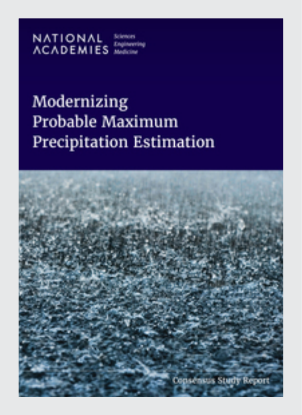

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Modernizing Probable Maximum Precipitation Estimation

Committee on Modernizing Probable Maximum Precipitation Estimation

Board on Atmospheric Sciences and Climate

Water Science and Technology Board

Division on Earth and Life Studies

Consensus Study Report

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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by **GEORGE M. HORNBERGER (NAE),** Vanderbilt University, and **ANA P. BARROS (NAE),** University of Illinois. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Contents

APPENDICES

BOXES, FIGURES, AND TABLES

BOXES

TABLES

FIGURES

Acronyms and Abbreviations

AEP	Annual Exceedance Probability
AMS	American Meteorological Society
AR	atmospheric river
ASDSO	Association of State Dam Safety Officials
BAF	Barrier Adjustment Factor
CC	Clausius-Clapeyron
CONUS	Continental United States
CPM	convection-permitting model
CRM	cloud-resolving model
DAD	Depth-Area-Duration
DDF	Depth-Duration-Frequency
DYAMOND	Dynamics of the Atmospheric General Circulation Modeled on Nonhydrostatic Domains
EVA	extreme value analysis
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
GCM	General Circulation Model
GEV	Generalized Extreme Value
GIS	Geographic Information System
HMR	Hydrometeorological Report
IDF	Intensity-Duration-Frequency
LES	large-eddy simulation
MCS	mesoscale convective system
MEP	Model Evaluation Project
MPP	Maximum Possible Precipitation
MRMS	Multi-Radar Multi-Sensor
MTF	Moisture Transposition Factor
NEXRAD	Next Generation Weather Radar
NID	National Inventory of Dams
NOAA	National Oceanic and Atmospheric Administration

NRC	National Research Council
NWP	Numerical Weather Prediction
NWS	National Weather Service
OTF	Orographic Transposition Factor
PFA	Precipitation Frequency Analysis
PGW	pseudo-global warming
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PMS	Probable Maximum Storm
PW	precipitable water
RIDM	Risk-Informed Decision Making
SSM	Storm Separation Method
SST	Stochastic Storm Transposition
TC	tropical cyclone
TVA	Tennessee Valley Authority
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
USWB	U.S. Weather Bureau
WMO	World Meteorological Organization

Summary

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.

Although they have changed over time, definitions of PMP have always been based on the assumption that rainfall is bounded. The National Oceanic and Atmospheric Administration (NOAA) has defined PMP as “theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year.” A compelling case for the existence of upper bounds on rainfall, however, has yet to emerge, either through physical arguments or statistical analyses. PMP is 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 NEED TO MODERNIZE PMP AND ITS ESTIMATION

Current PMP estimation methodologies are based on observations contained in storm catalogs and are grounded on three fundamental components: storm transposition, moisture maximization, and orographic adjustment. Each component has significant limitations as outlined below.

Storm catalogs containing observations of rainfall from extreme storms provide the data used to estimate PMP. Rainfall observations from non-standard rain gauges obtained from **bucket surveys** play a critical role in PMP estimation. U.S. and world record rainfall accumulations from bucket surveys include 305 mm in 42 minutes from the Holt, Missouri, storm on 22 June 1947; 560 mm in 2.75 hours from the D’Hanis, Texas, storm on 31 May 1935; and 780 mm in 4.5 hours from the Smethport, Pennsylvania, storm on 18−19 July 1942. A cattle trough was the instrument used for the D’Hanis measurement, and a mason jar was the instrument used for the Smethport measurement. Bucket surveys have also provided the observations needed to effectively assess the "given storm area" requirement of the PMP definition. For the Smethport storm, more than 400 bucket survey rainfall observations were obtained around the area of peak rainfall; the region had no conventional rain gauges.

It is not entirely fortuitous that world record rainfall accumulations were obtained in 1935, 1942 and 1947. The era of flood studies with carefully developed bucket surveys of extreme rainfall waxed and waned as the priorities of the federal dam building program changed. A fundamental limitation of storm catalogs used for PMP estimation is the incomplete temporal and spatial sampling of storms. Storm catalog records are incomplete, and it is not possible to detail what is missing, either in time or space. This limitation precludes statistical characterization of uncertainty of current PMP estimates.

The most important component of PMP estimation based on storm catalogs is **storm transposition,** which aims to specify—for each storm—the geographic region over which it could be transported and thus be used to estimate PMP. Specification of storm transposition regions relies on the scientific judgement of PMP practitioners and is therefore inherently subjective. Storm transposition, more than any other component of PMP estimation, depends on the effective application of scientific understanding of extreme storms. Previous studies have shown that PMP estimates are generally more sensitive to storm transposition than to any other component of PMP estimation. For example, PMP estimates for much of the eastern United States are strongly dependent on decisions specifying the storm transposition region for the July 1942 Smethport storm. Similar patterns of sensitivity to storm transposition hold for regions across the United States.

Moisture maximization is a procedure used to amplify rainfall observations from the storm catalog events in an attempt to reflect the maximum rainfall that could occur from similar storms but under even more extreme moisture conditions. An underlying assumption is that rainfall varies linearly with precipitable water, which is the total water vapor content in an atmospheric column. The moisture maximization factor used to amplify storm rainfall is the ratio of maximum precipitable water at the storm location to the actual precipitable water for the storm. Modeling and observational studies have not provided support for the assumptions underlying moisture maximization. Significant challenges in developing the data needed to implement moisture maximization have also been noted. Moisture maximization provides a plausible engineering safety factor for PMP estimation, but it lacks a solid scientific and observational foundation.

The challenges to estimating PMP in mountainous terrain were highlighted in the 1994 NASEM study *Estimating Bounds on Extreme Precipitation Events: A Brief Assessment* and remain largely unresolved. The principal tools used to address terrain effects on extreme rainfall center are **orographic transposition factors**, which amplify or decrease observed storm rainfall based on precipitation frequency products. In transposing a storm from point A to point B, an orographic transposition factor is computed as the ratio of T-year rainfall at point B to T-year rainfall at point A (the return interval T is often taken to be 100 years). Orographic transposition factors nudge PMP estimates toward the spatial patterns of precipitation frequency maps. They address the long-recognized challenge of estimating PMP in mountainous terrain where observations are often severely limited, but they do not adequately address the scientific challenges imposed by orographic precipitation mechanisms. Observational, modeling, and theoretical advances are required to effectively estimate PMP in mountainous regions.

The principal weaknesses of current PMP methods are listed below. They reflect many of the issues identified in the 1994 NASEM study.

- 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 statistical uncertainty of PMP estimates

A VISION FOR PMP

Given these limitations and the importance of ensuring the safety of our critical infrastructure, the concept of PMP and its estimation methodology must be revisited. This report presents the committee's conclusions and recommendations, including a revised definition of PMP, near-term enhancements to PMP estimation, and a transition to a long-term approach to PMP estimation that is based on computer simulations using physics-based climate models, which would facilitate the effective treatment of climate change effects on extreme precipitation and the characterization of uncertainty of PMP estimates. The committee's vision is as follows:

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.

Toward this vision, this report presents a set of recommendations that are summarized below and expanded in the chapters that follow.

A NEW DEFINITION OF PMP

The committee recommends revising the definition of PMP 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."** Federal and state agencies, in partnership with state dam safety officials, would develop national guidelines for specifying the annual exceedance probability (AEP) as detailed in recommendations below. 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.

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) adds "for a specified climate period" so that PMP estimates can change with climate. The revised definition addresses the two most critical weaknesses of current PMP methods: the assumption that rainfall is bounded does not provide a tenable foundation for estimation of PMP, and climate change has resulted in historical changes in extreme rainfall and will likely cause even greater changes over the coming decades. These changes are essential for developing scientifically grounded methods for estimating PMP. "Time of year" is omitted from the revised definition because the model-based approach can readily provide seasonally varying estimates in settings where they are useful.

Specification of the AEPs 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 assures their safety. Rough assessments of the AEPs corresponding to current PMP estimates are on the order of 10^{-4} to 10^{-7}. However, if the AEP were set to 10^{-4} for all high-hazard dams in the United States, roughly two dams per year on average would be subject to catastrophic failure, a rate that would likely prove societally unacceptable. The committee recommends that federal and state agencies, in partnership with the Association of State Dam Safety Officials (ASDSO), develop national guidance for specifying AEPs used for PMP estimation.

As challenging as it is, specifying the AEPs of PMP is only one step in modern dam and nuclear safety programs. Another crucial step and a key element of risk-informed decision making (RIDM) is quantitative assessment of the uncertainty in PMP estimates. The recommended model-based method for PMP estimation provides a natural path for developing statistical estimates of uncertainty, enabling the development of objective, robust, and site-specific approaches for risk analysis and decision making. The dam and nuclear safety communities have developed procedures for integrating uncertainty characterization into RIDM-based safety programs.

Another consideration in dam and nuclear safety is the central role of the Probable Maximum Flood (PMF), which is largely, but not entirely, dependent on PMP. The PMF provides a design hydrograph at the outlet of a drainage basin specified by the location of the dam or nuclear power plant. Tailoring PMP estimates to a specific drainage basin has long been recognized as significantly challenging. The proposed model-based approach provides the capability to develop PMP estimates that are naturally linked to PMF estimation over drainage basins. Temporal and spatial patterns of rainfall over drainage basins, as well as antecedent basin conditions, can be readily provided. The detailed methods used to compute PMF are beyond the scope of this study, but the linkages between PMP and PMF are important to consider in pursuing methods for modernizing PMP estimation.

Use of an extremely low rainfall AEP poses distinctive scientific challenges. One of the most daunting challenges arises from the contrast between record lengths of historical observations (~10^1 to 10^2 years) and the return intervals of PMP storms (~10^4 to 10^7 years). This problem is amplified by the rapid pace of climate change over the period of historical observations. 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.

The observational and modeling challenges for PMP estimation are most pronounced for small-area, short-duration convective rainfall, as noted in the 1994 PMP study. The practical importance of this is the fact that half of the high-hazard dams in the United States have watersheds with drainage areas less than 20 km^2. Furthermore, the impacts of climate change on extreme precipitation are arguably most difficult to assess for small-area, short-duration storms.

PATH TO MODERNIZING PMP ESTIMATION

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 (Figure S-1). An important component of this proposed process is a Model Evaluation Project (MEP), which will provide scientific grounding for model-based PMP estimation, inform development of the necessary modeling infrastructure, and provide the foundation for determining when the transition should occur. Results from the MEP will also provide key tools for enhancing PMP estimation in the near term.

Near-term enhancements to current methods can be applied to update PMP estimates for the United States over the next several years. These enhancements can be grounded in improved data for storm catalogs, integration of model-based analyses of PMP-magnitude storms into PMP estimation procedures, and synthesis of advances in scientific understanding of extreme rainfall into the approaches used to implement storm transposition, moisture maximization, and transposition factors. 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. Reconstructions of major historical storms also contribute to development of model-based PMP estimation procedures and are an important component of the MEP. For near-term PMP estimation, the effects of climate change can be incorporated through climate change adjustment factors developed from model-based temperature scaling relationships.

The long-term model-based approach will employ kilometer-scale climate models capable of resolving PMP storms and producing PMP-magnitude precipitation. To estimate the depth of precipitation with an extremely low AEP over a particular duration and areal extent, researchers will need initial-condition large ensemble simulations to construct the appropriate probability density functions of precipitation. Large ensemble simulations driven by different external forcings will provide precipitation data for estimating PMP for the present-day and for the future under different socioeconomic scenarios or global warming levels. By capturing natural variability, large ensemble simulations will also enable statistical quantification of the uncertainty of the PMP estimates. PMP uncertainty can be used to improve PMF estimates for risk assessments and designs with RIDM. Furthermore, high-resolution space-time fields can be beneficial to a wide variety of other hydrologic and climatological applications.

In specifying the AEP that defines PMP, the user community must consider the relationship between PMP estimates derived from near-term enhancements and from models. Large changes in PMP estimates due to changes in methods would create major problems for the user community and could undermine confidence in new methods. Assessment of model-based exceedance probabilities of the PMP estimates obtained using near-term enhancements will guide selection of AEPs that define PMP.

KEY RECOMMENDATIONS

A New Definition of PMP

Based on a review and discussion of existing PMP definitions, a review of PMP estimation methods, and assessment of user needs, the committee concludes that a new PMP definition is needed.

> **Recommendation 5-3: NOAA, federal and state agencies involved in dam safety and nuclear regulation, the American Meteorological Society, the American Society of Civil Engineers, and the Association of State Dam Safety Officials should adopt a revised PMP definition: Probable Maximum Precipitation—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.**

Specification of Annual Exceedance Probabilities for PMP

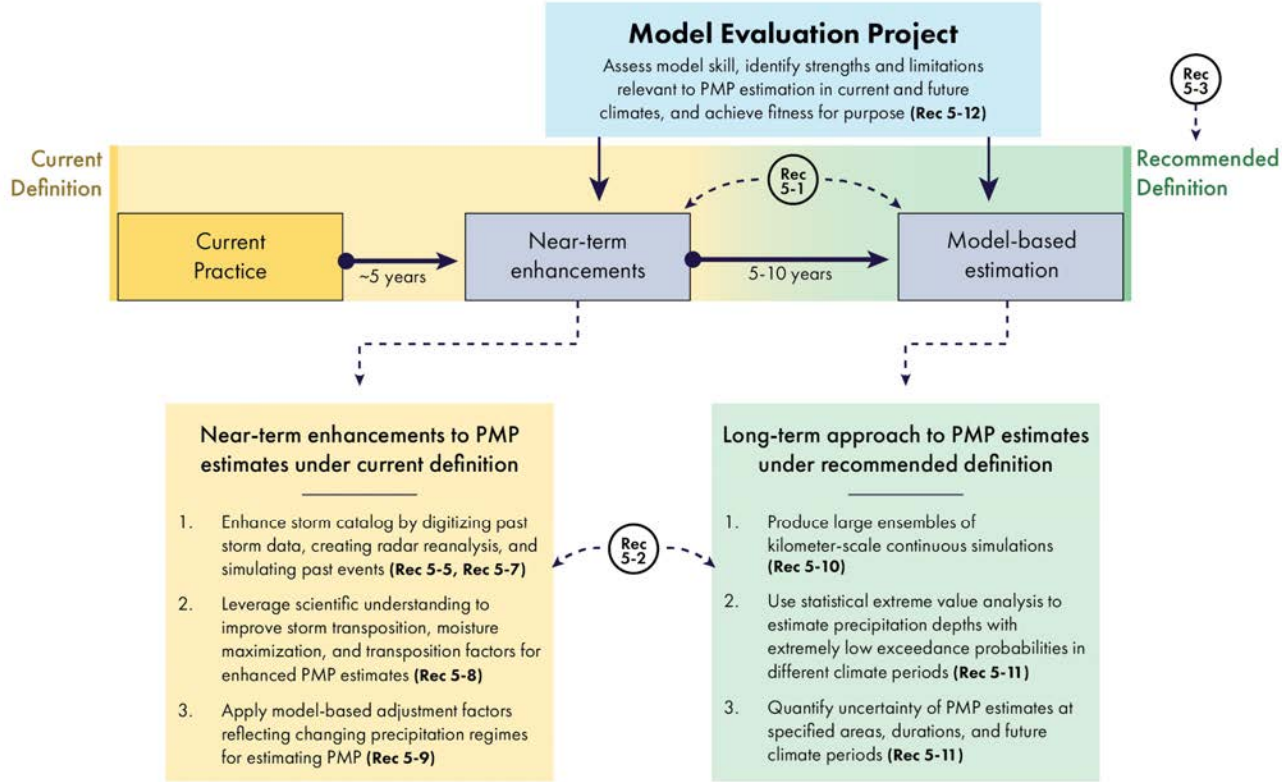
National guidance for specifying AEPs that define PMP is needed. The AEPs derived from model-based analyses of near-term PMP estimates (to be completed over the next several years) will provide a key tool for developing national guidance.

> **Recommendation 5-4: Commensurate with the new definition, NOAA and the FEMA National Dam Safety Program, in partnership with federal agencies, states, and ASDSO, should develop guidance for specifying AEPs for PMP that are acceptable for infrastructure decisions and society.**

Phased Approach to Modernizing PMP Estimation

The committee recommends a phased approach to achieving the vision of model-based PMP estimation conforming to the new definition. The framework for the phased approach is summarized in Figure S-1.

> **Recommendation 5-1: NOAA should pursue a phased approach to modernizing PMP estimation, with the near-term approach building on enhancements to conventional PMP procedures and leading to a long-term model-based framework that can provide uncertainty characterization of PMP estimates, fully incorporating the effects of climate change.**



Assess model skill, identify strengths and limitations relevant to PMP estimation in current and future climates, and achieve fitness for purpose **(Rec 5-12)**

Near-term enhancements to PMP estimates under current definition

1. Enhance storm catalog by digitizing past storm data, creating radar reanalysis, and simulating past events **(Rec 5-5, Rec 5-7)**
2. Leverage scientific understanding to improve storm transposition, moisture maximization, and transposition factors for enhanced PMP estimates **(Rec 5-8)**
3. Apply model-based adjustment factors reflecting changing precipitation regimes for estimating PMP **(Rec 5-9)**

Long-term approach to PMP estimates under recommended definition

1. Produce large ensembles of kilometer-scale continuous simulations **(Rec 5-10)**
2. Use statistical extreme value analysis to estimate precipitation depths with extremely low exceedance probabilities in different climate periods **(Rec 5-11)**
3. Quantify uncertainty of PMP estimates at specified areas, durations, and future climate periods **(Rec 5-11)**

FIGURE S-1 Overview of modernized PMP estimation.

Enhanced Data for Near-Term PMP Estimation

Weather radar is a key observational resource for enhancing storm catalogs used for near-term PMP estimation. Digitizing and enhancing the historical storm catalogs are also important steps to making near-term enhancements to PMP.

> **Recommendation 5-5: USACE should make its existing storm catalog publicly available. NOAA should facilitate digitization and enhancement of the existing storm catalog of historical extreme storms used in PMP for the United States to contain gridded rainfall fields and moisture data for each event. NOAA should facilitate development of an expanded storm catalog including high-resolution radar rainfall fields and available surface rainfall measurements for the United States to improve near-term estimation of PMP.**

Storm Reconstructions for Near-Term PMP Estimation

Model reconstructions of extreme historical storms can improve the data and scientific understanding incorporated in near-term enhancements of PMP. Such reconstructions also provide critical guidance for simulating PMP-magnitude storms, which is needed to implement model-based estimation methods.

Recommendation 5-7: NOAA should facilitate model simulations of historical storm events that (1) may be added to the expanded storm catalog, (2) enhance scientific understanding of PMP-magnitude storms and their precipitation distributions, and (3) contribute to the MEP.

Scientific Guidance for Near-Term Enhancements to PMP Estimation

Subjective judgement plays an important role in implementation of current PMP procedures. Advances in scientific understanding could significantly improve PMP estimates during the near-term enhancement phase.

Recommendation 5-8: NOAA should include a summary of scientific principles in its national guidance for near-term PMP estimation. Near-term enhancements to storm transposition, moisture maximization, and transposition factors—especially for components involving subjective decisions—should be grounded in advances in scientific understanding, as detailed in this guidance.

Climate Change and Near-Term Enhancements to PMP Estimation

Physical understanding, historical trends, and model simulations and projections all signal an increase in extreme precipitation with warming. Near-term enhancements should address the effects of climate change on PMP.

Recommendation 5-9: For near-term enhancements to PMP estimation, NOAA should adopt climate change adjustment factors based on the model-based scaling relationship between extreme precipitation and temperature.

Model-Based PMP Estimation

Ensembles of long-term simulated rainfall fields over the United States from high-fidelity and high-resolution storm-resolving climate models can provide the foundation for long-term modernized PMP estimation, including statistical characterization of uncertainty and incorporation of climate change effects on rainfall extremes.

Recommendation 5-10: In the long term, NOAA should adopt a model-based approach to PMP estimation that aligns with the revised PMP definition, consisting of multi-model large ensemble kilometer-scale or finer-resolution modeling to construct the probability distribution of precipitation for PMP estimation under different climates.

Recommendation 5-11: For the long-term approach and in agreement with the recommended PMP definition, NOAA should use statistical approaches to estimate PMP (with associated uncertainty) as the precipitation depth corresponding to an extremely low AEP from the model-simulated precipitation distribution, with particular consideration of extreme value analysis based on threshold exceedance levels.

Model Evaluation Project

The MEP is a critical step in transitioning from near-term enhancements to PMP estimation to implementation of model-based PMP estimation methods. The advances in modeling capabilities necessary for PMP estimation will be developed and demonstrated, including approaches for incorporating the effects of climate change.

> **Recommendation 5-12: NOAA should embark on a Model Evaluation Project to assess model skill, identify strengths and limitations relevant to PMP estimation in current and future climate states, and achieve fitness for purpose, which is necessary for community confidence in models for estimating PMP.**

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 enable 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 principles (findable, accessible, interoperable, reusable). **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.

In addition to the above core principles, the committee advocates for sustained collaboration between NOAA and stakeholder groups throughout the process of modernizing PMP estimation. Collaborative efforts should focus on developing long-term relationships between NOAA and end-users, establishing two-way communication pathways between groups, and emphasizing the creation of usable science and products.

> **Recommendation 5-2: NOAA should deliberately engage the scientific and practitioner communities to enhance understanding of the scientific process, clarify methodological considerations, increase awareness of practitioner needs, and collaboratively shape resulting products in support of modernized PMP estimates.**

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

The recommended approach for modernizing PMP estimation 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 model-based PMP estimation, 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 between federal agencies, academia, and the private sector. Scientific and modeling advances along this front will contribute not only to modernizing PMP estimation, but 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 our infrastructure and society.

Accurate high-resolution simulations of storms and precipitation in the current and future climates will enable rigorous assessment of how space-time patterns of precipitation for extreme storms will change at different spatial and temporal scales, from sub-hourly and kilometer scales to the scales of large basins upstream of high-hazard dams. The information gained from these assessments is essential for modeling extreme floods, for planning and water management decisions, and for vulnerability assessment of communities and critical infrastructure to extremes. The kilometer-scale simulations will also provide critically needed information for assessing future changes in hazards that are often coupled with extreme rainfall, including coastal storm surge and compound flooding.

1

Need and Opportunity for a Modernized PMP Approach

High-hazard structures in the United States, including dams and nuclear power plants, have been engineered for more than 75 years to withstand floods resulting from the Probable Maximum Precipitation (PMP), a design standard based on the assumption that nature imposes limits on depths of precipitation that are physically possible across the United States (AMS, 2022; Hansen et al., 1982). PMP has remained a successful engineering standard for high-hazard infrastructure in the United States, because failures due to exceedance of flood design criteria are exceedingly rare. However, many of the more than 16,000 high-hazard dams and 50 nuclear power plants in the United States 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 hydrometeorological procedures required for estimating PMP, when developed, represented significant advances in understanding and characterizing extreme rainfall. However, although recent work has advanced many of the details, the fundamental assumptions and principles underpinning PMP estimation have changed little since the 1940s. National efforts to estimate PMP values ceased in 1999, and some regions have not seen updates in more than 60 years. Meanwhile, the risk of extreme precipitation is generally increasing. Therefore, a critical examination of the assumptions and procedures behind PMP estimation is appropriate and a new vision for the future of PMP estimation is timely.

COMMITTEE CHARGE AND STATEMENT OF TASK

At the request of the National Oceanic and Atmospheric Administration (NOAA), the National Academies of Sciences, Engineering, and Medicine has been tasked to critically assess the current procedures used to determine PMP and recommend an updated methodology. The National Academies convened a committee of 12 experts including hydrometeorologists, hydrologists, hydraulic engineers, PMP practitioners, atmospheric and climate scientists, and statisticians (Appendix A). The committee's full statement of task is given in Box 1-1.

Despite advances in many of the procedural steps over the decades, the principal components of PMP are grounded in ideas and assumptions formulated around a century ago. Therefore, in critically assessing the current PMP practice, the committee considered whether the procedures are consistent with current scientific understanding of extreme rainfall. For example, the assumption of the existence of a physical upper limit to the amount of rainfall possible at a given location underpins the current definition of PMP and the approach for estimating it. The critical need to modernize PMP estimation based on methods with a solid scientific foundation (Chapter 3) has been recognized for more than three decades (NRC, 1994).

BOX 1-1
Statement of Task

The National Academies of Sciences, Engineering, and Medicine will convene an ad hoc committee to consider approaches for estimating probable maximum precipitation (PMP) in a changing climate, with the goal of recommending an updated approach, appropriate for decision-maker needs.

More specifically, the study will:

- Establish a common understanding of PMP, considering the range of public- and private-sector users, current and future uses, and spatial and temporal scales for decision-making based on PMP estimates, from state to regional levels.
- Review and assess: 1) existing and emerging approaches for PMP estimation, including novel numerical weather prediction and high-performance computing techniques, and 2) approaches to incorporate the impacts of climate change on extreme precipitation into PMP estimation.
- Assess data needs and sources, for PMP estimation and evaluation, and best practices for transparency and accessibility of resulting PMP estimate data and information.
- Recommend a preferred approach for PMP estimation that incorporates the impacts of climate change and the characterization of uncertainty.

The Committee will make recommendations for the development of an updated approach that can serve as a national standard for estimating probable maximum precipitation in a changing climate.

Furthermore, the committee is tasked with recommending an approach for PMP estimation that “incorporates the characterization of uncertainty.” The committee interprets this task to mean statistical uncertainty of PMP estimates. Characterization of statistical uncertainty is needed for effective implementation of dam and nuclear safety programs through Risk-Informed Decision Making (RIDM) procedures. However, current approaches for PMP estimation are not suitable for characterization of statistical uncertainty, in part because of the sparse datasets employed (Chapter 4). Methods have been developed for assessing *sensitivity* of PMP estimates to assumptions used in PMP computation (Chapter 4) and for comparing PMP estimates to other data-driven analyses of rainfall extremes. These tools provide useful insights on PMP estimates for decision-makers, but they do not enable characterization of statistical uncertainty. Scientific advances that enable characterization of the statistical uncertainty of extreme precipitation estimates are detailed in Chapter 3.

Finally, over the coming decades, dam and nuclear safety programs will grapple with the challenges posed by impacts of climate change. Despite recognition that climate change will likely influence extreme precipitation (Chapter 3), current practice typically excludes consideration of climate change in PMP estimation (Chapter 4).

Since the publication of the 1994 National Academies report on PMP three decades ago (NRC, 1994), significant advances have been made in precipitation data acquisition, hydrometeorological science, numerical weather prediction, statistical methods, and climate modeling, as outlined in this report. Further advances in these areas are on the horizon. These advances will provide the foundation for implementing the major changes that are needed to modernize PMP estimation. This report, in addition to critically assessing the current practice, provides a roadmap of recommendations that NOAA, the scientific community, and the PMP practitioner community may follow to leverage these advances to modernize PMP estimation.

ROADMAP FOR REPORT

This report is organized by five principal chapters:

1. This first chapter provides the **motivation for this study** and a description of the committee's task.
2. The second chapter establishes a "**common understanding of PMP**" by providing a historical summary of the development of PMP and its constituent parts, an overview of the primary PMP uses and users, and a description of the spatial and temporal timescales of PMP estimation.
3. The **state of scientific knowledge** in fields relevant to PMP, including recent advances, are presented in Chapter 3. These fields include the meteorology of extreme rainfall, rainfall data, numerical modeling and computing, climate change, and statistical methods.
4. A **critical assessment** of current PMP estimation methods is presented in Chapter 4.
5. The committee's **recommended approach for modernizing PMP estimation** is detailed in Chapter 5. The committee recommends a phased approach in which near-term enhancements to current PMP estimation methods is followed by a longer-term model-based PMP estimation method. The transition is facilitated by a proposed Model Evaluation Project.

The report also contains the following appendices, which provide additional context for analyses and recommendations:

- History and evolution of PMP definitions
- Characteristics of dams in the United States
- Criteria for modern PMP estimation

The responses to the four main study tasks can be found in the following sections of this report:

Task 1: Common Understanding of PMP. This task is principally addressed in Chapter 2. Additional details on PMP definitions and methods are provided in the critical assessment in Chapter 4 and Appendix B.

Task 2: Review and assess methods for PMP estimation. Existing approaches are introduced in Chapter 2 and critically reviewed and assessed in Chapter 4. Emerging approaches are principally treated in Chapter 3, with additional detail provided in Chapter 5.

Task 3: Assess data needs and sources for PMP estimation and evaluation, and best practices for transparency and accessibility. Data needs are principally discussed in the Rainfall Data sections in Chapters 3 and 5. Transparency and accessibility are treated in the data section of Chapter 5.

Task 4: Recommend a preferred approach for PMP estimation that incorporates the impacts of climate change and the characterization of uncertainty. Chapter 5 is devoted exclusively to addressing this task.

2

Common Understanding of PMP

The Great Flood of March 1913 devastated cities along the Miami River of Ohio and resulted in more than 600 fatalities across Ohio, Indiana, and other states—a total eclipsed in the United States only by the Johnstown, Pennsylvania, Flood of 1889. The origins of PMP can be traced to the March 1913 flood through the scientific ideas that were subsequently formulated to characterize flood hazards and the engineering tools developed to protect the Miami River basin. PMP has provided a rational foundation for design of high-hazard structures and assessing the safety of these structures, but the core methods (Figure 2-1) remain grounded in scientific ideas from the early 20th century.

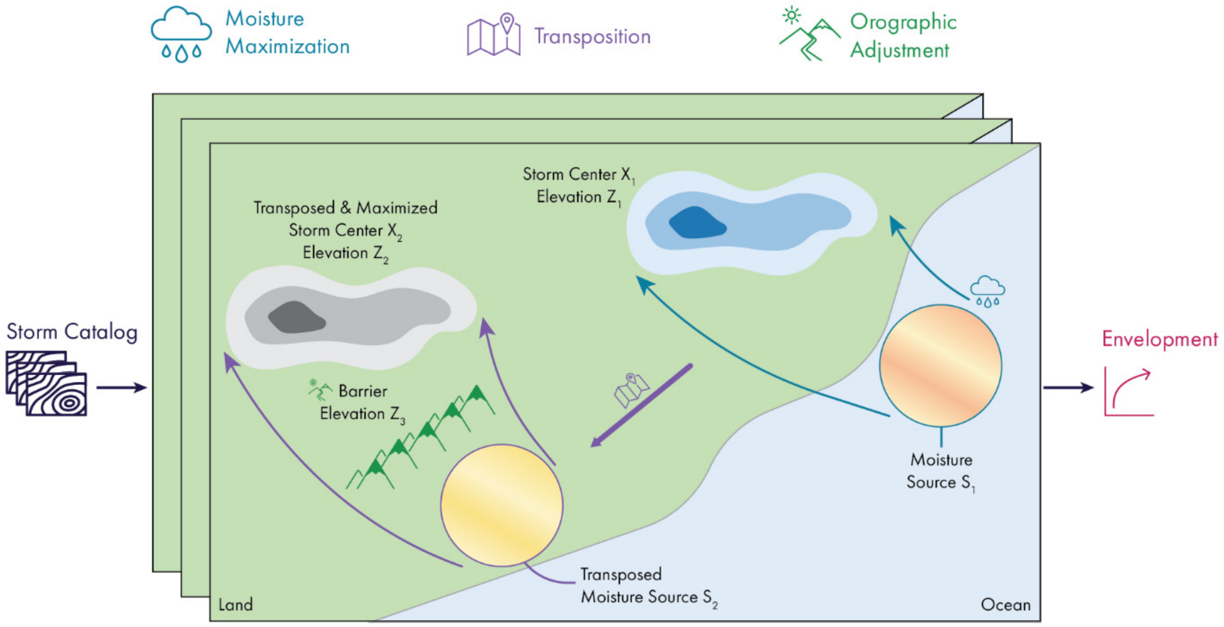


FIGURE 2-1 Fundamental components of PMP, including storm catalog, transposition, maximization, and orographic adjustment.
NOTE: Other components including barrier elevation and envelopment are discussed in Chapter 4.

DEFINITION

Probable Maximum Precipitation is currently defined in the United States as:

> Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year (AMS, 2022; Hansen et al., 1982).

Many countries around the world have adopted PMP as a design standard for high-hazard structures; the World Meteorological Organization (WMO) definition of PMP is:

> The greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends (WMO, 2009).

The notion that rainfall and floods are bounded and that engineering design for high-hazard structures should revolve around assessments of the largest possible flood evolved rapidly through the development of flood control plans for the Miami River (Miami Conservancy, 1916; Morgan, 1917). The preeminent hydrologist of the era, Robert Horton, argued for the existence of upper bounds of rainfall, based on both statistical arguments and physical reasoning (Horton, 1919, 1948a). The notion that a physical upper bound exists has remained implicit in the concept of PMP through its definitions and estimation methodologies since its earliest conception (see additional discussion in Chapters 4, 5, and Appendix B).

Also explicit in the WMO definition, and implicit in others (Appendix B), is the notion of stationarity—that PMP values are only associated with the current climate state. The WMO definition acknowledges the challenge of climate change, but current practice typically neglects consideration of climate change.

FUNDAMENTAL COMPONENTS OF PMP

Major Components: Storm Catalog and Storm Transposition

Tasked with estimating the largest rainfall accumulations possible over the Miami River basin, the Miami Conservancy developed a **storm catalog**, consisting of extreme rainfall accumulations from around the United States, and a method called **storm transposition**, which specifies procedures for taking storms that occurred in other locations and placing them over the Miami River watershed. These two ingredients remain the cornerstone of PMP estimation in 2024.

Spurred by the rapid acceleration of dam building in the United States during the 1930s, interest in meteorological assessments of "maximum possible precipitation" (Showalter and Solot, 1942) led the U.S. Army Corps of Engineers (USACE) to adopt the Miami Conservancy storm catalog and implement a program for updating it (USACE, 1973; see also England et al., 2020). USACE advanced meteorological studies through a joint research program with the U.S. Weather Bureau (USWB) (Hathaway, 1944). Collaboration between the two agencies was facilitated through the creation in 1937 of the Hydrometeorology Section of the USWB, which was "invested with the responsibility of determining limiting rates of precipitation" (Showalter and Solot, 1942). This group, with changing names over time, played a central role in the development and implementation of PMP procedures during the federal dam building era from the 1930s to the 1980s (e.g., Hansen, 1987). In 1970 the USWB was renamed the National Weather Service (NWS) and became a component of the National Oceanic and Atmospheric Administration (NOAA).

