The British Dam Society

PMP - Maximum Precipitation, Probably

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SYNOPSIS Climate change poses significant challenges to the accurate estimation of probable maximum precipitation (PMP), a crucial parameter used in the design and assessment of flood control infrastructure. This paper investigates the potential implications of climate change on current predictions of PMP and its derived parameter, probable maximum flood (PMF). Case studies from Scotland, Wales and England highlight real-world examples of the challenges posed by climate change and the importance of incorporating climate change considerations in PMP and PMF estimations.

INTRODUCTION

Climate change is recognised as one of the most pressing global challenges of our time. Its impacts are widespread (Figure 1), affecting various aspects of the Earth's systems, including the hydrological cycle and precipitation patterns. In the reservoir industry one of the critical concerns related to climate change is its potential implications on the estimation of probable maximum precipitation (PMP). Understanding the potential changes in extreme precipitation events is crucial for effective flood management, infrastructure design, and the protection of vulnerable communities.

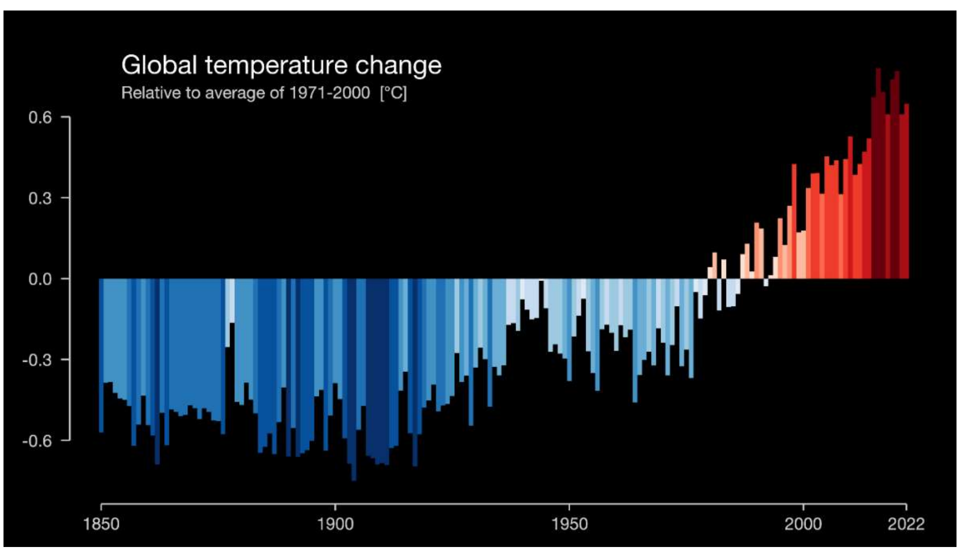

Figure 1. Global temperature change due to climate change
(Graphics and lead scientist: Ed Hawkins, National Centre for Atmospheric Science, University of Reading., National Centre for Atmospheric Science, UoR.Data: Berkeley Earth, NOAA, UK Met Office, MeteoSwiss, DWD, SMHI, UoR & ZAMG)

PROBABLE MAXIMUM PRECIPITATION (PMP)

PMP is defined as the ''theoretical maximum precipitation for a given duration under modern meteorological conditions" (WMO, 2009, p1). Hydrologists use a PMP magnitude to calculate the Probable Maximum Flood (PMF) in the case where the consequence of a dam overtopping is deemed unacceptable.

Probable Maximum Precipitation (PMP) refers to the theoretically maximum amount of precipitation that could occur over a given area within a specific duration. It represents an extreme weather event that is unlikely to occur but is used as a design criterion for high hazard reservoir systems. PMP estimation helps engineers and planners assess the maximum potential flood that a structure needs to be designed to withstand, ensuring the safety and resilience of infrastructure.

The most common methods used to derive PMP are the storm maximisation (hydrometeorological) approach (WMO, 1973 and 2009) and the statistical approach – Hershfield method (1965). The storm maximisation and transposition method requires more site-specific data. Where site-specific data are limited, a statistical method is applied. This method requires annual maximum rainfall series in the region for required storm durations for which the PMP to be estimated. Factors that influence calculations of PMP values are:

- rainfall of intended storm durations,
- temperature,
- relative humidity,
- altitude,
- wind direction,
- dew point temperature, etc.

The prediction of PMP has evolved over time, driven by advancements in meteorology, hydrology, and statistical analysis. Early approaches relied on empirical methods that utilised historical rainfall data and simple statistical extrapolation techniques. However, these methods had limitations in terms of their spatial and temporal representation of extreme precipitation events.

