BRIDGE, RAVENS NEST	4,501
25/06/2007	Dearne at Barnsley Weir	RYHILL	9,236	RYHILL	9,236
25/06/2007	Heighington Beck at Heighington	WADDINGTON	6,717	WADDINGTON	6,717
06/09/2008	Derwent at Eddys Bridge	WESTGATE NO 2	17,550	WESTGATE NO 2	17,550
05/12/2015	Kent at Sedgwick	LEVENS HALL	2,690	MORECAMBE NO 2	23,664
23/08/2017	Abhainn Roag at Mill Croft	SOUTH UIST RANGE	7,855	SOUTH UIST RANGE	7,855
16/02/2020	Taff at Merthyr Tydfil	No data[(a)]	No data[(a)]	No data[(a)]	No data[(a)]

Note for Table 22: (a) no data available for 2020

Appendix 3: Peak flows from NRFA excluded from catalogue of extreme floods

Table 23: List of peak flows that exceeded one or more of the thresholds and yet were excluded from the catalogue

Station ID	Station name	OK for QMED?	OK for pooling?	Year	AMAX (m3/s)	AMAX/ AREA	AMAX/ QMED	Comment
21017	Brockhoperig	yes	yes	2005	150.5	4.0	2.5	Exclude - less than 2.5 QMED, high SAAR
23009	Alston	yes	no	2012	338.3	2.9	2.3	Exclude - less than 2.5 QMED, high SAAR
47025	Germansweek	no	no	2015	45.0	4.0	4.2	Flow suspect as not suitable for pooling or even QMED. Exclude as not the highest AMAX
47025	Germansweek	no	no	1994	51.3	4.5	4.8	Flow suspect as not suitable for pooling or even QMED. NRFA: "Maximum flows may be considerable over-estimates as out of bank section of rating is simply an extrapolation of the in-bank rating"
54023	Offenham	yes	no	1997	100.4	1.0	9.9	Flow may be suspect as not suitable for pooling. Exclude this - not the highest AMAX at the gauge

Station ID	Station name	OK for QMED?	OK for pooling?	Year	AMAX (m3/s)	AMAX/ AREA	AMAX/ QMED	Comment
55008	Cefn Brwyn	no	no	1972	59.1	5.6	3.5	Flow suspect as not suitable for pooling or even QMED. Exclude as not the highest AMAX
55008	Cefn Brwyn	no	no	1956	68.7	6.5	4.0	Flow suspect as not suitable for pooling or even QMED. No gaugings available. "Treat early record with caution"
55010	Pant Mawr	yes	no	2001	94.9	3.5	1.9	Exclude - less than twice QMED, very high SAAR
55010	Pant Mawr	yes	no	1972	113.8	4.2	2.3	Exclude - less than 2.5 QMED, very high SAAR
55010	Pant Mawr	yes	no	1956	133.7	4.9	2.7	Flow may be suspect as not suitable for pooling. Also not high compared with QMED
58002	Resolven	yes	yes	2019	529.0	2.8	2.4	Exclude - less than 2.5 QMED, very high SAAR
60009	Felin-y-cwm	yes	no	2013	241.1	3.1	1.9	Exclude - less than twice QMED, high SAAR
60009	Felin-y-cwm	yes	no	2005	327.8	4.2	2.6	Flow may be suspect as not suitable for pooling. Exclude as not the highest AMAX

Station ID	Station name	OK for QMED?	OK for pooling?	Year	AMAX (m3/s)	AMAX/ AREA	AMAX/ QMED	Comment
60009	Felin-y-cwm	yes	no	2002	240.3	3.1	1.9	Exclude - less than twice QMED, high SAAR
60009	Felin-y-cwm	yes	no	1998	407.2	5.3	3.2	Flow may be suspect as not suitable for pooling. Exclude as not the highest AMAX
60009	Felin-y-cwm	yes	no	1985	311.0	4.0	2.5	Exclude - less than 2.5 QMED, very high SAAR
60009	Felin-y-cwm	yes	no	1979	268.9	3.5	2.1	Exclude - less than 2.5 QMED, very high SAAR
72005	Killington	yes	yes	2015	626.9	2.9	2.3	Storm Desmond. Exclude - less than 2.5 QMED, very high SAAR
72015	Lunes Bridge	yes	yes	2015	409.0	2.9	2.0	Storm Desmond. Exclude - less than 2.5 QMED, very high SAAR
73014	Jeffy Knotts	yes	no	2009	200.0	3.5	2.3	Exclude - less than 2.5 QMED, very high SAAR
74001	Duddon Hall	yes	yes	2009	267.9	3.1	2.2	Exclude - less than 2.5 QMED, very high SAAR