Rainfall analyses for PMP storm catalogs are often based on observations from non-standard rain gauges obtained from **bucket surveys** conducted following major storms. These observations include the United States and world record rainfall accumulations of 305 mm in 42 minutes on 22 June 1947 at Holt, Missouri (Lott, 1954; WMO, 2009), 560 mm in 2.75 hours on 31 May 1935 at D'Hanis, Texas (Dalrymple, 1939; WMO, 2009) and 780 mm in 4.5 hours on 18–19 July 1942 near Smethport, Pennsylvania (Eisenlohr, 1952; WMO, 2009). In a bucket survey, a container left outside can be a potential rain gauge; rainfall accumulation is computed as the ratio of the volume of water in the container to the cross-sectional area of the opening. A cattle trough was the instrument used for the D'Hanis measurement, and a mason jar was the instrument used for the Smethport measurement. The methods used to conduct bucket surveys of extreme storms have played a critical role in PMP estimation for more than 70 years and will continue to play an important role in the procedures used for near-term enhancements to PMP estimation (Chapter 5).

More than 400 rainfall measurements were obtained via bucket survey for the Smethport storm (no standard rain gauges existed in the area affected by the storm), providing the observations used to perform detailed spatial analyses of rainfall for the storm. Such analyses are critical for constructing Depth-Area-Duration (DAD) tables (USACE, 1973), which are the key rainfall products used for computing PMP (see additional discussion below). Bucket surveys provide the capability for "going to the storm" to obtain rainfall measurements for PMP estimation.

Storm catalog datasets used for computing PMP differ markedly from datasets used for **precipitation frequency analysis** (e.g., Perica et al., 2018; see Box 2-1). A key difference is the sampling of rainfall extremes. Bucket surveys provide rainfall observations by "going to the storm"; precipitation frequency studies rely on storms going to the gauges. The sparse distribution of rain gauges with long records needed for precipitation frequency studies introduces obstacles for assessment of rainfall extremes (see Foufoula-Georgiou, 1989b, for discussion of the sampling problem for extreme rainfall). For sub-daily time scales, the network of long-term rain gauge records is exceedingly sparse in many regions and not suitable for monitoring rainfall from extreme convective storms that control PMP estimation (see, e.g., Giordano and Fritsch, 1991).

PMP estimates require rainfall observations that are both temporally and spatially resolved. NOAA precipitation frequency studies use rain gauge observations to develop point assessments of rainfall extremes. Bucket surveys are well suited to provide spatial analyses of rainfall extremes, as detailed above, and radar rainfall estimates have been integrated into recent PMP studies, providing a key resource for developing spatially and temporally resolved rainfall analyses. The density of climatological rain gauge networks, especially for sub-daily time scales, limits the ability to spatially resolve rainfall extremes, except for the small number of dense rain gauge networks, typically located in urban settings.

The focus of PMP on the most extreme events over a wide range of time (1 to 72 hours) and space (1 to 20,000 mi^2) scales has dictated that PMP estimation rely on rainfall analyses derived from non-standard observations, like those obtained in bucket surveys. Unlike rain gauge datasets used for precipitation frequency analysis, storm catalog data do not, however, provide systematic observations over time. The nature and completeness of storm data vary significantly over the period represented in the catalog (England et al., 2020).

BOX 2-1
Precipitation Frequency Analysis

Definition: Whereas PMP provides estimates of the "maximum precipitation, for a given areal extent, for a given duration storm," precipitation frequency analyses provide precipitation accumulations that have a specified annual exceedance probability (AEP); they are provided for point locations, for a given duration, for a given AEP (NWS, 2020).

Products: The National Oceanic and Atmospheric Administration (NOAA) has published precipitation frequency estimates for most of the United States in NOAA Atlas 14 (https://hdsc.nws.noaa.gov/pfds/) for storm durations between 5 minutes and 60 days and for recurrence intervals up to 1,000 years (AEP of 10^{-3}) and is currently working on an updated Atlas 15. NOAA Atlas 14 precipitation frequency estimates also include 90% confidence intervals. Some federal agencies and states have made precipitation frequency estimates with very low AEPs (10^{-7}) (with uncertainty) for dam safety and risk-informed designs. (Holman et al., 2019; H. Smith et al., 2018; State of Colorado, 2018).

Use: Whereas PMP has been used as a design criterion for high-hazard structures such as dams and nuclear power plants, precipitation frequency is used in the design of a wide variety of engineering projects to an acceptable level of risk. Thes projects include transportation infrastructure, agricultural and urban drainage systems, flood detention ponds, levees, low- and significant-hazard dams, and some high-hazard dams (with very low AEPs) (FEMA, 2013; USBR, 2013).

Data: Precipitation frequency estimates are developed using a statistical analysis of historical precipitation observations from rain gauge observations with long, high-quality observations (see Chapter 3 for additional details). The network of daily rain gauge stations is sparse in some regions; sub-daily rain gauge stations are exceedingly sparse in many regions.

Moisture Maximization

Recognizing that observed storms could potentially be larger given optimal atmospheric conditions, USWB grounded its approach to determining physical limits to precipitation in the **atmospheric water balance** (Bernard, 1944; Showalter and Solot, 1942). The atmospheric water balance relates precipitation to three terms: evaporation from the surface to the atmosphere, time changes in precipitable water (the column-integrated amount of water vapor in the atmosphere), and convergence of water vapor. For extreme rainfall, the atmospheric water balance simplifies to the following: precipitation equals convergence of water vapor. The enduring difficulty with determining bounds on rainfall has centered on convergence of the wind field, which has been "notoriously elusive" (Myers, 1967).

The solution adopted by USWB meteorologists for PMP was "to use storm precipitation itself as the effective measure of convergence" of the wind field (Myers, 1967). The approach adopts the cornerstone of Miami Conservancy analyses—the transposition of storms from a storm catalog. To determine limiting rates of precipitation, an additional step, **moisture maximization**, was added. This step scales observed rainfall for a storm catalog event by the ratio of the maximum precipitable water for the location to the observed precipitable water from the storm. These PMP methods are detailed in two seminal papers by USWB scientists, Showalter and Solot (1942) and Bernard (1944). Bernard's "Primary Role of Meteorology in Flood Flow Estimation" appeared in *Transactions of the American Society of Civil Engineers* and is paired with discussions from the leading agency and consulting engineers involved in developing design standards for high-hazard dams. These papers, along with endorsements of methods by the practitioner community in the discussions to Bernard (1944), are milestones in the evolution of PMP.

Orographic Adjustment

From the earliest work of the Miami Conservancy, it was recognized that **orographic precipitation** mechanisms in mountainous terrain introduce serious difficulties for estimating PMP (Morgan, 1917; see additional discussion in Chapters 3 and 4 and in Appendix B). Later, NWS developed a method of separating storm rainfall in mountainous regions into orographic and non-orographic components (Hansen, 1987). The latter component is obtained by using conventional PMP moisture maximization and storm transposition approaches. The orographic component is an empirical adjustment factor based on precipitation frequency products (Box 2-1). The ratio of 100-year, 24-hour rainfall at the transposition location to the 100-year, 24-hour value at the observed storm location is termed an “orographic intensification factor” in Hansen (1987). Similar corrections, termed **orographic transposition factors** and **geographic transposition factors**, are important components of regional PMP studies conducted over the past decade (see, e.g., AWA, 2018).

These tools, which nudge PMP estimates toward the spatial pattern of precipitation frequency estimates, place precipitation frequency analysis in the realm of current methods used for PMP estimation. The orographic separation approach introduced by NWS has become the main path for addressing orographic effects in PMP estimation, but “the concept has not been critically reviewed” (England et al., 2020).

PMP ESTIMATES IN THE UNITED STATES

Hydrometeorological Reports

USWB, in collaboration with USACE and the U.S. Bureau of Reclamation (USBR), produced a series of Hydrometeorological Reports (HMRs) and Technical Papers (TPs) providing PMP estimates across the United States and its territories (ACWI, 2018; England et al., 2020). The first HMRs (HMR 1 through HMR 22) provided site-specific and regional PMP estimates for specific USACE dam designs. The first generalized PMP study (HMR 23) was published in 1947 and provided estimates for the United States east of the 105th meridian and for areas of 10, 200, and 500 mi^2 (USWB, 1947b). Other generalized HMRs provided PMP estimates for regions across the United States (see Figure 4-1 in ACWI, 2018). PMP methodologies changed over time as outlined above but have remained relatively static since Hansen’s 1987 paper. “Probable Maximum Precipitation for California” (HMR 59) is the last of the NOAA generalized PMP studies and was completed in 1999 (Corrigan et al., 1999). In many areas across the United States, the HMRs have remained the authoritative source of PMP estimates.

Post-HMR Era

In the 1990s, as the federal agencies reduced and then ceased funding the updates to generalized PMP estimates (ACWI, 2018; England et al., 2020), USBR and USACE transitioned to site-specific PMP and precipitation frequency studies to address risk-informed decisions at specific sites. These studies contributed to advances in use of numerical modeling for PMP and precipitation frequency (Chapter 4) but were not geographically comprehensive enough to meet the needs of other federal agencies or states. States started to invest in both PMP and extreme precipitation frequency updates to address changing information needs for dam safety. Over the past three decades, engineering and meteorological consultants have produced these updates, focusing on state-level and site-specific studies (see, for example, AWA, 2015).

These statewide studies have advanced the practice of PMP estimation in several ways, including the incorporation of radar rainfall estimates into storm catalogs (see Chapter 4), use of geospatial and modeling techniques to offer PMP products that incorporate gridded delivery formats, and direct applications to watersheds. PMP estimates for several statewide studies in the eastern United States are 20 to 60 percent less than values from the most recent federal estimates in HMR 51. This reduction is due in large part to restrictions on transposition regions for several crucial storms, especially the July 1942 Smethport, Pennsylvania, storm. It also demonstrates that updated PMP studies do not necessarily result in increases in PMP estimates (see Appendix B for additional examples and discussion).

PMP estimates have been updated or revised in 16 states and Puerto Rico (Figure 2-2). States that fund these studies consider them to be replacements of HMR PMP estimates for their dam safety programs. The levels of acceptance of state PMP estimates vary among federal agencies. The Federal Energy Regulatory Commission (FERC) has generally accepted them; USACE currently relies on HMR or site-specific PMP estimates. New precipitation frequency estimates for dam safety have been developed in Washington, Montana, and California for their state dam safety programs. PMP and new precipitation frequency estimates have been made in Colorado and New Mexico, and for the Tennessee Valley Authority. Additionally, statewide PMP studies are currently (as of 2023) in progress for Hawaii, New Jersey, and Maryland. Oregon is currently updating PMP and precipitation frequency estimates (AEP 1/100,000 or less frequent) for dam safety. The precipitation frequency studies listed above generally provide 24-hour precipitation depths for AEPs from 2×10^{-4} (MT) to 1×10^{-6} (CO and NM), all beyond NOAA Atlas 14 products (0.001 AEP). These studies rely on regionalization procedures that are based on strong statistical assumptions concerning spatial homogeneity of rainfall extremes. They also fail to account for nonstationarities in rainfall observations due to climate change. As noted above, the sparse density and short record lengths of sub-daily rain gauge networks create serious challenges for estimating rainfall extremes.

USES AND USERS OF PMP

The use of PMP expanded rapidly in the 1940s based on a consensus among federal, state, and local agencies and various professional meteorological and engineering societies about the need for an engineering standard with which to design dams to avoid potential failure due to extreme precipitation events and their associated flood flows. Although the period of major dam building has passed, the need for accurate, uniform, and transparent PMP estimates continues. Today, the primary users of PMP are the federal, state, and local government agencies and private-sector owners of dams and nuclear facilities, as well as their consultants and contractors who are engaged in the review, evaluation, rehabilitation, and regulation of these facilities and who must demonstrate compliance with safety regulations.

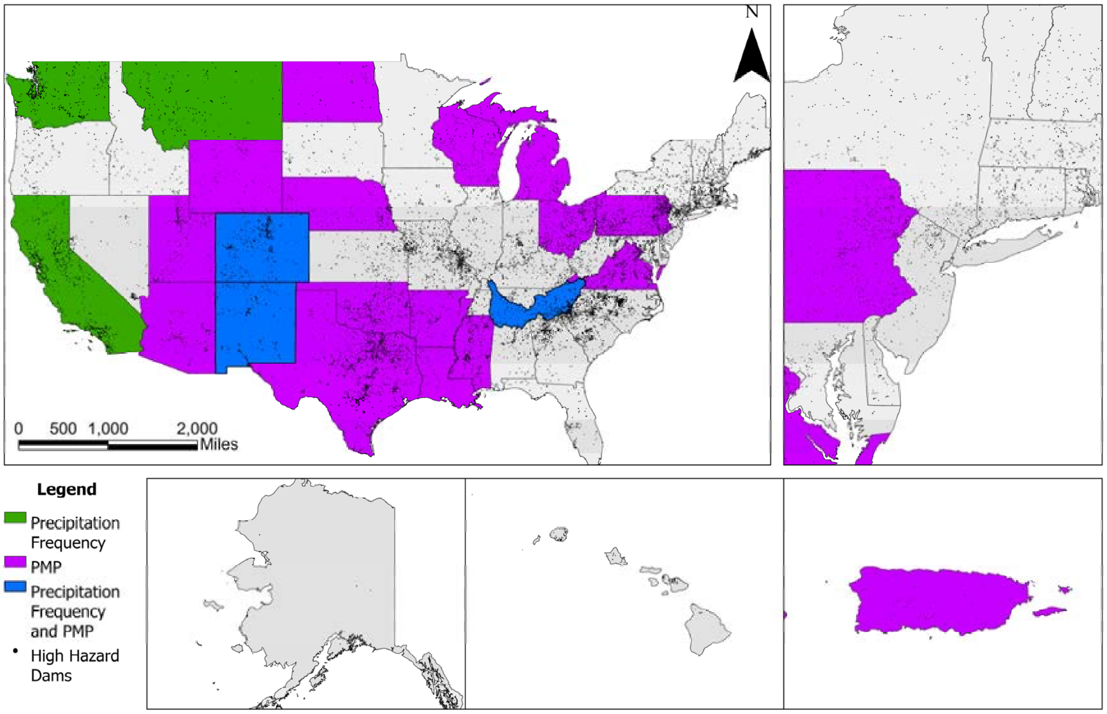


FIGURE 2-2 Statewide PMP and precipitation frequency studies for dam safety.

Importance of PMP for Dam Safety

Since the 1940s, many federal and state dam safety programs have utilized PMP in dam design and construction (Billington et al., 2005) and to assess the safety of existing high- and significant-hazard dams (FEMA, 2012, 2013). Modern PMP estimates are important in understanding and assessing the potential for failure of existing critical infrastructure and in developing new infrastructure. PMP estimates are critical inputs for estimating the design floods for spillways. A design flood is defined as “the maximum flood hydrograph or a range of flood hydrographs for a given AEP, used in the design of a dam and its appurtenant structures, particularly for sizing the dam, spillway, and outlet works” (USBR, 2013). Design floods are used in the rehabilitation, modernization, and new construction of dams (examples of these applications to dam rehabilitation and new construction are provided in Box 2-2), which provide enhanced water supply, flood protection, hydropower, recreation, and other benefits at tens of thousands of locations across the United States.

Extreme Storm Rainfall, Dam Failures, and Fatalities

Despite excellent safety records for the vast majority of dam owners and regulators, some notable extreme storm rainfall events have led to overtopping, dam failure, and fatalities. The Association of State Dam Safety Officials (ASDSO) provides numerous case histories across the United States on floods and dam failures from extreme rainfall (ASDSO, 2023). These events are then used to estimate PMP and revise PMP estimates. A few examples that illustrate the ongoing importance of collecting and synthesizing extreme rainfall data and revising PMP (and precipitation frequency) estimates include:

- The record 6–8 June 1964 rainfall in northern Montana resulted in two dam failures that caused 19 fatalities; this event defines PMP for much of the Rocky Mountain region in HMR 55A (Hansen et al., 1988).
- The 9 June 1972 record rainfall in Rapid City, South Dakota, led to the failure of Canyon Lake Dam and 238 fatalities.
- The 20 July 1977 rainfall in Johnstown, Pennsylvania, of about 11.8 inches in 8 hours resulted in the overtopping failure of Laurel Run Dam with 40 fatalities.
- The 23–24 September 1983 Prescott, Arizona, storm caused extensive property damage and breaching of small dams. The maximum 6-hour rainfall accumulations at 100 km^2 spatial scale was 1.14 times larger than the General Storm PMP (Leverson, 1986).
- The 14 March 2006 heavy rainfall in Kauai, Hawaii, led to the Ka Loko dam failure and caused 7 fatalities.
- Record July 2010 rainfall and flooding in Iowa led to the failure of Lake Delhi Dam.

BOX 2-2
Dam Rehabilitation, Expansion, and Construction

Despite the end of the federal dam building era in the 1980s, dam rehabilitation and expansion projects and new dam construction have continued. Four examples for high-hazard dams are described here and shown in Figure 2-3. The Gross Reservoir and Chimney Hollow projects utilized updated design precipitation estimates that included an atmospheric moisture factor (1.07) to account for expected increases in temperature and atmospheric moisture over the 50-year period 2020−2070 (State of Colorado, 2020).

North Fork Dam, North Carolina

The City of Asheville, North Carolina, sought to improve its North Fork Reservoir, which provides 70 percent of the city's water supply. The dam's design was based on industry standards and best practices that have greatly improved since construction in 1955, especially for extreme flood and seismic hazards. A new spillway was constructed to safely pass floods from extreme rainfalls. This project was recognized as the ASDSO National Rehabilitation Project of 2021.

Prado Dam, California

Prado Dam is a 124-foot-high flood control dam that was constructed in 1941 and is located on the Santa Ana River in Southern California. Prado Dam provides major flood protection for Anaheim, Orange, Santa Ana, and nearby cities. The U.S. Army Corps of Engineers has recognized the need for safety improvements to address potential spillway erosion, overtopping, and weir deficiencies. Modifications are currently in final design to address these deficiencies.

Gross Reservoir, Colorado

Denver Water is currently expanding Gross Reservoir in Boulder County, Colorado, to provide additional water storage for the Denver Water system and the nearby cities of Boulder and Lafayette. The project (currently under construction) will raise the height of the existing dam by 131 feet, which will more than triple Gross Reservoir's capacity from approximately 42,000 acre-feet to 119,000 acre-feet.

continued

BOX 2-2 *continued*

Chimney Hollow Dam, Colorado

Chimney Hollow Dam is currently under construction and will be one of the first asphalt core rockfill dams in the United States. It will be 350 feet tall and 3,700 feet long, spanning the Chimney Hollow valley west of Loveland, Colorado. When built, the reservoir will store 90,000 acre-feet of water for nine municipalities, two water districts, and a power provider.

FIGURE 2-3 Example dam projects that use PMP for rehabilitations, expansions, and new designs (clockwise from upper left): North Fork Dam, Prado Dam, Gross Dam, Chimney Hollow Dam. SOURCE: City of Asheville; USACE (2021); Mitch Tobin/WaterDesk.org, with aerial support provided by Lighthawk; Northern Water.

Events in 2015 and 2016 in the Carolinas illustrate the need to modernize the storm catalog, PMP estimates, and precipitation frequency estimates. The historic 1–5 October 2015 rainfall and flooding across South Carolina resulted in 50 dam failures in that state (FEMA, 2016). During this event, point rainfall depths at many locations exceeded 20 inches in 3 days (Figure 2-4) and exceeded the NOAA Atlas 14 10^{-3} AEP depth for the 2-day through 7-day durations (FEMA, 2016). The 50 dam failures, including Old Mill Pond (Figure 2-5), were located across the state, with most on small watersheds less than 30 mi^2. One year later, Hurricane Matthew resulted in the failure of 12 state-regulated dams in North Carolina and 20 in South Carolina (FEMA, 2017). Rainfall totals again were extreme, exceeding the 10^{-3} 24-hour AEP depth on 9 October 2016.

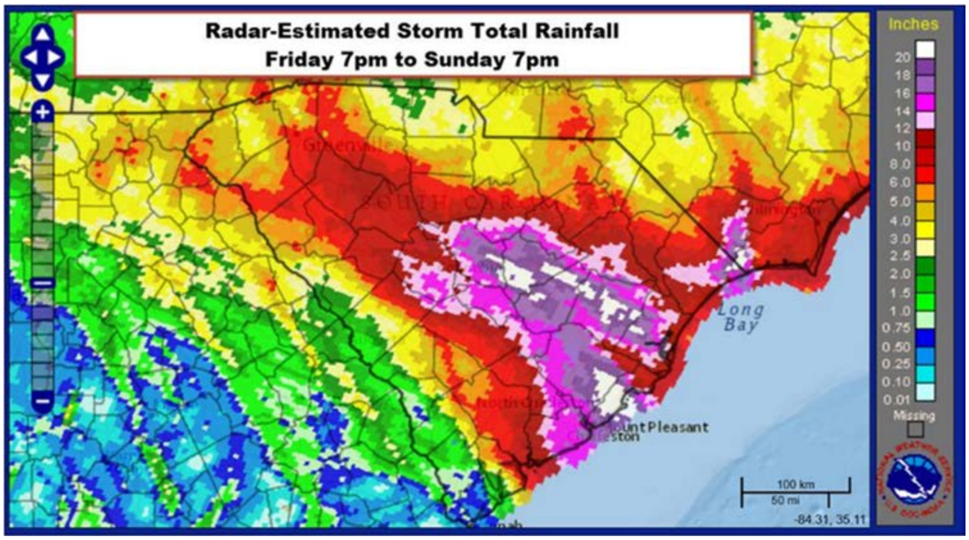


FIGURE 2-4 South Carolina rainfall totals for 2–4 October 2015.
SOURCE: https://www.weather.gov/cae/HistoricFloodingOct2015.html.

FIGURE 2-5 Old Mill Pond Dam failure in Lexington, South Carolina, October 2015.
SOURCE: https://www.weather.gov/cae/HistoricFloodingOct2015.html.

Many of the events described above are not included in current extreme rainfall guidelines. For example, NOAA Atlas 14 input data ended in 2000 and PMP in the Carolinas is set by HMR 51, published in 1978. PMP estimates in the Carolinas could change significantly with the consideration of Hurricanes Floyd (1999), Fran (1996), Matthew (2016), and Florence (2018) (Caldwell et al., 2011; M. Liu et al., 2022).

Regulators and Dam Safety Criteria

A dam safety regulator is a governmental or regulatory authority responsible for overseeing and enforcing dam safety regulations and guidelines within a specific region or state. Their primary role is to ensure that dams are designed, constructed, operated, and maintained in a manner that minimizes the risk of failure and protects public safety, property, and the environment. This protection includes the ability of dams to successfully pass extreme floods without failure or misoperation (FEMA, 2013). The criteria used for flood control design are based principally on dam size and hazard classification. Size classification is derived from dam height and/or reservoir storage volume. Hazard classifications are high, significant, and low, where high hazard indicates the probable loss of human life caused by dam failure or misoperation, and significant hazard indicates nonfatal impacts including economic loss, environmental damage, or disruption of lifeline facilities (FEMA, 2004). The methods used to assess dam safety may include prescriptive inflow design floods based on PMP or its derivative Probable Maximum Flood (PMF), site-specific PMP studies, incremental consequence analysis, and risk-informed flood hazard analysis (FEMA, 2013, 2015).

PMP usage and application vary among state regulators, as reviewed in FEMA (2012). In assessing high-hazard dams, many states use full PMP estimates, some states use PMP fractions, and others (WA, CO, CA) use precipitation frequency estimates. FEMA has discouraged the use of PMP fractions (FEMA, 2013). To assess significant-hazard dams, states use either PMP fractions or precipitation frequency estimates. In some cases, different safety criteria (usually more stringent) are used for new dams as compared to existing dams. Federal agencies have broadly moved to risk-informed flood-hazard analysis (see below); PMP/PMF estimates are used when potential dam modifications are considered to reduce risk.

> *Conclusion 2-1: Both PMP and extreme precipitation frequency estimates are important for dam safety, and national updates are needed.*

NOAA Atlas 15 will provide national updates to precipitation frequency estimates, including the effects of climate change. These updated estimates will not provide rainfall frequency products at AEPs needed for risk-informed decision making (RIDM; see Boxes 2-1 and 2-3) and do not address high-hazard infrastructure. The model-based PMP estimates that form a central component of modernized PMP (Chapter 5) can provide the information needed for risk-informed dam safety programs over the entire United States (as detailed below).

Overview of High-hazard Dam Characteristics

Out of the 91,750 dams in the National Inventory of Dams (NID), 16,564 (about 18%) dams are classified as high hazard. The number of high-hazard dams has increased by about 18 percent from 13,990 in NRC (2012) and about 52 percent from 10,856 in FEMA (2012). This increase may be due to updated data, reclassification, and possibly a sign of "hazard creep" (Schoolmeesters, 2023) resulting from urbanization (NASEM, 2019). Hazard reclassification is frequently necessary when new development occurs downstream of a previously classified low- and/or significant-hazard dam, creating the potential for loss of life.

The locations of high-hazard dams in the United States are shown in Figure 2-6. High-hazard dams are concentrated in the eastern United States. Texas, Missouri, and North Carolina have more than 1,000 each. California, Pennsylvania, South Carolina, and Georgia have more than 500 each. Drainage areas for high-hazard dams extend from 0.1 mi^2 to about 20,000 mi^2 (discussed below in subsection on Spatial and Temporal Scales for PMP Estimates). Nearly 82 percent of high-hazard dams are classified as earthen embankment dams, a dam type particularly susceptible to overtopping failure (USACE, 2019b). A program to provide consistent and reliable PMP estimates across the United States would be useful for understanding and potentially mitigating hazards at many of these locations.

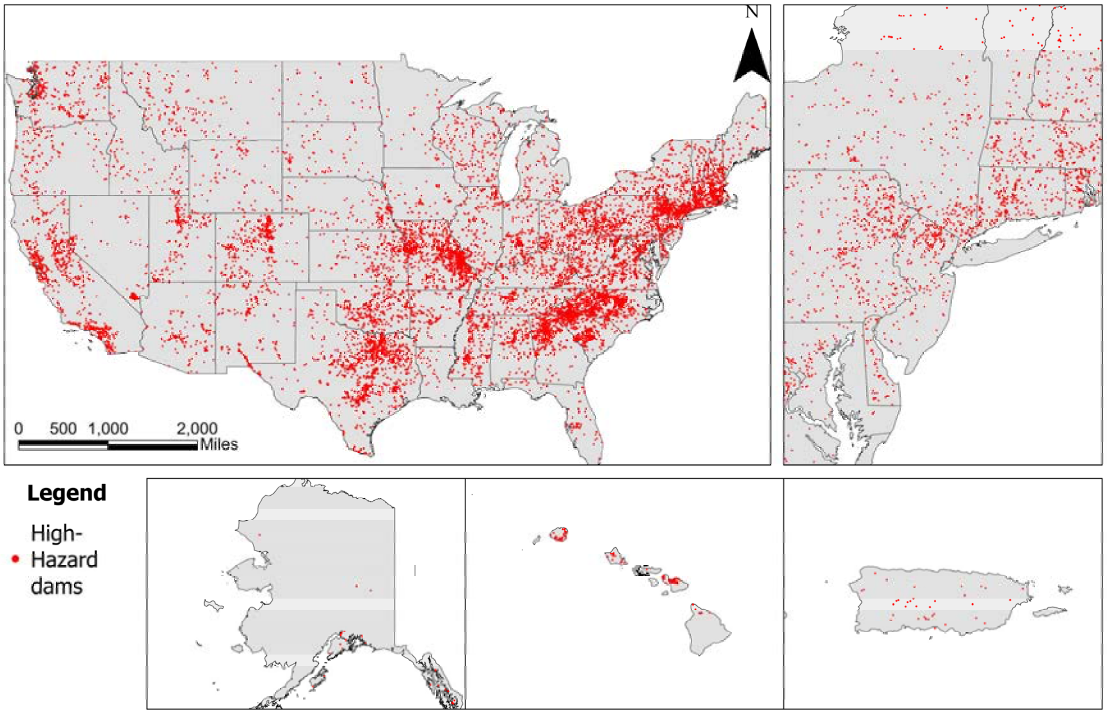


FIGURE 2-6 Locations of high-hazard dams.
SOURCE: McGraw (2023), using data from National Inventory of Dams (https://nid.sec.usace.army.mil), accessed 6 July 2023.

The vast majority of high-hazard dams are owned by either private entities (44 percent) or local governments (32 percent). Local government owners include cities, towns, counties, and/or their associated public work departments. The federal government, state governments, tribal governments, and public utilities comprise the remainder. Consequently, more than three quarters of dams are regulated by states. Self-regulating federal dam owners include USACE (and Department of Defense agencies), Tennessee Valley Authority (TVA), USBR (and Department of Interior Bureaus), International Boundary and Water Commission, and several other federal agencies. Privately owned hydropower and mine tailings dams are regulated by FERC and the Mine Safety and Health Administration, respectively. Additional details on dams and NID are provided in Appendix C.

Importance of PMP for Nuclear Power Plant Safety

There are currently 53 operating nuclear reactors and two planned reactors in the United States, based on data from the U.S. Energy Information Administration. Reactor locations are shown in Figure 2-7. Nuclear facilities must be resilient to both pluvial flooding driven by localized PMP-magnitude precipitation events and to fluvial inundation arising from flooding from nearby rivers or coasts. Thus, PMP estimates for U.S. nuclear reactors are needed for drainage areas ranging from 1 mi^2 (for localized flooding) to about 1,112,293 mi^2 for riverine flooding on the lower Mississippi River.

The drainage areas at reactor sites are generally much larger than for high-hazard dams because most are located along major rivers or lakes. For reactor sites, the median drainage area is 3,325 mi^2 and the mean drainage area is 88,591 mi^2. Given this diversity in drainage areas and locations concentrated along major lakes, coastlines, and other large water bodies (Figure 2-7), site-specific PMP estimates are warranted.

FIGURE 2-7 Locations of currently operable and proposed nuclear reactors.
SOURCE: Data from U.S. Energy Information Administration EIA-860.

As in the case of dam safety, requirements for hydrologic screening and analysis of nuclear facilities are undergoing an evolution from use of prescriptive performance criteria based on PMP and PMF estimates to performance criteria based on RIDM processes. This evolution has been broadly supported. The American Nuclear Society (ANS, 2019) in its revision to ANSI/ANS 2.8 rescinded the use of PMP and PMF as a design flood standard and replaced it with a probabilistic flood hazard evaluation. Relevant excerpts from the ANSI document are as follows.

> "This standard differs from its predecessor in the following areas:
>
> - The applicability of the standard extends to all nuclear facilities, not just power reactors.
> - Probabilistic assessment: This standard replaces the prescriptive "probable maximum" approach for establishing design flood hazards with a probabilistic approach for analyzing the frequency and magnitude of flood hazards. Thus, this standard focuses on the performance of a probabilistic flood hazard assessment and development of site probabilistic hazard frequency curves. An integral part of this process is the treatment of uncertainty."

The Nuclear Regulatory Commission utilizes PMP in performing safety assessments of licensed and operating nuclear reactors, and in evaluating and reviewing new reactor applications (Kanney, 2023). Extensive reviews of potential flooding at reactors were undertaken using existing PMP estimates after the 2011 Fukushima tsunami nuclear disaster. This disaster spurred reanalysis of all potential failure modes and vulnerabilities, especially those related to flooding. In general, insights from probabilistic risk assessment (PRA) are considered with other engineering information. PMP augments RIDM (see below) and enhances conservatism.

The Evolution of PMP Use and Risk-Informed Decision Making

In both the dam safety and nuclear facilities arenas, the use of PMP has evolved, somewhat independently, at the federal and state levels. For dams, federal agencies have increasingly adopted RIDM concepts as the basis for safety reviews and assessments; some state dam safety agencies are also pursuing risk-based approaches. Box 2-3 provides an overview of RIDM. For nuclear facilities, the Nuclear Regulatory Commission and industry are using RIDM techniques. Instead of basing an investment decision or corrective action on whether a facility meets a design standard such as PMP, RIDM requires the use of a broad range of probabilistic estimates of initiating events (floods), structural response(s), and associated consequences (e.g., damages, service interruptions, deaths) to develop a comprehensive risk estimate for each facility and for all facilities in a portfolio. Thus, where PMP was once used as the primary, sometimes sole, design and safety standard among the federal agencies, it is increasingly one (very important) metric that supplements the use of risk estimates.

The current PMP estimation process cannot provide AEP estimates or quantitative assessments of uncertainty. The resulting dichotomy between the direct use of PMP estimates to assess dam performance at project overflow and risk analyses requiring AEP estimates is currently bridged only by using the PMP and PMF estimates as informal guides with which to assess the reasonableness of the AEP-based flood hazard curves. The proposed model-based approach to PMP estimation (Chapter 5) provides a path for risk-based methods to be applied to dam safety across the United States.

Conclusion 2-2: Many practitioners are using or moving toward RIDM processes. Current PMP estimates, and arbitrary fractions of them, do not include AEP estimates or uncertainty characterizations, making them less useful for RIDM.

BOX 2-3
Risk-Informed Decision Making

Over the past two decades, major federal dam safety agencies (USBR, USACE, FERC, TVA) and some states (WA, MT, CA, CO) have moved to utilize risk-informed decision making (RIDM) for their dam safety programs (FEMA, 2015; FERC, 2016; USACE, 2014; USBR, 2022) rather than rely on deterministic standards such as PMP and Probably Maximum Flood (PMF). Safety assessments and designs for nuclear facilities also focus on risk (ANS, 2019). RIDM is required in engineering regulations (USACE, 2014) and in design standards (USBR, 2013), and is one of the guiding principles for critical infrastructure (ASCE, 2009).

Entities that own or regulate dams make various decisions regarding an individual structure or a portfolio of structures, including about the safety of a structure, necessary actions to reduce risks, and prioritization of actions for a portfolio of structures. In terms of safety, RIDM considers risk estimates and many other factors such as confidence in the risk estimates, risk uncertainty, deterministic analyses, the overall dam safety case, and local or regional considerations. Risk is defined as the product of the likelihood of a structure being loaded, adverse structural performance (e.g., dam failure), and the magnitude of the resulting consequences (FEMA, 2015). The critical risk input is a flood hazard curve (Swain et al., 2006; USBR, 2013; H. Smith et al., 2018; USACE, 2019a); an example is shown in Figure 2-8.