With advancements in computing power and access to more extensive datasets, modern techniques for predicting PMP have emerged. These techniques incorporate more sophisticated statistical models, numerical weather prediction models, and storm transposition methods. They aim to simulate extreme precipitation events by considering the physical processes and atmospheric conditions that contribute to their occurrence.

To calculate the Probable Maximum Precipitation (PMP), one typically follows established guidelines and methods. The specific approach may vary depending on the region and the available data. However, a general overview of the process is shown in Figure 2.

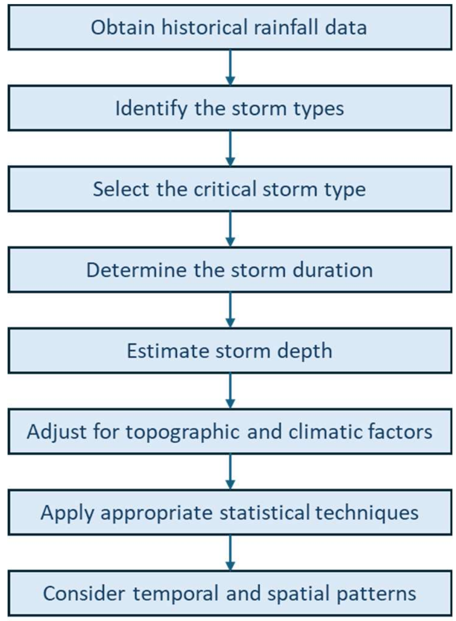

Figure 2. Typical process of PMP determination

PMP is not a probabilistic estimate. It represents a theoretical maximum precipitation value. However, PMP estimation does involve the consideration of probabilities associated with extreme weather events. PMP is probably the maximum precipitation. In applying PMP/PMF, the terminology, nature of the estimation process, and confidence limits need to be understood.

PMP is primarily used as a design criterion for hydraulic structures in flood-prone areas. It provides a basis for determining the capacity and resilience of infrastructure, such as reservoir and spillway systems, to withstand extreme precipitation events.

By considering PMP in the design process, engineers ensure that these structures can safely accommodate the maximum potential flood and prevent catastrophic failures. The accurate estimation of PMP is crucial for protecting lives and property, enhancing the resilience of infrastructure, and enabling effective flood risk management. As climate change continues to alter precipitation patterns and most of the factors used to estimate PMP, understanding the potential implications on PMP becomes increasingly important for ensuring the safety and sustainability of our communities.

PROBABLE MAXIMUM FLOOD (PMF)

In the United Kingdom, the estimation of probable maximum flood (PMF) is an integral part of flood management and the design of reservoir and spillway systems. The Floods and Reservoir Safety (ICE, 2015) Table 2.1 sets guidelines for scale of floods that must be accommodated by spillways depending on the threat posed by the structure. It outlines the recommended standard for determining the maximum flood that a hydraulic structure should be designed to withstand.

PMP serves as a fundamental input for estimating PMF. The relationship between PMP and PMF is established based on hydrological principles and historical flood data. PMP represents the upper limit of potential precipitation, while PMF reflects the maximum flood that could result from that extreme precipitation at any given location.

Managing Risks for Dams and Reservoirs

To evaluate PMF, engineers combine PMP with additional factors such as catchment characteristics, rainfall-runoff processes, and hydraulic routing. These factors help determine how the extreme precipitation would translate into a flood event, considering the local hydrological conditions and the response of the watershed.

The calculation of PMP and PMF involves an analysis of several factors that influence the magnitude and behaviour of extreme precipitation events and resulting floods. The following factors are considered:

- Storm Characteristics: This includes the intensity, duration, and spatial distribution of rainfall associated with the extreme event. Historical storm data and statistical methods are used to estimate the maximum possible storm characteristics.
- Watershed Characteristics: The physical characteristics of the catchment, such as size, shape, topography, land cover, soil type, and infiltration capacity, play a significant role in determining the response of the watershed to extreme precipitation. Hydrological models are employed to simulate the rainfall-runoff processes within the catchment.
- Climatic Conditions: Local climate patterns, including atmospheric moisture availability, prevailing weather systems and snowmelt, are important considerations. Climate data, such as historical rainfall records, are analysed to understand the likelihood and magnitude of extreme precipitation events.
- Hydraulic Routing: Once the flood hydrograph is derived from the combination of PMP and watershed response, hydraulic routing techniques are employed to simulate how the flood hydrograph propagates through the river system. This step allows engineers to determine the flood peak and associated flood levels at various locations downstream.