Station ID	Station name	OK for QMED?	OK for pooling?	Year	AMAX (m3/s)	AMAX/ AREA	AMAX/ QMED	Comment
74006	Calder Hall	yes	no	2011	143.2	3.2	2.4	Exclude - less than 2.5 QMED, very high SAAR
74006	Calder Hall	yes	no	1997	173.3	3.9	2.9	Flow may be suspect as not suitable for pooling. "Thought to drown at very high flows." Not all that high compared with QMED.
96004	Allnabad	yes	yes	2005	376.3	3.6	1.9	Exclude - less than twice QMED, very high SAAR
96004	Allnabad	yes	yes	2004	308.4	2.9	1.6	Exclude - less than twice QMED, very high SAAR
96004	Allnabad	yes	yes	2001	313.1	3.0	1.6	Exclude - less than twice QMED, very high SAAR
96004	Allnabad	yes	yes	1999	331.0	3.2	1.7	Exclude - less than twice QMED, very high SAAR

Appendix 4: Details of rainfall-runoff modelling for comparison study

This appendix gives information on how the rainfall-runoff models used in comparison test were set up and parameterised, and on their results.

ReFH2

Introduction

This case study applies both the standard ReFH2 method and also a modification proposed by Pucknell and others (2020) for applying the framework of the existing FSR-based PMF estimation method within the structure of the ReFH rainfall-runoff model.

Within the FSR PMF method for summer, the initial soil moisture conditions are modified (to increase the resulting percentage run-off) to reflect the possibility that the PMP storm has occurred after a period of wet weather. In addition, the unit hydrograph time to peak is adjusted to reflect the assumed increase in speed of routing within the catchment. The methodology outlined within Pucknell and otherx (2020) reflects these 2 changes by modifying the initial soil moisture conditions (C_{ini}) and the unit hydrograph time to peak (Tp).

ReFH2 parameters

The ReFH2 model parameters are estimated using the FEH catchment descriptors. These are presented in Table 24.

Modification of the initial soil moisture conditions

The initial soil moisture is adjusted using the following ratio, for summer conditions:

$$\frac{PMF\ C_{ini}}{C_{ini}} = 0.9842105\ \exp\left[0.8849\left(\frac{C_{max}}{1000}\right)\right]$$

Note that the default value of the summer C_{ini} is the same as the winter value. This is due to the linking equation which would (due to the low permeability and high rainfall) provide a summer C_{ini} that is higher than the winter value. In practice, this is unlikely and relates to the form of the linking equation rather than being a physical phenomenon, therefore, the summer C_{ini} value is limited to the winter C_{ini}. Similarly, when the adjustment equation for the PMF is used, the summer PMF C_{ini} adjustment ratio would be higher than the winter. Following the same reasoning, the summer PMF C_{ini} is limited to be the same as the winter value. This means that the increase in the summer C_{ini} (and the subsequent increase in percentage run-off) for this case study catchment is less than within other catchments.

Modification of the unit hydrograph time to peak

The default catchment descriptor derived Tp for this small, steep catchment is 1.1 hours. Within the ReFH methodology, following the outputs from research within small catchments, the lower limit of Tp is one hour. The PMF one-third reduction in Tp, which would reduce it to 0.758, less than one hour, is, therefore, not fully implemented. This means the impact of the changes in routing is more limited in this case study catchment, compared to other catchments.

PMF parameters

The final parameters used within the ReFH2 model are presented within Table 24.