In RIDM, PMP and PMF estimates are used for comparison with flood hazard estimates, as potential upper limits to magnitudes from flood hazard curves, and in alternative designs to reduce risks at specific facilities where needed. In these cases, it is assumed that PMP and PMF are adequate estimates of an upper bound to rainfall and floods.

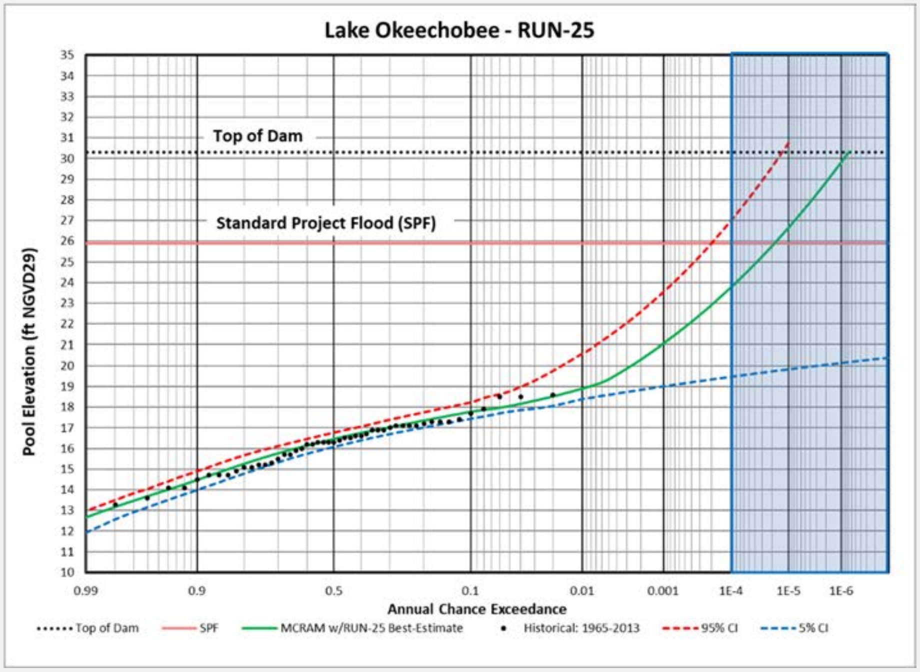


FIGURE 2-8 Example flood hazard curve (maximum reservoir stages) for Lake Okeechobee, Florida. NOTES: The curve is estimated from observed data (black dots) and a rainfall-runoff model with stochastic weather generation of extreme rainfalls. Green solid line shows the best estimate stage-frequency curve; confidence limits are shown as red (95%) and blue (5%) dashed lines.
SOURCE: H. Smith et al. (2015).

SPATIAL AND TEMPORAL SCALES FOR PMP ESTIMATES

The most important and relevant applications that use PMP are for high-hazard dams and nuclear reactors. The relevant spatial areas for these applications are drainage areas (watersheds), detailed below and in Appendix C, which typically range from 1 mi^2 to larger than 10,000 mi^2, and very small areas (about 1 mi^2) directly over reactor sites.

Drainage Areas

PMP estimates are applied as area estimates over specific drainage areas (e.g., Hansen et al., 1982) to estimate PMF. Thus, drainage area summary statistics are useful for inferring the relevant spatial and temporal scales of PMP needed for watershed applications. Figure 2-9 shows empirical cumulative distribution functions (ECDFs) of drainage areas for high-hazard dams in the United States by owner type. Similar ECDF results are obtained for significant-hazard dams (see Appendix C). The median drainage area for all high-hazard dams is about 8 mi^2. Local government dams are located on the smallest watersheds (median of 4 mi^2) and federally owned dams on the largest (median of 200 mi^2). The median drainage area of most state-owned dams is about 10 mi^2. About 98 percent of drainage areas are smaller than 10,000 mi^2, suggesting that the largest storm area (10,000 mi^2) provided in generalized PMP estimates (HMR 49, 55A, 57, 59) is adequate (see also summary Table C-1 in NRC, 1985).

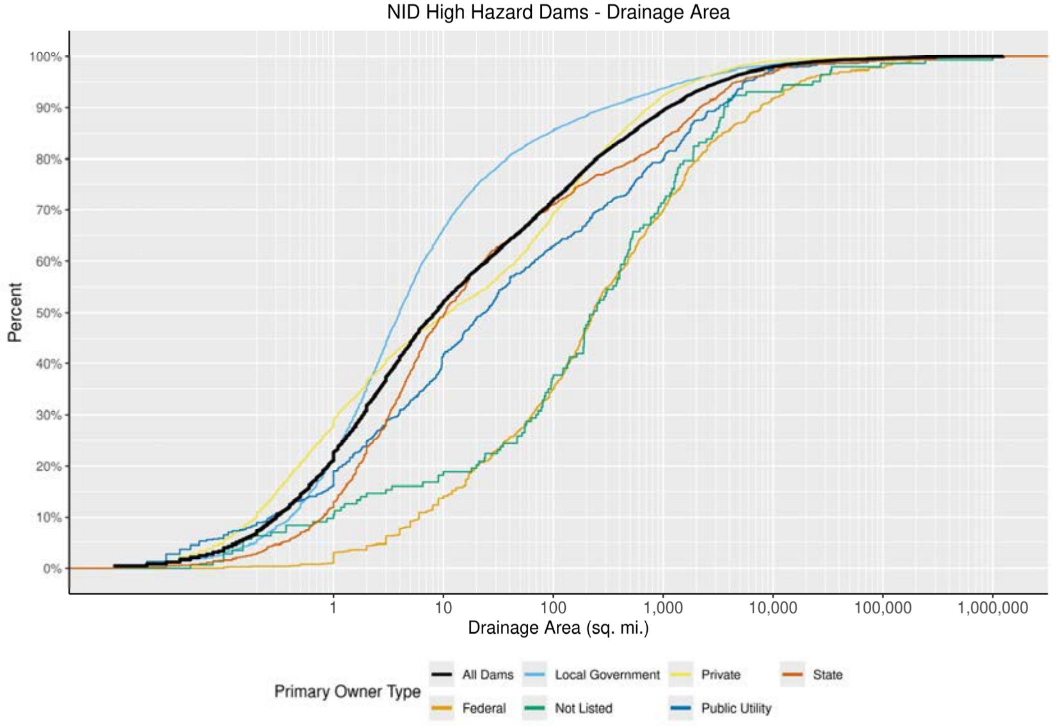


FIGURE 2-9 Empirical cumulative distributions of drainage areas, shown by primary owner type, for high-hazard dams.
SOURCE: McGraw (2023), using data from National Inventory of Dams (https://nid.sec.usace.army.mil/), accessed 6 July 2023.

Conclusion 2-3: The concentration of high-hazard dams in small watersheds points to the particular importance of PMP estimates for short durations and small areas, as noted in NRC (1994).

Dam safety regulations used by states have historically considered dam height and reservoir storage as factors in hazard classification of dams and selection of rainfalls and floods for spillway design/assessments (FEMA, 2012). Drainage area distributions for four classes of dam heights and three hazard classifications are shown in Appendix C. Although the distributions and median statistics differ significantly, the range of drainage areas does not. The range of drainage areas covered by any new PMP estimation process should be similarly broad, especially for high- and significant-hazard dams.

Areal Extent of PMP Studies

Development of PMP estimates is based on generalized, regional, and site-specific studies (England et al., 2020). Generalized PMP studies cover large regions of the United States; regional studies focus on states or major river basins; and site-specific studies provide PMP estimates for the hazard region of a specific structure (dam or nuclear power plant). The spatial scale for generalized and regional PMP studies ranges from 1 to 20,000 mi^2 and the temporal scale from 1 to 72 hours.

The 1982 generalized PMP study for the eastern United States (HMR 52; Hansen et al., 1982) distinguished between "storm PMP" (defined as PMP computed over an arbitrary area of a given size) and "basin PMP" (defined as the PMP computed over a particular river basin of a given shape and areal extent) and introduced procedures for estimating basin PMP from storm PMP. Conventional PMP procedures provide estimates of storm PMP, although basin PMP is needed for computing PMF. Methods for converting storm PMP to basin PMP require additional information on the spatial and temporal structure of rainfall, which are assumed to vary with PMP type.

Storm Sizes Relevant to PMP Estimates

Two broad storm classifications are often used by PMP practitioners: a general storm and a local storm (WMO, 1986). A general storm is defined as "a storm event which produces precipitation over areas in excess of around 1,300 km^2 (500 mi^2) and durations longer than 6 hours and is associated with a major synoptic weather feature" (WMO, 2009). A local storm is defined in WMO (2009) as "a storm event that occurs over a small area in a short time period. Precipitation rarely exceeds 6 hours in duration and the area covered by precipitation is less than around 1,300 km^2. Frequently, local storms will last only 1 or 2 hours and precipitation will occur over area sizes up to 500 km^2. Precipitation in local storms will be isolated from general-storm rainfall."

Two storm rainfall examples highlight the vastly different spatial and temporal scales for events that contribute to PMP estimation and that are applied to dams and nuclear facilities. The 6–12 May 1943 storm rainfall was a broad-scale, large-area general storm centered in Oklahoma (Figure 2-10a). This 144-hour event is a "controlling storm" (one that is used to estimate PMP for several area sizes and durations) in HMR 51 and is within 50 percent of PMP for numerous larger area sizes (5,000 to 20,000 mi^2) and durations (Riedel and Schreiner, 1980). This storm was used in the design of Keystone Dam on the Arkansas River near Tulsa (Figure 2-10b) and numerous other dams in the central United States; the watershed area is larger than 74,000 mi^2 with an estimated contributing storm area (that area that generates flood runoff) over the lower watershed area of 24,000 mi^2. This figure illustrates a partial-area case, where the storm area is much less than the watershed area, and the storm area is the critical input. Less than 2 percent of high-hazard dams are on watersheds that exceed 20,000 mi^2 (such as this one), thus there is lack of need for PMP estimates at scales larger than this.

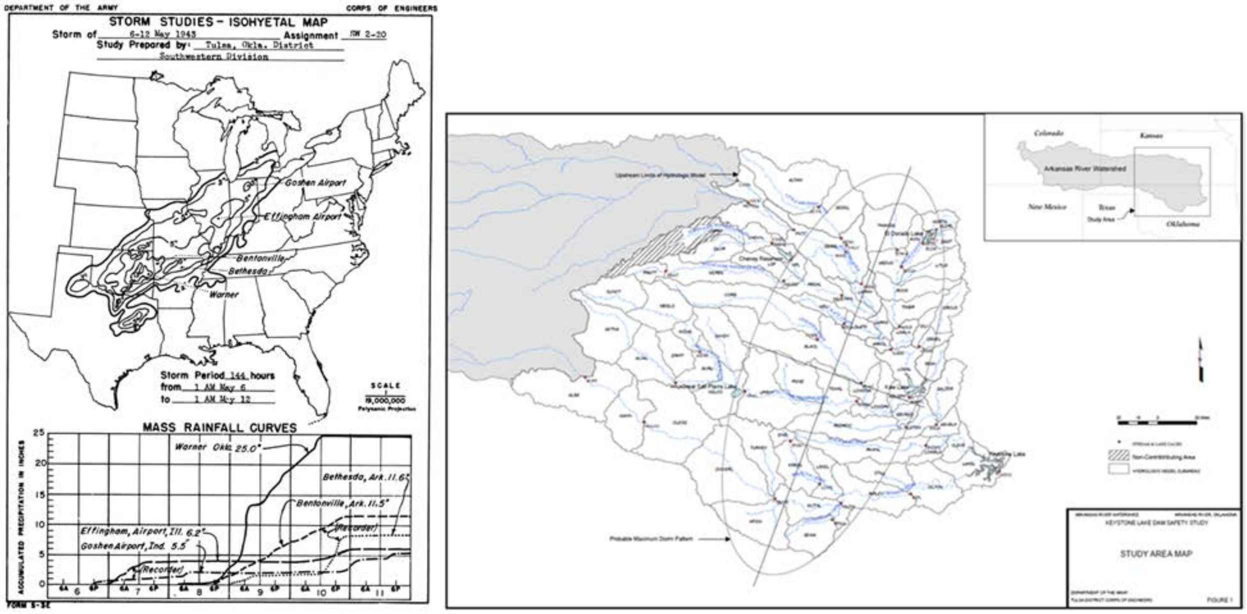


FIGURE 2-10 (a) Isohyetal (lines of equal rainfall) map and mass curves of the 6–12 May 1943 storm (top) and (b) the storm transposed and rotated to the critical location for the design rainfall of Keystone Dam on the Arkansas River near Tulsa, Oklahoma.
NOTES: Flood runoff in the watershed occurs within the ellipse and southeast toward Keystone Lake. An elliptical pattern, the HMR 52 model (Hansen et al., 1982), has been traditionally used to represent the PMP spatial and temporal distributions within the eastern United States.
SOURCES: (a) USACE (1973) and (b) USACE (2018).

In contrast, the 31 July 1976 extreme rainstorm and flood in the Big Thompson canyon in Colorado is a prototypical local storm characterized by its small area (Figure 2-11a) and short duration (4 hours), exceeding 12 inches over 0.2 mi^2 (Figure 2-11b) (Hansen et al., 1988), with most of the observations from bucket surveys (Miller et al., 1978). This storm was utilized to estimate local-storm PMP in the generalized PMP report HMR 55A (Hansen et al., 1988) and in the Colorado-New Mexico statewide study (AWA, 2018). Local storms such as this one are critical for estimating PMP and locally intense precipitation (LIP) at 1 mi^2 scales for nuclear reactors (Figure 2-12). LIP is defined as the 1-hour, 2.56-km^2 (1-mi^2) PMP at the location of the site (Prasad et al., 2011), but it is sometimes estimated using the 6-hour, 10-mi^2 PMP rainfall depth (DeNeale et al., 2021).

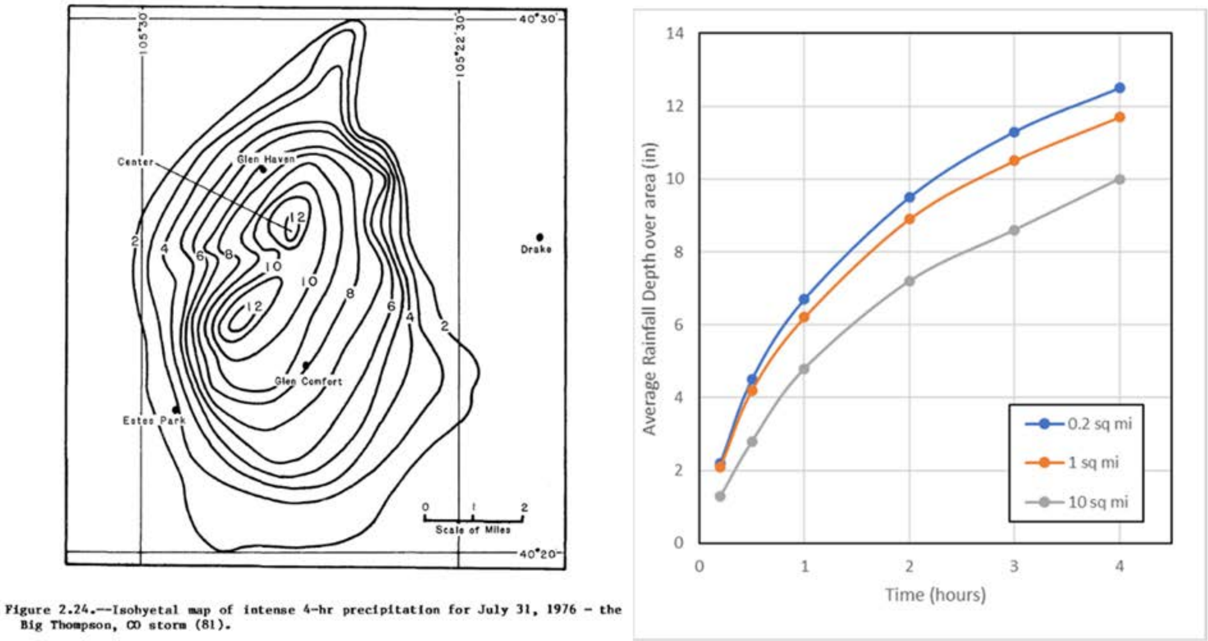


Figure 2.24.--Isohyetal map of intense 4-hr precipitation for July 31, 1976 - the Big Thompson, CO storm (81).

FIGURE 2-11 (a) Isohyetal map of the intense 4-hour rainfall and (b) mass curves for the 31 July 1976 Big Thompson, Colorado, storm, showing that the local storm rainfall decreases rapidly over a short distance (in this case 2 mi^2).
NOTES: At 4 hours, the rainfall at 10 mi^2 (10 inches) is significantly less than at 1 mi^2 (12 inches) (bottom). The watershed flood runoff response is controlled by these intense local storm spatial and temporal characteristics.
SOURCES: (a) HMR 55A and (b) data from HMR 55A.

PMP AND PROBABLE MAXIMUM FLOODS

For flood hydrologists and engineers conducting safety assessments and designing critical infrastructure, PMP is just the start of the process. PMP serves as a critical input to estimate PMF, which is the operative flood metric against which many high-hazard dams and nuclear facilities are generally designed and with which their vulnerability and safety are continually assessed using RIDM. Failure of a dam to competently pass the simulated PMF event or of a nuclear facility to survive simulated PMF inundation without damage indicates the need for potential safety enhancements to the structure, such as extending upward the elevation of a dam crest or lowering the normal operating level of the reservoir.

The PMP analysis provides the spatial and temporal rainfall inputs that drive the rainfall-runoff simulation process to estimate maximum peak flows, flood hydrograph shapes, total runoff volumes, and maximum reservoir and river stage levels that govern dam and facility designs and assessments. The modern hydrologic models used to simulate extreme floods and PMFs are spatially explicit, with inputs and computations on a 1 kilometer or smaller (250 meter) grid. Examples of modern hydrologic models for watershed flood applications at these scales are the two-dimensional runoff, erosion, and export (TREX) model (England et al., 2007); the gridded surface-subsurface hydrological analysis (GSSHA) model (Sharif et al., 2010); the Hydrologic Engineering Center hydrologic modeling system (HEC-HMS) two-dimensional model (HEC, 2023); the watershed environmental hydrology hydroclimate model (WEHY-

HCM) (Trinh et al., 2022a); and the national water model (NWM) (Cosgrove et al., 2024). These models require, or at least greatly benefit from, spatiotemporally distributed rainfall information in ways that earlier models did not. Key PMP and atmospheric variables to estimate extreme floods and PMF are described in Box 2-4.

In addition to the PMP rainfall, the PMF simulation requires estimates of (1) infiltration (loss) rates, (2) antecedent storms and soil moisture conditions within the watershed, (3) the nature, extent, and condition of vegetation that may intercept and slow the flow of runoff into streams, (4) the level of receiving streams and reservoirs that convey or temporally hold flood waters before they reach the location of the dam or nuclear facility, and (5) potential sequences of successive storms for large watersheds. Snowpack depth, distribution, and conditions are contributors in the northern portion of the United States. Finally, the PMF analysis requires the analyst to input operational rule curves of the dams or nuclear facilities at and upstream of the design site. Rule curves represent plans that describe how dam and nuclear facility operators are expected to respond to evolving flood conditions.

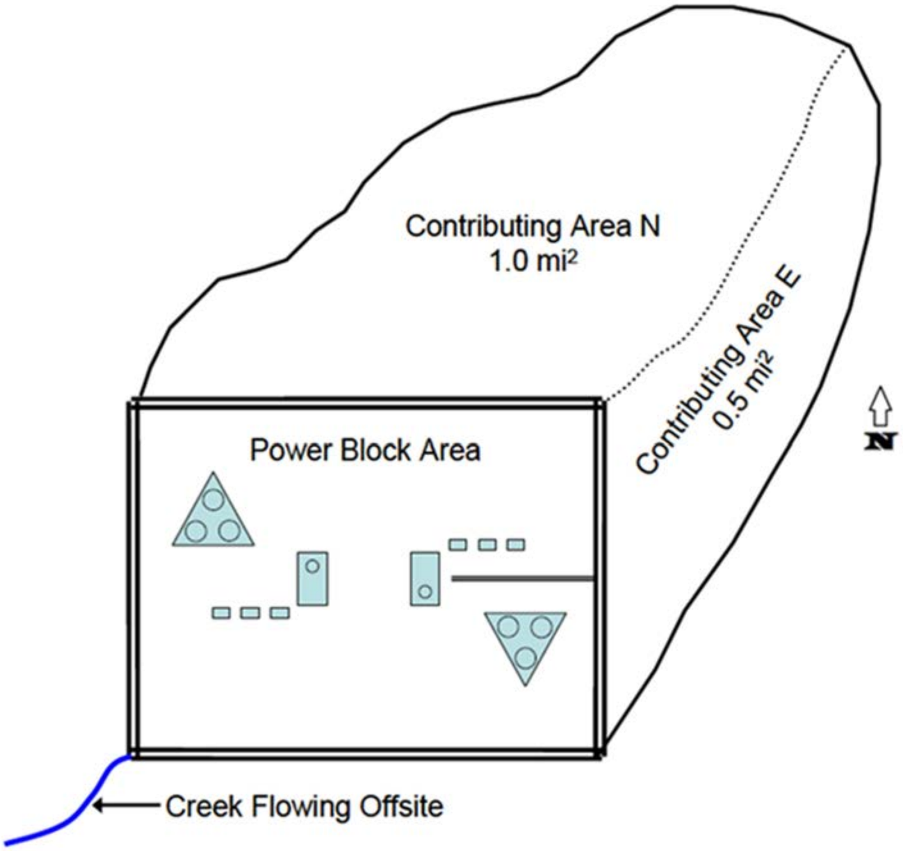


FIGURE 2-12 Hypothetical example of a 1-mi^2 nuclear reactor site (not a watershed) to apply locally intense precipitation.
NOTES: PMP rainfall is assumed uniform over this small area and equivalent to a “point.” The total depth and temporal pattern are the critical variables for estimating the PMF for sites such as this.
SOURCE: Prasad et al. (2011).

BOX 2-4
Atmospheric Variables for Estimating Extreme Floods and Probable Maximum Floods

Extreme floods and Probably Maximum Floods (PMFs) are estimated over watersheds, which range from 1 mi^2 to about 10,000 mi^2. The important Probable Maximum Precipitation (PMP) variable is a watershed-average precipitation depth, for a user-specified duration. The location of the storm center, the storm orientation, and the spatial and temporal distributions of precipitation across the watershed are critical factors in estimating this PMP watershed-average depth and PMF. The PMF peak discharge, flood runoff volume, and maximum water levels in reservoirs and rivers can be very sensitive to these factors. Storm type and watershed scale are also important factors. The PMF response on smaller watersheds (nominally less than 50 mi^2) is typically dominated by the temporal distribution. Short-duration (less than 24 hours), local-convective rainfall depths with very high rain rates typically control extreme flood response. The spatial distribution of extreme precipitation is important where there is variable terrain and high precipitation gradients in the watershed, such as in Figure 2-13. Spatial patterns are particularly important on watersheds larger than about 500 mi^2.

Atmospheric variables and information used for estimating antecedent soil moisture and snowmelt are also important for extreme floods and estimation of PMFs. High-resolution depiction of air temperature, wind speed, specific humidity, and shortwave and longwave radiation are important for estimation of snowpack and snowmelt.

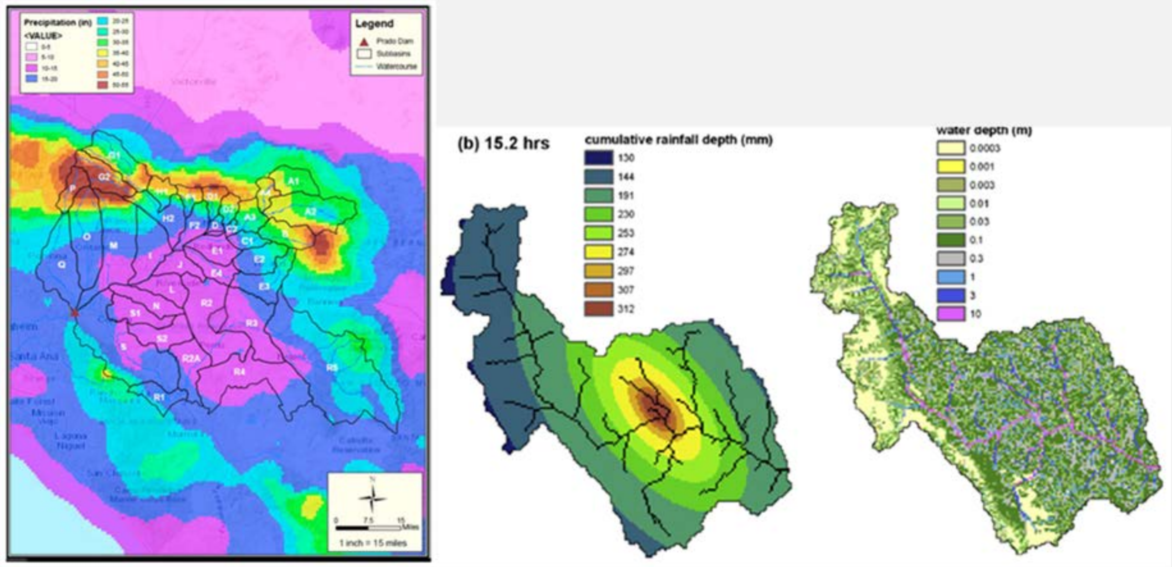


FIGURE 2-13 Example spatial distributions of extreme storm rainfall over a watershed (a) 72-hour PMP over the Santa Ana River watershed (Southern California) for the Prado Dam spillway rehabilitation design and (b) spatially distributed extreme rainfall and flood runoff depths, Arkansas River watershed upstream of Pueblo, Colorado.
SOURCES: (a) Sasaki and Margo (2021) and (b) England et al. (2014).

Different PMP rainfall distributions, either spatial or temporal, different antecedent soil moisture conditions, reservoir and river water levels prior to the PMF event, and different operational rules can each result in vastly different PMF estimates (Salas et al., 2014). Often, statistical distributions representing the likelihood of multiple possible combinations of each input are sampled in a generalized sensitivity analysis to identify a set of risk-informed design flood flows (e.g., Hall et al., 2018). The practicing community recognizes various sampling strategies, some of which can be used to assess the impacts of climate change on flood flows (e.g., Bahls and Holman, 2014).

Federal agencies have developed RIDM and design procedures that include sensitivity studies of the PMP and PMF, recognizing that PMF is not a single (deterministic) number, but an estimate with uncertainty (Salas et al., 2014). The USBR design standard for spillways provides procedures to account for uncertainties in flood estimates through scenarios and sensitivity analyses, with provisions for changes in hydrology and climate change (USBR, 2013). The USACE PMF estimation and inflow design flood procedures have evolved to include sensitivity analyses and to provide ranges on PMF hydrographs and reservoir elevations, with "recommended" PMF and "upper" PMF estimates (e.g., Sasaki and Margo, 2021.) These procedures can be improved to utilize PMP uncertainty estimates and ensembles through RIDM (Box 2-3) and include climate resilience (ASCE, 2018).

One aspect of PMF analysis is that, unlike PMP analysis, it can be informed by flood data based on pre-instrumental, even prehistoric flood events. Floods, past and present, leave various geological and biological markers that can be used to infer the magnitude (peak flow) of those events. Paleoflood techniques may involve exposure and dating of rock or soil terraces and strata deposited by past floods on adjoining floodplains, identification and dating of highwater marks and slackwater deposits in nearby caves, biological markers such as tree scars, and stable geologic features and soils that are used to estimate limits on floods (Figure 2-14). These paleoflood markers and non-exceedance bounds can be used with well-established hydraulic models to estimate past flood flows, often resulting in estimates of multiple floods occurring at the same site and spanning hundreds or thousands of years. Such flood evidence, together with radiocarbon and tree ring data can extend flood records back thousands of years in time and permit development of an "observed" flood record that can greatly augment the extreme flood record. These data can serve as an independent reference with which to judge and improve PMF estimates based on PMP simulations alone. Paleoflood data are being used by USBR (Swain et al., 2006), USACE (2020), and numerous other federal and state agencies (TVA, Colorado Division of Water Resources) in RIDM for dam safety. The U.S. Geological Survey, in cooperation with the Nuclear Regulatory Commission, has demonstrated the applicability of paleoflood and record-extension techniques to better characterize flood-inundation risks at nuclear facilitates (Harden et al., 2021; O'Connor, 2014).

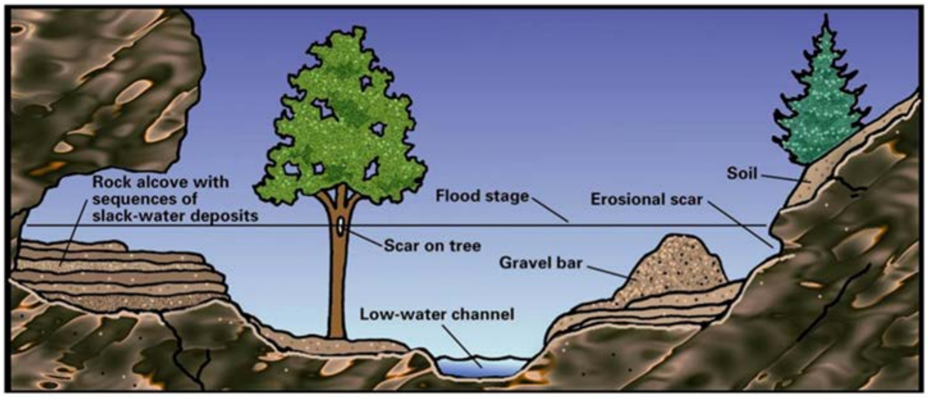


FIGURE 2-14 Diagram of a section showing typical paleoflood features used as paleostage indicators. SOURCE: Jarrett and England (2002).

3

State of the Science and Recent Advances in Understanding Extreme Precipitation

Development of a deep scientific understanding of extreme rainfall is critical for addressing the challenges to estimating PMP in the current and future climate state. Recent advances in the understanding of atmospheric processes at the synoptic to microphysical scales, the accuracy and resolution of numerical weather prediction, and enhancements to observations of precipitation from weather radar provide the foundation for major advances in understanding storms that produce rainfall accumulations with an "extremely low annual exceedance probability."

A greater understanding of the physical processes associated with extreme rainfall can enhance current PMP procedures and guide the development of model-based methods for PMP estimation. Availability of long radar rainfall datasets, in conjunction with surface rainfall measurements, can provide the observational grounding for assessing the climatology of rainfall extremes across the United States. Advanced atmospheric models and computing resources point to the potential for modeling extreme precipitation across the range of spatial scales and durations needed for PMP estimation. Recent studies that link changes in climate to the processes that produce extreme rainfall provide insights into how a changing climate will likely affect the frequency and intensity of extreme precipitation events. Taken together, these advances make it possible to understand and model the impacts of climate change on PMP-magnitude storms and lay the groundwork for model-based approaches for estimating PMP under different scenarios of future climate.

The incomplete sampling of extreme rainfall events in storm catalogs precludes the use of extreme value analysis (EVA) for PMP estimation. As opposed to current PMP practice which requires an assumption of an upper bound, EVA methods can accommodate bounded and unbounded distributions. Although the question of bounds on rainfall is unresolved, available evidence does not support the bounded assumption (as discussed below). EVA methods have substantial benefits for the estimation of PMP under a revised definition; when applied to climate model output EVA methods can enable quantitative assessment of uncertainty in PMP estimates.

The application of these advances to PMP estimation pose some challenges, but, taken together, they could modernize PMP estimation in a manner that accounts for uncertainty and the impacts of a changing climate.

SCIENTIFIC ADVANCES: METEOROLOGY OF EXTREME RAINFALL

Storms and Storm Features Producing Extreme Rainfall

The previous National Academies study of PMP concluded that "major new research initiatives are needed to improve scientific understanding of extreme rainfall events" (NRC, 1994). The past three decades have seen important advances in the understanding, characterization, and prediction of extreme rainfall, many of which are applicable to PMP estimation.

Doswell et al. (1996) established a fundamental conceptual framework for understanding and forecasting heavy rain. This "ingredients-based methodology" built on some of the earlier ideas of Showalter and Solot (1942) and is framed around the key concept that large rainfall accumulations result from high rainfall rates that are sustained over a long duration. Doswell et al. expressed this mathematically as $P = \bar{R}D$, where P is the accumulated precipitation at a point, $\bar{R}$ is the average rain rate, and D is the duration of the rain. Rain rate R was in turn approximated by the simple equation $R = Ewq$, where E is the precipitation efficiency, w is the average ascent rate in the saturated updraft, and q is the water vapor mixing ratio at the base of the saturated updraft. This equation implies that high rain rates are the result of ascending moist air (from atmospheric convection, orographic "upslope" flow, frontal uplift, or their combinations) that is efficient at producing cloud and precipitation particles that fall to the ground as rain prior to evaporating. Long-duration rainfall events occur when the size, organization, and motion of the precipitation system promotes the repeated passage of rain cells with high rain rates, when favorable synoptic conditions lead to the repeated passage of storm systems over the same location, or both.

The ingredients required for heavy rainfall can be difficult to measure and quantify, however. For example, convective rainfall is very sensitive to small differences in atmospheric water vapor, especially close to the surface (e.g., Schumacher and Peters, 2017). Yet vertical profiles of water vapor are not well observed: twice-daily balloon soundings are insufficient for capturing spatial and temporal variability; observations from aircraft ascents and descents are irregular and inconsistent in space and time; and remotely sensed vertical moisture profiles are promising but have not yet been widely deployed or evaluated operationally. Accurate measurements of updraft speeds are very difficult to obtain, which is discussed in greater depth below. Likewise, precipitation efficiency depends on complex interactions between environmental conditions and cloud microphysical processes that are not fully understood. Thus, although the "ingredients-based methodology" is highly useful conceptually, it is not easy to deploy for quantitative predictions of precipitation.

