























































































































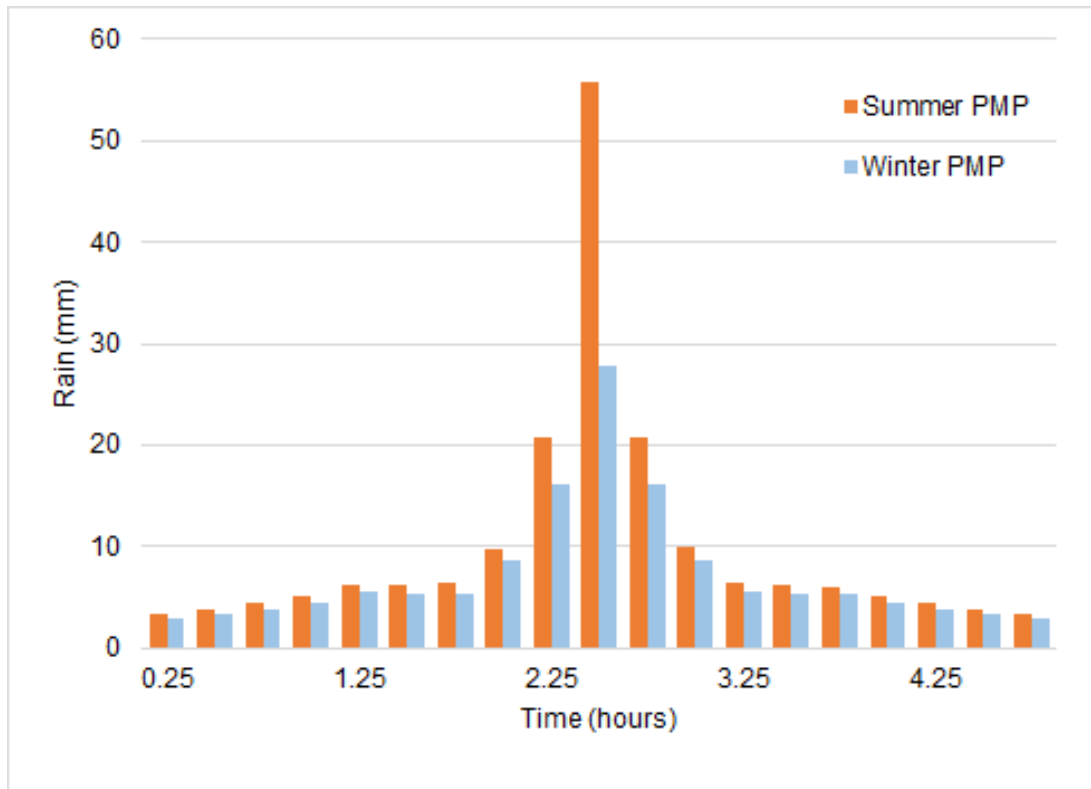








shared between the 2 outer 0.25-hour periods, with 20.7 mm in each. The quantities for the remaining parts of the hyetograph are shown in the final 2 columns of the table. The resulting catchment PMP hyetographs, for the 2 seasons, are shown in Figure 19. The hyetograph is tabulated in Table 12, which 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.