The estimation of PMF involves uncertainties associated with each factor considered in the calculation. Confidence limits could be assigned to these factors to quantify the range of uncertainty. These limits represent the confidence interval within which the true value of the factor is expected to lie. The confidence limits for individual factors could be determined through statistical analysis, historical data analysis, and expert judgment. By considering the range of possible values for each factor and their associated probabilities, a comprehensive assessment of the uncertainties could be obtained.

The aggregate confidence limit on PMF is a composite measure that accounts for the combined uncertainties from all the factors involved in its calculation. It represents the overall range within which the true PMF is expected to lie, considering the uncertainties in storm characteristics, watershed response, climatic conditions, and hydraulic routing. Micovic et al (2015) assessed the variation in these factors for a dam in British Columbia and found that PMP could be more than 40% higher than the single-value PMP estimate. They recommended presenting PMP as a range within confidence limits as opposed to the single value which implies a, perhaps false, degree of certainty.

The PMP/PMF method differs from probabilistic methods of flood prediction in its approach to extreme events. PMP/PMF represents a deterministic approach that focuses on estimating the maximum potential precipitation and the corresponding flood event. It provides a conservative design criterion to ensure the safety of hydraulic structures.

In contrast, probabilistic methods of flood prediction consider a range of probabilities associated with different return periods or exceedance probabilities. These methods analyse historical data and statistical distributions to estimate the likelihood of various flood magnitudes occurring within a specific time frame.

For example, a 1 in 10,000-year flood event corresponds to a low probability event, like throwing five sixes in succession with a fair die. Probabilistic methods provide a quantitative assessment of the probabilities associated with different flood magnitudes and return periods.

One would expect probabilistic precipitation predictions would asymptotically approach the PMP at the extremes.

PMF is used as a design standard instead of a more extreme probabilistic flood event for several reasons:

- Safety and Risk Management: PMF provides a conservative estimate of the maximum flood that a hydraulic structure needs to withstand. It incorporates safety margins and ensures that the structure is designed to accommodate extreme events with a high level of confidence. This approach helps mitigate the risks associated with catastrophic failures.
- Infrastructure Resilience: Designing hydraulic structures based on PMF ensures their resilience to a wide range of extreme flood events. By considering the upper limit of potential precipitation, engineers can create structures that can handle a significant range of flood magnitudes, providing a level of protection for both the infrastructure itself and the communities downstream.
- Regulatory Compliance: Many countries have regulatory requirements that mandate the use of PMF as a design criterion for flood control infrastructure. Compliance with these regulations ensures that the structures meet the specified safety standards and contribute to overall flood risk reduction efforts.
- Data Limitations: Probabilistic methods rely heavily on historical data for accurate estimation of probabilities and return periods. However, historical data may be limited in duration or quality, especially for rare or extreme events. PMF estimation, on the other hand, provides a more conservative approach that is not solely reliant on historical records, making it suitable for cases where data limitations exist.

CLIMATE CHANGE

Climate change is projected to bring significant changes to the climate of the United Kingdom. The Intergovernmental Panel on Climate Change (IPCC) and other scientific studies provide insights into the potential climate scenarios. While specific projections may vary, some key changes anticipated in the UK include:

- Increased Temperature: Rising global temperatures are expected to lead to warmer conditions in the UK (Figure). This can result in changes in precipitation patterns, evaporation rates, and the overall water cycle dynamics.
- Altered Precipitation Patterns: Climate models indicate that the UK may experience changes in precipitation patterns, including alterations in the frequency, intensity, and distribution of rainfall events. This can lead to more intense rainfall during certain periods and regions, potentially increasing the risk of extreme precipitation events.

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- Sea Level Rise: The ongoing warming of the planet is causing the melting of polar ice and thermal expansion of seawater, resulting in rising sea levels. This can lead to increased coastal flooding and enhanced vulnerability of low-lying areas, particularly during storm events.

