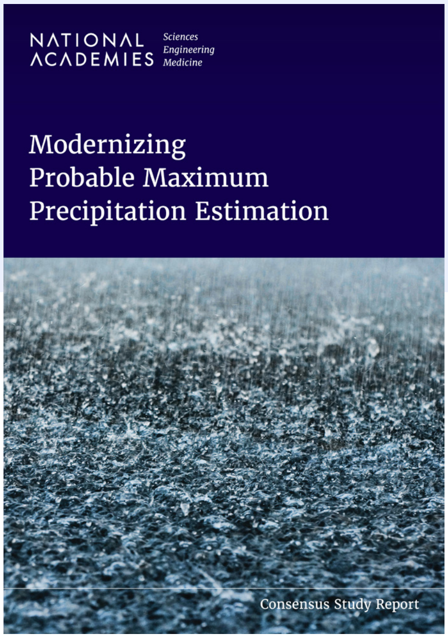
NATIONAL ACADEMIES Sciences Engineering Medicine

Consensus Study Report
Highlights

Modernizing Probable Maximum Precipitation Estimation



For more than 75 years, high-hazard structures in the United States, including dams and nuclear power plants, have been engineered to withstand floods resulting from the most unlikely but possible precipitation, termed Probable Maximum Precipitation (PMP). More than 16,000 high-hazard dams and 50 nuclear power plants are located in the United States, many of which are approaching or exceeding their design lifetime. Failure of any one of these structures will likely result in loss of life and could impose significant economic losses and widespread environmental damage. The pressures of climate change on flood hazards further highlight the urgent need to re-assess the safety of and flood protection provided by structures designed decades ago.

The scientific and engineering foundations of PMP are old. The key ideas underlying PMP were developed by the Miami Conservancy more than a century ago to address the catastrophic impacts of the Great Flood of 1913 in the Upper Ohio River. The rapidly accelerating pace of dam building in the United States led to the standardization of PMP procedures by federal agencies in the 1940s. PMP informed rational engineering solutions for the U.S. water and power infrastructure to diminish risks of flood hazards. However, weaknesses in the scientific foundations of PMP, combined with advances in understanding, observing, and modeling extreme storms, call for fundamental changes to the definition of PMP and the methods used to estimate it.

THE NEED TO MODERNIZE PMP AND ITS ESTIMATION

The principal weaknesses of current PMP methods identified by the committee are listed below.

- The assumption that rainfall is bounded;
- The absence of procedures to account for the effects of climate change on rainfall extremes;
- The incomplete temporal and spatial sampling of extreme rainfall events in storm catalogs;
- The inherently subjective implementation of storm transposition procedures;
- The absence of a sound scientific foundation for moisture maximization;
- The empirical correction factors used to account for the effects of complex terrain on extreme rainfall;
- The absence of procedures to account for the statistical uncertainty of PMP estimates.

A NEW DEFINITION OF PMP

PMP has been defined as an upper bound on rainfall, and thus as a value that cannot be exceeded. Yet, PMP estimates are based on limited observations and subjective estimation procedures—they can be and have been exceeded in the past.

The committee recommends revising the definition of Probable Maximum Precipitation to become:

The depth of precipitation for a particular duration, location, and areal extent, such as a drainage basin, with an extremely low annual probability of being exceeded, for a specified climate period.

The revised definition of PMP differs from the previous one in two primary ways: (1) it replaces an "upper bound" on rainfall with an "extremely low exceedance probability," and (2) it adds "for a specified climate period" so that PMP estimates can change with climate. The two changes to the definition are essential for developing scientifically grounded methods for estimating PMP.

A VISION FOR PMP

Given the limitations of the current definition and estimation methodology for PMP and the importance of ensuring the safety of critical infrastructure, it is imperative to revisit the concept of PMP and its estimation methodology. **The committee's vision is:**

Model-based probabilistic estimates of extremely low exceedance probability precipitation depths under current and future climates will be attainable at space and time scales relevant for design and safety analysis of critical infrastructure within the next decade.

The proposed long-term methodology for PMP estimation is based on statistical analysis of long-term simulated rainfall fields from high-fidelity and high-resolution storm-resolving climate models (model-based PMP estimates). This model-based approach permits incorporation of advances in physical understanding and numerical modeling of extreme storms, the effects of climate change, and uncertainty characterization of PMP estimates. It also permits the incorporation of PMP into risk-informed, decision-making frameworks and provides additional links for probable maximum flood estimation over drainage basins.

Specification of the annual exceedance probabilities that define PMP presents a challenging societal question regarding the level of risk judged to be acceptable for high-hazard dams and nuclear power plants that still ensures their safety. **The committee recommends that federal and state agencies, in partnership with the Association of State Dam Safety Officials, develop national guidance for specifying the annual exceedance probabilities used for PMP estimation.**

Use of an extremely low annual exceedance probability poses distinctive scientific challenges. Modernization of PMP estimation will require innovative and synergistic development of observational, statistical, and modeling tools that focus on the rainfall extremes that define PMP.

PATH TO MODERNIZING PMP

The path toward implementation of model-based PMP estimation is impeded by two significant challenges to the development of kilometer-scale or finer resolution models necessary to resolve storms that produce PMP-magnitude precipitation. First, increased model resolution is not a sufficient guarantee that models that will be fit-for-purpose, because storm-resolving simulations are sensitive to parameterized processes such as cloud microphysics and boundary layer turbulence. Second, significant computational resources are needed to produce large ensembles of storm-resolving simulations to address model uncertainty and internal variability.

The committee proposes a phased approach to addressing these challenges, whereby near-term enhancements to current PMP methods based on observations will transition to the long-term, model-based approach (see Figure 1).