> *Conclusion 3-1: Shortcomings in observations of water vapor, including its spatial and vertical structure, and water vapor flux limit quantitative estimates of possible upper bounds of heavy precipitation.*

A wide variety of storm types (Box 3-1) can combine in characteristic ways the necessary ingredients for extreme precipitation, from large-scale weather systems such as tropical cyclones and atmospheric rivers, to mesoscale convective systems, to supercell thunderstorms and even isolated convective cells (e.g., Schumacher, 2017). In some geographic regions, only one or two storm types may be likely to yield extreme precipitation, whereas in other regions a broader range of heavy-rain-producing storm types is possible. The availability of radar observations in the late 1940s rapidly transformed the scientific understanding of storms that produce extreme rainfall (Byers and Braham, 1949). Similar advances have followed from deployment of the Next Generation Weather Radar (NEXRAD) network across the United States in the 1990s, especially through the availability of high-resolution quantitative precipitation estimates (Fulton et al., 1998). For example, Schumacher and Johnson (2005, 2006) summarized the storm types associated with 184 24-hour extreme rainfall events in the central and eastern United States based on their characteristics as observed by radar. They found that a large proportion of the events were associated with mesoscale convective systems (MCSs), or collections of individual thunderstorm cells that act in concert, a finding confirmed in a larger dataset by Stevenson and Schumacher (2014). MCSs that produce extreme rainfall are often characterized by “echo training,” whereby individual convective cells repeatedly pass over a location, as if they were train cars lined up along tracks. The findings above used radar observations to build upon previous analyses (e.g., Chappell, 1986; Maddox et al., 1979) that established the importance of mesoscale meteorological processes to extreme rain production on temporal scales of 3-24 hours and spatial scales of tens to hundreds of kilometers (see also Gochis et al., 2015; Hitchens et al., 2013; Moore et al., 2015).

BOX 3-1
Storm Types

Storm types based on physical characteristics

Tropical Cyclone (TC): Encompassing term for hurricanes of various strength designations (i.e., tropical depressions/storms and hurricanes), typhoons, and cyclones that form in the ocean and draw energy from high ocean temperatures and are characterized by large synoptic scale and organized deep convection. Extreme precipitation over land can be caused when landfalling tropical cyclones slow down so that single areas are exposed to the intense rainfall from the TC over an extended period of time. TCs are also capable of producing very heavy short-term rain rates.

Extratropical Cyclone: A large (1,000 km or more in spatial scale) weather system at middle or high latitudes with low pressure at the center, typically with warm and cold fronts extending outward from the low-pressure center. Extratropical cyclones occasionally produce extreme precipitation along their fronts; atmospheric rivers (defined below) often develop in association with an extratropical cyclone or a series of them.

Extratropical Transition: The process by which TCs transition into extratropical cyclones as they turn poleward. Fronts develop during this transition process, and heavy precipitation often occurs along these fronts. Many extreme rainfall events along the U.S. East Coast have been associated with extratropical transition.

Atmospheric River (AR): Narrow plumes of intense horizontal water vapor transport, typically associated with an extratropical cyclone. Extreme precipitation can be produced when ARs encounter topography that forces the large amounts of available moisture to rise and precipitate rapidly.

Ordinary Thunderstorms: A single updraft and downdraft; these occur on small spatial scales and generally last less than 1 hour. They serve as the building blocks for larger, organized clusters and lines of storms, including mesoscale convective systems.

Mesoscale Convective System (MCS): Collections of thunderstorm cells, often organized into clusters or lines, that move together and produce precipitation over a spatial area of hundreds of km and last up to 24 hours. Extreme precipitation can be caused by multiple cells in a system passing over the same location one after another.

continued

BOX 3-1 *continued*

Supercell Thunderstorm: Rotating storms characterized by strong, persistent updrafts of air. Extreme precipitation can be created through rotating updrafts of higher strength and longer durations than are found in many storm types, producing higher intensity and longer durations of precipitation.

Orographic Precipitation: Precipitation that is produced because of interactions of moist air with mountainous terrain that forces the air to ascend. Orographic precipitation associated with synoptic systems preferentially falls on the windward slopes, but warm season orographic precipitation associated with convection may produce more diverse spatial distribution.

Storm types based on PMP applications

General Storm: A designation for a storm event that produces precipitation on a relatively large scale (>1,300 km^2) and long duration (>6 hours), typically associated with a major synoptic (i.e., large scale) weather feature, such as an extratropical cyclone.

Local Storm: A designation for a storm event that produces precipitation on a relatively small scale (<1,300 km^2, frequently around 500 km^2) and short duration (<6 hours, frequently around 1-2 hours). These could include mesoscale convective systems, supercell thunderstorms, orographic precipitation, or even ordinary thunderstorm cells.

Tropical Storm: A designation for a storm event that generally aligns with the meteorological definition above of a tropical cyclone.

Hybrid Storm: A designation generally associated with storms undergoing extratropical transition, such that they are “hybrids” between tropical and extratropical cyclones. This designation has been used in some PMP studies for the eastern United States.

Cool-Season Storm: A special case of the General Storm category that occurs in the cool season (typically November-March). These storms are particularly needed to estimate critical cool season hazards such as rain on snow and extreme floods from atmospheric rivers.

Radar observations have also been used to develop storm catalog data for PMP studies. Smith et al. (1996) performed analyses of the 27 June 1995 Rapidan storm using reflectivity and Doppler velocity observations from the Sterling, Virginia, WSR-88D radar. Rainfall fields derived from reflectivity-based rainfall estimates and bucket survey observations have been integrated into recent PMP studies, in which the Rapidan storm controls PMP estimates for time periods less than 6 hours over large regions in the Central Appalachians (AWA, 2015). Storm tracking analyses based on 3-D reflectivity fields illustrate the role of storm size and motion as drivers of Doswell’s ingredients-based formulation of extreme rainfall. Storm tracking analyses also contribute to interpretations of orographic precipitation mechanisms and assessments of storm transposition assumptions in the Central Appalachians. Doppler velocity observations are used with humidity measurements to examine the atmospheric water balance of the Rapidan storm, providing insights into assumptions underlying moisture maximization procedures.

Another major advance has been an increase in understanding of the importance of atmospheric rivers (ARs) for extreme rainfall (Ralph and Dettinger, 2011; Zhu and Newell, 1998). ARs are focused plumes of intense water vapor transport, typically associated with an extratropical cyclone. They include both the well-studied ARs that collide with the mountain ranges of the western United States (e.g., Ralph et al., 2006), as well as those that originate in the Gulf of Mexico or Atlantic Ocean and provide a favorable environment for extreme precipitation in the eastern United States (e.g., Barros and Kuligowski, 1998; Mahoney et al., 2016; Moore et al., 2012). ARs can enhance all three variables in the rain rate equation. By quickly transporting moisture in a focused area, they both increase the water vapor available to updrafts (increased q) and the precipitation efficiency E. Furthermore, their position near atmospheric frontal zones is often associated with increased synoptic-scale ascent, which can promote individual updrafts and heavy orographic precipitation (increased w).

Another important process that has been identified as a potential contributor to PMP-type storms over short durations is updraft rotation, which enhances the updraft speed and duration of individual thunderstorms. Smith et al. (2001) demonstrated that the intense updrafts in rotating thunderstorms, known as supercells, can produce exceptionally high rain rates, in some cases exceeding 300 mm/hour. They hypothesized that many of the most extreme short-term rain events in the contiguous United States are associated with supercells. Nielsen and Schumacher (2018, 2020) confirmed these findings using observations and numerical model experiments, showing that environments with stronger low-level shear result in more storm-scale rotation, stronger low-level updrafts, and more rainfall. However, the interplay between storm dynamics and thermodynamics in the production of extreme rainfall remains an active area of research, and these processes are far from fully understood. In general, updraft speeds (i.e., w in the rain rate equation) remain very difficult to measure or estimate, especially for the intense updrafts in supercells, which are challenging to quantify from both in situ and remotely sensed measurements (e.g., Marinescu et al., 2020).

> *Conclusion 3-2: Interactions between storm dynamics and thermodynamics in extreme rain-producing storms remain difficult to both measure and simulate.*

The "convective intensity" problem concerns the climatology of extreme rainfall, with supercells representing the high end of convective intensity and convective storms that do not produce lightning representing the low end of convective intensity. Are storms controlling PMP estimates at short durations and small areas concentrated on the low end or the high end of the convective intensity spectrum? The importance of the problem for PMP estimation is tied to the concentration of high-hazard structures (both dams and nuclear plants) in small watersheds (Chapter 2). Cotton et al. (2010) note that "we should not expect that the storm systems producing the largest hailstones [supercells] are also heavy rain producing storms." Their arguments focus on storm speed and water balance, in particular the low precipitation efficiency observed in some hailstorms. The 28 July 1997 Fort Collins, Colorado, storm (Petersen et al., 1999) is an archetype for "warm rain" storm systems that produce extreme rainfall over short durations and small areas with little or no lightning (see Zipser and Liu, 2021 for climatological context).

As noted above, observational evidence and numerical modeling studies show the potential for extreme rainfall at the high end of the convective intensity spectrum (see also Giordano and Fritsch, 1991). Observational evidence from the U.S. Geological Survey (USGS) suggests that storms at the high end of the convective intensity spectrum are principal agents of extreme floods in small watersheds for much of the conterminous United States (Costa, 1987; Crippen and Bue, 1977; J. Smith et al., 2018). In a recent review of the convective intensity problem, Zipser and Liu (2021) examine "notable examples of excessive rain events over the United States, with and without intense convection." They conclude that "evidence now amply supports the prevailing view that intense convection indeed is frequently associated with extreme rainfall rates."

> *Conclusion 3-3: Storms controlling PMP estimates at short durations and small areas are concentrated at the high end of the convective intensity spectrum for much of the conterminous United States. Continued research is required on how convective intensity modulates rainfall production, especially for supercells and mesoscale convective systems.*

Although they occur less frequently than some of the other storm types discussed above, the weather systems with perhaps the greatest potential for high-end rainfall accumulations over 1 to 4 days are landfalling tropical cyclones. For example, Kunkel and Champion (2019) showed that 5 of the top 10 rainiest 4-day storms over an area of 50,000 km^2 were TCs (Figure 3-1). The largest multi-day rain accumulations are produced by tropical cyclones with slow forward motion, with Hurricane Harvey (2017) along the Gulf of Mexico coast being an exceptional example (e.g., Galarneau and Zeng, 2020; Figure 3-1). Harvey produced more than 1,000 mm of rainfall over a 7-day period in Texas and exceeded earlier PMP estimates at 3-day durations (Kao et al., 2019). Galarneau and Zeng (2020) argued that "the extended period in which deep tropical moisture overlapped with quasigeostrophic forcing for ascent is what set Harvey apart from other rainstorms in 1979–2018." Li et al. (2020) estimated that Harvey's maximum rainfall totals would have been much larger if the storm had followed a slower track consistent with earlier forecasts.

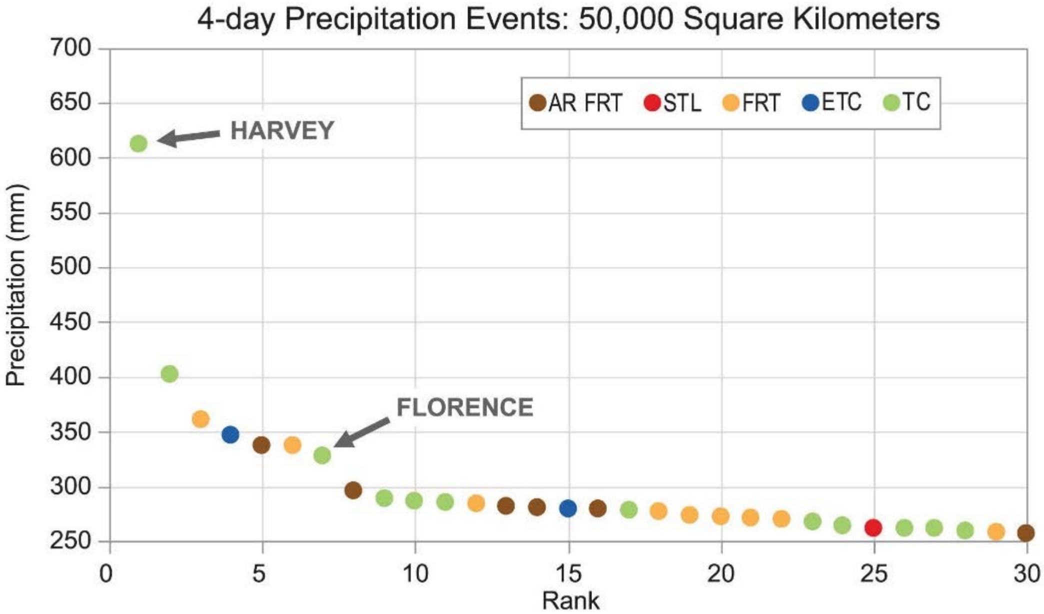


FIGURE 3-1 Precipitation magnitudes and meteorological causes for the 30 largest 4-day events for an area size of ~50,000 km^2.
NOTE: Hurricanes Harvey and Florence events are indicated.
SOURCE: Kunkel and Champion (2019).

Topography and Extreme Rainfall

Many of the storms with rainfall totals that approach PMP magnitudes occur near topographic features, where enhancement by upslope flow is possible. These include storms along the east side of the Rocky Mountains and Black Hills (e.g., Gochis et al., 2015; Maddox et al., 1978; Petersen et al., 1999), arid/semi-arid regions of the intermountain western United States (Smith et al., 2019), the Balcones Escarpment of Texas (e.g., Nielsen et al., 2016), and both sides of the Appalachian Mountains (e.g., Hicks et al., 2005; Konrad, 2001; Martinaitis et al., 2020; Pontrelli et al., 1999; Smith et al., 1996, 2001), in addition to the storms occurring along the western U.S. mountain ranges associated with ARs as described above. The detailed meteorological processes associated with these events have perhaps received less research attention in recent years, but pioneering studies of major flash floods in the 1970s remain relevant for describing how the ascent of very moist air along sloped terrain can result in rain accumulations that approach PMP. Observing the distribution of heavy precipitation in complex terrain remains a major challenge owing to sharp spatial gradients and radar beam blockage. In fact, it has been suggested that advances in modeling orographic precipitation have outpaced the ability to observe that precipitation, especially for atmospheric rivers in the western United States (Lundquist et al., 2019). The challenges to observing and modeling orographic precipitation are summarized in Banta (1990), Kirshbaum et al. (2018), and Chow et al. (2019); see also Miglietta and Rotunno (2012) and Wilson and Barros (2014).

Paleoflood and geomorphic studies have pointed to "hotspots" of extreme flood events in the topographic settings detailed above. Harden et al. (2011) combine paleoflood studies and analyses of major historical storms to support a "hypothesis of distinct differences in flood generation within the central Black Hills." Similar hypotheses have been proposed for the Front Range of the Rocky Mountains (Jarrett and Costa, 1988), the Central Appalachians (Scott Eaton et al. 2003; Smith et al., 1996), the Balcones Escarpment of Texas (Baker, 1975), and the Colorado Plateau (Webb et al., 1988). The existence of hotspots, as described by these and other studies, raise questions for PMP estimation. What is the scientific rationale for transposing major storm catalog events, such as the June 1972 Black Hills South Dakota storm and the June 1995 Rapidan Virginia storm, if these events are linked to distinctive topographic features in the settings where they occurred?

Another meteorological situation that can lead to extremely large rainfall accumulations is the impingement of a landfalling tropical cyclone on elevated terrain. For example, the world record rainfalls at durations of 12, 24, 72, and 96 hours all come from tropical cyclones approaching the steeply sloped terrain on the island of La Reunion in the Indian Ocean (e.g., 4,936 mm in 96 hours in February 2007; Arizona State University, 2023). These world record-setting storms inform understanding of the processes that govern extreme orographic precipitation and may be relevant to assessing the potential for extreme rainfall in U.S. island locations such as Hawaii and Puerto Rico. Although the contiguous United States generally does not have steep terrain near the coastlines where tropical cyclones make landfall, orographic precipitation mechanisms play an important role in amplifying tropical cyclone rainfall in the Appalachian region of the eastern United States (see, e.g., AWA, 2015).

Overall, research in recent decades has provided much better characterization of the types of weather systems that are responsible for extreme precipitation. This characterization enables a more informed consideration of storm types in PMP estimates, which is discussed in Chapter 4. These advances have not yet been incorporated into the approaches that are currently in use.

> *Conclusion 3-4: Major scientific advances have been made in understanding extreme rainfall since the 1994 National Research Council study of PMP, but they have not translated to major advances in methods for estimating PMP.*

SCIENTIFIC ADVANCES: RAINFALL DATA

Advances and Current State of Radar Observation for Extreme Rainfall

Over the past three decades, evolving methods for estimation of rainfall from radar measurements (Berne and Krajewski, 2013; Cifelli et al., 2011; Krajewski and Smith, 2002; Ryzhkov et al., 2005, 2022) have helped to advance PMP estimation (see, e.g., AWA, 2015, 2019). Radar measurements alone are generally not sufficient for accurate estimation of rainfall; surface rainfall measurements are with merged with radar observations in flood forecasting and PMP application. Surface rainfall observations from rain gauges and from bucket surveys play a critical role in developing rainfall fields from radar for PMP estimation (AWA, 2015; Baeck and Smith, 1998; Petersen et al., 1999).

Storm catalog rainfall fields at spatial scales as small as 1 km and time scales as short as 5 minutes can be constructed from radar and surface rainfall observations during the current “NEXRAD era,” which began with the initial deployments of WSR-88D radars in 1992. For time periods prior to 2012, radar rainfall estimates are based on power law equations, termed Z-R relationships, relating rainfall rate R to radar reflectivity factor Z. Since the polarimetric upgrade of the NEXRAD radar network in 2012, rainfall estimates are based on polarimetric measurements, including horizontal reflectivity, differential reflectivity, and differential phase shift. Two derived variables, specific differential phase shift (K_{DP}) and specific attenuation (A) play an important role in polarimetric algorithms for rainfall estimation (Ryzhkov et al., 2022). Like the reflectivity-only case, polarimetric algorithms are based on simple estimation equations—often power laws, with empirical parameters that must be specified.

There are two paths for developing storm catalog rainfall data during the NEXRAD era. The first begins with the “raw” radar observations (termed NEXRAD Level II data) and computes rainfall fields from radar rainfall algorithms and gauge-radar merging algorithms. Existing storm catalog data have been derived in this fashion using reflectivity-only algorithms (see, e.g., AWA, 2015 and Smith et al., 1996). The second path is based on long-term radar rainfall datasets, developed either as “analysis” fields from operational radar rainfall products or as “reanalysis” rainfall datasets computed after the fact using a standardized algorithm over the entire period of record. “Stage IV” is an analysis dataset produced by compositing operational radar rainfall estimates from radars across the United States and covers the period from 2000 to the present (Nelson et al., 2016). It has a spatial resolution of approximately 4 km and a time resolution of 1 hour. Due to a range of error sources (Nelson et al., 2016), the Stage IV dataset is not suitable for PMP applications without extensive quality control and homogenization. The Multi-Radar Multi-Sensor (MRMS) rainfall estimates developed by the NOAA National Severe Storm Laboratory (Zhang et al., 2016; see also Lengfeld et al., 2020) provide an improved rainfall dataset relative to Stage IV at high temporal and spatial resolution. Archives of operational MRMS analysis products and MRMS reanalysis products are available for limited time periods. The MRMS rainfall products are designed for a broad range of hydrologic applications but are not tailored specifically for extreme rainfall events.

Errors in estimating rainfall from radar arise from measurement properties—especially the range-dependent sampling of the atmosphere (Berne and Krajewski, 2013); microphysical processes that determine the number, size, and type of hydrometeors (rain, graupel, hail and snow) in a radar sample volume (Krajewski and Smith, 2002; Ryzhkov, 2022); and dynamical processes, especially through the role of updrafts and downdrafts in convective rainfall (Austin, 1987). The role of vertical motion in updrafts and downdrafts imposes fundamental limitations on the accuracy of radar rainfall estimates (Austin, 1987). A key assumption underlying radar rainfall estimation is that hydrometeors (raindrops, graupel and hail) fall at their terminal velocity, which implies that there is no vertical movement of air in the radar sample volume.

Convective intensity, as discussed in the previous section, is linked to both microphysical and dynamical sources of errors in radar rainfall estimates. Long lists of empirical Z-R parameters have been tabulated and used for rainfall estimation in differing settings, with convective intensity arguments often invoked to explain the variation in empirical parameters (Battan, 1973; Krajewski and Smith, 2002). Similar issues arise for polarimetric algorithms, with "cold rain" microphysical processes in intense convection creating major challenges to estimation of extreme rainfall (Ryzhkov et al., 2022). Convective intensity is also at the heart of underestimation of extreme rainfall in strong downdrafts.

Merging Radar and Surface Rainfall Observations

Two general classes of procedures have been used for "merging" radar and surface rainfall observations: mean field bias correction and "local" corrections that exploit the spatial correlation structure of rainfall (Berne and Krajewski, 2013; Krajewski, 1987). Correction of mean field bias in radar rainfall estimates using rain gauge observations has long been recognized as one of the most important tools for improving the accuracy of radar rainfall estimates (Krajewski and Smith, 2002; Steiner et al., 1999). For reflectivity-based rainfall estimates, a mean field bias correction translates to changing the pre-factor in Z-R relationships, thereby providing a data-driven tool for addressing the variability of Z-R parameters noted above. Large bias corrections for PMP magnitude storms have been reported for reflectivity-only rainfall estimates (Baeck and Smith, 1998) and for polarimetric estimates (Smith et al., 2023, 2024).

"Conditional bias," in which errors in radar rainfall estimates systematically underestimate peak rain rates, can be an important factor in extreme rainfall estimation (Ciach et al., 2000). Local corrections have been used to develop rainfall fields for recent PMP studies (AWA, 2018; Parzybok and Tomlinson, 2006) and provide a path for addressing underestimation of peak rainfall. Procedures that provide local corrections impose a heavy burden on determining the accuracy of surface rainfall observations, especially in the region of most extreme rainfall. Enhancements to PMP estimation based on radar will require a concerted effort to obtain high-quality surface rainfall measurements. Availability, accuracy, and sampling properties of extreme surface rainfall measurements point to the importance of radar rainfall estimates based on the full volume-scale radar fields.

> *Conclusion 3-5: Surface rainfall observations should be used in combination with radar observations, from both the polarimetric and reflectivity-only eras, for development of rainfall fields for modernized storm catalogs. Mean field bias algorithms and local*

correction algorithms tailored for PMP application should be developed, standardized, and documented.

Conclusion 3-6: Enhancements to radar algorithms for estimating rainfall fields from PMP-magnitude storms, both for reflectivity-based algorithms and for polarimetric-era algorithms, are needed to reduce the dependence on surface rainfall measurements. Standardization and documentation of these algorithms is an important step in assuring transparency in data and methods for estimating PMP.

Recommendation 3-1: NOAA should facilitate development of continuous "reanalysis" rainfall datasets covering the NEXRAD era. The reanalysis should build on advances developed by NOAA through the MRMS program and target algorithm structure and parameters for estimation of extreme rainfall. The reanalysis dataset will contribute to identification of storm catalog events and development and evaluation of model-based PMP estimation methods.

Radar Capabilities for Climatological Applications

Radar rainfall datasets are increasingly used for climatological applications (e.g., Lengfeld et al., 2020; Saltikoff et al., 2019; Smith et al., 2024). With full deployment of radars and implementation of systematic archiving procedures (Droegemeier et al., 2002), near-complete datasets from the NEXRAD network can be developed for the period from 2000 to 2024.

Conclusion 3-7: Continuous reanalysis rainfall data and storm catalog data developed from radar observations during the period 2000–2024 can provide a useful observational tool for characterizing current-climate rainfall extremes over much of the United States. Radar-based products provide the ability to assess rainfall across the range of spatial and temporal scales needed for PMP estimation.

Radar rainfall estimates are of greatest utility for "local" and TC storm types. Range-dependent sampling by radar typically results in large errors in estimates of stratiform rainfall in which precipitation processes are concentrated in the lowest levels of the atmosphere. This translates to significant errors in estimates of extreme rainfall for many AR episodes along the west coast of the United States. In mountainous terrain, beam blockage and partial beam blockage complicates estimation of radar rainfall. Radar observations are, however, especially valuable for analyses of extreme rainfall in mountainous regions that are not affected by blockage issues. For the Model Evaluation Project (Chapter 5), the long-term radar rainfall dataset will provide a key observational resource for evaluating model simulations.

NUMERICAL MODELING AND COMPUTING

Numerical modeling of storms and extreme precipitation using models that solve the mathematical equations that describe the dynamical and physical processes of the atmosphere can augment observation-based estimation of PMP, which encounters various limitations related to the sampling and measurement errors noted above. Modeling of storms that might be capable of producing PMP must be done at a fine scale to resolve the intricate, highly transient physical and dynamical processes associated with the storms that produce the extreme precipitation. Since the 1970s, two classes of models, large-eddy simulation (LES) and cloud-resolving model (CRM), have been developed to explicitly simulate convective clouds to gain a better understanding of their lifecycle. Designed to explicitly resolve turbulent motions in an inertial subrange, LES (resolutions of ~100 m) is capable of modeling atmospheric convective boundary layers (Bryan et al., 2003), while at resolutions of ~1 km, CRM is more suited for modeling deep convective clouds and associated motions (Guichard and Couvreux, 2017). LES is more often used to simulate shallow convective clouds involving warm-phase microphysical processes; CRM must represent microphysical processes for both warm and ice phases to better simulate deep convective clouds that extend vertically above the freezing level. Besides explicit modeling of clouds and convection, LES and CRM have also been used to inform the development of parameterizations for clouds and convection for large-scale models and to better connect such efforts with local-scale field and aircraft measurements.

With advances in computing in the past two decades, LES and CRM models can be used in simulations over relatively large domains, enabling the study of convective cloud ensembles and organized shallow and deep convection spanning tens-to-hundreds of kilometers in scale. At the same time, most regional weather and climate models are now equipped with nonhydrostatic solvers (hence no assumption of hydrostatic balance), allowing them to model atmospheric processes at grid spacings of a few kilometers where deep convection and the mesoscale dynamics of precipitating storm systems are beginning to be explicitly resolved. These models, known as convection-permitting models (CPM) and storm-resolving models (SRM), have played an instrumental role in bridging modeling of individual storms to modeling storms on climate timescales (Prein et al., 2015). Seasonal-to-decadal regional convection-permitting climate simulations have been performed in the past decade covering regional to continental domains, providing important insights on how storms and extreme precipitation may change under global warming (Ban et al., 2015, 2021; Chen et al., 2023; Kendon et al., 2014; Prein et al., 2017b, 2023). For example, comparing regional CPM simulations at 1.5 km grid spacing over the United Kingdom for the present day and future, Kendon et al. (2014) found significant increases in short-duration summer rain exceeding the high thresholds due to changes in the local storm dynamics with warming. However, such trends could be concealed by natural variability, as shown in an ensemble of 12 CPM simulations that capture internal variability (Kendon et al., 2023). CPM simulations covering a much larger domain across the continental United States (CONUS) also showed intensification of hourly precipitation extremes (Prein et al., 2017c).

Along with CPM, computationally efficient algorithms for tracking storms such as MCSs, tropical and extratropical cyclones, and ARs in large datasets have expanded our ability to analyze and compare storms in observations and climate simulations (e.g., Feng et al., 2018, 2023; Ullrich et al., 2021). By tracking MCSs in the CONUS simulations, Prein et al. (2017) further showed an increased frequency of intense summertime MCSs, which has also been found through tracking MCS in observations of the past decades (Feng et al., 2016). Identifying precipitation objects in CPM simulations over the western United States, Chen et al. (2023) noted a sharpening of cold season storms (i.e., decreasing area-reduction-factor corresponding to a larger increase in storm peak precipitation intensity than storm area averaged precipitation intensity), particularly for AR-related heavy precipitation events. Tracking ARs in a large ensemble of global climate simulations at low resolution, Huang and Swain (2022) identified a multiweek sequence of AR storms capable of giving rise to a megaflood similar to the “Great

Flood of 1861–1862" in California. By downscaling the scenario using a regional CPM, they investigated how such an event may unfold in the future.

Although the use of regional CPMs in climate research has increased in the recent decade, global CPMs have emerged in the past two decades, thanks to the development of computationally efficient algorithms for nonhydrostatic dynamical solver and mesh generation (e.g., icosahedral and cubed sphere grids) and the availability of large high-performance computing platforms (Satoh et al., 2019). Unlike regional CPMs, which have been employed to produce decadal simulations and projections, global CPMs have mostly been employed in shorter simulations because of their high computational cost. For example, the first intercomparison of global CPM, Dynamics of the Atmospheric general circulation Modeled On Nonhydrostatic Domains (DYAMOND), includes eight models running for 40 days in a boreal summer (Satoh et al., 2019; Stevens et al., 2019). With unstructured grids, global CPMs can be configured for global simulations with convection-permitting modeling limited to regions of interest. Compared to global CPMs, such regionally refined CPM simulations are computationally more affordable, because the computational cost scales with the size of the refined region, and they demonstrate comparable skill to regional CPM simulations for modeling extreme weather events (Z. Liu et al., 2022).

To realize the use of global CPMs for climate and Earth system modeling, some efforts have started to couple global CPMs with land and ocean models (Hohenegger et al., 2023), but results have not yet been widely reported. Also importantly, global CPMs must achieve a minimum throughput of 1 simulated year per day (SYPD) to be practically useful for climate production runs. However, all the global CPMs that participated in DYAMOND were Fortran-based codes running on moderate-sized CPU-based supercomputers, with throughput ranging from 0.007 to 0.05 SYPD (Stevens et al., 2019). Because global CPMs must solve the governing equations on billions of grid cells, they are well suited for GPU-based exascale computers built for parallel computations on thousands of nodes. Building global CPMs for efficient and performance portable implementation on exascale computers is a significant technical challenge requiring upgrading of the CPM codes to work with GPU-programming paradigms. As an example, two global CPMs, ICON and SCREAM, have been adapted to GPU-based computers using Fortran/OpenACC and C++/Kokkos, respectively. Because C++/Kokkos allows a single code to run efficiently on a variety of high-performance computing architectures, SCREAM has demonstrated performance portability across CPUs and both NVIDIA and AMD GPUs, achieving a throughput of more than 1 SYPD on Frontier, the first exascale computer on the TOP500 list, and thereby demonstrating the viability of using global CPM for climate simulations (Taylor et al., 2023) (Figure 3-2).

Compared to coarser resolution simulations with parameterized deep convection, regional and global CPM simulations have shown clear improvements in their ability to reproduce important observed features. For precipitation, the most notable improvements relate to the diurnal cycle such as the nocturnal peak in regions frequented by MCS, which has been a longstanding challenge for simulations with parameterized deep convection (Feng et al., 2023). Because complex terrain is better resolved by CPM, precipitation in mountainous regions is also noticeably improved compared to lower resolution simulations (e.g., Ban et al., 2014). CPM simulations also show significant improvements in representing the probability density function of daily precipitation rates, reducing the frequent occurrence of drizzles found in lower resolution simulations (Stephens et al., 2010), and producing more realistic intense/extreme precipitation amounts (Kendon et al., 2017; Patricola and Wehner, 2018; Prein et al., 2017a).

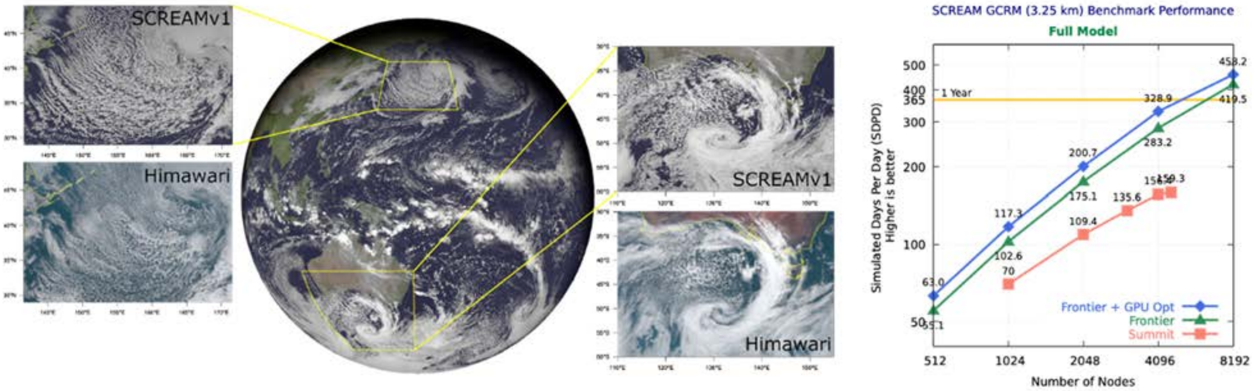


FIGURE 3-2 Left panel: Examples of clouds simulated by SCREAM, a global CPM, at 3.25 km grid spacing and comparison with satellite data. Right panel: Throughput of SCREAM in Simulated Days per day of wall clock time (SDYD) vs. node count on the Frontier (AMD GPUs) and Summit (Nvidia GPUs) demonstrating a throughput of more than 1 SYPD on the exascale Frontier machine.
SOURCE: Taylor et al. (2023).

There is, however, a tendency for heavy rainfall in CPM to be too intense, because convection is still not fully resolved at kilometer scales. For example, at grid spacings of a few kilometers, entrainment is too weak to mix drier environmental air into the updrafts, leading to overly wide and strong convective updrafts and excessive convective precipitation. Such biases have been found in regional CPMs and consistently across the DYAMOND global CPM simulations (Feng et al., 2023). Despite this similarity, the DYAMOND models simulated diverse frequencies of both deep convection and organized convective systems in the tropics (Feng et al., 2023), suggesting that large uncertainties remain in CPMs because processes such as turbulence and cloud microphysics are parameterized in these models using different formulations. Lastly, although MCSs are much better simulated in CPMs than models with parameterized deep convection, CPMs still exhibit dry biases in MCS precipitation over land regions such as the central United States (Feng et al., 2018; Prein et al., 2017a). Recent studies suggested the need to improve modeling of land surface and coupled land-atmosphere processes to address the dry biases (Barlage et al., 2021; Qin et al., 2023).

In summary, advances in numerical modeling and computing have enabled the employment of regional and global CPMs to model intense precipitation of different durations associated with different storm types. Although these advances lay the foundation for model-based estimation of PMP, more efforts are needed to address CPM biases and uncertainties and to improve computational efficiency for more robust estimation of current and future PMP. Dramatic improvements in artificial intelligence (AI)/machine learning (ML) techniques during the past decade offer some promise for further advancing modeling of PMP by improving physics parameterizations used in CPM (e.g., Gentine et al., 2018; Yuval and O'Gorman, 2020) and bias-correcting CPM simulations (Bretherton et al., 2022). AI/ML can also be used to develop emulators of CPMs, which can then be used for effective model calibration and uncertainty quantification (Hourdin et al., 2023) and for production of a much larger ensemble of CPM-like simulations, known as ensemble boosting, at a much lower computational cost (Gibson et al., 2021).

Conclusion 3-8: Model-based estimation of PMP requires very high-resolution simulations that explicitly represent convection and storm structures that produce extreme precipitation. Advances in regional and global CPMs and high-performance computing have made it feasible to model PMP-magnitude storms on climate timescales.