Table 24: Catchment descriptor ReFH2 parameters

Parameter	Standard ReFH2 value	Modified PMF value
C^{ini} (mm) Summer	115.2	132.9
C^{max} (mm)	209.9	Unchanged
Tp (hours)	1.1	1.0
BL (hours)	23.3	Unchanged

Discussion

As noted above, the impact of the PMF modifications will be less in this case study catchment compared to many others. It is a very wet, impermeable catchment, therefore, the percentage run-off is already relatively high. The method constraints, for example Tp being limited to one, could be overridden, but have been retained within this case study. However, even without these method constraints, the changes in the percentage run-off and the routing would still not be as large as they are likely to be in many other catchments. This means the final peak flow is not significantly higher than the default parameterisation. Larger differences would be found within permeable, drier, larger and less steep catchments.

IHACRES

Derivation of parameters

IHACRES consists of 2 components: a loss model to determine how much precipitation becomes effective and a routing model (transfer functions) to distribute the effective precipitation over time at the catchment outlet. The product of these makes up the total streamflow. For the River Wye at Cefn Brwyn (National River Flow Archive ID: 55008) transfer function parameters estimated at an hourly time step have been made available for this study (personal communication from Dr Ian Littlewood, March 2022):

$$\alpha_q = -0.76663 \alpha q = -0.76663$$

$$\alpha_s = -0.99539 \alpha s = -0.99539$$

$$\beta_q = 0.116 \beta q = 0.116$$

$$\beta_s = 0.002 \beta s = 0.002$$

The parameters for the soil moisture accounting component are C (the catchment wetness index) and τ_w. Table 13 of Littlewood (2022) provides 22.5 and 23 for C and τ_w, respectively for the same catchment. These parameters have been used with a one-hour timestep PMP.

Initial conditions are necessary for modelling an input of rainfall. These are the initial flow and the initial catchment wetness index (s_k). Daily mean flow (DMF), and the flow that is exceeded on 5% of days (Q5) were applied in combinations with initial soil moisture (CWI) values of 0, 0.5, and 1. Depending on the choice of initial conditions, the resulting simulated peak discharge varies between 246 m^3/s and 287 m^3/s.

Limitation

The s_k is supposed to be a proportional wetness between 0 and one, however it can exceed one (Littlewood, 2022). Given the uncertainty in the rainfall, it may not be a problem if it does not exceed one significantly. However, it is often significantly above one and this is the case with the PMP. This leads to the effective rainfall exceeding the rainfall. For this reason, there is little confidence in the resulting peak flows. It is considered that further work is needed before IHACRES can be used as a design hydrograph model, especially for the purposes of estimating the probable maximum flood.

HEC-RAS

HEC-RAS v6 allows for modelling of overland flow from rainfall applied directly to a 2D terrain grid, with or without application of losses.

The catchment terrain data was defined using the Environment Agency’s Integrated Height Model (IHM). The mesh size was set to 5 m resolution across the entire catchment.

The 2D perimeter was created according to a catchment boundary shapefile obtained from the NRFA. The perimeter was only edited from this shape at the downstream end to provide a straight edge in which to draw a profile line to determine flow.

Break lines were drawn near the downstream end to align the mesh to features such as roads and prevent water pooling at the edge.

A normal depth boundary of gradient 0.03 was drawn at the downstream end to allow water to drain, this value was determined based on the slope of the catchment in this area.

A single soil, landcover and infiltration type was applied to the entire catchment.

Landcover (Manning's n) – value of 0.08 applied (indicative of herbaceous vegetation, natural grassland, moors).

Infiltration (US SCS Curve Number method) – value of CN=80 applied (indicative of the above landcover type with low permeability.) An additional run of the model was carried out with no infiltration.

A flow hydrograph was extracted from the profile line at the downstream end of the catchment.