Near-term enhancements to PMP can be grounded in several approaches. Building on recent advances in PMP studies, improved rainfall data for PMP estimation can be developed from radar and surface rainfall observations. Model-based reconstruction of storm catalog events that control historical PMP estimates can refine rainfall analyses for these storms and provide scientific grounding for subjective decisions used to implement PMP methods. For near-term PMP estimation, the effects of climate change can be incorporated through climate change adjustment factors. Near-term enhancements to PMP methods can be used to produce updated PMP estimates for the United States over the next several years.

Long-term, model-based PMP estimation will employ kilometer-scale climate models capable of resolving PMP storms and producing PMP-magnitude precipitation. By capturing natural variability, large ensemble simulations will enable statistical quantification of the uncertainty of the PMP estimates. Assessment of model-based exceedance probabilities of the PMP estimates obtained using near-term enhancements will guide the selection of the annual exceedance probabilities that define PMP.

A Model Evaluation Project will provide scientific grounding for model-based PMP estimation, inform the development of the necessary modeling infrastructure, and provide the foundation for determining when the transition should occur. Results from this effort will also provide key tools for enhancing PMP estimation in the near term as well as build community confidence in models for estimating PMP.

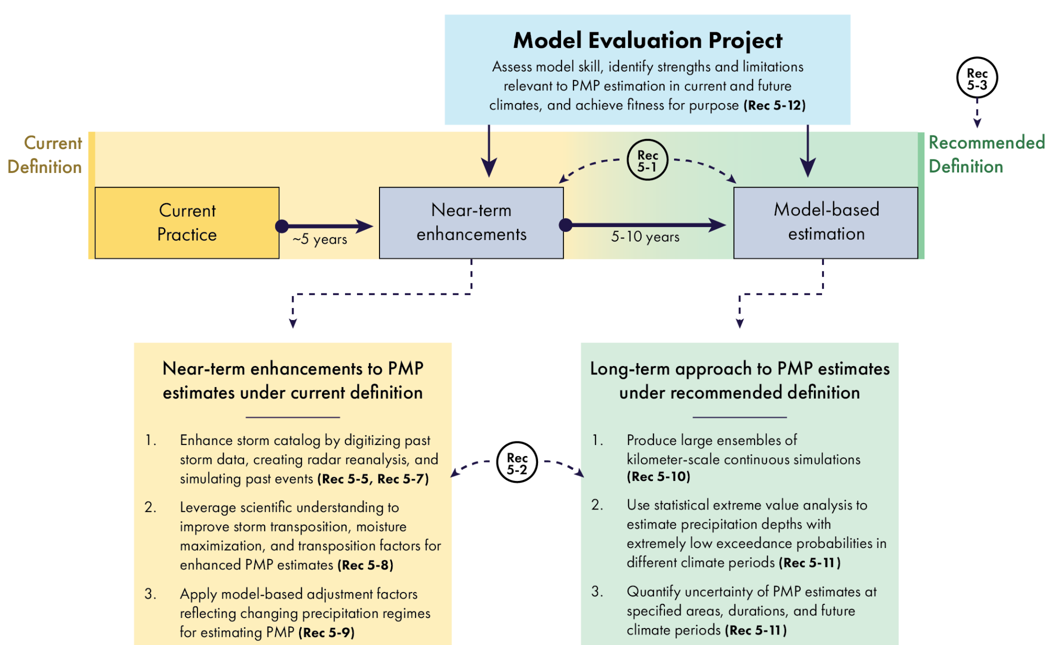


FIGURE 1 Overview of modernized PMP estimation.

CORE PRINCIPLES FOR THE DEVELOPMENT AND USE OF MODERNIZED PMP ESTIMATES

The development and use of modernized PMP estimates should be guided by four principles: transparency, objectivity, accessibility, and reproducibility.

Transparency plays a pivotal role in building trust among practitioners, regulators, researchers, and the public and lays the groundwork for independent assessment of PMP products that facilitate evidence-based policymaking.

Objectivity aims to minimize the reliance on subjective judgments. Advances in data, tools, and scientific understanding of extreme rainfall will allow practitioners to more objectively implement the near-term enhancements of PMP estimation and to transition to model-based methods.

Accessibility of data and methodologies should be emphasized throughout the entire process of PMP development. PMP products should be regarded as public goods readily available to the general public with minimum restrictions, as well as adhering to the FAIR (findable, accessible, interoperable, reusable) principles.

Reproducibility refers to the expectation that PMP products should be broadly reproducible using the same data and methods. Reproducibility is closely linked to the preceding core standards, because transparency, objectivity, and accessibility are essential for ensuring the reproducibility of PMP products.

GOING BEYOND PMP: INFRASTRUCTURE SAFETY UNDER EXTREMES IN A CHANGING CLIMATE

The recommended approach for modernizing PMP is based on the premise that state-of-the-art observations, physical understanding of extreme storms, and the capacity for high-fidelity, high-resolution simulations under different climatic forcings can transform the capabilities for assessing precipitation extremes in a warming climate. Significant research is needed to achieve the vision of a model-based PMP, and this endeavor will require scientific and modeling advances that should engage researchers across a broad array of disciplines.

It will also require synergistic collaborations among federal agencies, academia, and the private sector. Scientific and modeling advances along this front will contribute not only to modernizing PMP estimation but also more broadly to addressing the societal challenges linked to the changes in extreme storms and precipitation in a warming climate—critical steps to ensuring the safety of infrastructure and society.

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FOR MORE INFORMATION This Consensus Study Report Highlights was prepared by the Board on Atmospheric Sciences and Climate and the Water Science and Technology Board based on the Consensus Study Report *Modernizing Probable Maximum Precipitation Estimation* (2024).

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