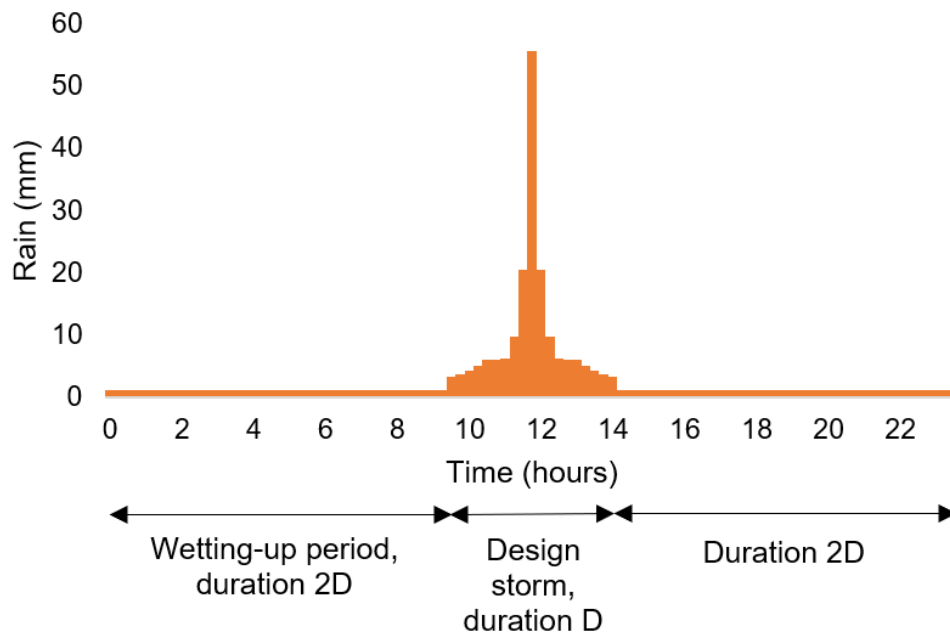
Note that the Figure 19 PMP hyetograph has the same intensity-duration relationship no matter what its total duration. This is fundamentally different to the way in which T-year design rainfall hyetographs are constructed in the FEH or ReFH rainfall-runoff methods. One consequence is that there is no 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.























































## 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<sup>2</sup> 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.

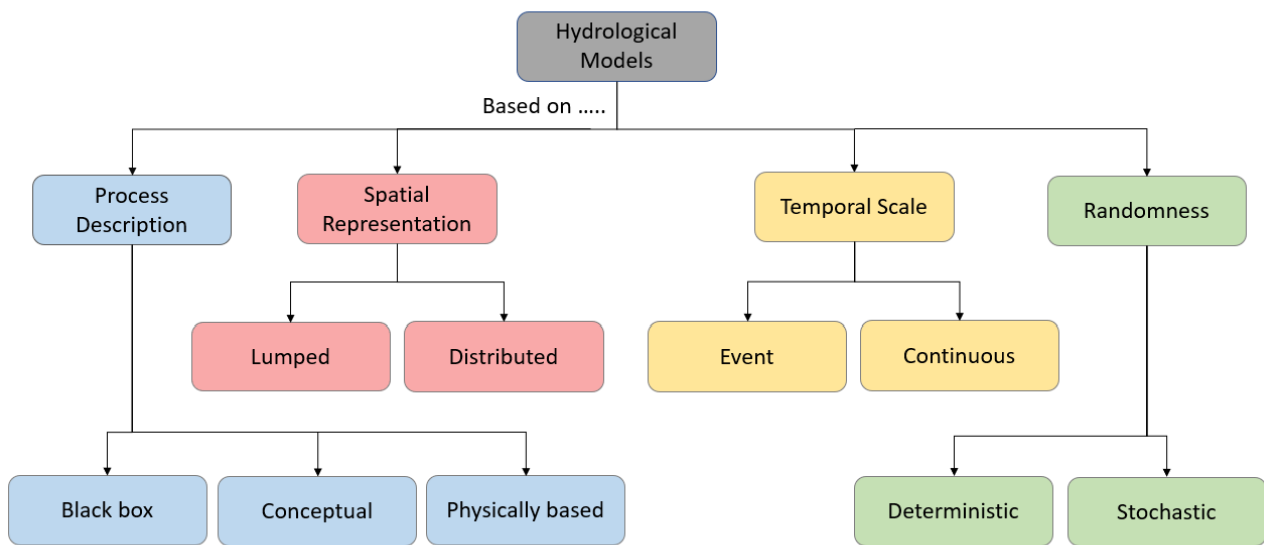
Regionalised rainfall-runoff models, where parameters can be estimated from catchment descriptors (physical features which are described by spatial data sets, for example, average slope), are, therefore, required for ungauged sites. Both the existing FSR/FEH model and ReFH2 are examples of regionalised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