Appendix 5: International approaches for estimating PMP

Australia

Information on the approach

Official guidance: Three ‘generalised’ approaches are used: Generalised methods of estimating PMP use data from all available storms over a large region and include adjustments for moisture availability and differing topographic effects on rainfall depth. The adjusted storm data are enveloped by smoothing over a range of areas and durations. Generalised methods also provide design, spatial and temporal patterns of PMP for the catchment. The 3 methods are: Generalised Short-Duration Method (GSDM) - for durations up to 6 hours and areas up to 1,000 km2; Revised Generalised Tropical Storm Method (GTSMR) - for durations up to 120 hours and areas up to 150,000 km2 in the region of Australia where tropical storms are the source of the greatest depths of rainfall; and Generalised Southeast Australia Method (GSAM) - for durations up to 96 hours and areas up to 100,000 km2 in the region of Australia where tropical storms are not the source of the greatest depths of rainfall.

Meteorological methods used

Storm transposition

Storm maximisation

Precipitable water/storm efficiency

Spatial rainfall distribution information

Storms approximate to concentric circles

Climatological reasons for the approach

Three methods for different catchment size and different event duration – some for tropical storms. GSDM probably most applicable to UK context.

Canada

Information on the approach

Official guidance: A report for Natural Resources Canada (Ouranos, 2015) evaluated PMP for a dam safety project focused on 5 lakes in eastern Canada. The method of storm maximisation and transposition was applied to major historical storms affecting Canada.

Meteorological methods used

Storm transposition

Storm maximisation

Precipitable water/storm efficiency

Spatial rainfall distribution information

Storm centres used. BOSS HMR52 used to size storms optimally for 2 of 5 dams

Climatological reasons for the approach

Overall method similar, but storms used were selected subjectively for each dam

China (including Taiwan)

Information on the approach

Research application: The moisture and wind maximisation with storm transposition are used to derive the 24-hour PMP. The main moisture inflow direction of a catchment is chosen using a wind rose and local topography (Zhan and Zhou, 1984, Zhou and others, 2020). Regionally, for Taiwan and Hong Kong, storm separation and transposition are used involving a regional L-moments of a probability distribution approach and an index flood procedure for a homogeneous region (Liao and others, 2020). Additionally, Lan and others (2017) have applied a revised Hershfield method in Hong Kong.

Statistical methods used

Hershfield technique

Meteorological methods used

Storm transposition

Storm maximisation

Precipitable water/storm efficiency

Spatial rainfall distribution information

Use elliptical isohyets, analysis

Areal reduction factor applied

Depth-area relation for convergence rainfall

Czech Republic

Information on the approach

Research application: Rezacova and others (2005) develop PMP estimates for sub-daily and multi-day durations using the Storm Models and Hershfield techniques, respectively for multiple river basins across the CR as part of a national project based on gauge data. Area reduction factors are estimated based on radar data. PMP estimates are validated across rainfall in 1997 and 2002 flood events.

Statistical methods used

Hershfield technique

Meteorological methods used

Storm model

Spatial rainfall distribution information

Spatial interpolation of point values

Areal reduction factor applied

Depth-area relation for convergence rainfall

Climatological reasons for the approach

<1day, Storm model approach used. Insufficient data to apply Hershfield sub-daily. Where comparison could be made for sub-daily, storm model PMP consistently exceeded Hershfield.

Greece

Information on the approach

Research application: The concept of PMP has been challenged in a series of papers using rainfall data in Greece (for example, Koutsoyiannis, 1999 and Papalexiou and Koutsoyiannis, 2006). PMP in Greece has been estimated using the Hershfield approach and the moisture maximisation method accompanied with a Gumbel distribution, and compared to high return period (low AEP) estimates derived using conventional extreme value analysis. The authors contend that PMP estimates can be reached using extreme value analysis and, therefore, cannot represent an upper bound on rainfall amounts.

Statistical methods used

Statistical extrapolation: GEV ,L-moments

India

Information on the approach

Official guidance: The Indian Institute of Tropical Meteorology (IITM, 1989) produced a national atlas of PMP values for one-day duration using the Hershfield technique. Additionally, for a single catchment, these estimates have been compared to those determined using statistical methods (IITM, 2005). On a regional approach, multiple methods have been investigated to produce a multiple duration atlas of PMP values for the west-flowing rivers in the Western Ghats region (CWC and IMD, 2015).