SCIENTIFIC ADVANCES: CLIMATE CHANGE AND EXTREME RAINFALL

According to the National Academies of Sciences, Engineering, and Medicine (NASEM; 2016), scientific confidence in climate-driven changes in extreme weather depends on three separate lines of evidence: a clear trend in observations, a clear trend in climate model simulations, and physical understanding of the connection between climate change and extreme trends, with confidence highest if all three lines are present. Fischer and Knutti (2016) argue that extreme precipitation is an example of a scientific prediction of a consequence of climate change that was made first using global climate model output and physical understanding and subsequently was verified by observations as a trend emerged. Because of the high societal importance of extreme precipitation, the relationship between climate change and extreme precipitation remains an active area of research, and improved model simulations, an ever-expanding historical data record, and improved statistical techniques are continually refining our understanding of trends around the globe.

Physical Understanding

The most direct mechanism by which climate change affects extreme precipitation is through the effect of temperature on saturation specific humidity (Allen and Ingram, 2002; Trenberth, 1999; Trenberth et al., 2003). As discussed in the subsection Meteorology of Extreme Rainfall above, the precipitation rate is directly proportional to the specific humidity when and where the air is saturated. Well-established laws of thermodynamics show that the amount of water vapor in saturated air increases rapidly with temperature. The equation relating water vapor and temperature is known as the Clausius-Clapeyron equation. The proportionality constant itself depends on temperature, but the rate of increase of moisture is approximately 7 percent for each degree Celsius of lower tropospheric temperature increase. Consequently, a baseline expectation for the change in precipitation amount from the strongest storms, assuming 100 percent precipitation efficiency and no change in updraft strength, would be 7 percent per degree of warming. This rate of increase is known as Clausius-Clapeyron scaling*,* or C-C scaling for short.

Considerable research in recent years has been directed toward investigating the dependence of rain rate on local temperatures in the present-day climate, sometimes called “apparent” C-C scaling. However, in model simulations the correlations between temperature fluctuations and precipitation intensity on weather timescales can substantially differ from the effect of long-term warming on precipitation intensity (Bao et al., 2017; Lenderink et al., 2021; Sun et al., 2020; Wang et al., 2017; Zhang et al., 2017). Analyses of extreme precipitation change in observations and models tend to show that average changes have a similar magnitude to C-C scaling, but with larger changes in the tropics and for sub-daily events, and considerable spatial variability, including changes in sign, elsewhere (Förster and Thiele, 2020; Guerreiro et al., 2018; Pall et al., 2007).

C-C scaling is problematic because it is an incomplete theory of extreme precipitation. It does not specify how extreme the precipitation must be to follow C-C scaling. C-C scaling is not expected to apply to precipitation overall. Surface evaporation is the primary means of net energy transfer from Earth's surface to the atmosphere, and therefore it is constrained at around 1.5−2.0 percent per degree of warming by changes in the radiative energy transfer from the ground to the lower atmosphere under warming (Allen and Ingram, 2002). Lastly, as discussed in the subsection Meteorology of Extreme Rainfall, the total precipitation in a given interval of time can be characterized as $P = EqwD$, or precipitation efficiency times total column moisture times mean column vertical motion times storm duration. Expecting C-C to hold everywhere is tantamount to assuming that precipitation efficiency, updraft strength, and storm duration are unaffected by climate change. C-C scaling turns out to be more like a rule of thumb than a constraint, and differences between observed or simulated scaling and C-C scaling are useful for identifying the effects of E, w, and D. In addition, changes in the frequency of events F can be affected by climate change through changes in weather patterns or environmental conditions.

These other effects are collectively referred to as the dynamic effects of climate change on extreme precipitation (O'Gorman and Schneider, 2009), while C-C scaling represents the thermodynamic effect of climate change on extreme precipitation. There is no basic theory that states whether the dynamic effect should be positive or negative, nor whether it should be larger or smaller than the thermodynamic effect. Physical principles only help somewhat with these other factors. With tropospheric relative humidity expected to change very little and even decrease over land (Byrne and O'Gorman, 2016; O'Gorman and Muller, 2010), the increasing temperatures of climate change imply an increasing vapor pressure deficit, which could decrease precipitation efficiency, though radiative-convective equilibrium simulations have found the opposite (Lutsko and Cronin, 2018). In addition, increased precipitation through C-C scaling may directly imply increased vertical motion in some circumstances, suggesting that super-CC scaling of extreme precipitation changes is quite reasonable in moist environments such as the tropics and for the most extreme events (Neelin et al., 2022).

The absence of a comprehensive physical theory for extreme precipitation changes means that it will be necessary to rely upon historical trends and climate model projections to quantify the impacts of climate change on extreme rainfall at any given location. However, physical understanding justifies the assumption that climate change affects extreme precipitation intensity, most clearly through the C-C effect.

Results from Modeling

Climate model output provides an opportunity for scientists to test their understanding of the relationship between extreme precipitation and climate change. With climate model simulations, many years of simulated extreme precipitation values can be produced, and cause and effect tested. For example, Kunkel et al. (2013a) found that very extreme precipitable water magnitudes increases over CONUS by 25–42 percent over a century under RCP 8.5, while convergence and vertical motion extremes do not increase nearly as much.

One major disadvantage of global climate models, however, is their resolution, which is too coarse to directly simulate thunderstorms or atmospheric moist convection in general. Such precipitation is estimated (parameterized) based on historical observed relationships between environmental conditions and rainfall. Those estimations have limited validity at the extreme end of the precipitation spectrum. Therefore, the Kunkel et al. (2013a) finding regarding convergence is probably much more resolution-dependent than their finding regarding precipitable water. Only recently have CPMs been applied to the question of changes in extreme rainfall frequency. In addition, most modeling studies use metrics that are nowhere near as extreme as PMP, usually something like annual maximum 1-day or 5-day precipitation.

With the expectation that extreme precipitation is increasing faster than overall precipitation, days with lighter precipitation should be decreasing in frequency. Model simulations generally find that the crossover point is around the 90th percentile of precipitation (Pendergrass and Hartmann, 2014). In other words, only the top 10 percent wettest days are increasing in precipitation intensity in the global average. In addition, studies that have looked at changes in intensity at different return frequencies find that the fractional climate change effect increases as return frequency decreases (Gründemann et al., 2022; Martel et al., 2021; Myhre et al., 2019). Simulated rainfall intensity at durations shorter than 1 day increase faster than daily or multi-day rainfall amounts (Fosser et al., 2020; Martel et al., 2020, 2021; Westra et al., 2014). The thermodynamic effect seems generally to be larger than the dynamic effect over land in midlatitudes, at least for 1-day annual maximum precipitation (Pfahl et al., 2017). The limited number of higher-resolution simulations confirm the trends from larger-scale models but generally tend to show larger trends (Cannon and Innocenti, 2019; Helsen et al., 2020; Kendon et al., 2014; van der Wiel et al., 2016).

Some model-based studies have looked specifically at climate change impacts on TCs, generally finding that structural changes lead to an increase in precipitation intensity in addition to thermodynamic enhancements (Gutmann et al., 2018; Liu et al., 2019; Patricola and Wehner, 2018; Reed et al., 2022). MCSs are projected to increase in both intensity (roughly following C-C scaling) and area (Dougherty et al., 2023; Prein et al., 2017c), with the latter possibly leading to greater PMP increases in larger basins. Individual thunderstorms are projected to become rarer and more intense because of simultaneous increases in instability and convective inhibition (Rasmussen et al., 2017). An extensive modeling study of moisture-maximized storms in past and future climates in the southeast United States found that the modeled PMP-magnitude storms exhibited an increase in intensity larger than C-C scaling (Rastogi et al., 2017).

Observed Trends in the United States

At the individual station level, statistically significant trends in extreme precipitation are relatively rare, because of a small signal-to-noise ratio. However, regional aggregation of station data consistently shows a tendency for increasing 1-day or 2-day extreme precipitation in the central and eastern United States (DeGaetano, 2009; Groisman et al., 2012; Janssen et al., 2014; Kunkel et al., 2013b; Risser et al., 2019a; Westra et al., 2013; Wright et al., 2019; see Figure 3-3). As with climate model output, the rarer the event, the larger the observed trend (Fischer and Knutti, 2016), both globally and regionally (Sun et al., 2021; Westra et al., 2013). Barbero et al. (2017) found that increases in 1-day annual maxima in the United States have been larger than increases in hourly maxima, contrary to modeling studies. Global changes in the frequency of record-setting daily precipitation are on average close to what would be expected from C-C scaling, except larger in the tropics (Lehmann et al., 2015).

Some studies have looked at trends in estimated PMP in the United States by, for example, analyzing PMP over subperiods and constructing a time series of estimates. Although such studies are generally not able to estimate trend values with much precision, the general tendency is for a historical upward trend in PMP to be found (Gu et al., 2022; Lee and Singh, 2020). It is also possible to assume that the dynamical effect of climate change is zero and to estimate the PMP trend due to increases in maximum dew point temperature or precipitable water; such studies generally find a positive historical (or projected) trend in moisture, directly implying that PMP magnitudes will increase because of the moisture maximization step even if no new storms are incorporated (Kao et al., 2019; Kunkel et al., 2020; Stratz and Hossain, 2014; Visser et al., 2022). It seems particularly unlikely that dynamical effects will be so negative as to offset thermodynamic effects (Kunkel et al., 2013a).

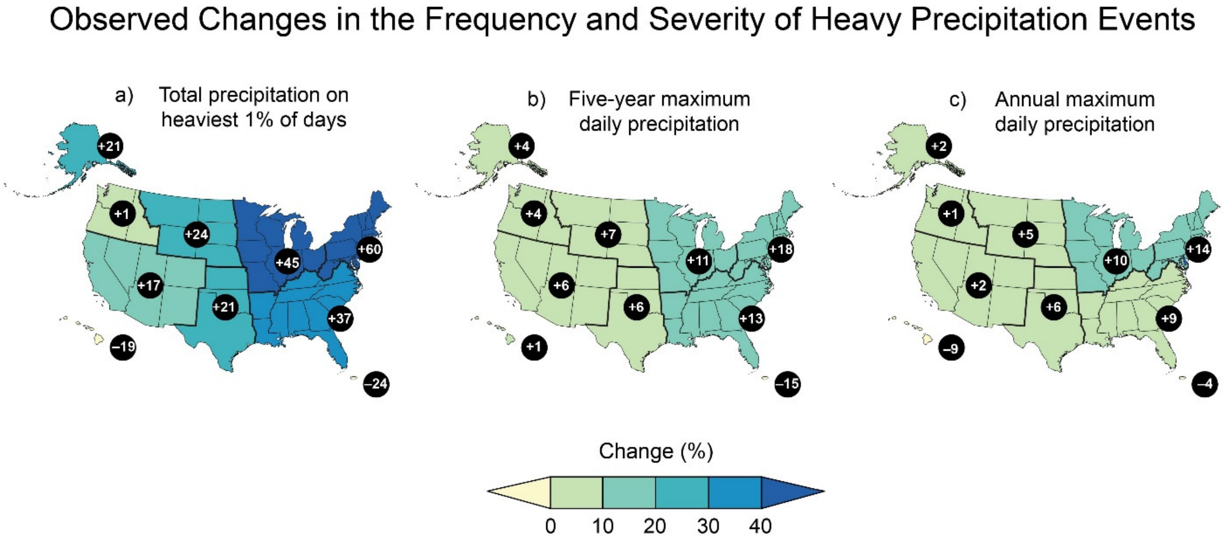


FIGURE 3-3 Observed changes in three measures of extreme precipitation: (a) total precipitation falling on the heaviest 1 percent of days, (b) daily maximum precipitation in a 5-year period, and (c) the annual heaviest daily precipitation amount over 1958–2021.
NOTES: The frequency and intensity of heavy precipitation events have increased across much of the United States, particularly the eastern part of CONUS, with implications for flood risk and infrastructure planning. Numbers in black circles depict percent changes at the regional level. Data were not available for the U.S.-Affiliated Pacific Islands and the U.S. Virgin Islands.
SOURCE: Figure, caption, and notes from NCA5, Figure 2.8 (https://nca2023.globalchange.gov/chapter/2/).

Detection and Attribution Studies

Changes in the frequency or intensity of precipitation at very long return intervals are challenging to analyze because of the limited historical record. Most current knowledge of climate change effects on the frequency of extremely rare storms comes from detection and attribution studies of extreme rainfall events.

Hurricane Harvey, in August 2017, brought PMP-magnitude precipitation to southeast Texas and has been the focus of several detection and attribution studies. Studies by van Oldenborgh et al. (2017) and Risser and Wehner (2017) analyzed historical trends in extreme precipitation but with different choices for event definition and other analysis aspects. Van Oldenborgh et al. (2017) estimated how much the probability of exceeding about 1043 mm in 3 days had changed, assuming that similar extreme event probabilities apply to the entire northern Gulf of Mexico coastal region. This total was the highest total observed at a long-term climate station. Using global mean surface temperature as a covariate, they estimated a roughly 20 percent observed increase over 1880–2017 in the rainfall amount corresponding to the present-day probability of 1043 mm, and an increase in the probability of an event of given intensity over the same period of a factor of four. This estimate leads to a present-day return period of about 9,000 years. One of two Global Circulation Models (GCMs) showed a similar increase, while the other's increase was about half as large. Risser and Wehner (2017) used gauge data over a smaller area and temporal window but considered average storm-total precipitation over 33,000 km^2 or 105,000 km^2. They estimated an anthropogenic increase of 20−40 percent in amount and a probability increase of about a factor of 10. However, this analysis excluded gauge data prior to 1950, and any other starting point for the period of record of extreme rainfall yields a smaller estimated anthropogenic increase.

Other detection and attribution studies have considered events that were rare but still well below PMP values. Despite differences in methods and geographical setting, they all find increases due to climate change. For example, Tradowsky et al. (2023) finds an increase in the intensity of 1-day point rainfall in West Germany at a return period of about 1,000 years of 22 percent (7–34%) in observations and 5 percent (2–8%) in a model synthesis.

Summary

Intense precipitation is increasing over the majority of the globe. In the United States, historical trends, model projections, and physical understanding all point to more intense precipitation in the future, with the greatest increases at sub-daily durations and the longest return periods. However, the challenge of relating these trends to PMP is illustrated schematically in Figure 3-4. The portion on the left is from Pendergrass (2018), illustrating that greater return periods (higher percentiles) tend to have larger increases due to climate change. The graph has been extended toward even greater return periods to show those that correspond to PMP in the United States (Caldwell et al., 2011; Schaefer, 2023) and Australia (Nathan and Weinmann, 2019; Nathan et al., 2016). Various annual exceedance probabilities have been estimated for particular PMP values; that range of possible probabilities leads to uncertainty in the climate change effect because (at least at lower return frequencies) the climate change effect increases as the annual exceedance probability decreases (see also Jayaweera et al., 2023). Uncertainty also arises from uncertainty in the climate change effect at easier-to-estimate return frequencies and the need to then extrapolate those values to return intervals consistent with PMP. Extrapolation of the bottom quartile of estimates of the climate change effect yields something in the neighborhood of C-C scaling for PMP, but central and upper estimates for the climate change effect imply enhancements much greater than C-C. In addition, the climate change effect on short-duration storms is thought to be greater than that for daily precipitation. Estimates in the neighborhood of twice C-C scaling seem plausible, but the uncertainty associated with extrapolation over such a large data gap is massive. C-C scaling is a conservative, physically justified assumption, while neglect of climate change entirely is dangerously contrary to the evidence for extreme rainfall in general (e.g., Visser et al., 2022).

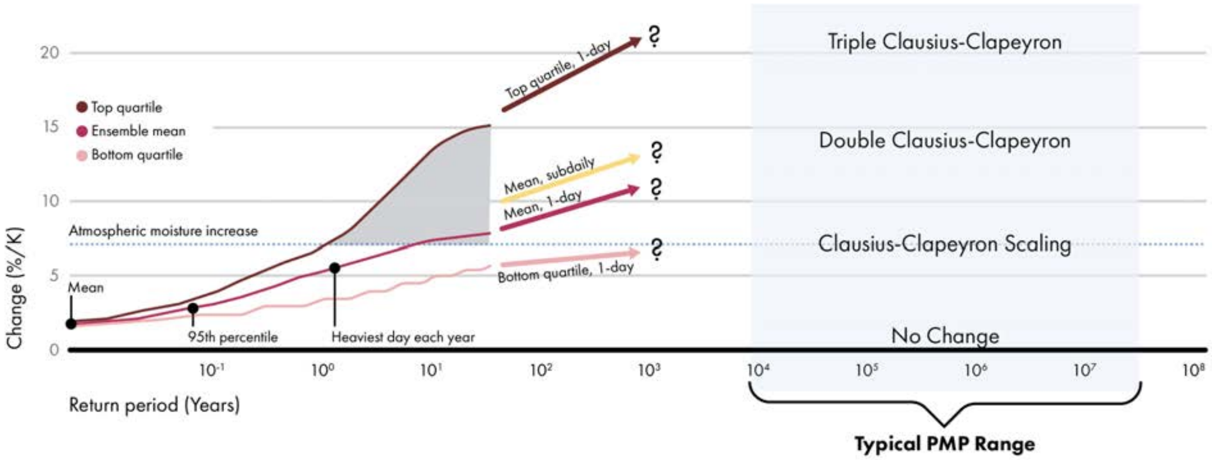


FIGURE 3-4 Illustration of the possible change in intensity of PMP due to climate change, expressed as a percent change per degree of increase of global mean surface temperatures.
NOTES: Estimates from shorter return periods are depicted as in Pendergrass (2018), but those provide limited information regarding the appropriate scaling at PMP-like return periods. In addition, evidence indicates that sub-daily extremes are intensifying more rapidly than daily extremes, but the magnitude of that difference is also poorly quantified. As a result, the actual scaling of PMP with climate change is not yet known and is poorly constrained.
SOURCE: Adapted from Pendergrass (2018).

Figure 3-4 uses global mean surface temperature (GMST) for C-C scaling. This is a common approach (Barbero et al., 2017; Chen et al., 2021; Guerriero et al., 2018; Liang et al., 2023; Jorgensen and Nielsen-Gammon, 2024; Myhre et al., 2019; Pendergrass and Hartmann, 2014; Westra and Sisson, 2011; Westra et al., 2013). Other reference temperatures have also been employed, such as regional mean surface temperature, often in conjunction with regional climate modeling studies (Fujibe, 2013; Förster and Thiele, 2020; Qin et al., 2021; Wood and Ludwig, 2020; Zeder and Fischer, 2020), regional mean surface dew point (Lenderink et al., 2019), local annual mean surface temperature (Bao et al., 2017; Pall et al., 2007), and local surface dew point conditioned on the occurrence of extreme precipitation (Lenderink et al., 2021). The latter approach has the most in common with the traditional PMP estimation procedures and may be most useful for understanding dynamic and thermodynamic contributions to changes of individual storms. GMST is much less directly related to the thermodynamic enhancement of individual storms, but scaling extreme precipitation by GMST has the virtues of (1) GMST being more robustly estimated and projected; (2) empirical and model-based estimates incorporate both dynamic and thermodynamic effects; and (3) the results are easily translated to future climate scenarios. The true C-C scaling factor based on any reference temperature is likely to vary geographically because of changes in weather patterns and differing dynamical changes across different storm types.

> *Conclusion 3-9: The assumption that climate change does not affect extreme rainfall, implicit in traditional stationary analyses, is contrary to multiple lines of evidence. Neglecting climate change generally underestimates both present-day and future risk of extreme rainfall.*

Conclusion 3-10: Clausius-Clapeyron scaling provides a useful means for quantifying changes in extreme rainfall due to warming. A 7 percent per degree scaling using global mean surface temperature is a handy rule of thumb, but it neglects dynamical influences on storm structure and frequency, and those seem likely to further amplify very extreme precipitation, including PMP-magnitude storms, particularly those of short duration. The overall magnitude of amplification is likely to vary with location and storm type.

ADVANCES: STATISTICAL METHODS

Colloquially, extreme precipitation events are described by "return levels," for example, a "100-year storm." Because terms such as 100-year storm can be misinterpreted by the public, and because such terminology is difficult to reconcile with changes in risk due to a changing climate, we choose instead to refer to event magnitudes in terms of their annual exceedance probability (AEP) depth. For a specified rainfall duration d, and a p between 0 and 1, the $p-$AEP precipitation depth is the precipitation magnitude that has a probability p of being exceeded in a particular year. Thus, the AEP depth is the $1-p$ quantile of the distribution of *annual maximum* precipitation for the duration of interest, which translates to a very high quantile of the overall precipitation distribution of duration d. For small p, the data records are often too short to estimate the AEP depth by standard quantile estimation methods; under a stationary climate, the $p-$AEP depth would require well over $1/p$ years of precipitation data.

The statistical approach to estimating an AEP depth that requires extrapolation into the tail beyond the range of the observed data is based on extreme value analysis (EVA). EVA is now a well-established area of statistics used heavily in climate science, hydrology, and other areas of environmental/earth science to characterize the behavior of extremes. The book *An Introduction to Statistical Modeling of Extreme Values* (Coles, 2001) serves as a widely used reference in this area.

Statistical EVA relies on the fundamental principle of fitting an extreme value distribution using only observations that are extreme, so that inference is not contaminated by data from the bulk of the distribution. The *block maxima approach* uses the maximum value from each block of data, which in earth/environmental science is often a year (and is also known as the annual maximum series approach). The use of the Generalized Extreme Value (GEV) distribution for modeling block maxima is theoretically justified because it is the appropriate distribution in the hypothetical as the block size goes to infinity. In practice this is interpreted as the block size is "large enough" to justify use of the GEV. The *threshold exceedance approach* uses values above a carefully chosen threshold, often empirically chosen as a high quantile (and is also known as the partial duration series approach). The theoretical justification for use of the extreme value distribution in this approach is that the distribution is the appropriate distribution in the hypothetical as the threshold goes to infinity. There are two common representations of the distribution in this approach: the generalized Pareto distribution and the closely related point process-based representation. For this approach certain tools can aid in choosing a sufficiently large threshold. Box 3-2 provides characterizations of the GEV and generalized Pareto distributions corresponding to those given in Coles (2001). In both the block maxima and threshold exceedance approaches, one can fit the available extremal data (block maxima or threshold exceedances) and obtain a characterization of the distribution's tail, which is governed by the three parameters that characterize these distributions. AEP depths are, in turn, simple functions of the three parameters.

BOX 3-2
Generalized Extreme Value and Generalized Pareto Distributions

The cumulative distribution function of the of the Generalized Extreme Value (GEV) distribution is

$$F(z) = \exp\left\{-\left[1+\xi\left(\frac{z-\mu}{\sigma}\right)\right]^{-\frac{1}{\xi}}\right\}. \qquad (1)$$

The parameter μ is the location parameter and as it changes the distribution shifts to the left or right. The parameter σ is the scale parameter, and it stretches or shrinks the distribution similar to a standard deviation. The parameter ξ is the shape parameter. The GEV distribution encompasses the Weibull distribution ($\xi < 0$), which has a finite upper bound; the Gumbel distribution ($\xi = 0$), which has no upper bound but has a light tail similar to the tail of a normal distribution; and the Fréchet distribution ($\xi > 0$), which has no upper bound and a heavy tail. To be precise, the Gumbel distribution's cumulative distribution function is given

by $F(z) = \exp\left\{-\left[\exp\left(-\frac{z-\mu}{\sigma}\right)\right]\right\}$, which is the limit of Equation 1 as $\xi \to 0$.

The $(1-p)$th quantile, z_p, of the GEV distribution (aka the $(1-p)\cdot 100$th percentile) is

$$z_p = \mu - \frac{\sigma}{\xi}\left[1-\{-\log(1-p)\}^{-\xi}\right] \qquad (2)$$

for $\xi \neq 0$ (there is a different equation when $\xi = 0$). When considering block sizes of 1 year (annual maxima), z_p is the precipitation depth with an annual exceedance probability (AEP) of p. In the case of a bounded distribution, the bound is $\mu - \frac{\sigma}{\xi}$. The presence of ξ in the denominator of these expressions helps to explain the sensitivity of AEP depth and upper bound (if it exists) estimates and their uncertainty to the value of the shape parameter.

z_p is estimated by substituting estimates for the three parameters into Equation 2 to obtain $\hat{z}_p$. The sampling variance (the statistical uncertainty) of $\hat{z}_p$ can be derived from the functional relationship in Equation 2 and the variance-covariance matrix for the estimates of the three parameters (when using maximum likelihood estimation, this is estimated by the inverse of the information matrix). This first-order approximation for the sampling variance is known as the delta method. Other methods such as bootstrapping or profile likelihood are also available and have been shown to have improved coverage performance.

Considering the threshold exceedance approach, the Generalized Pareto (GP) distribution has cumulative distribution function,

$$F(z|z>u) = 1-\left(1+\frac{\xi(z-u)}{\tilde{\sigma}}\right)^{-\frac{1}{\xi}},$$

for values $z > u$ above a threshold u , where $\tilde{\sigma} = \sigma + \xi(u-\mu)$, and μ , σ , and ξ are as in the GEV distribution. A convenient alternative representation of the threshold exceedance model uses a Poisson process representation to derive the probability density function (not shown) for threshold exceedance observations as a function of the GEV parameters, $\{\mu, \sigma, \xi\}$.

The fundamental behavior of the tail of the distribution (and therefore AEP depths for very small probabilities) is determined by the shape parameter ξ, also known as the tail index. Using the representation (parameterization) of the distributions given in Coles (2001), the distribution is unbounded when the shape parameter is non-negative. Note that this parametrization is not universal, and in the hydrology literature ξ is sometimes replaced by $-\kappa$ implying the distribution is unbounded when κ is not positive. Figure 3-5 shows how the upper bound and AEP depth are affected by changing the value of the shape parameter while holding the location and scale parameters fixed. For the most negative shape parameter values, the upper bound is not very different from small-p AEP depths, but it increases quickly, tending to infinity, as the shape parameter approaches zero. AEP depths increase with the shape parameter, but not as quickly.

Under stationarity (i.e., assuming the parameters do not change over time), these models can be fit to observations (either block maxima or values over the threshold) using a variety of statistical fitting techniques, including maximum likelihood, L-moments, and Bayesian methods. To account for variation over time, it is common to represent the parameters (particularly the location parameter) as regression-style functions of time or proxies for time such as global mean temperature or CO_2 concentration, and to estimate the parameters using maximum likelihood or Bayesian methods. In such analyses, AEP depth estimates change with time or the proxy variable.

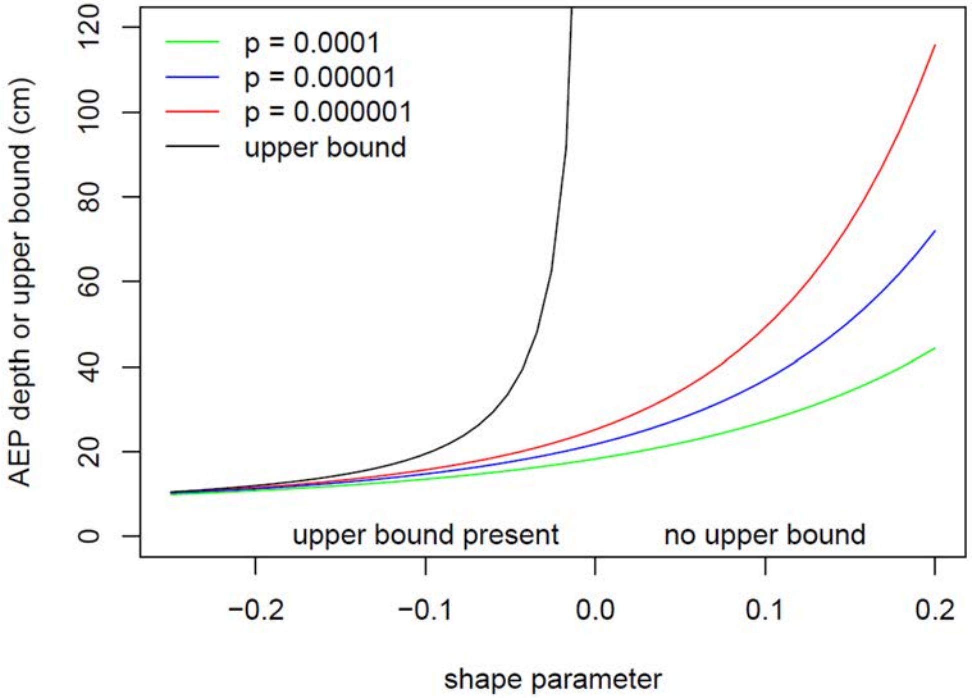


FIGURE 3-5 Relationships of the upper bound (black curve) and of precipitation depths corresponding to extreme AEPs (green, blue, and red curves for return periods of 10^4, 10^5, and 10^6 years, respectively) to the shape parameter of the extreme value distribution. The upper bound exists only for negative values of the shape parameter.
NOTE: The location and scale parameter values are based on a GEV fit to GHCN daily precipitation data for Berkeley, California, but the qualitative results (i.e., the curve behavior) are similar for parameters from GEV fits for other U.S. locations.

Uncertainty for the parameter estimates and estimated AEP depth can be characterized using a variety of standard statistical approaches, including likelihood-based, moment-based, and Bayesian approaches. In particular, for maximum likelihood, standard statistical theory enables approximation of the sampling distribution of the AEP depth estimator and therefore computation of a confidence interval (see Box 3-2). These approaches can also be used determine the sample size needed to achieve a chosen sampling variance (or equivalently the length of a confidence interval, as presented in Chapter 5). As is typical when quantifying statistical uncertainty, uncertainty associated with parameter and AEP depth estimates decreases as the sample size increases. By its nature, EVA is often limited by relatively short data records, resulting in a relatively small dataset of extreme values. In particular, the shape parameter that governs the fundamental tail behavior is often found to have large uncertainty (e.g., see Martins and Stedinger 2000 for hydrologic examples). The amount of uncertainty associated with AEP depth can be uncomfortably large and grows as extrapolation moves further into the tail (estimates more extreme AEP depths).

One possibility for increasing the amount of information is to borrow strength from nearby locations. Borrowing strength has a long history in the study of extreme precipitation and can be done via many methods such as regional frequency analysis, hierarchical Bayesian methods, distance-weighted local likelihood, or by directly smoothing return values estimated at individual locations. By borrowing strength across locations, uncertainty associated with parameter estimates, and in turn AEP depth estimates, are reduced. NOAA Atlas 14, the national precipitation frequency estimates currently in use, uses regional frequency analysis to combine data from regions determined to be homogeneous. Various approaches for borrowing strength across locations are being considered for use in the development of NOAA Atlas 15.

The extreme value methods described thus far are essentially univariate in that they aim to describe the tail of an individual variable. Even the aforementioned methods that borrow strength across multiple locations do so to better estimate the univariate distribution's parameters. The more advanced topic of analyzing the dependence of extremes for different variables, either reflecting different physical variables (de Haan and de Ronde, 1998; Heffernan and Tawn, 2004; Zscheischler et al., 2020) or the same variable at different spatial locations (Davison et al., 2012, Huser and Wadsworth, 2022), has seen an explosion of interest over the past couple of decades. Questions arising from the compound effects of coincident extremes require knowledge of dependence in the multivariate tail. Multivariate, spatial, and time series models have been developed to characterize extremal dependence and can be used to quantify risk of compound extreme events. Models for multivariate extremes are often computationally challenging, and the development of computationally tractable multivariate models is a continuing focus of extremes research.

If beginning with a locationwise characterization of extreme precipitation, PMP estimates for a spatial area (e.g., basin) encompassing multiple locations would require accounting for spatial dependence in the extremes. Similarly, PMP estimates for an aggregated temporal duration could require modeling of temporal dependence. However, with access to complete space-time fields (as recommended in the long-term model-based approach to estimating PMP), precipitation data can be aggregated to the space-time resolution of interest (e.g., 3-day precipitation over a basin of interest) and standard univariate EVA methods described above can be applied; the dependence is captured in the space-time fields and propagates into the aggregated statistics. Multivariate methods could still be relevant for describing and understanding the dependence of extreme precipitation at different spatial and temporal resolutions. Practitioners could also use multivariate extremes methods in conjuncture with the space-time field data to quantify risk of specific compound events not captured in PMP estimates.

In EVA, because the focus is on return values for precipitation over a given time duration, the notion of an individual event (a storm) is not directly relevant, and standard analysis would include precipitation from all types of events. To include data only from specific storm types, the standard EVA must be modified to account for the probability of the storm type occurring, in addition to modeling the distribution of precipitation given the storm type.

However, mixtures of storm types do create challenges for standard use of EVA. Fitting extreme value distributions using block maxima or threshold exceedances is justified based on asymptotic arguments and therefore assumes long blocks or large thresholds to achieve unbiased statistical estimation. When shorter blocks (e.g., annual maxima) or smaller thresholds are used, as is often needed with short observational records, the data being fit likely represent a mixture distribution across different types that cannot be well represented by a single extreme value distribution (e.g., Ben Alaya et al., 2020; Morrison and Smith, 2002; Villarini and Smith, 2010). A different type of mixture occurs in arid lands. Annual maximum rainfall and flood records in arid and semi-arid regions of the western United States exhibit mixtures in which some years have large events, but most years have effectively no events (J. Smith et al., 2018; Wang, 1990).

> *Conclusion 3-11: Extreme Value Analysis (EVA) is a well-developed branch of statistics specifically aimed at quantifying the magnitude of very rare events. Applying EVA to estimate PMP-relevant precipitation depths has specific challenges: the precipitation observational record is relatively short for estimating AEP depths associated with PMP-relevant probabilities, and data arising from mixtures of storm types or in arid regions can require specific consideration to avoid statistical bias.*

Precipitation frequency approaches that are not grounded in EVA have been proposed for PMP applications. Hershfield introduced an influential method for estimating extreme rainfall accumulations that is based on moment-based frequency analyses (Hershfield, 1961; see also Hershfield, 1965 and Koutsoyiannis, 1999). Douglas and Barros (2003) introduced multifractal methods for precipitation frequency analysis and applied them to daily and monthly rainfall series. Paired with methods for precipitation frequency analysis, the authors introduced Fractal Maximum Precipitation as a potential replacement for PMP. Multifractal methods provide innovative insights into the problem of PMP estimation, but they do not have the mature statistical foundations of EVA methods.

PMP AS AN UPPER BOUND?

The philosophy for engineering design developed by the Miami Conservancy (Chapter 2) was grounded in the assumption that rainfall and flood magnitudes cannot exceed an intrinsic physical upper limit (Miami Conservancy, 1916; Morgan, 1917). This view was expressed by the preeminent hydrologist of the era, Robert Horton, in a 1927 letter to the editor of *Engineering News Record*: “It is not difficult to show from sound meteorological reasoning, and aside from any statistical proof, that there is a natural limitation to rain intensity for any given duration” (Horton Archive, see Vimal and Singh, 2022).