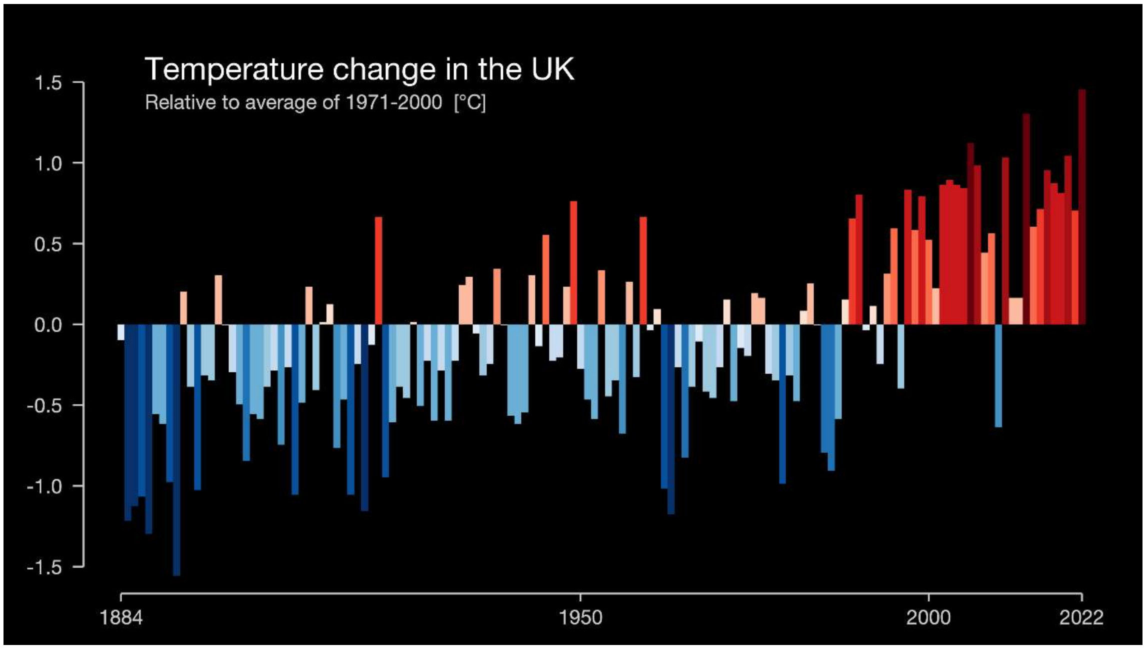

Figure 3. Temperature change in the UK due to climate change
(Graphics and lead scientist: Ed Hawkins, National Centre for Atmospheric Science, University of Reading., National Centre for Atmospheric Science, UoR.Data: Berkeley Earth, NOAA, UK Met Office, MeteoSwiss, DWD, SMHI, UoR & ZAMG)

The estimation of PMP and PMF can be affected by climate change in several ways. Some of the factors considered in their calculation that could be influenced by climate change include:

- Precipitation Intensity: Changes in precipitation patterns may result in altered rainfall intensities. Higher intensity rainfall events can impact the estimation of PMP and subsequently affect the estimation of PMF.
- Rainfall Distribution: Climate change can lead to changes in the spatial and temporal distribution of rainfall. This can impact the design and operation of hydraulic structures as the timing and duration of extreme events may shift.
- Seasonality: Climate change may also influence the seasonality of rainfall, potentially affecting the frequency and magnitude of extreme precipitation events during specific times of the year. This can have implications for estimating PMP and PMF.
- Temperature Effects: Rising temperatures associated with climate change can impact the hydrological cycle, including evaporation rates, soil moisture, and snowmelt dynamics. These temperature-related factors can influence the estimation of PMP and PMF.

It is important to note that the exact nature and magnitude of these climate change impacts on PMP and PMF are subject to uncertainties and depend on regional climate characteristics and specific climate change scenarios.

In the UK, the impact of climate change on reservoirs has been considered in previous studies such as those by:

- Babtie (2002), which found a typical +5% sensitivity in total surcharge level to worst case UKCIP98 projected rainfall and windspeed changes to the 2050s.
- Atkins (2013) referred to an earlier study by Collier (2009) that showed increases in 1-hour rainfall accumulations of 7% for each degree of temperature rise up to 25°C but also found decreases of 8-hour rainfall accumulations with temperature. The Atkins study concluded that "currently research is not robust enough to include as guidance values".

Our understanding is that the ongoing Environment Agency research project (FRS19222) to assess existing methods for estimating PMP and PMF, and to develop new UK methods and guidelines does not include climate change within its remit.