Statistical methods used

Hershfield technique

Statistical extrapolation

Meteorological methods used

Storm transposition

Storm maximisation

Precipitable water/storm efficiency

Spatial rainfall distribution information

Use elliptical isohyets, analysis

Areal reduction factor applied

Based on envelope of DAD curves of major storms

Climatological reasons for the approach

Western Ghats study is fairly comprehensive and uses multiple methods

Information on the approach

Research applications: Storm transposition and maximisation have been used to estimate PMP. The persisting dew point during a storm is compared with the maximum persisting dew point at the same location and the same time of year. The 50 or 100-year dew point is determined from frequency analysis (Rakhecha and Clark, 1999 and 2000).

Meteorological methods used

Storm transposition

Storm maximisation

Precipitable water/storm efficiency

Areal reduction factor applied

Based on envelope curves of major storms

Iran

Information on the approach

Research application: The Hershfield method is used (Afzali-Gorouh, Z. and others, 2018). More recently, a multifractal model has been used to estimate the design maximum precipitation for specified exceedance probability in the Bakhtiari Dam region of south-west Iran (Gheidari and others, 2011).

Statistical methods used

Hershfield technique

Meteorological methods used

Storm transposition

Storm maximisation

Spatial rainfall distribution information

Use moisture and wind maximisation, isohyet maps

Areal reduction factor applied

DAD curves

Climatological reasons for the approach

Developed for 8 severe storms only

Japan

Information on the approach

Research application: A moisture maximisation method was employed at 30 locations around Japan using precipitable water from the Japanese 55-year numerical model reanalysis data set (JRA-55) and also derived precipitable water estimated using surface dew point from the same data set (Kim and others, 2020). It was confirmed that the estimated precipitable water was the largest source of error in PMP estimates.

Statistical methods used

Hershfield technique

Meteorological methods used

Storm maximisation

Precipitable water/storm efficiency

Ensemble NWP data – based on Japan reanalysis.

Myanmar

Statistical methods used

Hershfield technique

Nepal

Information on the approach

Official guidance: Nayava and Simon (2002) use the Hershfield method applied to rainfall data from 109 gauges across Western Nepal to obtain both point and areal PMP estimates at multiple durations including >24 hours.

Statistical methods used

Hershfield technique

Spatial rainfall distribution information

Thiessen polygons to generalise point to catchment

Areal reduction factor applied

DAD curves

Climatological reasons for the approach

Generate Km-RMAX relationship for longer durations

New Zealand

Information on the approach

Official guidance: The National Institute for Water and Atmospheric Research estimated PMP for New Zealand using a generalised method (storm maximisation and transposition) as described in Thompson and Tomlinson (1995). Additional follow-on work has investigated appropriate DAD curves for ARF methods for New Zealand (Singh and others, 2018) reaching the conclusion that insufficient data was available for their development in New Zealand.

Meteorological methods used

Storm maximisation

Spatial rainfall distribution information

Procedure is catchment focused

Areal reduction factor applied

Envelope DAD curves based on US data

Climatological reasons for the approach

Distinction made between short and long duration processes

Norway

Information on the approach

Official guidance: The FSR method has been adopted and adjusted by changing M5 (based on 2-day rainfall) by a factor of 1.13 to represent an arbitrary 24-hour period (Førland and Kristofferssen 1989). This is then used as the basis for estimating extreme precipitation values with return periods longer the 5 years, including PMP (see Dyrrdal, 2012). Alexandersson and others (2001) also include a comparison of the PMP estimate with that from the Hershfield method.

Statistical methods used

NERC Method

Hershfield technique

Spatial rainfall distribution information

Use moisture and wind maximisation, isohyet maps

Areal reduction factor applied

Yes, storm centred only for PMP

Climatological reasons for the approach

PMP not as high as Hershfield method

Poland

Information on the approach

Research application: Walega and Michalec (2014) use Hershfield's statistical method for rainfall in Krakow at various durations, similarly Suligowski (2013) does the same for Kielce Upland region.