For short-duration small-area rainfall, Horton's arguments for limiting rates of rainfall initially centered on updraft velocity, updraft size, and water vapor content (Horton, 1919). Subsequent studies expanded the conceptual formulations to address downdraft properties, microphysical processes, and storm rotation (Horton, 1948a, 1948b, 1949; these studies were all published posthumously). Horton recognized that the size of downdrafts and rainfall distribution in downdrafts are important determinants of rainfall extremes for small time and space scales (Horton 1948a, 1948b). He also concluded that size sorting of hydrometeors in updrafts and downdrafts plays an important role in dictating raindrop size distributions and the distribution of rainfall rates in downdrafts (Horton, 1948b). Horton also examined the role of rotational motion as a significant component of hailstorms that produce extreme short-duration rainfall (Horton, 1949). Horton never produced a comprehensive theory for bounds on rainfall, although research on the topic continued intermittently until his death in 1945. Much of Horton's research on extreme rainfall was unpublished when he died (Horton, 1948a, 1948b, 1949), reflecting the incomplete picture that had emerged on the question of bounds. Fundamental problems, such as specifying maximum updraft velocities remain unsolved (see Horton, 1949, Marinescu et al., 2020, and discussion above). Little research has been carried out on limiting rates of precipitation subsequent to Horton's studies.

> *Conclusion 3-12: A first-principles theory has not emerged to support the existence and characterize the magnitudes of upper bounds on precipitation.*

To some hydrologists and hydrometeorologists, compelling arguments for the existence of bounds on rainfall and flood peaks can be based on empirical evidence provided by "envelope curves" relating maximum rainfall observations to duration (Figure 3-6; Jennings, 1950; Shands, 1947) and maximum flood peaks to drainage area (e.g., Costa, 1987; Crippen, 1982; Enzel et al., 1993). Jennings' summary of world record rainfall observations stimulated research on scaling laws relating rainfall to duration, with results pointing to maximum rainfall scaling with the square root of duration. These curves typically show world record (or near record) point rainfall accumulations for various durations. For example, in NRC (1994), their Figure 1 shows an envelope curve with the equation $R = 16.4\ D^{0.48}$, where R is in inches and D in hours, as an apparent upper bound. However, since this time, the purported "upper bound" has been exceeded by large amounts. For example, the February 2007 rain event at La Réunion, a small, mountainous island in the Indian Ocean, exceeded this estimate by 500 to more than 1,000 mm over 3–6-day durations (Figure 3-6). This event indicates that the past empirical estimates of upper bounds are not necessarily well supported. Recent studies have taken a different perspective on record values, focusing on exceedance probabilities of envelope curves (Castellarin et al., 2005; Vogel et al., 2007). Envelope curve analyses provide insights into bounds on rainfall but have not provided tools that are used for specifying bounds on point rainfall as a function of duration for particular locations or regions.

Statistical Nature of an Upper Bound

Extensive statistical research has addressed the question of bounds on rainfall and floods, partly motivating the development of extreme value analysis (Gumbel, 1941). EVA has been applied to precipitation data from around the world in a large number of analyses in recent

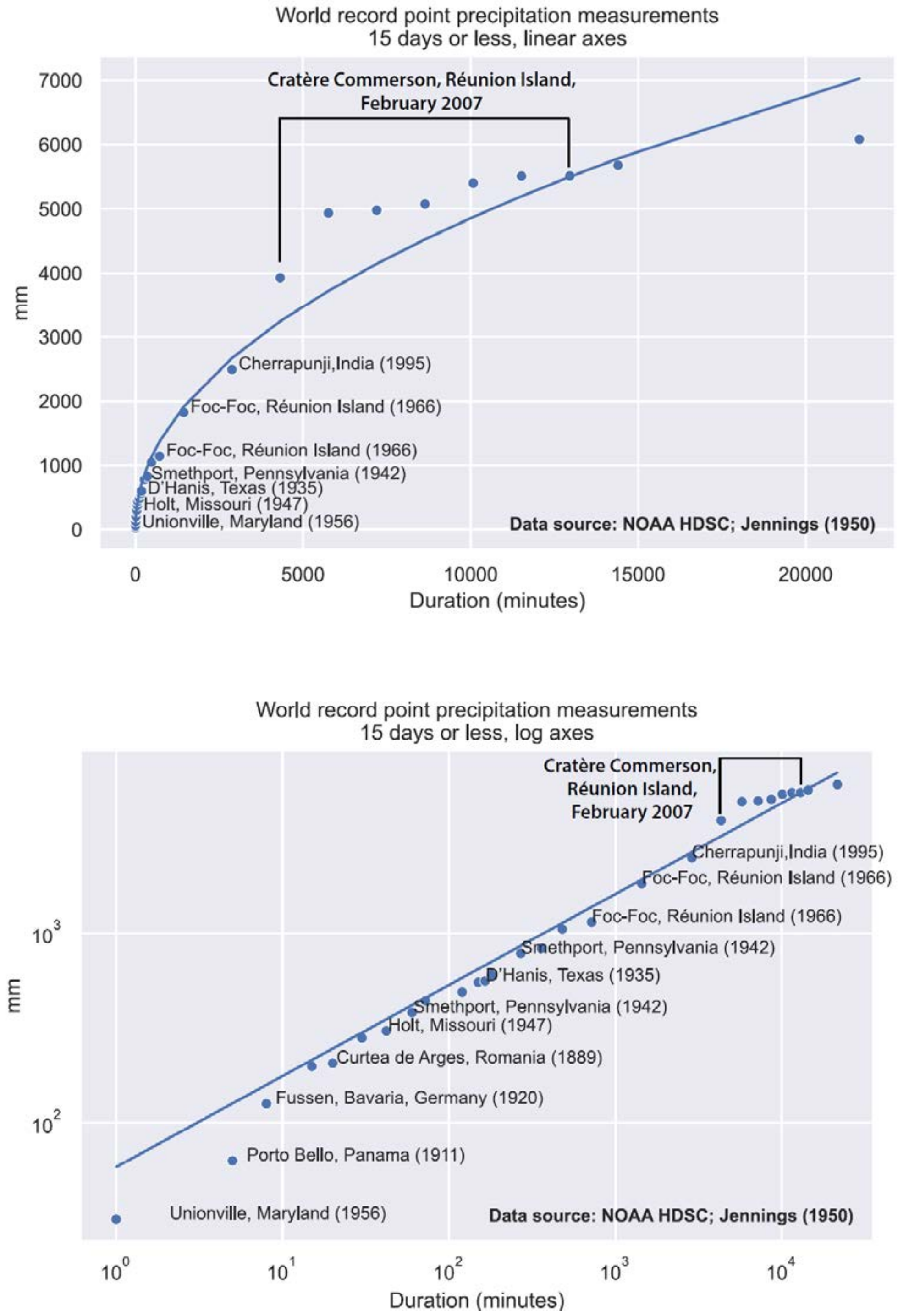


FIGURE 3-6 Envelope curves (linear and log scales), with world record point rainfall measurements with respect to duration.

NOTES: The blue line shows the function $R = 16.4\ D^{0.48}$ (with R in inches and D in hours; converted to mm) that was shown in Figure 1 of NRC (1994). The February 2007 observations at La Réunion that exceeded this line are highlighted in both panels.

SOURCES: Data from https://www.weather.gov/owp/hdsc_record_precip and Jennings (1950).

decades, with fitting usually done to individual station data. In many cases the estimated shape parameter is non-negative, suggesting unbounded precipitation distributions (Cavanaugh et al., 2015; Papalexiou and Koutsoyiannis, 2013; Papalexiou et al., 2018 and references therein; Serinaldi and Kilsby, 2014), as also seen in Figure 3-7. Analyses of more than 5,000 flood records in the United States also point in the unbounded, heavy-tailed direction (J. Smith et al., 2018). Koutsoyiannis (1999) advocates for abandoning PMP as an upper bound and replacing it with a very high quantile estimate obtained via EVA methods. There are caveats (limited sample sizes, statistical assumptions needed to carry out EVA) to the EVA of rainfall and floods, but there is little statistical evidence supporting the bounded assumption. Horton (1919) assumed that over time, large rainfall observations would pile up close to the bound, providing a natural path for statistical estimation of the bound, in line with modern extreme value statistics for bounded distributions. However, subsequent analyses of rainfall observations have not supported that path. For example, Hurricane Harvey, which approached or exceeded some multi-day PMP estimates, could have produced much larger precipitation totals if the storm had followed a slightly different path (Li et al., 2020). Given that PMP is often interpreted as a depth that cannot be exceeded, it is difficult to reconcile the current PMP definition with extreme value analyses that tend to indicate that precipitation is unbounded and difficult to empirically estimate an upper bound for use as a PMP estimate.

> *Conclusion 3-13: Statistical evidence does not support the assumption that precipitation is bounded; the evidence points to unbounded, heavy-tailed distributions.*

From a statistical perspective, even if an upper limit exists, use of the upper bound of a distribution as the quantity of interest has critical shortcomings relative to use of an AEP depth for a very small probability, as illustrated in Figure 3-5. First, even if the upper bound exists in principle, the quantity cannot be estimated empirically when the distribution is estimated to be unbounded. Second, in the case of a bounded tail, as the shape parameter increases toward zero, the upper bound becomes much larger than depths for even very extreme AEPs, such as for an AEP of 10^{-6}. The estimate of the upper bound in this situation will also likely be highly sensitive to the exact data used and the statistical estimation procedure chosen. Finally, as the shape parameter becomes more negative, the case where it is most practical to use the upper bound, the upper bound is very similar to depths for very extreme AEPs.

Climate Change

Global, regional, and local temperature increases are occurring, which results in increased moisture-holding capacity of the atmosphere through the Clausius-Clapeyron relation. The concept of a physical upper limit to rainfall must be referenced to a particular climate state under the presence of climate change.

The current PMP definition does not address climate change and thereby neglects the increase in atmospheric water vapor due to climate change, which can lead to an increase in PMP (e.g., Kunkel et al., 2013b) (see section on Implications of Climate Change for PMP in Chapter 4 for further details). Recent studies and summaries on extreme event rainfalls (e.g., Risser and Wehner, 2017; van Oldenborgh et al., 2017) and PMP (Visser et al., 2022) suggest that extreme rainfall magnitudes are increasing and PMP estimates will increase in the future.

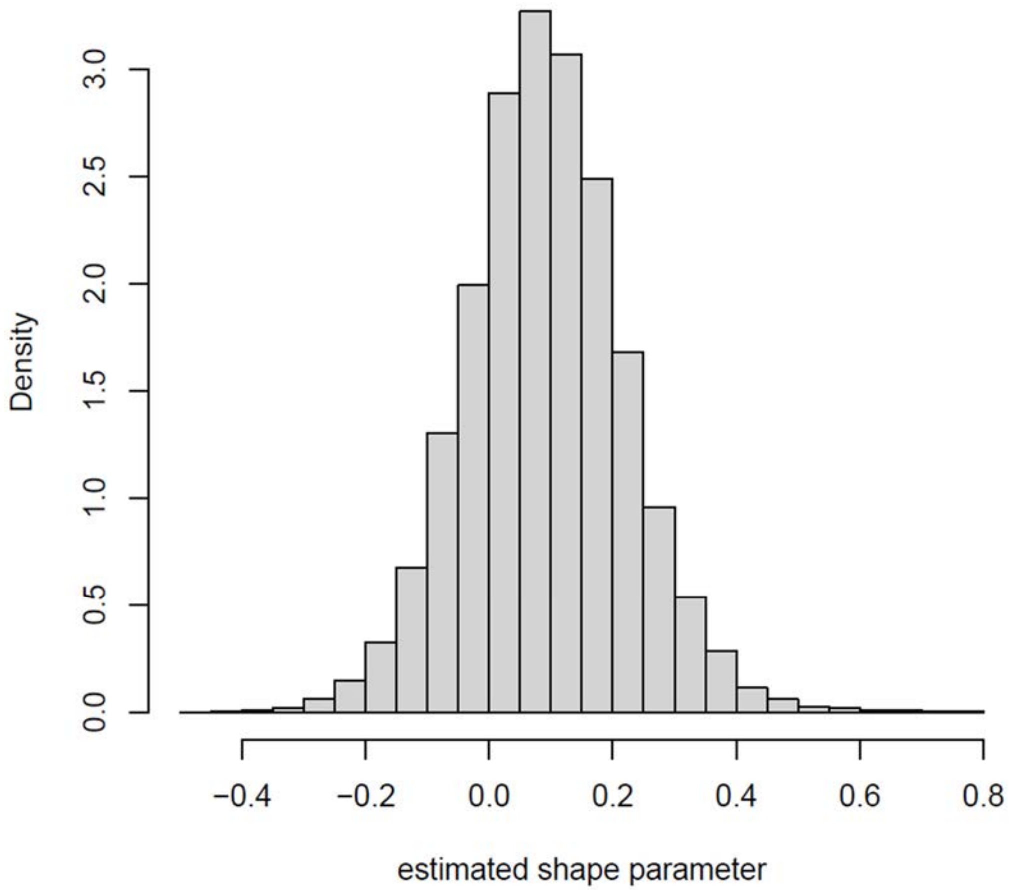


FIGURE 3-7 Distribution of shape parameter estimates from fitting individual station- and season-specific GEV distributions to GHCN daily precipitation data from stations in the contiguous United States.
NOTES: Estimated shape parameter values of zero or more correspond to unbounded distributions. The spread in the estimates reflects both statistical sampling uncertainty in the estimates for a specific location and season and variability in the true parameter values across locations and seasons.
SOURCE: Plot is based on parameter estimates from Risser et al. (2019b), provided to the committee.

4

Critical Assessment of Current PMP Methods

OVERVIEW

In 1992, the Nuclear Regulatory Commission requested a National Academies review of methods used to estimate PMP. The assessment concluded that “despite flaws in the PMP estimates developed by the NWS [National Weather Service], there is no compelling argument for making immediate widespread changes… This recommendation is based in part on lack of a clearly better alternative” (NRC, 1994). The assessment recommended critical areas requiring improvement of PMP estimation, notably for short-duration, small-area storms and for extreme storms in mountainous terrain. That committee also recommended pursuing advances in numerical modeling of extreme storms and integration of radar rainfall estimates from the NWS WSR-88D radar network into PMP studies. A final recommendation was for a “major new research initiative to improve scientific understanding of extreme rainfall events” (NRC, 1994). Chapter 3 of this report summarizes the current state of science and recent advances in science and methods, including those developed since the 1994 report.

PMP has provided a rational foundation for designing high-hazard structures and assessing the safety of these structures, but despite recent innovations, the core methods remain grounded in scientific ideas from the early 20th century. The PMP “flaws” identified in NRC (1994) centered on the core methods used for PMP estimation—storm catalogs, storm transposition, moisture maximization, and orographic separation—as well as foundational concepts including that of upper bounds on rainfall. PMP estimation has the appearance of a statistical procedure in which data are collected and an unknown parameter, the upper bound of the distribution, is estimated. This is a reasonable statistical problem, provided that an upper bound exists and a suitable statistical sample is available to estimate the bound. The incomplete nature of storm catalog data does not, however, mesh with notions of conventional statistical samples, and the methods for converting data to estimates do not align with conventional statistical procedures. The question of bounds on rainfall is at best unsettled.

PMP DEFINITIONS

PMP definitions and the concept of a theoretical upper bound on rainfall have been subject to criticism over the past 60 to 70 years. As noted in NRC (1994), “the dual definition of PMP as a physical upper limit of precipitation and as the collection of procedures used to compute an upper limit has created confusion and has hindered procedural developments.” The concept of a physical upper bound has remained explicit in PMP definitions. PMP is defined in the United States as “theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year” (AMS, 2022; Hansen et al., 1982). Appendix B provides an expanded treatment of evolving definitions of PMP including those developed by the World Meteorological Organization (WMO) (see also Chapter 2 for a summary).

Concept of Zero Risk and Risk-Informed Decision Making

Previous studies (Alexander, 1965; Ben Alaya et al., 2018; Klemeš, 1993; Kunkel et al., 2013b; Papalexiou and Koutsoyiannis, 2006; Salas et al., 2014; Yevjevich, 1968) have criticized standard PMP definitions and PMP estimation because they do not achieve "no risk," neglect uncertainty, and exclude increases in moisture in a changing climate. Criticisms have focused on risk and the dual nature of the PMP definition and methods used for PMP estimation. Alexander (1965) pointed to PMP definitions that dispense with upper bounds and focus on estimation of annual exceedance probability (AEP). Australian rainfall and runoff studies have included AEP estimates of the PMP since 1987 and note that "Assigning an AEP to the PMP is consistent with the concept of operational PMP estimates, which should not be regarded as theoretical upper limits of rainfall, as they may conceivably be exceeded" (Nathan and Weinmann, 2019).

Over the past two decades, major federal dam safety agencies, such as the U.S. Bureau of Reclamation (USBR), U.S. Army Corps of Engineers (USACE), Federal Energy Regulatory Commission (FERC), and the Tennessee Valley Authority (TVA), and some states (WA, CA) have moved to utilize risk-informed decision making (RIDM) for their dam safety programs (FEMA, 2015; FERC, 2016; USACE, 2014; USBR, 2022) rather than rely solely on standards such as PMP and Probable Maximum Flood (PMF). Designs and assessments for nuclear facilities also focus on risk (ANS, 2019). The critical risk input is a flood hazard curve (USACE, 2019a; USBR, 2013; H. Smith et al., 2018; Swain et al., 2006). Schaefer (1994) introduced methods for evaluating AEP of PMP estimates to enhance their utility for RIDM.

Key Observations

A review of current PMP definitions (Hansen et al., 1982; WMO, 1986, 2009), published literature, and assessment of user needs leads to the following key points, with history, details, context, and evolution in Appendix B.

- The original definition of PMP was developed by the NWS in collaboration with USACE and USBR and has changed over time.
- The definitions of PMP center on a physical upper bound on rainfall, which is not supported by observational evidence (see Chapter 3).
- The definition of PMP as an upper bound and methods used to estimate PMP have been subject to confusion. PMP is defined as an upper bound of rainfall, but PMP estimates can be exceeded.
- The definitions of PMP do not fully meet the present needs of the dam and nuclear safety communities, which must consider the uncertainty of the PMP estimate and the connection to probability estimates of extreme rainfall in RIDM for critical facilities.
- The definitions of PMP do not reflect potential changes in extreme rainfall due to climate change.

Conclusion 4-1: The current definitions of PMP are deficient, and a new definition is needed. This definition should acknowledge that PMP (1) is a quantity that is estimated from data, (2) should not be constrained by the assumption of an upper bound, and (3) can change as climate changes.

PMP DATA AND METHODS

Storm Catalog

To estimate PMP for a variety of storm areas and storm durations, a rich collection of major historic storms, that is, a storm catalog, is needed as a starting point (Myers, 1967). The original Miami Conservancy storm catalog published in 1916 (see Chapter 2) was updated in 1936 and included data from 283 storms in the eastern United States occurring between 1891 and 1933. In addition, the Miami Conservancy introduced techniques for depth-duration-area analysis that became central components of PMP estimation.

USACE adopted the Miami Conservancy storm catalog in the 1930s as a cornerstone of its evolving program for design and construction of high-hazard dams. Published in 1945, the initial USACE storm catalog included events from the Miami Conservancy catalog along with events from regions of the United States not covered by the Miami Conservancy (USACE, 1945). The USACE storm catalog still serves as a foundation for PMP estimation (England et al., 2020), but the geographic and temporal sampling of U.S. storms has not been consistent during the past eight decades.

Rainfall Observations for Extreme Events

Rainfall data for PMP-magnitude storms include many observations from bucket surveys, especially for short-duration, small-area storms. Development of storm catalogs during the middle decades of the 20th century involved close collaboration between USACE and the U.S. Geological Survey (USGS). Bucket surveys were often carried out by the USGS as a component of special studies of major floods. The July 1942 Smethport, Pennsylvania, storm (Eisenlohr, 1952) and the May 1935 D'Hanis, Texas, storm (Dalrymple, 1939) are notable examples.

The D'Hanis storm defines the United States and world envelope curve of rainfall for time scales around 2 hours, and the resulting Seco Creek Texas flood of 31 May 1935 defines the U.S. and world envelope curve of flood peaks for drainage areas around 300 km^2 (Costa, 1987). The extraordinary rainfall observations for the Smethport storm are paired with comparably extreme measurements of discharge and mass wasting from debris flows (Eisenlohr, 1952). Confidence in the rainfall analyses for these and other extreme storms is enhanced by their correspondence with the location, timing, duration, magnitude, and, where determined, the relative rarity (very low AEP) of the resulting flood flows, typically provided by the USGS.

Incomplete sampling of PMP-magnitude events in the USACE storm catalog is due in part to problems of observer bias. USGS flood studies that produced storm catalog events were triggered by observer reports that reflected the perceived societal importance of a particular event weighed against the availability of funding to perform the work. Loss of life was a key factor in close examination of the D'Hanis storm (Dalrymple, 1939); extensive damage to railroad infrastructure was a driver for examination of the Smethport storm. However, many events that resulted in USGS measurements of extreme flood peaks include little or no information on rainfall (Costa, 1987; Crippen and Bue, 1977; Smith et al., 2018). The USGS flood record implies that many PMP-magnitude storms are not included in storm catalog datasets. Another consequence of observer bias is that PMP-magnitude events in sparsely populated regions are less likely to be represented in the USACE storm catalog.

The current USACE storm catalog reflects changing engineering priorities over the course of the federal dam building era (Billington et al., 2005). Rainfall information was most critical during the period of accelerating dam construction from the 1930s and 1940s. When the last major federal dam was completed in the early 1980s, the need and funding for flood studies that enhanced the storm catalog and served PMP estimation had greatly diminished.

> *Conclusion 4-2: Coverage and completeness of storms in storm catalogs have varied over time and geographically across the United States in ways that are not consistent with conventional statistical samples and therefore preclude conventional characterization of uncertainty in PMP estimates.*

Rainfall Estimates from Radar

Following the recommendations of the 1994 NRC study, radar rainfall estimates from the NWS network of WSR-88D radars have become important data sources for storm catalogs and PMP studies (see, e.g., AWA, 2015, 2016, 2019). The 27 June 1995 Rapidan, Virginia, storm is a prominent example of a storm for which radar rainfall estimates control PMP for short durations and small areas (AWA, 2018). Radar rainfall estimates for the storm were constructed using reflectivity measurements with standard Z-R relationships and bias correction using surface rainfall measurements (Smith et al., 1996). Bias correction is an important component of rainfall estimation for the Rapidan storm, as is the case for other PMP-magnitude storms for which reflectivity-only algorithms are used (Baeck and Smith, 1998, Smith et al., 2000, 2005).

Bias remains an important issue for estimating rainfall from PMP-magnitude storms using polarimetric radar observations (Smith et al., 2023, 2024). Rainfall observations from the Community Collaborative Rain Hail & Snow (CoCoRaHS; Reges et al., 2016) network have provided an important source of storm total measurements for computing bias in radar rainfall estimates during the polarimetric era (Martinaitis et al., 2021).

> *Conclusion 4-3: Radar rainfall estimates have emerged over the past 25 years as a principal source of data for storm catalogs and PMP studies.*
>
> *Conclusion 4-4: Development of surface rainfall observations from both conventional and nonconventional sources is important for accurate estimation of PMP-magnitude rainfall, especially through assessments of bias in radar rainfall estimates.*
>
> *Conclusion 4-5: Enhanced information from gauge and observational networks and forensic precipitation-intensity and flood-flow field investigations are critical to accurate storm catalogs. Continued investments and enhancements to NOAA, USGS, CoCoRaHS and similar gauge and observational networks and post-event field campaigns are necessary to enable more accurate and complete information for understanding and interpreting radar-based observations and model simulations.*

Recommendation 5-6 (Chapter 5) is linked to conclusion 4-5.

Although polarimetric measurements from the U.S. radar network have been available for more than a decade, they have not been adequately integrated into estimation of rainfall for storm catalog events (e.g., AWA, 2019). Relative to reflectivity-only methods, there is significant potential for enhancing local corrections of radar rainfall estimates (Chapter 3) using polarimetric measurements (Ryzhkov et al., 2022; Smith et al., 2024). Enhanced polarimetric radar estimation algorithms for PMP-magnitude storms remain a key area of emerging methods to catalog storm data.

Extensive effort has been committed to development of phased array radar technology as a successor to the current generation of weather radars (Zrnic et al., 2007). This emerging technology holds potential for improving estimation of extreme rainfall, especially for short-duration, small-area storms. However, the time scales for development and deployment of phased array radars preclude major impacts on storm catalog development for near-term enhancements to PMP estimation.

Storm Types

Since national generalized PMP estimates were last updated in the 1970s through the 1990s, major advances in scientific understanding of extreme-rain-producing storms have emerged. As discussed in Chapter 3, extreme precipitation can be caused by a wide variety of storm types, including tropical cyclones (TCs), mesoscale convective systems (MCSs), atmospheric rivers (ARs), orographic “upslope” flow, supercell thunderstorms, and even ordinary thunderstorms in some cases. The temporal and spatial distribution of extreme rainfall is closely tied to the type of storm producing it. TCs and ARs may produce large accumulations over multiple days that cover vast areas, but they tend not to produce the most extreme short-term rain accumulations. In contrast, supercell storms can cause extreme short-term rain accumulations, but with relatively small spatial extent.

Storm types were integral to developing and implementing PMP estimation methods, including storm transposition, orographic transposition factors, and moisture maximization. For example, one of the first PMP studies (HMR 3) defined the “Sacramento storm type” (USWB, 1943b) for the Sacramento River, California, watershed using synoptic analysis, cyclone intensity, and 72-hour storm rainfall. Storm typing and storm classification systems played important roles in developing orographic precipitation models for PMP in the western United States such as in California (USWB, 1961), based on synoptic analysis, location and strength of blocking, and evaluation of wind, moisture, and moisture transport (Weaver, 1962). Various storm classification schemes and terms have been used that generally reflect the meteorology and geographic area under consideration. For example, in the Rocky Mountain region, storms were classified as “cyclonic” (with subclassifications as tropical or extratropical with a low-pressure center or front) or “convective” (convex or simple) (Hansen et al., 1988).

Storm types play an important role in determining transposition regions and in setting explicit transposition limits for observed storm rainfall (Hansen et al., 1988; Myers, 1966). Storm types are also used in restricting observed storm rainfalls to certain area sizes or Depth-Area-Duration (DAD) “zones” and storm durations for subsequent maximization and estimation of specific PMP “types.” Many recent statewide PMP studies have used simplified storm types and PMP types in a qualitative and subjective manner to develop PMP estimates (AWA, 2016. 2019).

Storm classification schemes in current use generally reflect concepts from the 1980s and do not reflect recent understanding and knowledge of synoptic and mesoscale meteorology. PMP studies at the time of Hansen (1987) separated storms into “General,” “Local,” “Tropical,” and “Orographic.” General storms are principally linked to extratropical cyclones, Local storms to thunderstorms, and Tropical storms to TCs. Standard practice in PMP studies over the past several decades has involved separate PMP computations for General, Local, and Tropical storms (e.g., AWA, 2016); these categories mix storm type and PMP type.

Abundant research has shown that storm classification is tricky, especially for PMP-magnitude storms (see Hirschboeck, 1987 for early developments). Similar to prescribing storm transposition regions, dividing storm events into different storm types creates abrupt "boundaries" in PMP storm properties. The remnants of Hurricane Ida (2021) in the northeastern United States produced PMP-magnitude rainfall at time scales less than 4 hours. The storm could be plausibly classified as Tropical, Extratropical, or Local (Smith et al., 2023). Under existing PMP procedures, the choice would have an impact on PMP estimates in candidate transposition areas.

Moreover, "storm types," as understood meteorologically, and "PMP types," as used in practice, are not necessarily aligned with one another. For example, in the formulations of Showalter and Solot (1942) and Bernard (1944), the principal storm types identified were (1) quasi-stationary cold fronts, (2) rapidly developing waves along a cold front, (3) major occluded cyclones, (4) TCs, (5) local or frontal thunderstorms, and (6) moist air flow up mountain slopes. In PMP analyses, these storms often been reduced to the categories of "general" storms, with precipitation lasting 24 hours or more and areas exceeding 500 mi^2, "local" storms, reflecting intense rainfall occurring over 6 hours or less (see Spatial and Temporal Scales in Chapter 2), and in regions proximate to coastlines, "tropical" storms, reflecting rain from TCs. Some studies also specifically include MCSs and storms that are a hybrid between different storm types. Yet in some state-level PMP studies, the classification of a storm based on meteorological data (such as an MCS) is not used in the PMP estimate for this type.

These classifications also often include implicit, but not explicit, information about seasonality. For example, in some parts of the United States, some storm types are limited to a particular time of year (e.g., TCs in summer and fall, convective storms almost exclusively in the warm season). Therefore, current PMP estimates for "local" storms may only be of concern in one part of the year. On the other hand, some users may require seasonal PMP calculations, for example, for floods that could be caused by rain on snow. The amount of precipitation needed for a dam failure in a rain-on-snow event may be less than if it were rain falling on dry ground.

For many reasons, it makes sense to consider storm type as a component of PMP estimation, and indeed this has been a major consideration in past PMP studies. Although in one sense, infrastructure does not "care" whether the extreme rainfall affecting it came from a TC or MCS, the temporal and spatial distribution of the extreme rainfall will vary depending on the type of storm. Climate change impacts on changes of extreme rainfall may also depend upon storm type. Accurate constraints on rainfall accumulations over defined time and space scales will necessarily be aligned with the types of storms that produce the rainfall. Different storm types may also have different levels of suitability or readiness for model-based PMP analyses, with AR events possibly most suitable.

Conclusion 4-6: Knowledge of storm types will remain a core component of PMP estimation at least until PMP can be estimated from long-term model simulations. New scientific knowledge should be incorporated in refining methods for specifying PMP storm types.

Storm Transposition

Storm catalogs and storm transposition have provided the inseparable foundation of PMP estimation from the 1940s to the present. The pairing of the two elements reflects the regionalization philosophy of trading space for time (Box 4-1) in estimating limiting rates of rainfall (Miami Conservancy, 1916; Myers, 1967; Showalter and Solot, 1942). Given a storm catalog of extreme events, PMP estimation revolves around a storm-by-storm decision on the extent of storm transposition regions (plus "maximization" corrections, as detailed below).

BOX 4-1
Trading Space for Time

The robustness of estimates of the expected frequency of particular extreme rainfall depths depends directly on the number of possible occurrences of such a depth in the data record. If such a depth has occurred several times, a better estimate of its likelihood of occurring in any given future year can be made than if it occurred only once, or not at all. Even if a depth has never been exceeded, it is still possible to estimate the depth's future frequency by fitting a probability distribution such as a Generalized Extreme Value to the data and essentially inferring how rapidly the frequency of such depths dies off as rainfall intensity increases. The expected quality of such a fit still depends on how many historical events came close to the particular magnitude of interest. In an ideal world, rainfall data would be available at a particular location from hundreds of thousands or even millions of years, and the climate would have not changed at all during that long period of time. Neither of these things is true in the real world.

The idea behind trading space for time is that climates are broadly similar across large geographical areas, and hence a particular rainfall depth or sequence of depths that actually occurred in one location might just as easily have occurred elsewhere in a place with similar climatic conditions. This assumption makes it possible to use information on weather events occurring in a broad region to estimate expected frequencies at individual locations.

In traditional PMP analysis, trading space for time corresponds to storm transposition. The locations where an extreme historical storm might be able to occur are estimated from considerations of climate and geography. Then various adjustment factors are applied to deal with observed or inferred climatic and geographical differences, such as moisture availability.

In regional frequency analysis, commonly used to estimate annual exceedance probabilities of 0.5–0.001 (events with a return period of 2 to 1,000 of years), regionalization is applied on a station-by-station basis rather than on a storm-by-storm basis. In this approach, extreme precipitation records from a set of adjacent stations are pooled, thereby providing a larger sample size for extreme frequency analysis. Often an "index storm" paradigm is used to correct for expected spatial inhomogeneities in extreme rainfall intensity, analogous to the orographic and moisture transposition factors used in traditional PMP analysis. The choice of which nearby stations should be pooled is made semi-objectively, based on subjectively established thresholds for proximity, time series similarity, and other issues.

Other approaches for trading space for time also exist. Newer approaches to precipitation frequency analysis utilize spatial statistical modeling to simultaneously pool data among nearby stations and interpolate to locations between stations, using the statistical properties of the data to infer how much influence distant observations should have on any given local estimate. Alternatively, stochastic storm transposition applies the semi-objective methods of regional frequency analysis to infer possible equivalent locations of the full set of individual historical storms, as opposed to the traditional PMP approach of treating each storm uniquely and subjectively.

Storm transposition decisions are intended to reflect sound meteorological reasoning, but scientific understanding has often lagged practice. For the Miami Conservancy design studies, a critical question was whether to transpose a storm that occurred in July 1916 along the eastern margin of the Blue Ridge Mountains in North Carolina to the Miami River basin; rainfall accumulations for the July 1916 storm were markedly larger than other events in the Miami Conservancy storm catalog. The decision to omit the 1916 storm was based on the assessment that “such storms cannot cross the mountain barrier” (Morgan, 1917). Although reasonable, this decision highlights the limitations of the current subjective approach to storm transposition, which can be overcome with the proposed physics-based modeling approach.