Researchers around the world are also considering the potential implications of climate change on PMP and PMF estimation. There are studies applying climate models to derive updated PMP and PMF estimates for specific reservoir catchments. For example:

- United States: Gangrade et al (2018) tested future climate conditions for the Alabama-Coosa-Tallapoosa river basin and found significant increases in PMF in the near-future (+18%) and far-future (+69%).
- Australia: Visser et al (2022) found evidence of increasing dew point temperatures over the past 60 years with further increases predicted over the coming decades and concluded this is incompatible with the assumption of a fixed PMP. PMP estimates across Australia are predicted to increase by 13%-33% on average by 2100.
- Canada: Clavet-Gaumont et al (2017) considered five Canadian river basins, applied regional climate model simulation results to PMP and snowpack and found increases of up to 20% to future spring PMF. Similarly, in a study of PMP and PMF within Quebec, Rouhani (2016) found increases of up to 25% to the PMF, although reductions of up to 25% were also found for other catchments.
- Malaysia: Sammen et al (2022) estimated increases of 49% (2031-2045) and 123% (2060-2075) to the PMF inflow to a Malaysian reservoir, based on projected rainfall from a regional climate model.
- Chile: Lagos-Zuniga and Vargas (2014) found an increase of as much as 175% to PMF inflows for an Andean reservoir basin in Chile by 2045-2065.
- Japan: Kobayashi et al (2022) described their application of future climate change meteorological model outputs to estimate PMP and PMF for reservoir catchments in Japan.
- Thailand: Jothityangkoon et al (2013) tested climate change scenarios for a large reservoir catchment and found an increase to the PMF of up to 7.5%.

These examples highlight the global recognition of the importance of assessing the impacts of climate change on extreme precipitation events and their implications for flood management and infrastructure design. However, there is currently a lack of strong guidance on how this should be applied for reservoir safety assessments.

Managing Risks for Dams and Reservoirs

Assessing the specific changes in confidence intervals for PMF predictions due to climate change is a complex task that requires comprehensive climate modelling and hydrological analysis. While specific comparisons may vary depending on regional characteristics and climate change scenarios, some general observations can be made.

Climate change can introduce additional uncertainties in estimating PMF due to the uncertainties associated with projecting future climate conditions. The changes in precipitation patterns, intensities, and seasonality add complexity to the estimation process, potentially widening the confidence intervals. However, advancements in climate modelling and downscaling techniques can help improve the accuracy of climate projections and reduce uncertainties. Incorporating climate change scenarios in PMP and PMF estimation can provide a more comprehensive understanding of potential future flood risks and contribute to more robust design and management strategies.

RESERVOIR RELATED FLOOD PREDICTIONS

The consideration of climate change allowance in the estimation of PMP and PMF can have significant implications for flood management and the design of reservoir and spillway systems. Some potential implications include:

- Increased Design Capacity: Incorporating climate change projections in PMP and PMF estimation may require an increase in the design capacity of hydraulic structures. Higher precipitation intensities and altered rainfall patterns may necessitate the construction of larger reservoirs or the modification of existing ones to accommodate the anticipated increase in flood magnitudes.
- Adaptation Measures: Climate change allowance may require the implementation of adaptation measures to enhance the resilience of hydraulic structures. This could include the construction of additional spillways, higher wave walls, the installation of flood control gates, or the implementation of improved monitoring and early warning systems to mitigate the potential impacts of more frequent and intense flood events.
- Risk Assessment and Management: Climate change allowance in PMP and PMF estimation can inform more comprehensive risk assessments and management strategies. It enables decision-makers to evaluate the potential consequences of extreme floods under future climate scenarios and prioritise investments in flood control infrastructure and emergency response systems accordingly.

Climate change poses challenges to the use of past data for probabilistic flood event prediction. Historical data, which forms the basis of probabilistic methods, may not adequately capture the changing climate conditions and the associated shifts in flood patterns.

Climate change introduces non-stationarity, implying that past flood records may no longer provide a reliable representation of future flood probabilities. As the climate changes, the underlying assumptions about the probability distributions and return periods of flood events may become outdated.

To address this challenge, climate-informed approaches are being developed to incorporate projected climate change scenarios into probabilistic flood event prediction. These approaches integrate historical data with climate models and statistical techniques to account for the changing hydrological conditions and provide more robust estimates of future flood probabilities.

CASE STUDIES

To investigate potential climate change impacts on existing reservoirs, specific case studies and examples from Scotland, Wales and England have been developed to highlight the regional implications of climate change on PMP and PMF estimation and flood management practices as described below.