Statistical methods used

Hershfield technique

Climatological reasons for the approach

Walega and Michalec (2014) suggest PMP is slightly outlandish and not in line with observed values

Portugal

Information on the approach

Research application: Indicative estimates of PMP for multiple durations at 5 locations in Portugal are made using the moisture maximisation approach (Brandão and Rodrigues, 1999). Resulting PMP values are higher than 1000-year IDF values.

Meteorological methods used

Storm maximisation

Spatial rainfall distribution information

Point locations only using gauge records

Climatological reasons for the approach

Indicative estimates only

Russia

Information on the approach

Research application: The method estimates daily PMP for the Middle Ural using the evaluation of moisture content from the characteristics of vertical temperature distribution, convection rate and the height of the upper cloud boundary (Klimenko, 2020). Resulting values re comparable to those using the Hershfield method.

Statistical methods used

Hershfield technique

Meteorological methods used

Storm maximisation

Precipitable water/storm efficiency

Saudi Arabia

Information on the approach

Research application: Şen and others (2017) derive PMP estimates generated using statistical and probabilistic methods based on AMAX daily rainfall from 12 locations around Jeddah City. Maps of PMP used as input to regional PMF calculations.

Statistical methods used

Hershfield technique

Statistical extrapolation

South Africa

Information on the approach

Research application: PMP is estimated for large area storms by storm maximisation and transposition. For small area storms, empirically derived curves generated from the highest recorded point precipitation for a range of durations in various parts of the country are used (Johnson and Smithers, 2019).

Statistical methods used

Hershfield technique

Statistical extrapolation - GEV

Meteorological methods used

Storm transposition

Storm maximisation

Spatial rainfall distribution information

Isohyetal patterns

Areal reduction factor applied

Depth-area-duration; regression equations

South Korea

Information on the approach

Official guidance: National estimates of PMP, created following contemporary WMO guidance, were first produced by the Ministry of Construction and Transportation (MOCT, 2000), with a subsequent revision (MOCT, 2004).

Statistical methods used

Statistical extrapolation

Meteorological methods used

Storm transposition

Storm maximisation

Areal reduction factor applied

Envelope DAD curves; storm centred

Climatological reasons for the approach

Original PMP values found too low following typhoons

Information on the approach

Research application: Further updates to the national PMP estimates using longer rainfall records were made following updated WMO guidance (Lee and others, 2018). Areal reduction factors were also investigated (Kim and others, 2009), as were alternative methods of for catchment PMP estimates (Kim and others, 2016), and more recently testing of more sophisticated methods of PMP estimation for Seoul (Na and Yoo, 2019).

Meteorological methods used

Storm transposition

Storm maximisation

Precipitable water/storm efficiency

Spatial rainfall distribution information

Catchment rainfall

Areal reduction factor applied

Envelope DAD curves; splines using polynomial fit

Climatological reasons for the approach

Bayesian statistics used to extend existing PMP estimates rather than recalculate

Spain

Information on the approach

Research application: For Catalonia and Barcelona several approaches are used to estimate PMP estimation (Casas and others, 2008, 2011). The maximisation of precipitable water for selected storms (MPW) multiplied by the storm efficiency is used, together with the Hershfield technique for durations from 5 to 1800 minutes.

Statistical methods used

Hershfield technique

Meteorological methods used

Storm maximisation

Precipitable water/storm efficiency

Areal reduction factor applied

Depth-duration

USA

Information on the approach

Official guidance: The generalised method (WMO, 2009) is used in different regions of the United States involving maximum observed events, moisture maximisation, transposition and envelopment. A number of reports from the National Weather Service were published between 1980 and 1999 (for example, Hydrometeorological Report 59, Corrigan and others, 1999). These basic procedures are the same as those described in WMO (2009). Different values are derived for the orographic and the storm intensity factors in different regions.