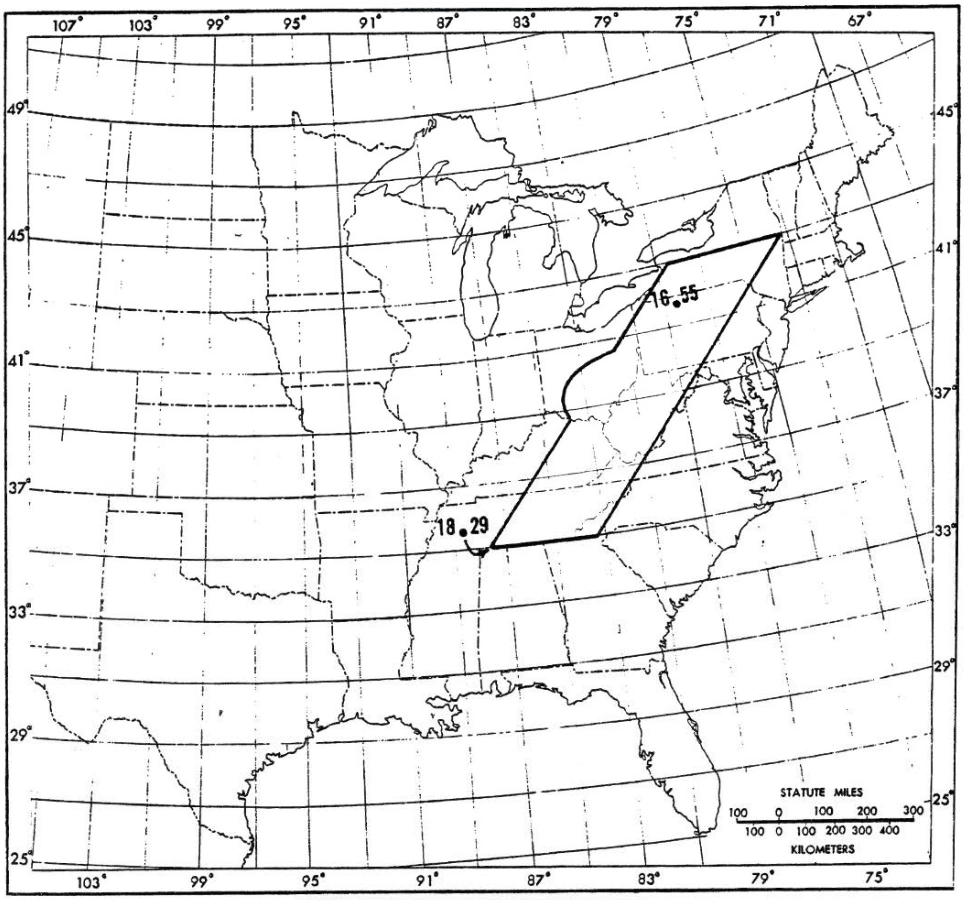


FIGURE 4-1 Importance of storm transposition and subjectivity: Smethport.
SOURCE: HMR 52 (Hansen et al., 1982).

Similar arguments have formed the basis for storm transposition decisions up to the present. The transposition region for the July 1942 Smethport storm in HMR 51 extends for approximately 1,000 miles from northern Alabama into central New York state (Figure 4-1). The eastern boundary of the transposition region is close to the western crest of the Appalachians (Allegheny Front), reflecting the conclusion that such storms cannot cross the mountain barrier. The decision is plausible, but compelling scientific arguments supporting transposition regions for the Smethport storm have not been presented. The supporting arguments used to justify transposition regions are often organized around specified storm types but ultimately rely on the scientific judgement of the meteorologists performing PMP studies (see, e.g., AWA, 2018).

In many regions of the United States, PMP estimates are very sensitive to the transposition region specification, which is based only on a small number of storms (see, e.g., Micovic et al., 2015). For instance, over large portions of the eastern United States, PMP estimates for sub-daily time scales depend strongly on whether the July 1942 Smethport storm is within the transposition region. Transposition decisions for the Smethport storm feature prominently in recent PMP studies for states in the eastern United States (e.g., AWA, 2018). Similar decisions will play an important role in PMP estimates based on near-term enhancements (Chapter 5).

Probabilistic Storm Transposition

Probabilistic concepts of storm transposition have been introduced to account for varying probabilities of storm timing, storm location, and storm characteristics (e.g., storm magnitude, storm pattern/orientation, or a set of meteorological variables associated with a storm) within a transposition region (Foufoula-Georgiou, 1989a). The Stochastic Storm Transposition (SST) approach allows for "uncertainty quantification of extreme rainfall amounts" (not of the uncertainty of the PMP as an "upper limit"), as one can create a relatively large number of storm patterns that could have occurred at a specific location at a specific time of the year and thus compute probabilities of exceedance of extreme rainfall amounts at any desired space and time scale relevant for flood estimation over a basin of interest.

SST has experienced a resurgence of interest in part because of advances in observations, especially from radar (Wright et al., 2014). Advances have been made in addressing spatial heterogeneities of extreme rainfall (England et al., 2014, Wright and Holman, 2019; Yu et al., 2021). However, even with these new observations and advances, record lengths are not sufficiently long for estimation of PMP-magnitude storms.

As illustrated by Arthur Morgan's 1917 discussion of transposition across the Blue Ridge, mountainous terrain has introduced troublesome issues for the concept of storm transposition from its inception. These issues are manifested both in the decision-making process for storm transposition regions in and around mountainous terrain (see, e.g., Hansen, 1987) and in the range of "correction factors" (such as moisture maximization discussed below) used to address spatial heterogeneities in the properties of extreme storms. Similar problems arise in other areas of complex terrain, especially regions adjacent to land-water boundaries and urban regions (see, e.g., Perica, 2018).

> *Conclusion 4-7: Storm transposition is a cornerstone of PMP estimation, but methods used to specify storm transposition regions have relied on subjective meteorological judgement; a solid scientific foundation for storm transposition is not available.*
>
> *Conclusion 4-8: A model-based approach for developing estimates of PMP (Chapter 5) eliminates the need for subjective storm transposition and associated correction factors that were historically used to address spatial heterogeneities in PMP-magnitude storms across the United States.*

Moisture Maximization

The purpose of moisture maximization is to maximize each selected storm to its theoretical upper bound. It involves multiple key assumptions, some of which have not been scientifically validated to date. It also involves subjective judgments that may not be independently reproducible and could at times seem arbitrary. Nevertheless, it is an important step in the conventional PMP estimation paradigm.

Conventional Approach in Estimating PMP

Following the paradigm discussed earlier that $P = EqwD$, and, assuming that PMP represents a physical upper bound to precipitation, the conventional approach to estimating PMP seeks to estimate that upper bound using observed quantities. Recognizing that an insufficient number of historical storms approach the hypothetical upper bound to permit direct estimation of that upper bound, the conventional approach estimates the maximum value of the components of P individually.

Only certain maximum values can be estimated, however. The duration D is pre-defined by the particular PMP being estimated. Historical observations provide extensive information on the range of possible values of moisture q. The precipitation efficiency E is not measured directly but is known to approach 1 for the heaviest rainstorms and even exceeds 1 for short periods of time through horizontal convergence of hydrometeors. Doppler radar observations in the modern era provide a means of directly determining the distribution of w, the maximum vertical motion maintained over a period of time D. But historical observations of vertical motion w, or equivalently convergence, were unavailable when conventional PMP methods were developed.

To overcome this deficiency, the conventional approach identifies “PMP-type” storms, those for which Ew is largest for a given D. Because $EwD = P/q$, and assuming a PMP-type storm can be identified that features the upper bound on combined vertical motion and precipitation efficiency for a given duration $(EwD)_{ub}$, within that storm we have $(EwD)_{ub} = P_{obs} / q_{obs}$. If moisture and dynamics are quasi-independent, $P_{ub} = (EwD)_{ub}\, q_{ub}$, and therefore $PMP = P_{ub}$ can be estimated from a PMP-type storm as $PMP = P_{obs}\, q_{ub} / q_{obs}$.

This approach is explained by Myers (1967) as assuming that extreme events provide “the effective measure of convergence” of the wind field. The storm transposition step translates observed storm rainfall (i.e., the indicator for maximum convergence of the wind field) to the location where a PMP estimate is to be computed. The quantity that is interpolated is interpreted as the “convergence and vertical motion” of the wind field, which is “unmeasured but is indicated by the precipitation.” It is further assumed that a sufficiently large sample of extreme storms has been detected and “at least one of them contained a convergent wind mechanism very near the maximum that nature can be expected to produce in the region.” Overall, this concept leads to an in-place maximization factor (IPMF) in practice:

$$IPMF = \frac{PW_{Max,S1,Z1}}{PW_{Storm,S1,Z1}} \tag{1}$$

where $PW_{Storm,S1,Z1}$ is calculated by a selected storm representative dew point temperature, at a location (S_1) that may represent the main source of moisture controlling the storm event, and from the storm elevation center elevation (Z_1) to the top of atmosphere (i.e., 30,000 ft elevation in the conventional calculation). Similarly, $PW_{Max,S1,Z1}$ is calculated by the historically maximum dew point climatology at the same location and elevation. In practice, an upper bound of 1.5 is imposed to avoid over-adjustment; however, no clear justification has been provided to support this specific value of upper bound (see DeNeale et al., 2021 for further discussion).

Both practical and theoretical assumptions are embedded within this approach. The practical assumptions are that both the moisture available to a given PMP-type storm and the upper bound on moisture can be estimated sufficiently accurately. The theoretical assumption is that the dynamics of the strongest storms, encapsulated in *EwD*, are independent of the thermodynamics *q*.

Moisture, Water Vapor, and Dew Point

In principle, the storm moisture should be the integrated water vapor within the saturated updraft of the storm averaged over the storm duration. In practice, direct observations of moisture within a storm are usually unavailable. If the storm is convective in nature—a class that includes ordinary thunderstorms, supercells, MCSs, and TCs—the updraft air originates from low levels in the atmosphere, and surface observations of dew point temperature in the inflow region of the storm can be used to characterize the moisture profile within the storm.

However, the process of estimating a representative dew point for an extreme storm involves important subjective judgments. As a result, different analysts may come up with different dew point values and arrive at different conclusions, which limits the reproducibility and credibility of the conventional PMP estimates. To estimate a representative dew point, a PMP analyst needs to review the storm track manually, identify stations with available dew point observations along or upwind of the storm track, and infer which upstream air will reach the storm location right before the occurrence of the storm event. Storms occurring near coastlines may have no upwind dew point observations available, in which case analysts must assume that atmospheric dew point temperatures can be estimated from nearby sea surface temperatures.

In larger-scale or orographically driven systems, such as extratropical cyclones and ARs, ascending air can cover horizontal distances of tens or hundreds of kilometers in its journey from the lower to the upper troposphere, with much or all of its ascent over cooler low-level air. For such storms, surface dew point or sea surface temperature may be grossly unrepresentative of moisture content in any given ascending column. In such circumstances, the upstream precipitable water (i.e., the total column water vapor) is a better measure of moisture within a storm system. However, vertically integrated water vapor measurements are rare for historical storms, so analysts must rely on computer-generated analyses of storm environments. Such analyses are inherently less accurate for storms prior to the satellite era (which began around 1979) and considerably less accurate prior to the rawinsonde network era (starting around 1948), rendering moisture maximization of older storms much less accurate than for newer storms.

The upper bound on the moisture that could hypothetically be available to a given storm also involves some arbitrariness and subjectivity. Different types of storms may only happen in particular seasons at particular locations, and the maximum possible moisture available to a storm thus depends on the time of year in which such a storm can occur. In the current practice, a 2-week window toward the warmer months is used to determine the applicable dew point climatology for estimating maximum possible moisture for a given storm (e.g., using the April 30 maximum dew point to maximize an April 16 storm). Depending on the type of available data, a 100-year return period dew point or a two standard deviation sea surface temperature may be used, although it is not obvious why different parts of the probability distribution should be used for dew point or sea surface temperature. Neither approach represents a theoretical or practical upper bound on moisture availability. In addition, no authoritative effort has been made to create and update dew point or precipitable water climatology maps to support PMP analysis (DeNeale et al., 2021).

> *Conclusion 4-9: The current process of estimating a representative dew point for an extreme storm involves subjective judgments and is difficult to independently reproduce.*

> *Conclusion 4-10: The upper bound on the moisture that could hypothetically be available to a given storm involves arbitrariness and subjectivity. Verifiable dew point or precipitable water climatologies, such as from modern reanalyses, would improve consistency and reduce, but not eliminate, subjectivity.*

Assumptions of Independence

One way to test the assumption of independence of dynamical and thermodynamic effects is by observed or simulated behavior of intense storms. Such studies have failed to find a linear relationship between total precipitation and available moisture. Observations of short-duration, small-area PMP storms such as the 1947 Holt, Missouri, storm have found surges of dynamical intensity occurring at the same time as increases of inflow moisture amounts (Lott, 1954). Studies using numerical simulations of intense storms with altered atmospheric moisture typically find nonlinear relationships between moisture and overall precipitation (Abbs, 1999; Chen and Bradley, 2007; Papalexiou and Koutsoyiannis, 2006; Rastogi et al., 2017; Yang and Smith, 2018; Zhao et al., 1997).

Whether independence within individual storms is absolutely necessary is not clear. A weaker constraint would require independence in a statistical sense, that is, that the population of high-end storm dynamics be uncorrelated with the population of high-end available storm moisture. For example, extreme precipitation from a supercell thunderstorm or MCS is maximized when the outflow boundary or gust front is stationary, which requires just the right amount of cold pool generation through evaporation and melting of falling rain, snow, and hail. A slight change in moisture could alter the production of cold air, causing the gust front to advance or retreat and preventing the most intense precipitation from being concentrated over a small area.

Toward that end, recent studies of statistical Clausius-Clapeyron scaling of extreme precipitation using dew point temperature are relevant. Observations of apparent C-C scaling tend to show annual maximum precipitation exhibiting scaling greater than Clausius-Clapeyron at sub-daily time scales but not daily or above (Ali et al., 2021; Guerriero et al., 2018; Wasko et al., 2018). Pérez Bello et al. (2021) compared observed annual extremes to seasonal mean dew points (which are more closely related to climate scaling than apparent scaling) and found a scaling of about 12%/°C. Modeling studies (Lenderink et al., 2021; Visser et al., 2021) find 10−14%/°C scaling at hourly accumulations, less at longer accumulations.

In summary, moisture maximization has practical challenges, both for conventional maximization of historical events and computer simulations that attempt moisture maximization of historical events. The overall concept of moisture maximization may approximately hold for long-duration precipitation extremes but underestimates the interaction between moisture and dynamics in short-duration extremes. Recent research suggests that for 1-hour extremes, rainfall totals increase by 1.5−2.0 times the increase in moisture.

Conclusion 4-11: The assumption of independence of dynamical and thermodynamical effects used in past studies is contradicted by research that suggests an intensification of convergence with an increase in moisture.

Transposition Factors

Following in-place moisture maximization, additional multiplicative correction factors are used to adjust a moisture-maximized storm from its original location to a targeted new location. These factors are also based on the concept that the relative change of maximum available moisture can be used to linearly adjust PMP. They also involve strong assumptions and subjective judgments, similar to the limitations encountered during in-place moisture maximization.

Moisture Transposition

When transposing a moisture-maximized storm from one location (X_1) to another (X_2), two types of adjustment factors are used: one to modify moisture availability at the new location, and another to account for the influence of terrain and orography.

Moisture transposition adjustment accounts for the differences in the maximum available moisture (i.e., PW_{Max}); in conventional practice, this is determined by dew point climatology. In particular, a moisture transposition factor (MTF) is used:

$$\mathrm{MTF} = \frac{\mathrm{PW}_{\mathrm{Max,S2,Z2}}}{\mathrm{PW}_{\mathrm{Max,S1,Z1}}} \tag{2}$$

where $PW_{Max,S2,Z2}$ is calculated by the maximum dew point climatology at the transposed moisture source location (S_2), and from the transposed storm elevation center elevation (Z_2) to the top of atmosphere (i.e., 30,000 ft elevation in the conventional calculation). The MTF is reduced (less than one) when transposing a storm to a location with a lower dew point climatology or a higher storm center elevation, and vice versa. Similar to Equation 1, the concept is based on the adjustment of the maximum available moisture based on dew point climatology. Therefore, the same limitations, such as the quality of dew point climatology maps and the determination of frequency levels, also apply.

While MTF accounts for differences in the maximum available moisture, it does not address other modifications resulting from terrain effects. Therefore, terrain and orography adjustments are needed. Broadly speaking, as air masses encounter mountains or elevated regions, they are forced to rise, leading to adiabatic cooling. This cooling can enhance condensation and precipitation on the windward side of the mountains, resulting in higher rainfall amounts than would be expected in a flat, homogeneous region. Therefore, when transposing a storm from flat terrain to a mountainous terrain, an orographic enhancement factor will be needed. If a major barrier exists along the storm track, the lower elevation moisture will not be able to cross the barrier and reach a targeted destination. In such a case, a barrier reduction factor will be needed.

Barrier Adjustment

In the conventional practice, when a barrier exists along the transposed storm track, a Barrier Adjustment Factor (BAF) is used to allow only a portion of the moisture to reach the transposed storm center.

$$\mathrm{BAF} = \frac{\mathrm{PW}_{\mathrm{Max,S2,Z3}}}{\mathrm{PW}_{\mathrm{Max,S2,Z2}}} \tag{3}$$

where $\mathrm{PW}_{\mathrm{Max,S2,Z3}}$ is still calculated by the historically maximum dew point climatology at the transposed moisture source location (S_2), but instead of using the transposed storm center elevation, it calculates PW from the average barrier elevation (Z_3) to the top of atmosphere, and hence reduces the amount of PW.

One issue that BAF does not consider is whether physical barriers in the original storm track caused moisture depletion, resulting in less total PW downwind of the barrier (DeNeale et al., 2021). Additionally, one may question whether it is reasonable to simplify the complex barrier into an average barrier elevation in the calculation. A larger issue is the assumption of an ideal and static distribution of water vapor as air crosses topography, which is unlikely the case during real moisture transport. Therefore, the BAF factor is an idealized approximation of orographic effects.

Orographic Enhancement

Orographic enhancement of extreme precipitation is a more challenging issue to address. Conventionally, a storm separation method (SSM), proposed in HMR55A (Hansen et al., 1988), has been used for orographic enhancement. SSM is based on the idea of estimating the amount of precipitation resulting only from dynamical ascent (i.e., convergence precipitation), and then increasing the values of the convergence rainfall to account for the orographic enhancement over the region, following empirically based methods to determine the adjustment factors. The process is complicated, and the rationale for the individual steps are not clearly documented. The complexity of SSM has prevented its use in recent PMP studies, and an alternative to SSM has not been developed (DeNeale et al., 2021).

Recent PMP studies have used the rainfall depth ratio from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 precipitation frequency product as an orographic adjustment factor. Specifically, an Orographic Transposition Factor (OTF) was proposed (AWA, 2013):

$$\mathrm{OTF} = \frac{\mathrm{P}_{\mathrm{Atlas14,100-year,X2}}}{\mathrm{P}_{\mathrm{Atlas14,100-year,X1}}} \tag{4}$$

where $\mathrm{P}_{\mathrm{Atlas14,100\text{-}year,X1}}$ represents the 100-year rainfall depth at location X_1 from the NOAA Atlas 14, and $\mathrm{P}_{\mathrm{Atlas14,100\text{-}year,X2}}$ is the value at location X_2.

The large geographic variation in NOAA Atlas 14 precipitation estimates over and around complex terrain makes the approach an appealing option for specifying orographic transposition factors, especially when transposing a storm from flat terrain to complex terrain. The question is whether the simple depth ratio in Equation 4 can indeed provide an accurate representation of the orographic enhancement. There are practical questions concerning the selection of 100-year return level as an index for orographic enhancement; other return levels may lead to different OTFs.

Additionally, a transposition factor of this kind incorporates a range of information unrelated to orography. When deriving an adjustment factor using NOAA Atlas 14 for two locations with similar orographic features, the adjustment factor could be very different. An OTF computed in this way includes other factors such as moisture availability, the availability and quality of rain gauge data for frequency analysis, the selection of probability density functions, goodness-of-fit, and more. Although the intent of SSM was to estimate the sole influence of orography based on the best understanding of rainfall processes, OTF in the current form is an unverified approximation to the complicated SSM process (see DeNeale et al., 2021 for further discussion).

Recent PMP studies have expanded the OTF to a Geographic Transposition Factor (GTF), in which this new factor can replace parts of the MTF functions, eliminate the use of BAF, and be applied everywhere even when the orographic adjustment is not needed. This practice also received some critical attention and remains unverified. There has not been a rigorous and independently validated study to evaluate the strengths and limitations of this approach.

In summary, multiple transposition factors are used in PMP studies to adjust the moisture-maximized storms to their new locations. Although in the long term the committee believes that these processes can be replaced by more justifiable numerical modeling approaches (discussed in the following chapter), in the short term a need to enhance these legacy methods remains.

> *Conclusion 4-12: Among the factors involved in storm transposition, the most significant challenge lies in addressing the orographic effect. There has not been a reproducible and scientifically justified method to handle all aspects of orographic adjustment. Although the storm separation method (SSM) remains a standard approach to estimate orographic enhancement, it is difficult to replicate results based on SSM analyses.*
>
> *Conclusion 4-13: Although rainfall frequency products may offer useful information to quantify the influence of orography on rainfall extremes, orographic transposition factors (OTFs) have not been rigorously and independently assessed to document the strengths and limitations of this approach. In particular, expansion of OTF to regions that do not require orography adjustment should be discouraged.*

Precipitation Frequency Analysis

As discussed previously, NOAA precipitation frequency products (Box 2-1) play a contributing role in PMP estimation by providing orography-related information for conventional SSM and OTF methods (AWA, 2018; Hansen, 1987). The underlying assumption is that rainfall frequency analyses for a long return interval (typically 100 years) can reflect spatial heterogeneities of PMP rainfall. This assumption has not been adequately examined for many regions of the United States and is especially problematic for sub-daily time scales, for which the density of rain gauges is extremely sparse, even for densely populated regions of the eastern United States. There are settings in which 100-year rainfall frequency fields are markedly different from PMP fields; the Upper Ohio Valley, for example, is a local minimum in sub-daily 100-year rainfall and a local maximum in PMP estimates.

In mountainous regions, the density of sub-daily rain gauges is typically sparse and in many settings the precipitation at low elevations is sampled more completely than at higher elevations. To address spatial heterogeneities in complex terrain, rainfall frequency analysis procedures have integrated mean rainfall fields derived from PRISM (Daly et al., 2008). These likely improve precipitation frequency results, but the relationships between mean rainfall from PRISM, 100-year rainfall from NOAA precipitation frequency products, and PMP estimates have not been adequately examined.

> *Conclusion 4-14: The sparsity of sub-daily rain gauges limits the utility of NOAA precipitation frequency products for implementing correction factors.*

Comparisons between NOAA precipitation frequency products and PMP estimates have also been used to provide assessments of potential inconsistencies in PMP estimates. For sub-daily time scales, the sparse distribution of rain gauges and the poor sampling of PMP-magnitude rainfall (see Chapter 2) results in large uncertainties in precipitation frequency estimates for long return intervals. Nonstationarities in sub-daily precipitation extremes over the historical record are also a serious challenge for Precipitation Frequency Analysis (PFA) (DeGaetano and Tran, 2022; Smith et al., 2024), introducing additional uncertainty in rainfall frequency estimates for low AEPs.

> *Conclusion 4-15: Gauge-based precipitation frequency products for sub-daily time scales are of limited utility for comparison with PMP estimates. Extreme value analyses based on sub-daily rain gauge data are not suitable for assessing return intervals of PMP estimates.*

NOAA Atlas 14 precipitation frequency products span a limited range of AEPs, with the smallest being 0.001 (see Box 2-1). NOAA states that PMP is used for assessment of critical infrastructure and that NOAA Atlas 14 frequency estimates are for low-hazard and minor structures, stating that estimates are “not intended for use beyond 1000-year average recurrence interval, or 1/1000 AEP” (NWS, 2020). NOAA does not provide precipitation frequency products (for any duration) with AEPs less than 0.001 or depth-area relations (ACWI, 2018), both of which are needed for RIDM.

Since the late 1990s, regional PFA (e.g., Coles, 2001; Hosking and Wallis, 1997) has been performed for dam safety RIDM applications (see summaries in England et al., 2011, 2023). These studies utilize the statistical advances described in Chapter 3 and provide watershed-average extreme precipitation distributions with AEPs usually ranging from 10^{-4} to 10^{-8} for individual dams. Durations are typically 24 hours to 72 hours, with data from precipitation gauges and storm catalogs. Studies have been conducted for USBR, USACE, TVA, and others to assess the safety of the largest dams in the United States (e.g., Friant and Shasta Dams in California) using RIDM, as well as for states (see Figure 2-2 in Chapter 2). While concerns exist about the ability to derive very low AEP depth estimates solely from limited historic observations, and the methodological limitations that regional frequency analysis cannot address nonstationarity or climate change, these estimates are used in designing risk reduction measures and modifications of high-hazard dams (e.g., USBR, 2013). In these settings, PMP has been used as an upper bound to precipitation frequency relationships.

Data and methods used in these regional precipitation frequency studies have been used to provide approximate estimates of the AEP of PMP, typically for large watersheds in the western United States, for integration with RIDM (Box 4-2). Schaefer (1994) notes that these studies were intended to provide magnitude-frequency relationships of extreme storm rainfall and not specifically targeted to estimate the AEP of the PMP. However, results give insights into the range of AEP estimates for PMP at various watersheds and across broad regions, with recognition of the uncertainty of the estimates.

Conclusion 4-16: A comprehensive study of methods to estimate the AEP of PMP has not been performed. There are limited locations where AEP estimates of PMP have been made.

Envelopment

Envelopment is a process to create the final PMP curves that encapsulate the largest values from all moisture-maximized storms (e.g., WMO, 1986). In particular, despite utilizing transposition techniques to increase the number of storms, there can still be gaps in areas and durations that need to be estimated during the envelopment process (Figure 4-4).

Envelopment is a key PMP concept that follows storm maximization and transposition. Maximization and transposition of major storms typically set the very lowest value of PMP at each grid point (Ho and Riedel, 1980). Envelopment establishes consistency throughout the study area and alleviates anomalies (Cudworth, 1989), so that the effects of using a limited number of storms can be reduced. Envelopment is typically performed for various area sizes and within various durations, to account for regional effects, and seasonal estimates (Corrigan et al., 1999; Ho and Riedel, 1980; WMO, 1986), so that PMP estimates are consistent throughout the region. Envelopment is typically applied to all basin-specific estimates as well as generalized PMP estimates. The basic envelopment process is to create maps of maximized and transposed PMP estimates from the largest (controlling) storms at pre-determined grid points (for regions) or the watershed centroid (for basin-specific estimates). At each grid point, smooth enveloping curves are estimated for each duration and for each area size (e.g., Figure 4-4). PMP maps are developed for each duration and area based on the envelope curves, and a final spatial smoothing step is performed to connect estimates at all locations. The PMP maps in HMR 51 (Schreiner and Riedel, 1978) are one example of this process.

Envelopment History and Applications

Envelopment methods and variables chosen for envelopment have changed over time. Envelopment was implemented in the first basin-specific PMP studies in the United States, HMRs 1 through 3. Envelopment was used in the first generalized PMP estimates for the eastern United States (HMR 23) and in subsequent generalized PMP estimates for this region (HMRs 23, 33, 51, 53). In California (HMR 36) and the Pacific Northwest (HMR 43), generalized PMP estimates were developed by estimating convergence and orographic PMP separately with an orographic precipitation model. Envelopment was applied to precipitation/moisture ratios for convergence PMP. In the Southwest (HMR 49), envelopment was applied to moisture-maximized storms in regions with minimal orographic influence. Envelopment of convergence PMP estimates (index map values) was performed for generalized estimates in the Rocky Mountain region (HMR 55A) and revised studies in the Pacific Northwest (HMR 57) and California (HMR 59). In each of the generalized HMRs, envelopment was also used in developing 12-hour maximum persisting dewpoints.

BOX 4-2
Annual Exceedance Probability of PMP

Limited estimates of the Annual Exceedance Probability (AEP) of PMP have been made using regional precipitation frequency analysis (advances described in Chapter 3) for 24- to 72-hour durations and various watershed scales (hundreds to several thousand square miles) in the United States. The AEP of PMP is not a constant value and depends on the following main factors:

- Storm duration and type,
- Storm and watershed scale, and
- Location.

For atmospheric rivers and mid-latitude cyclones examined in some western U.S. watersheds, AEP of PMP estimates range from 10^{-4} to 10^{-7}. A representative example for one watershed is shown in Figure 4-2. It is important to quantify the uncertainty in the AEP estimates, which can span three orders of magnitude at a location; point estimates are typically used.

Federal guidelines for dam safety risk management (FEMA, 2015) are useful in considering the range of AEPs of PMP that could meet Risk-Informed Decision Making (RIDM) guidelines as shown in Figure 4-3. The guidelines depict a relationship between probability of failure and consequences. For overtopping failure, the dominant factor is the flood hazard curve (magnitude and probability). Four example dams, representing potential failure from overtopping, illustrate that no unique flood hazard AEP would meet the Guidelines. Likewise, the AEP of PMP needed to meet the guidelines is variable and depends on consequences.

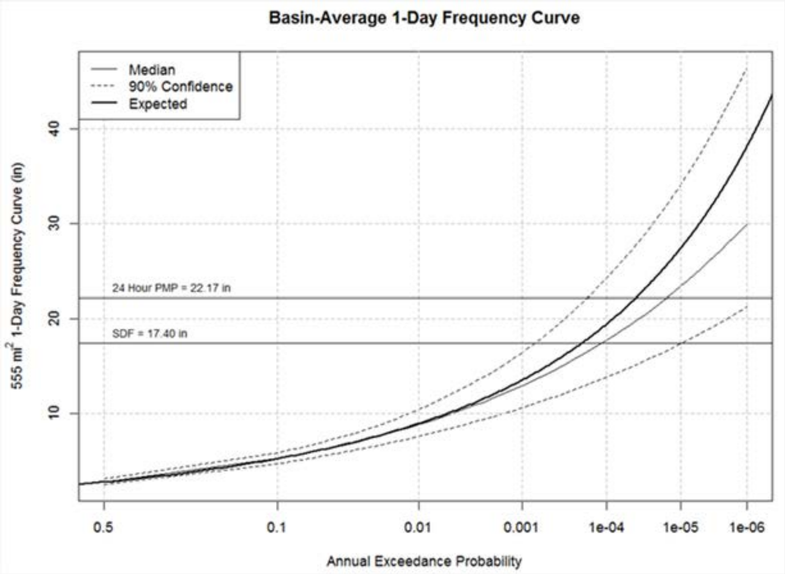


FIGURE 4-2 Example basin-average (555 mi^2) precipitation frequency curve with uncertainty and design rainfall estimates (horizontal lines) for Whittier Narrows Dam, California.
NOTE: (SDF – Spillway Design Flood precipitation depth used in the 1946 design).
The AEP of PMP for this watershed spans nearly three orders of magnitude, with a mean (expected) value of about 4.7×10^{-5}.
SOURCE: H. Smith et al. (2018).

continued

BOX 4-2 *continued*

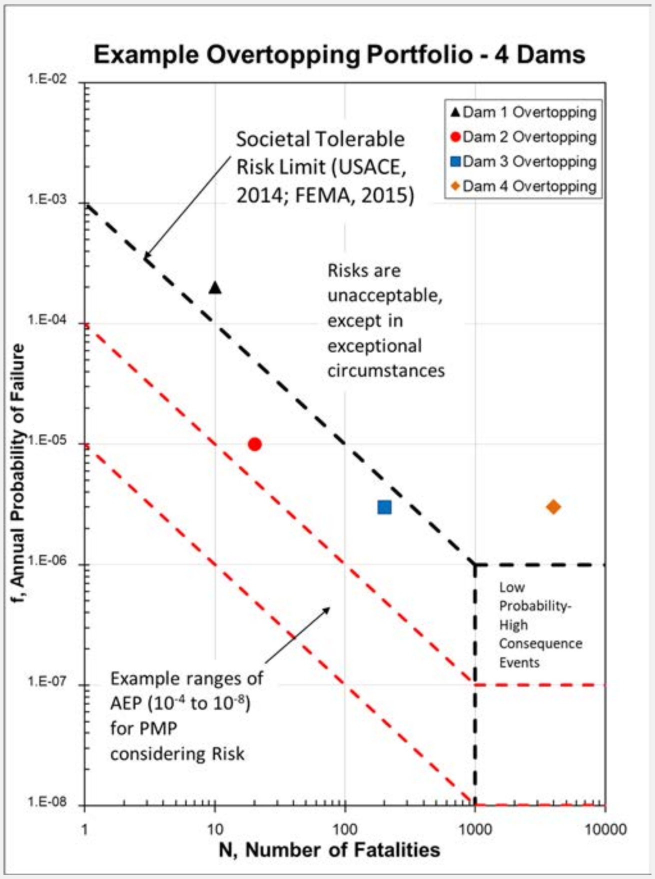


FIGURE 4-3 Example dam safety tolerable risk guideline used in RIDM (FEMA, 2015) illustrating risk estimates for four dams, with different overtopping failure probabilities and consequences.
NOTE: Risk estimates of dams 1 and 4 exceed the guidelines; risk estimates for dams 2 and 3 are less than the guidelines. The red lines represent conceptual PMP AEPs that could be considered consistent with this risk guideline.
SOURCE: Adapted from FEMA (2015).

The use of envelopment in statewide and regional PMP studies performed by consultants has varied, depending on the study. Envelopment of PMP estimates was performed in the Wisconsin-Michigan (EPRI, 1993), Nebraska, and Ohio statewide PMP studies, generally applied to depth-area curves by duration, similar to envelopment in HMR 51. Starting with the Arizona PMP study (AWA, 2013) and subsequent studies (e.g., VA, TX, CO-NM, PA, TVA), fixed geographic transposition zones were used. Storms were transposed to specific transposition zones, and envelopment was not performed across transposition zones, which can result in sharp discontinuities of PMP estimates in adjacent locations. Such discontinuities can be clearly seen in PMP maps from various statewide studies, such as the Virgina 72-hour, 100-mi^2 general storm map; the Colorado-New Mexico 24-hour 10-mi^2 general storm map, and the Texas 24-hour 100-mi^2 tropical storm map. Thus, transposing storm center locations without envelopment can result in artificial spatial gradients in PMP. Depth-duration envelopment and depth-area envelopment of PMP estimates were not performed in these studies, leading to lower estimates in some locations. The review board for the TVA PMP study recommended improvements and investigation of new methods, including using larger area storm centers, rather than single grid points (TVA, 2018); this would improve implicit transposition and envelopment.