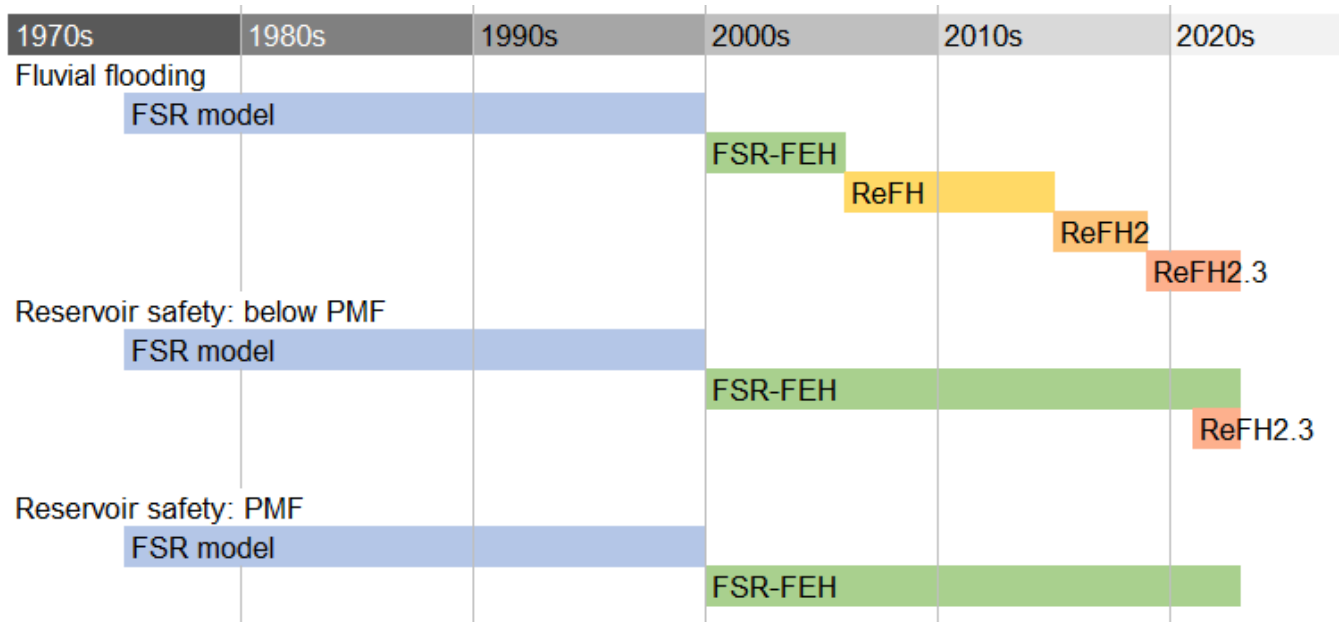
The FSR rainfall-runoff method was restated in the FEH (Houghton-Carr, 1999) introducing digital catchment descriptors and a new Depth-Duration-Frequency (DDF) rainfall model. The derivation of the PMP and PMF remained largely unchanged.

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,  $T_p(0)$  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 of 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 through 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











































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<sup>5</sup>-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





















































































- 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<sup>4</sup>, 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

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<sup>4</sup> For example, the on-going NERC FUTURE-DRAINAGE project ([http://gotw.nerc.ac.uk/list\\_full.asp?pcode=NE%2FS017348%2F1&cookieConsent=A](http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FS017348%2F1&cookieConsent=A))















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 similarly 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 Monte-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.





















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
<b>1. Do nothing</b>	1	1	1	5	5	5
<b>2. Improve the assumption by analysis of meteorological and hydrological data</b>	2	2	3	4	4	5
<b>3. Use climate models to extend option 2</b>	2	2	4	3	4	5
<b>4. Carry out a joint probability analysis of all relevant variables</b>	5	5	5	2	3	3
<b>5. Continuous simulation</b>	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
<b>1. Do nothing.</b>	1	1	1	1	5	5	5
<b>2. Update ReFH2 based on Pucknell and others (2020).</b>	1	2	2	3	5	5	4
<b>3. Enhance event-based conceptual modelling based on Pucknell and others (2020) and further research.</b>	4	2	2	3	4	2-5 depending on model	3-4 depending on model
<b>4. Develop new physically-based spatially distributed rainfall-runoff model.</b>	5	2	1-2	2-5	1	2-3	1
<b>5. Develop new design package for a conceptual rainfall-runoff model with Monte Carlo simulation approach.</b>	1-4	5	5	3-5	2	2-5 depending on model	1-2
<b>6. Develop new continuous simulation system.</b>	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.

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### 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.