Statistical methods used

Hershfield technique

Statistical extrapolation - GEV

Meteorological methods used

Storm transposition

Storm maximisation

Spatial rainfall distribution information

Depth-duration- frequency used

Information on the approach

Research application: NWP methods have particularly been used in the Pacific coastal states in the USA to investigate the PMP associated with atmospheric river type weather systems (Rastogi and others, 2017 and Tan, 2010). For the eastern US, statistical methods based on multifractals have been used (Douglas and Barros, 2003). Methods of estimating uncertainty in PMP have also been discussed in the context of official guidance from the US National Weather Service (Micovic and others, 2015). Using ensembles to estimate PMP has primarily focused on application to future climate estimates using downscaled climate model data (Chen and others, 2017).

Statistical methods used

Statistical extrapolation – Multifractal

Meteorological methods used

Ensemble NWP data

Climatological reasons for the approach

Quantifying uncertainty has been investigated

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List of abbreviations

This list does not include the names of the many hydrological models mentioned in the report. Although many of these were originally derived as acronyms, the name used to refer to the model is nearly always the abbreviated form.

AEP Annual exceedance probability

ALARP As low as reasonably practicable

ALTBAR Mean altitude in a catchment (m) (FEH catchment descriptor)

ANCOLD Australian National Commission on Large Dams

ANN Artificial neural network

AREA Catchment area (km^2)

ARF Areal reduction factor

ARR Australian Rainfall and Runoff

BFIHOST19 Baseflow Index estimated from Hydrology of Soil Types data set (FEH catchment descriptor)

CBHE Chronology of British Hydrological Events

C-C Clausius-Clapeyron

CEH Centre for Ecology and Hydrology

CEH-GEAR CEH Gridded Estimates of Areal Rainfall

CMIP Coupled Model Intercomparison Project

CWI Catchment wetness index

D Rainfall duration (hours)

DAYMOD Soil moisture accounting model, run at a daily time step

DCWW Dŵr Cymru Welsh Water

DDF Depth-duration-frequency

Defra Department for Environment, Food and Rural Affairs

DOE Department of the Environment

ECMWF European Centre for Medium-Range Weather Forecasts

EM-Dh	Estimated maximum rainfall of duration D hours
FEH	Flood Estimation Handbook
FEH99	Flood Estimation Handbook rainfall frequency statistics released in 1999
FEH 2013	Flood Estimation Handbook rainfall frequency statistics released in 2013
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FSR	Flood Studies Report
GSDR	Global Sub-Daily Rainfall
H&H	Hough and Hollis (1997)
HOST	Hydrology of Soil Types
HRU	Hydrological Response Unit
ICE	Institution of Civil Engineers
ICOLD	International Commission on Large Dams
IDF	Intensity-duration-frequency
MELTdry	Snowmelt without allowing for incoming rainfall
MELTwet	Snowmelt including additional heat energy from rain on the snowpack
MIDAS	Met Office Integrated Data Archive System
NCEP	National Centers for Environmental Prediction
NERC	Natural Environment Research Council
NIMROD	Rainfall radar storage and analysis system
NOAA	National Oceanographic and Atmospheric Administration
NRFA	National River Flow Archive
NWP	Numerical weather prediction
PMF	Probable maximum flood
PMP	Probable maximum precipitation
PMPa	Antecedent rainfall before the main PMP storm

PR	Percentage run-off
PROPWET	Proportion of time the soils in a catchment are wet (FEH catchment descriptor)
QMED	Median annual maximum flood
RLAG	Reservoir lag time (hours)
SAAR	Standard Annual Average Rainfall for 1961-90 (FEH catchment descriptor)
SPR	Standard Percentage Runoff
SPRHOST	SPR estimated from Hydrology of Soil Types (FEH catchment descriptor)
SST	Stochastic storm transposition
Tp(0)	Time to peak of the unit hydrograph in the FSR model
UKCEH	UK Centre for Ecology and Hydrology
UKGrsHP	UK high-resolution gauge–radar–satellite merged hourly precipitation
USACE	US Army Corps of Engineers
USBR	US Bureau of Reclamation
WHS	Wallingford HydroSolutions
WMO	World Meteorological Organisation
WRAP	Winter Rainfall Acceptance Potential

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