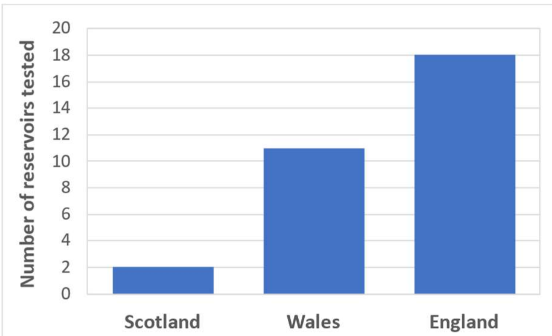

Figure 4. Reservoir locations within case studies

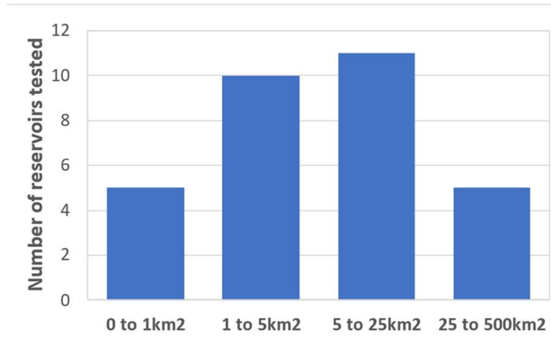

Figure 5. Catchment sizes within case studies

The data used within the case studies is summarised in **Figure 4** to **Figure 7**. These figures show the geographic locations of the reservoirs (**Figure 4**), the catchment sizes (**Figure 5**) and climate change factors applied to rainfall (**Figure 6**6) and runoff (**Figure 7**7).

The approach used for these case studies was to:

- Take a selection of reservoirs for which flood studies had previously and recently been undertaken by Binnies, which could easily be rerun for climate change scenarios. A total of 31 reservoirs was included.
- Include a range of locations, catchment sizes, reservoir sizes and reservoir types.
- Repeat the previous flood routing calculations with climate change allowances applied within the reservoir inflows.
- Test applying climate change allowances in two separate ways. Firstly, applying rainfall allowances to increase PMP and from this re-calculate PMF. Secondly, applying runoff allowances to directly scale the present-day PMF hydrograph.
- Apply glass walls to the dam crest to prevent stillwater overflowing. This is to give a fair indication of how much dam raising would be needed to prevent overflowing.
- Test the PMF – taking the present-day worst case of summer or winter PMFs only.

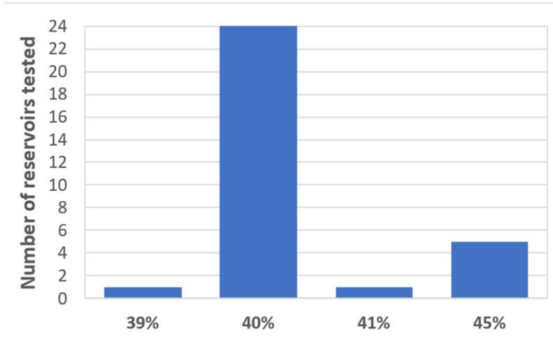

Figure 6. Climate change increase factors applied to rainfall within case studies

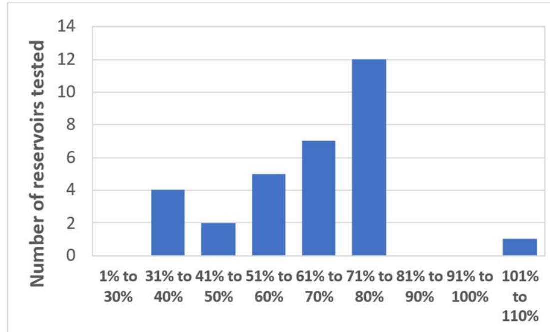

Figure 7. Climate change increase factors applied to runoff within case studies

Climate change was implemented using the allowance factors recommended within current Environment Agency (EA), Natural Resources Wales (NRW) and Scottish Environmental Protection Agency (SEPA) guidance for fluvial flood risk assessment and modelling. This guidance is not intended, or usually used, for reservoir flood studies. We readily acknowledge that the climate change factors used were developed to represent different flood generating mechanisms, but we are using them here in the absence of alternative PMP/PMF specific values.

The climate change guidance documents give different values for different emissions scenarios and timeframes. For this paper, we have used the largest change factors, represented the highest emission scenario and longest timeframe, so as to give an upper estimate for possible climate change impacts based on these allowances.