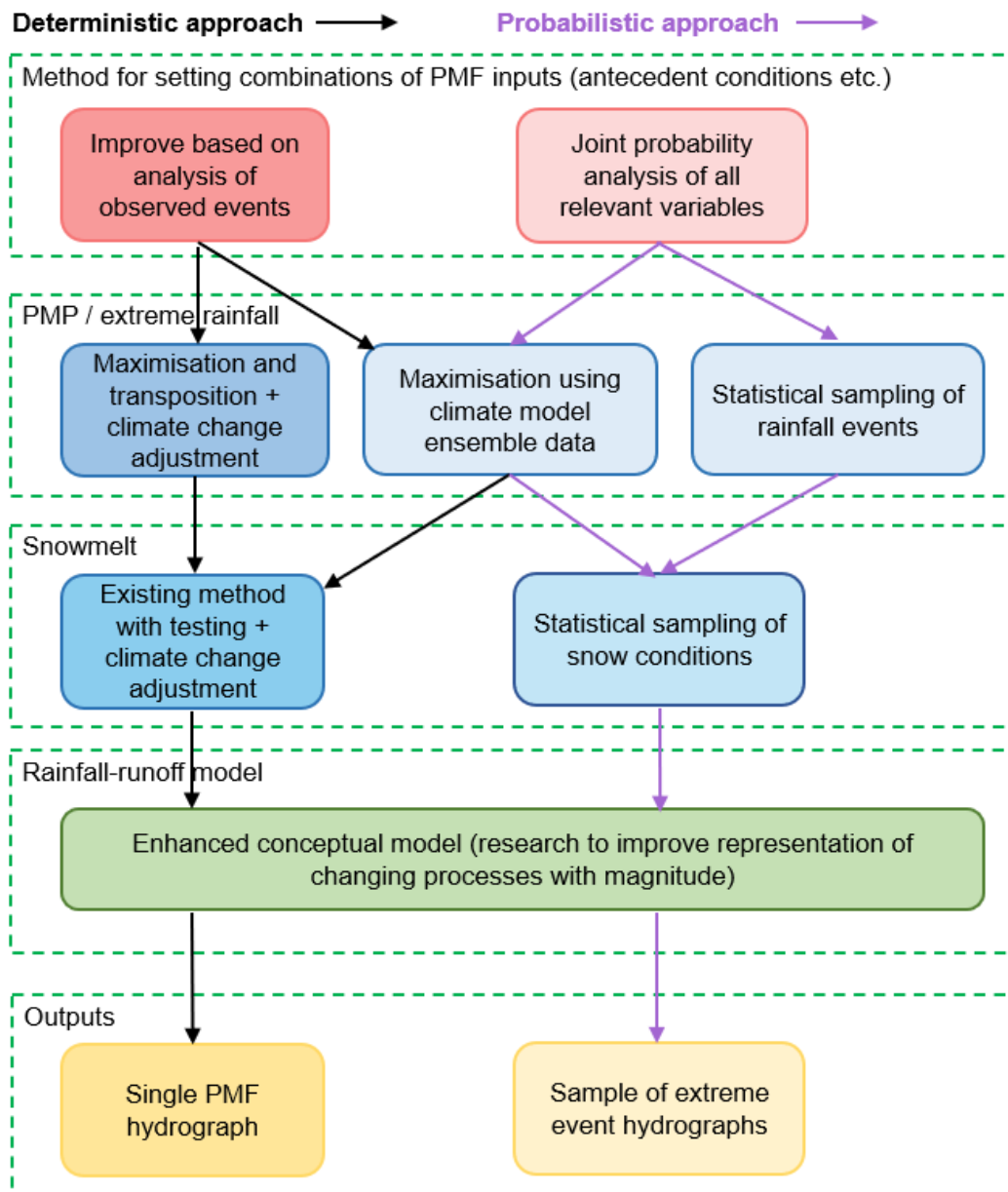
## 6.7 Discussion of recommended options for estimating PMP and PMF

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).



A lighter colour indicates that more effort/time is required for the given task.

**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 is 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 Monte-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 20<sup>th</sup> to the 21<sup>st</sup> 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.

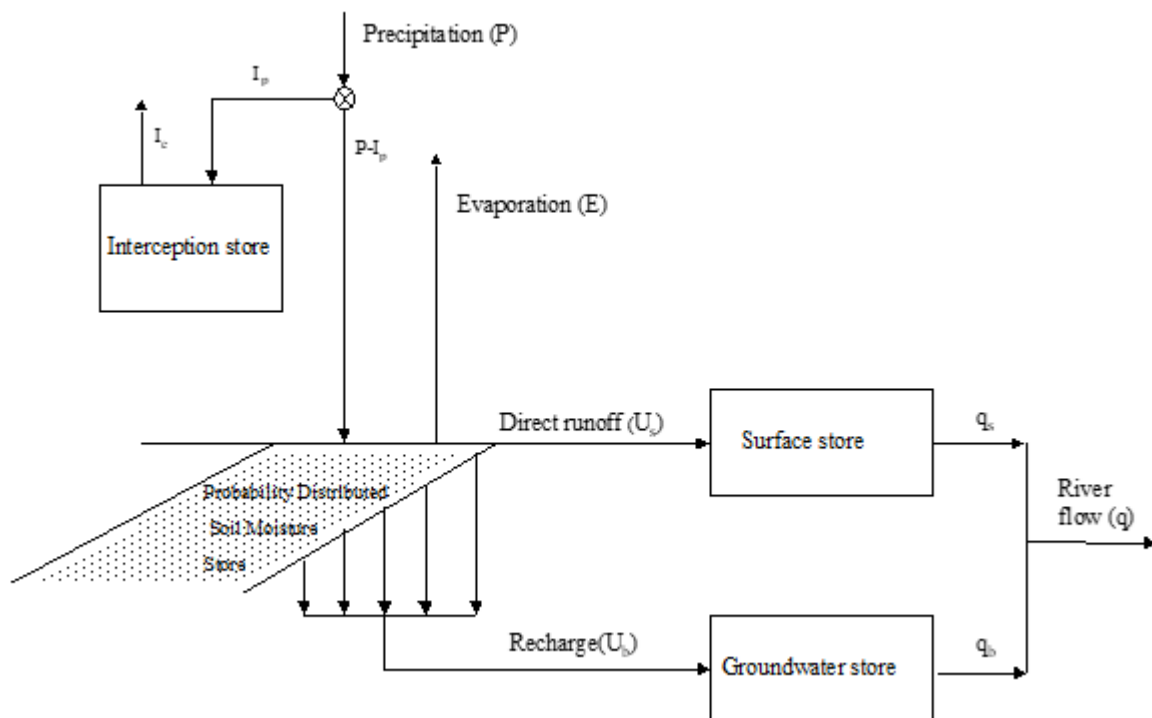


Figure 33: Conceptual structure of run-off model

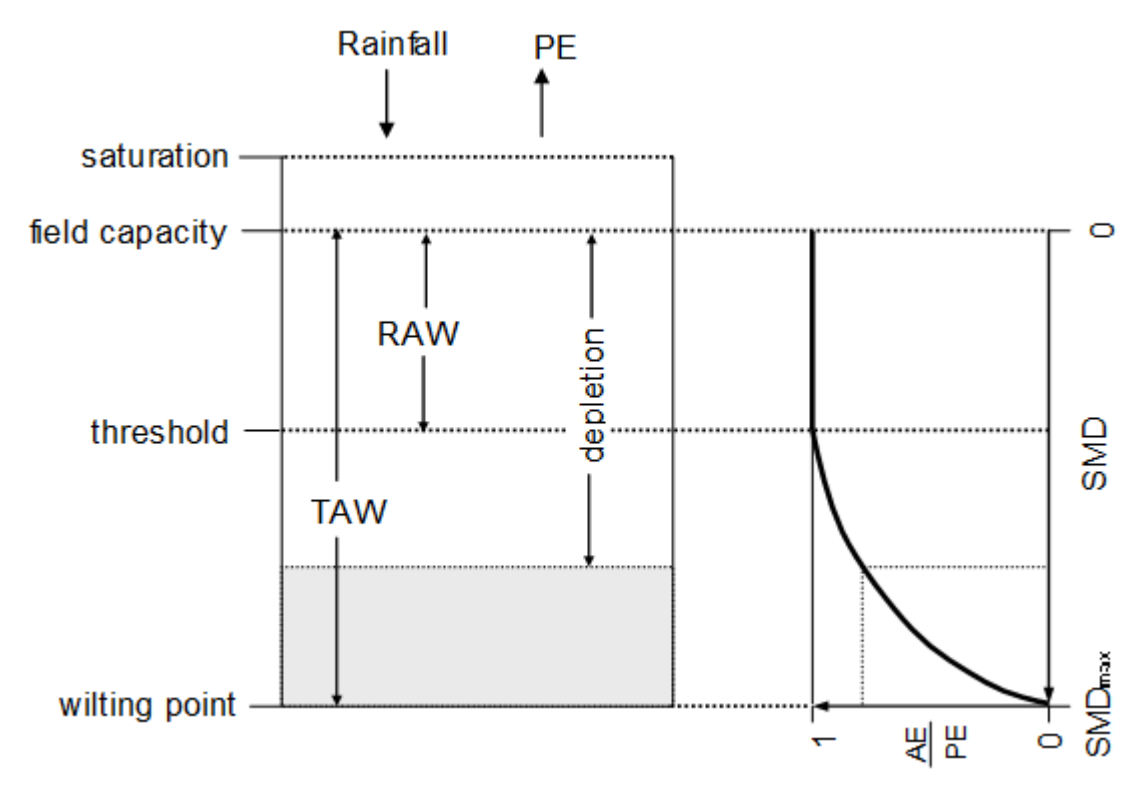
Figure 33 shows a conceptual structure of run-off model, based around 2 sub model components; the loss module that generates hydrologically effective precipitation (EP) and the routing module that subsequently routes the EP to the catchment outlet. The basic model structure for the loss module is a hydrological 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 ( $Z_r$ ), 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 ( $Z_r$ ) such that:

$$TAW = Z_t(FC-WP)$$

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  $K_I$ , 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,  $K_g$ .

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  $\leq FC$  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 moisture 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 runoff 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)
<b>21/08/2000</b>	Erch at Pencaenewydd	PORTHMADOG	15,260	PORTHMADOG	15,260
<b>30/07/2002</b>	Trout Beck a Moor House	HUNT HALL FARM	15,195	HUNT HALL FARM	15,194
<b>19/06/2005</b>	Rye at Broadway Foot	PATELEY BRIDGE, RAVENS NEST	4,501	PATELEY BRIDGE, RAVENS NEST	4,501
<b>25/06/2007</b>	Dearne at Barnsley Weir	RYHILL	9,236	RYHILL	9,236
<b>25/06/2007</b>	Heighington Beck at Heighington	WADDINGTON	6,717	WADDINGTON	6,717
<b>06/09/2008</b>	Derwent at Eddys Bridge	WESTGATE NO 2	17,550	WESTGATE NO 2	17,550
<b>05/12/2015</b>	Kent at Sedgwick	LEVENS HALL	2,690	MORECAMBE NO 2	23,664
<b>23/08/2017</b>	Abhainn Roag at Mill Croft	SOUTH UIST RANGE	7,855	SOUTH UIST RANGE	7,855
<b>16/02/2020</b>	Taff at Merthyr Tydfil	No data <sup>(a)</sup>	No data <sup>(a)</sup>	No data <sup>(a)</sup>	No data <sup>(a)</sup>

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 (m <sup>3</sup> /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 ( $T_p$ ).

### 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:

$$PMF_{Cini} = 0.9842105 \exp[0.8849(C_{max} - 1000)]$$

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  $T_p$  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  $T_p$  is one hour. The PMF one-third reduction in  $T_p$ , 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
$T_p$ (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  $T_p$  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):

$$\alpha_q = -0.76663 \alpha_s = -0.76663$$

$$\alpha_s = -0.99539 \alpha_s = -0.99539$$

$$\beta_q = 0.116 \beta_s = 0.116$$

$$\beta_s = 0.002 \beta_s = 0.002$$

The parameters for the soil moisture accounting component are C (the catchment wetness index) and  $\tau_w$ . Table 13 of Littlewood (2022) provides 22.5 and 23 for C and  $\tau_w$ , 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<sup>3</sup>/s and 287 m<sup>3</sup>/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 km<sup>2</sup>; Revised Generalised Tropical Storm Method (GTSMR) - for durations up to 120 hours and areas up to 150,000 km<sup>2</sup> 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 km<sup>2</sup> 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 than 5 years, including PMP (see Dyrørdal, 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 <sup>2</sup> )
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 descriptor)	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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