For Scotland (SEPA, 2023) rainfall and runoff change factors are given for ten river basin regions, for a single emissions case and one time frame (2100). We used:

- Peak rainfall intensity allowances for the year 2100. These are intended for catchments smaller than 30km^2 but were used for each reservoir for comparison to the other case studies. Rainfall factors range from +35% to +48% across Scotland.
- Peak river flow allowances for year 2100. These allowances are intended for catchments greater than 50km^2 but were used for each reservoir for comparison to the other case studies. Flow factors range from +34% to +59% across Scotland.

For Wales (NRW, 2021):

- Peak rainfall intensity allowances are provided as Central and Upper estimates for the 2020s, 2050s and 2080s. The same values apply across the whole of Wales. We used the 2080s Upper estimate (+40%).
- Peak river flow allowances are provided as Lower End, Central and Upper End estimates for the 2020s, 2050s and 2080s with three regions defined. We used the 2080s Upper End estimates (ranging from +45% to +75%).

For England (EA, 2022):

- Rainfall and flow datasets can be selected from an interactive map, which gives detailed subdivisions of river catchments across England.

- Peak rainfall intensity allowances are provided as Central and Upper End allowances for the 2050s and 2070s. Different values are given for the 3.3% (1 in 30) and 1% (1 in 100) annual exceedance rainfall events. We used the 2070s Upper End 1% exceedance factors (as the largest value available).
- Peak river flow allowances are provided as Central, Higher and Upper estimates for the 2020s, 2050s and 2080s. We used the 2080s Upper estimates.

Results of the case study flood routings are shown in **Figure 8** and **Figure** 9. In **Figure 8**, the stillwater flood rise with the present day PMP/PMF estimates is compared to the two climate change cases with rainfall and flow allowances applied. In **Figure** 9, the applied climate change peak flow allowances are plotted against the percentage increase in stillwater flood rise. There is little to be drawn from an equivalent plot of rainfall intensity allowances given that very similar change factors were applied to all the reservoirs.

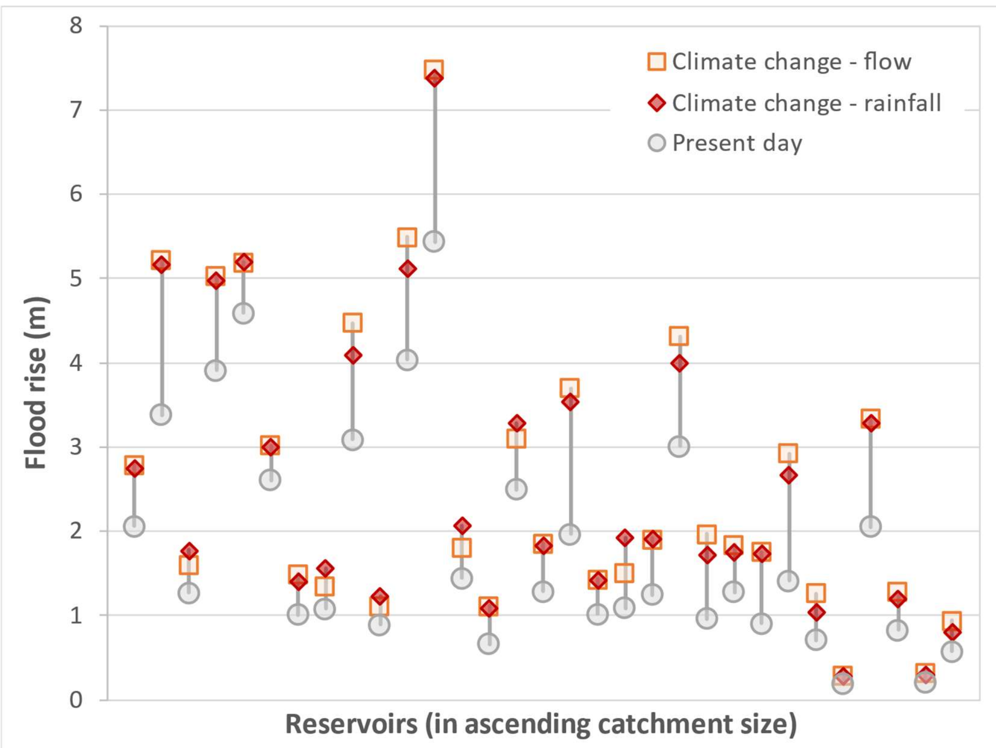

Figure 8. Case study results – impact on stillwater flood rise

The main findings from these case studies are that:

- The impact on stillwater flood rise from applying the peak rainfall intensity allowance or the peak flow allowance is generally similar. On average, the flow allowance gives slightly larger increases, but this is not the case for all locations.
- To quantify the predicted changes:
    - Rainfall intensity allowance gives a minimum increase of 0.09m, maximum increase of 1.94m and average increase of 0.74m.
    - Flow allowance gives a minimum increase of 0.10m, maximum increase of 2.04m and average increase of 0.78m.

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- The changes are significant:
    - At 6 of the reservoirs, the increased stillwater flood rise is enough for the dam to overflow, when it does not in present day conditions.
    - At 12 of the reservoirs, the available wave freeboard would be significantly reduced.
- At the other 13 reservoirs tested, the present day PMF peak stillwater level was already above the minimum dam crest level.
- There is not a consistent relationship between the increase in peak flow to the increase in flood rise (**Error! Reference source not found.**). This depends partly on the overflow arrangements at each reservoir:
    - Where there is an undrowned spill weir, the increase in flood rise will be less than the peak flow factor.
    - Where there is a constraint on the outflow, such as a culvert structure or bridge over the spillway entrance, the increase in flood rise can be higher than the peak flow factor.

We again note that we used the highest climate change allowances from the guidance. These are upper end estimates for the end of the century. In the shorter term, the recommended factors are smaller. However, these could still lead to significant reductions in the wave freeboard available at some of these reservoirs.

These case studies demonstrate that applying standard climate change allowances, which are widely used in fluvial flood risk assessment, to reservoirs for the PMP/PMF, results in significant increases to predicted stillwater flood rise. If climate change allowances were required within reservoir flood studies, it would inevitably result in many spillways no longer being able to fully discharge the PMF without dam overflowing or significant wave overtopping.

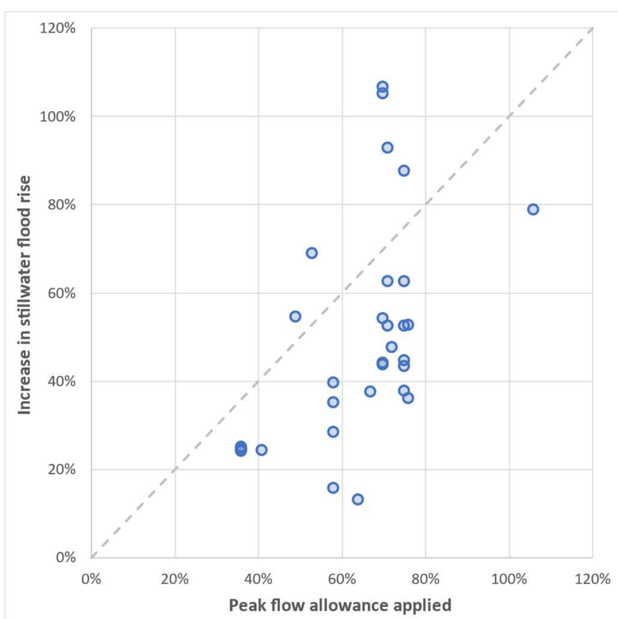

Figure 9. Case study results – peak flow allowance compared to stillwater flood rise increase

CONCLUSIONS

The factors considered in PMP and PMF calculations, including precipitation intensity, rainfall distribution, seasonality, and temperature effects, will be influenced by climate change.

Incorporating climate change allowances in PMP and PMF estimation is crucial to ensure the resilience of hydraulic structures in the face of future climate conditions. Our case studies for UK reservoirs using current flood risk climate change guidance indicate a typical increase in PMF stillwater flood rise of around 0.75m by the end of the century with the upper end emissions scenarios.

Researchers in many countries around the world, including the United States, Australia, and Malaysia, are actively considering the impacts of climate change on extreme precipitation events and assessing the impact on PMF predictions.

More research is required to understand confidence intervals for current PMF predictions even before uncertainties around climate change are introduced. While climate change introduces uncertainties in estimating PMF, advancements in climate modelling techniques and downscaling methods offer opportunities to enhance the accuracy of climate projections and reduce uncertainties.

The implications of climate change allowance for PMP and PMF include the potential need for increased design capacity, adaptation measures, and comprehensive risk assessment and management strategies.

Climate change also challenges the use of past data for probabilistic flood event prediction, emphasising the importance of climate-informed approaches that integrate historical data with climate projections.

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