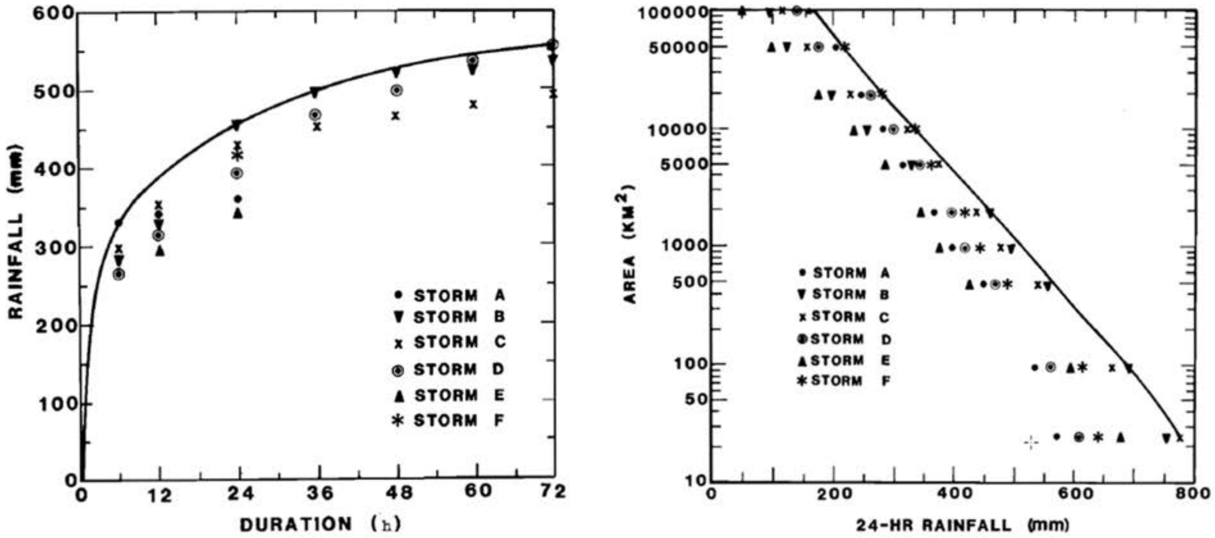


FIGURE 4-4 Examples of envelopment of generalized PMP estimates in time (across durations) and in space (across drainage areas).
NOTES: The left image illustrates depth-duration envelopment of transposed and maximized PMP estimates from 6 to 72 hours for a 2,000 km^2 storm area. The right image shows depth-area envelopment of transposed and maximized 24-hour estimates across storm areas ranging from 20 to 100,000 km^2.
SOURCE: WMO (1986).

Critical Assessment

Envelopment has been widely used in basin-specific and generalized PMP estimates from the 1940s through the early 2000s. Envelopment methods were largely conceived in the 1940s to smooth variations in sparse spatial and temporal storm rainfall data and subsequent PMP estimates. Envelopment concepts and methods are not sufficiently grounded in the physics of storm rainfall or in statistical methods. The concept and implementation have remained essentially static since the WMO (1973) definition (which was retained in subsequent WMO PMP manuals), other than minor variations in choice of variables for envelopment. This neglects advances in statistics (regionalization, scaling relations), storm mechanisms, storm types, transposition, and other physical insights on storm properties in space and time over a region. Envelopment has not been performed in recent statewide and regional studies; this generally leads to lower numbers and distinct discontinuities across states and state boundaries of studies. Envelopment procedures are not formalized across spatial scales or time scales in statewide or regional PMP studies. Ad-hoc grid-based procedures do not envelope and smooth across various transposition zones.

Conclusion 4-17: Although envelopment methods are widely used, their implementation has not been formalized and the procedures are not compatible with statistical approaches to PMP.

Uncertainty/Sensitivity Analysis

Current PMP practice begins with an assumption that the distribution of precipitation has an upper bound. This is the quantity (i.e., statistical parameter) that a PMP procedure seeks to estimate.

"Statistical" uncertainty (i.e., sampling uncertainty) is the familiar type of uncertainty associated with a statistical sample. Among other things, it can be used to produce uncertainty intervals (e.g., confidence or credible) for a population parameter or function of such parameters. A fundamental characteristic of sampling uncertainty is that as sample size increases, the uncertainty decreases, provided data are available that can inform the quantity of interest.

PMP estimation has the appearance of a statistical procedure, like the one Horton envisioned, in which data (precipitation measurements from historical storms) are collected and an unknown parameter, the upper bound of the distribution, is estimated. One can conceivably formulate the estimation of PMP as a well-defined statistical problem, provided an upper bound exists and a suitable statistical sample is available to estimate the bound. However, it is difficult to reconcile PMP practice (maximizing possible precipitation from an incomplete catalog of storms) with conventional statistical procedures for converting a statistical sample to an estimate for a quantity of interest. The number of storms, or even the number of observed/recorded years, is unclear, and the relevant storms are not used as a statistical sample. PMP is estimated from a single "controlling" transposed storm and subject to maximization and orographic adjustment, which does not fit within standard statistical estimation approaches. Although it would seem that over time the information about the PMP parameter (upper bound) would increase (the data record is more complete), how to use this information to narrow an uncertainty interval is unclear. (Of course, no uncertainty interval currently exists to improve upon.) Moreover, the practitioner community has not viewed or treated PMP as a statistical procedure, but rather a computation involving subjective choices about storm transposition, moisture maximization, and transposition factors. PMP practice has distinguished theoretical PMP from operational PMP, which consists of the steps used to compute PMP. One form of this approach is to treat operational PMP as the definition of PMP. For conventional PMP estimation, the distinction is not significant. But defining PMP by the steps used to compute it precludes statistical uncertainty estimation, one of the central tasks that the committee was asked to address.

Conclusion 4-18: Existing PMP methods do not characterize uncertainty in the standard statistical sense of sampling uncertainty and are not structured such that standard statistical techniques could be applied to estimate sampling uncertainty.

Other useful notions can provide insight about uncertainty, broadly defined.

Sensitivity

Because current PMP estimation requires various expert judgment-based decisions, the sensitivity of the PMP estimate to these decisions can be assessed. Rather than calculating PMP from single values of input quantities determining moisture maximization, transposition, and other factors provided by experts, one could instead conduct Monte Carlo experiments where one repeatedly draws from a distribution of possible values for those key quantities (e.g., Micovic et al., 2015). However, the width of a PMP interval obtained by a Monte Carlo experiment is not determined by the size of a sample, but only by an expert's a priori notion of uncertainty assigned to each unknown input component. Furthermore, given that PMP is focused on very unlikely events, the Monte Carlo results could be sensitive to the tails of the expert's distribution and to how the resulting distribution is used; for example, it is not clear how using a 95 percent interval when considering an upper bound could be justified. These ("prior") distributions are usually specified based largely on expert judgment but potentially informed, albeit perhaps qualitatively, by data. Thus, the uncertainty reflects the uncertainty in the expert judgment and decreases only when the variability encoded in the expert's distribution(s) decreases. Such Monte Carlo experiments can provide useful information about the sensitivity of the PMP estimate to the various input values and settings/configurations. However, the danger of such experiments that formally integrate over expert uncertainty (as opposed to, say, simple sensitivity analyses that vary an input parameter and report how the answer changes) is that consumers of such results will interpret them as reflecting standard statistical uncertainty. If all experts were to agree on the treatment of every storm, the Monte Carlo experiment would show zero sensitivity, yet uncertainty from the small sample of extreme storms would remain.

Stochastic storm transposition approaches can also produce uncertainty intervals (e.g. Foufoula-Georgiou, 1989a; Wright et al., 2013, 2020). The spread in these intervals results from drawing events and their characteristics from input distributions (e.g., distributions reflecting how far a storm might be transposed and in what direction). These input distributions are also based on expert judgment and therefore the resulting uncertainty can also be characterized as Monte Carlo uncertainty assessment. Again, the uncertainty interval does not have the standard statistical interpretation of statistical coverage.

Agreement

A second notion is agreement. Riedel and Schreiner (1980) compared PMP estimates over a range of spatial and temporal scales to the largest observed rainfall in the United States, focusing on events for which observed rainfall accumulations are greater than 50 percent of PMP estimates. Their results point to poor sampling of extreme storms in some regions of the United States (especially short-duration, small-area storms in the western United States). Riedel and Schreiner (1980) also compare PMP estimates to 100-year point rainfall accumulations, noting the inherent differences in the two products. Comparison with precipitation frequency estimates also points to sampling issues for short-duration rainfall extremes in portions of the United States. Comparisons of PMP estimates with observed rainfall and with rainfall frequency results in Riedel and Schreiner (1980) are not intended to provide direct assessments of agreement but to provide guidance on regions that are most likely to have significant errors.

Like PMP, PFA aims to characterize extreme precipitation events. Although there could be some overlap in the data that the two approaches use, PMP and PFA have been developed largely independently. It is difficult to reconcile PFA with current PMP practice, because PMP assumes an upper bound and PFA typically concludes that precipitation is unbounded and heavy-tailed. However, the notion of sample in PFA is well defined, and traditional notions of statistical uncertainty are readily available, although uncertainty intervals for PMP magnitudes are often too large to be useful for decision making. Despite their differences, a PMP estimate and a PFA characterization can be compared, and agencies performing RIDM are already doing this.

Synthesis of Critical Assessments of Current Methods

Current methods for PMP estimation are grounded in scientific concepts that are more than 70 years old and do not adequately reflect advances in scientific understanding of extreme rainfall that are detailed in Chapter 3. Recent PMP studies have integrated radar rainfall estimates into development of storm catalog datasets, but continued enhancements to rainfall data, especially through the full utilization of polarimetric radar observations, are needed. Historical storm catalogs have inherent limitations for PMP estimation because of the incomplete sampling of PMP-magnitude storms.

The principal components of PMP estimation—storm transposition, moisture maximization, application of transposition factors and envelopment—have weak scientific grounding and rely heavily on subjective judgment by PMP practitioners. The subjective nature of PMP estimation methods and the incomplete sample of PMP events in storm catalogs preclude assessment of statistical uncertainty in PMP estimates. The effects of climate change on extreme rainfall have been broadly recognized (Chapter 3), but procedures for integrating the effects of climate change on PMP have not been adequately assessed or implemented.

Standard methods for PMP estimation do not have a solid scientific grounding, but better integration of scientific understanding of extreme rainfall into the implementation of PMP procedures holds some potential for enhancing PMP estimates. Enhanced understanding of PMP-magnitude storms, especially through model-based reconstructions (e.g., Mahoney et al., 2022; see also discussion in Chapter 5), can provide a better foundation for determining transposition regions for critical storms. Advances in understanding orographic precipitation mechanisms can inform procedures used to implement orographic transposition factors. PMP estimation in mountainous terrain, especially for short durations and small areas, remains a major challenge for PMP estimation.

> *Conclusion 4-19: Current methods for PMP estimation do not have a solid scientific foundation, but more effective integration of scientific advances into the implementation of procedures can enhance PMP estimates. Model-based estimation methods are required to effectively address the impacts of climate change on PMP and to assess uncertainty of PMP estimates.*

NUMERICAL MODELING AND PMP

After the completion of HMR 59, the NWS discontinued PMP work (ACWI, 2018; England et al., 2011), and no advances in numerical weather prediction (NWP) modeling were applied to PMP estimation. The WMO (2009) PMP guidance did not include NWP and was critical of models, stating: “Physical models are not usable as they produce low-accuracy estimates of precipitation. The use of numerical weather models for PMP estimation is currently a topic of research (Cotton and others, 2003).” A recent summary of PMP methods did not mention storm models or use of NWP (Mukhopadhyay and Kappel, 2017).

The PMP practices from the 1970s though 1990s, the WMO statements, and recent summaries do not accurately reflect advances in NWP and modeling of extreme precipitation over the past 30 years that are relevant for PMP estimation (see Chapter 3). Recent statewide PMP studies generally follow HMR techniques of maximization and transposition. They utilize conceptual factors to transpose storms to account for terrain effects on moisture (see above section). These geographic transposition factors are not a conceptual model of atmospheric dynamics, storm mechanisms, or orographic precipitation; they only reflect climatological and geographical adjustment. NWP modeling conducted over the past decade provides potential opportunities for investigating and informing alternative approaches to estimating PMP.

Potential Opportunities and Insights from NWP

Atmospheric modeling has provided an alternative approach for addressing orographic precipitation mechanisms and estimating PMP using NWP (e.g., Chen and Hossain, 2016; Chen et al., 2017; Hiraga et al., 2021; Mahoney et al., 2013; Ohara et al., 2011; Toride et al., 2019; Trinh et al., 2022b; Yang and Smith 2018). The basic notion is to directly assess the geographic variation in PMP through modeling analyses that, in the best of worlds, can faithfully reproduce the physical processes at play. Modeling studies have also been used to examine assumptions underlying orographic precipitation procedures used for PMP (Cotton et al., 2003; Mahoney et al., 2012; Yang and Smith, 2018). The conclusions of the 1994 PMP study concerning PMP and orographic precipitation still hold. Advances in understanding and modeling extreme rainfall in complex terrain will be key to major advances in PMP.

Over the past decade, climate modeling has been explored as a component of PMP analyses, and to estimate PMP. Research includes a broad range of models and techniques (e.g., Chen et al., 2017; Gangrade et al., 2018; Hiraga et al., 2021; Ishida et al., 2018; Kunkel et al., 2013b; Mahoney et al., 2022; Ødemark et al., 2021; Ohara et al., 2011; Rastogi et al., 2017; Tarouilly et al., 2023; Trinh et al., 2022b). Maximum precipitation estimation using NWP (particularly for ARs along the West Coast) has been explored using variations of maximization and transposition methods, such as moisture maximization at the model boundary and shifting of the model domain (Ohara et al., 2011; Toride et al., 2019). Reconstruction of TC rainfall fields with models and exploration of transposition and potential maximization has been investigated (Mure-Ravaud et al., 2019a, 2019b). Modeling studies have been used for reconstructing major historical events for enhancing storm catalogs and for constructing storm catalogs based on climate change scenarios (e.g., Mahoney et al., 2022). A range of techniques has been employed to assess uncertainties in PMP based on climate model simulations. Climate modeling approaches to PMP create opportunities for statistical characterization of uncertainties in PMP estimates (see Chapters 3 and 5). These research studies illustrate the potential for using models to enhance PMP estimation. The results have not yet been translated to developing PMP products for many locations.

IMPLICATIONS OF CLIMATE CHANGE FOR PMP

Introduction

A notable limitation of traditional PMP estimation is its assumption of a stationary climate, disregarding evidence indicating shifts in extreme precipitation and in key meteorological factors linked to extreme storms, notably atmospheric moisture, in a warming climate. With rare exceptions, PMP estimates, as they are presently employed in decision making for federal, state, and local infrastructure in the United States, have not been directly influenced by information related to climate change (Mahoney et al., 2018). State-level and site-specific PMP studies often acknowledge the potential role of climate change on PMP but have recommended that the current practice should not be modified to address climate change (AWA, 2015; Mahoney et al., 2018). Among the federal agencies, USACE (2016) recognizes the lack of a substantial body of research to enable quantitative estimation of the relationship between climate change and extreme storms.

In the United States, only Colorado has explicitly included climate change in its official implementation of PMP (State of Colorado, 2020). Nonetheless, there are ways to at least partially include climate change effects in otherwise conventional PMP estimates, and emerging model-based techniques for estimating PMP can also partially include climate change effects. Future alterations in moisture levels, atmospheric dynamics, storm intensity, duration, and the efficiency and type of precipitation will collectively contribute to shifts in precipitation extremes. Of these, the thermodynamic effect is most easily incorporated into PMP estimates (see Conclusion 3-10). While there is robust confidence in the direction and approximate magnitude of change in thermodynamic aspects, including the rise in large-scale temperature and moisture levels, confidence wanes when it comes to alterations in circulation-based and dynamic effects, especially their manifestation in local-scale extreme events.

Because extreme precipitation events are highly localized occurrences, the substantial uncertainties surrounding dynamic effects pose a challenge to integrating climate change information into a fully deterministic framework (Mahoney et al., 2018). Nevertheless, considering the high degree of assurance that some form of change is likely, along with the relatively strong confidence in the mechanisms driving thermodynamic changes, incorporating basic estimates of trends into PMP estimates is justified.

Several approaches have been proposed but not implemented as standard practice. In the United States, USBR, focusing primarily on dam safety, has investigated the effects of climate change on PMP since about the mid-1990s (Eddy, 1996; England et al., 2011; Jensen, 1994; Sankovich et al., 2012; Toride et al., 2018). However, except in rare instances, such studies have not led to the formal adoption of climate change into operational practice. Because quantitative estimates of extreme rainfall, including PMP, require predictions of precipitation in an environment of future climate for which data are not available, all such approaches essentially require the use of information from climate model outputs corresponding to a future period. The literature suggests several techniques for the assessment of extreme precipitation under future conditions that include (1) nonstationary approaches using the Hershfield Method (Salas et al., 2020; Wasko et al., 2024); (2) nonstationary IDF curves (Schlef et al., 2023); (3) Clausius-Clapeyron scaling (Mahoney et al., 2018; Trenberth et al., 2003); and (4) hybrid approach for combining the conventional approach with Earth System Models (Chen and Hossain, 2019; Chen et al., 2017; Wasko et al., 2023). While all the above approaches have the potential for adoption in practice, the nonstationary formulation of Intensity-Duration-Frequency (IDF) curves and scaling approaches have seen the broadest use in estimation of extreme rainfall (Cheng and AghaKouchak, 2014; Ganguli and Coulibaly, 2019; Jorgensen and Nielsen-Gammon, 2024; Schlef et al., 2023).

Nonstationarity

The nonstationary approach in the context of extreme rainfall is largely focused on adjusting commonly used Depth-Duration-Frequency (DDF) or IDF curves (e.g., NOAA Atlas 14) to incorporate a temporal dimension that reflects the effects of climate change. Most DDF curves available today, including those in NOAA Atlas 14, have assumed stationarity during the historical and/or future period that is used for their derivation. Schlef et al. (2023) suggest two approaches for incorporating nonstationarity in DDF/IDF curves: covariate-based and simulated precipitation. The covariate approach to DDF curves is currently limited to AEPs of about 0.001, and extension to PMP-magnitude AEPs (e.g., 10^{-5}) is challenging because of broad uncertainties for such rare events in limited data. With respect to the "simulated precipitation" approach, both statistically and dynamically downscaled climate model data are being used to compute changes in extreme precipitation for a range of event durations and return frequencies. With sufficiently accurate present-day and future model output, it may be possible to apply conventional PMP techniques to the model output to project relative or absolute changes in PMP.

A simulated precipitation approach can also be applied to historical storms controlling PMP through a pseudo-global warming approach. Model output is increasingly being used to supplement or replace traditional transposition techniques, especially in mountainous areas (Ishida et al., 2015; Mahoney et al., 2022). The temperature and moisture fields prior to controlling rainfall events can be altered in models to reflect expected future temperature and moisture changes, thereby yielding a simulation of what such a storm might do in a future climate. This approach, discussed more fully elsewhere in this report, can simulate the most prominent effect of climate change, the thermodynamic one, but other effects such as changes in weather patterns are unaddressed.

Scaling Approaches

Change factors (C-C or otherwise) are a common way to deal with nonstationarity in extreme precipitation return value estimates, with basic 7%/K C-C scaling serving as a sort of default estimate of climate change impacts as discussed in Chapter 3. Similar change factors could be used for PMP (Manola et al., 2018; Martel et al., 2021; Visser et al., 2022). Although there is little or no information on how DDF/IDF curves may be adjusted to estimate PMP-magnitude extreme rainfall, current research documents several attempts using model-based projections of future precipitation. In its design standards, USBR (2013) recommended a factor of 5 to 10 percent increase in IDF for computing inflows before routing them through the reservoir. Irizarry-Ortiz et al. (2022) documented a comprehensive study to compute multiplicative changes in extreme precipitation from current to future (change factors) using extreme value analysis of several climate model datasets for all NOAA Atlas 14 stations within the South Florida region.

Specific challenges of this approach are (1) when and where temperature scaling could be higher than the C-C scaling of atmospheric moisture content (7% per degree of warming) and whether there is an upper bound on scaling rate; (2) whether such scaling may be region- or storm type-dependent (land vs. ocean, arid vs. humid land regions, convective vs. cold-season or orographic storms; Reed et al., 2023); and (3) whether any scaling is dependent upon climate state or may change over time.

Summary

Climate change has not been addressed systematically in the current practice of PMP estimation. Although numerous studies around the globe have investigated the effect of climate change on extreme precipitation, such studies on PMP-magnitude precipitation events are scarce. The C-C scaling approach, which has some physical basis, is appealing and with additional research may prove to be a promising approach for incorporating climate change in PMP estimation.

CRITERIA FOR A MODERN PMP ESTIMATION PROCESS

As the committee began its deliberations concerning the modernization and improvement of PMP estimation process, it sought to hear from various users and user groups about the deficiencies of the current PMP estimation process and the nature of needed improvements. On May 3, 2023, the committee held a public listening session to hear presentations and statements from various dam owners and PMP users and practitioners. Presenters included representatives of USACE, USBR, FERC, Nuclear Regulatory Commission, Federal Emergency Management Agency, Colorado Division of Water Resources, Colorado Dam Safety Unit, British Columbia Hydro, Applied Weather Associates, and MGS Engineering Consultants.

Although there was no unanimity, there was a surprising agreement among participants regarding major needs. Among the most frequently mentioned suggestions were the use of NWP models, a focus on gridded PMP products, better integration with RIDM approaches, more frequent updates, inclusion of longer storm durations and larger watersheds, finer spatial resolution, incorporation of radar data, and characterization of PMP uncertainty.

The committee also held information-gathering sessions to understand opportunities for improvements in data collection. Presentation topics included the use of polarized radar, satellite observations, the status and plans for various storm reanalysis programs, opportunities for improvements in earth system modeling including successes with storm-resolving models, and simulation including the use of artificial intelligence and machine learning.

Based on this broad and varied information, the committee developed a set of practical criteria to apply to assessment of the current PMP estimation process, as well as its own recommendations. Appendix D summaries these criteria. They include requirements for systematic and ongoing collection of extreme precipitation data and their publication as gridded time-histories in a nationally available and publicly accessible dataset; use of modern modeling methods; high spatial- and temporal-resolution PMP products; methods for linking the PMP estimates to probability and uncertainty characterizations; and a transparent production process with established time frames and systematic updates. Appendix D includes a general application of the criteria to the existing PMP estimation process as used in historical hydro-metrological reports published by NWS (e.g. HMR 51) and more recent state-sponsored PMP studies and reports.

Overall, the current PMP estimation processes, both those used by NWS and its predecessors, and those used by state-sponsored or individual investigators, failed to meet 20 criteria while partially meeting 3. Perhaps the most important of these were criteria for use of weather radar for routine data collection and modern NWP models. The committee recognizes that criteria based on these new technologies are predicated on their recent availability and in some ways represents a redefinition of success. Professional and public expectations for consistency between generations of PMP estimates and the lack of sustained national mechanisms for PMP estimation and related development have hampered the drive for and acceptance of new PMP modeling applications. Many of the modeling applications envisioned by the committee require advanced computational facilities and specialized expertise that are rare even among weather and climate researchers.

The committee assesses that two criteria that are key to use of PMP estimation in RIDM, AEP estimates and uncertainty characterization, could not be met under the current PMP definition. Reconsideration of the definition of PMP will be necessary before either criterion is likely to be met.

> *Conclusion 4-20: Current PMP methods are difficult to incorporate into risk-informed decision making processes.*

PMP Products

Over the past two decades, PMP products have evolved from generalized estimates provided as coarse resolution maps (e.g., HMR 51) and index maps (e.g., HMR 59) that cover large regions, to gridded, fine-scale (2.5 mi^2 or less) estimates over smaller regions or states. Generalized PMP estimates are characterized by higher values for all points in a region, even where smaller PMP values would result from topographic features in site-specific analyses (NRC, 1994). The newer PMP products that provide coverage for states and regions include considerations for topographic variations and local effects at these finer scales. These PMP estimates are generally lower (by 20−60%) than estimates from generalized HMRs for various durations and area sizes, because of limits placed on storm transposition and maximization and lack of envelopment. The newer products are limited in their spatial extent of PMP estimates and are restricted to specific states that have funded studies (see Figure 2-2). Nationwide coverage of consistent and reliable PMP estimates is lacking (see Appendix D for criteria).

An important advance for users of PMP products is the development of Geographic Information System (GIS) tools (in studies for states) that provide basin-average PMP estimates at a user-defined watershed of interest. These tools also provide separate estimates for each PMP type; recent PMP products include estimates for distinct categories such as General, Tropical, and Local. This practice followed from and expanded on the generalized HMRs in the western United States (HMRs 49, 55A, 57, and 59) that provided both General storm and Local storm PMP estimates. As discussed in the Storm Types section above, these mix storm type and PMP category in an attempt to provide PMP products at discrete spatial and temporal scales relevant for infrastructure designs and assessments.

The recent PMP tools for states are useful for practitioners because they provide basin-average PMP for a user watershed and storm temporal patterns (distribution of rainfall in time) for each PMP type. However, the tools do not provide comprehensive spatial patterns or integrated space-time storm rainfall distributions such as those provided in HMR 52 (Hansen et al., 1982) to spatially distribute PMP within a user-defined watershed. The spatial and temporal rainfall patterns are critically important in estimating the PMF peak flow and flood volume (Box 2-4). The HMR 52 spatial and temporal model to apply PMP over a watershed has been widely used but assumes a single PMP storm that encompasses all storm types. Notably, the recent Virginia (2015) and Pennsylvania (2019) statewide PMP studies abandoned the concept of using PMP for all durations and area sizes in one PMP storm as assumed in HMR 51 (Schreiner and

Riedel, 1978), and provided General, Local, and Tropical estimates. Earlier state studies for Michigan-Wisconsin (1993), Nebraska (2008), and Ohio (2013) had retained this single PMP storm assumption. The practice of specifying a PMP storm for a watershed using a depth-area relationship (or spatial pattern) and a temporal pattern that is separate and disconnected from the spatial pattern can be phased out of watershed applications of PMP estimates. A modern and comprehensive spatial and temporal model to distribute PMP estimates in space and time over a watershed is needed.

> *Conclusion 4-21: Space-time rainfall fields from the modernized storm catalog (using radar rainfall fields and model reconstructions) hold significant potential for enhancing methods used for specifying temporal and spatial rainfall patterns for watershed applications of PMP estimates.*

CRITICAL ASSESSMENT OF CURRENT PMP METHODS: SUMMARY

> *Conclusion 4-22: Current PMP practices rely heavily on subjective judgments, lack transparency, and can be challenging for third parties to independently reproduce. Furthermore, they do not permit the characterization of uncertainty and do not effectively address climate change.*

5
Recommended Approach

With the phased approach for modernizing PMP developed below, an initial phase of near-term enhancements to current PMP methods is followed by model-based methods for estimating precipitation depths with extremely low annual exceedance probability (AEP). The recommended approach is grounded in a broad vision to guide research and development:

Vision: **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.**

Achieving this vision will require scientific and modeling advances that should engage researchers across a broad array of disciplines. These advances will contribute not only to traditional PMP goals, but also more broadly to the societal challenges linked to the changes in extreme precipitation in a warming climate.

OVERVIEW OF A PHASED APPROACH

Near-term enhancements to PMP estimation will be based on improved data, expanded use of modeling, and effective use of scientific understanding in implementation of PMP procedures. Development of radar-rainfall data sets will provide improved data for PMP estimation, especially for the sub-daily, small-area context. Observations of precipitation in mountainous terrain can be flawed, owing to insufficient density of gauges and problems with radar beam blockage (e.g., Daly et al., 1994; Maddox et al., 2002). Reconstructions of storms producing PMP-magnitude rainfall through numerical models (see Chapter 3 on Numerical Modeling and Computing) can enhance storm catalogs and inform implementation of storm transposition and maximization procedures, especially in mountainous terrain. Greater scientific understanding will also guide implementation of PMP procedures, including the subjective decisions that are used for storm transposition. Approaches to addressing the effects of climate change can be based on temperature scaling relationships, with Clausius-Clapeyron (C-C) scaling providing the simplest method for computing climate adjustment factors until sufficiently credible model-based scaling is available.

Model-based simulations of precipitation over the United States will form the foundation for long-term modernized PMP estimation, including statistical characterization of uncertainty and incorporation of climate change effects on rainfall extremes. Large ensemble long simulations, produced by running multiple simulations with slightly different initial conditions, will provide the inputs for quantile-based statistical estimation of PMP over the watersheds of the United States based on precipitation depths associated with a pre-specified extremely low AEP. Estimates of PMP and their uncertainty will be obtained using extreme value methods. Decision makers will specify AEPs that define quantile-based PMP; PMP estimates derived from near-term enhancements will inform selection of probabilities for the long-term quantile-based PMP estimation. Model-based PMP estimation provides a natural framework for incorporating the impact of climate change, as detailed below.

The Model Evaluation Project (MEP) is a critical step in transitioning from near-term enhancements of PMP estimation to implementation of model-based PMP estimation. The advances in modeling capabilities necessary for PMP estimation will be developed and demonstrated, including approaches to incorporating the effects of climate change. At its core, the MEP will aim to determine when model-based approaches provide a suitable foundation for PMP estimation, as agreed upon by the broader community.

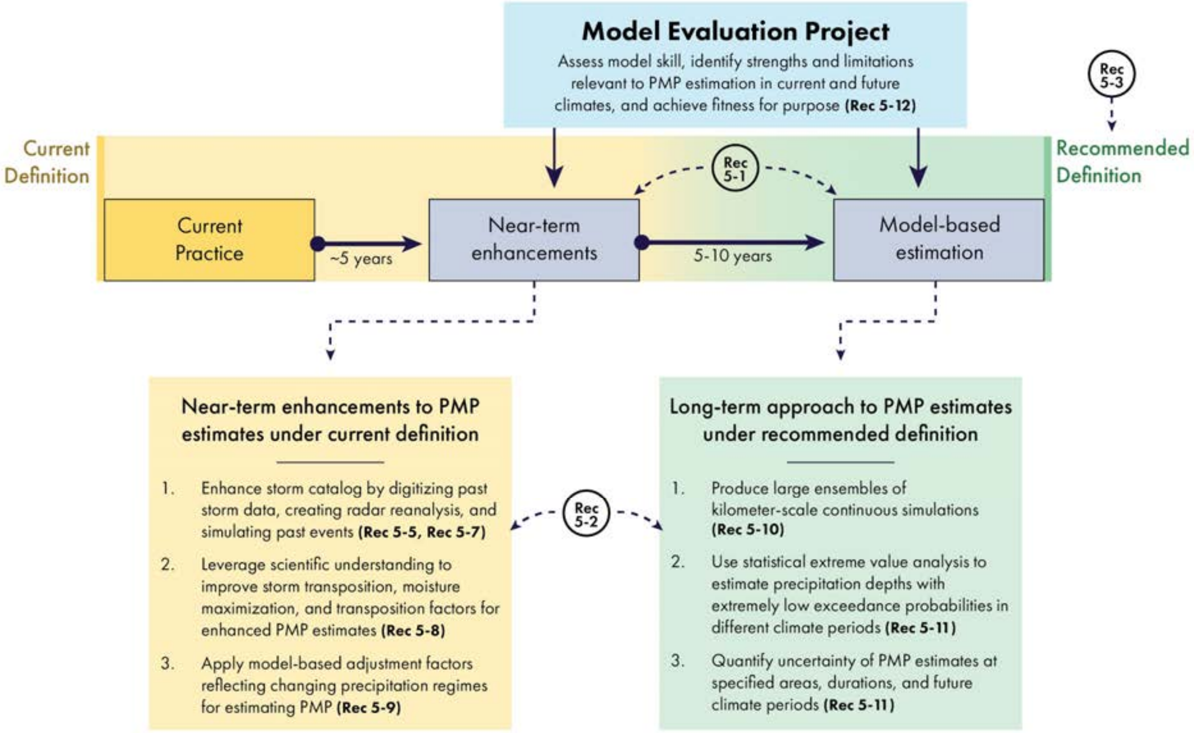


FIGURE 5-1 Overview of modernized PMP estimation.

> **Recommendation 5-1: NOAA should pursue a phased approach to modernizing PMP estimation, with the near-term approach building on enhancements to conventional PMP procedures and leading to a long-term model-based framework that can provide uncertainty characterization of PMP estimates, fully incorporating the effects of climate change.**

CORE PRINCIPLES

> *Conclusion 5-1: Four core principles should guide the development and use of modernized PMP estimates: transparency, objectivity, accessibility, and reproducibility.*

Transparency plays a pivotal role in building trust among practitioners, regulators, researchers, and the public. The concept should cover data and assumptions used to estimate PMP, PMP products, computer codes, and other ancillary information used in PMP estimation. It should also apply to timelines and schedules related to production milestones and opportunities for public review and comment. Transparency forms the groundwork for independent assessment of PMP products and facilitates evidence-based policymaking.

In pursuing objectivity, the aim is to minimize the reliance on subjective judgments. As detailed in Chapter 4, estimation of PMP using current PMP methods involves multiple subjective decisions by practitioners. Advances in data, tools, and scientific understanding of extreme rainfall can enable practitioners to more objectively implement PMP estimation based on near-term enhancements (as detailed below), provide guidelines to constrain and channel subjectivity where it is required, and document the subjective decisions that underlie PMP estimates. The transition to model-based methods will greatly reduce the need for subjective decisions in PMP estimation.

Accessibility of data and approaches should also be emphasized throughout the entire process of PMP estimation. Priority should be given to publicly accessible input data, analytical methodology, and computer codes. PMP products should be regarded as public goods within the public domain and be made available to the general public with minimum restrictions. In essence, adherence to the FAIR principles (findable, accessible, interoperable, reusable) is vital for improved data management and stewardship.

In terms of reproducibility, the expectation is that PMP products should be broadly reproducible using the same data and methods. For near-term enhancements to PMP estimation, differences in estimates can result from subjective decisions made by different practitioners, but key decisions in PMP estimation should be documented such that differences in PMP estimates can be readily assessed by PMP users. Model-based methods for PMP estimation will facilitate reproducibility of PMP estimates. Reproducibility is closely linked to the preceding core standards, as transparency, objectivity, and accessibility are essential for ensuring the reproducibility of PMP products.

In addition to the study principles described above, the committee advocates for sustained collaboration between the National Oceanographic and Atmospheric Administration (NOAA) and stakeholder groups throughout the process of modernizing PMP estimation. Collaboration efforts should focus on developing long-term relationships between NOAA and end-users, establishing two-way communication pathways between groups, and emphasizing the creation of usable science and products (Dilling and Lemos, 2011; Lemos and Morehouse, 2005; Meadow et al., 2015). Although collaboration among interested parties will likely be beneficial throughout the process, collaboration will essential for certain aspects of the process, as described in more detail below.

> **Recommendation 5-2: NOAA should deliberately engage the scientific and practitioner communities to enhance understanding of the scientific process, clarify methodological considerations, increase awareness of practitioner needs, and collaboratively shape resulting products in support of modernized PMP estimates.**

PMP DEFINITION

Based on a review and discussion of existing PMP definitions (Chapter 4, with supporting details in Appendix B), a review of PMP methods (Chapter 4), and assessment of user needs (Chapter 4 and Appendix D), the committee concludes that a revision to the current PMP definition is needed.

Recommendation 5-3: NOAA, federal and state agencies involved in dam safety and nuclear regulation, the American Meteorological Society, the American Society of Civil Engineers, and the Association of State Dam Safety Officials should adopt a revised PMP definition: Probable Maximum Precipitation—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 committee notes that this definition of PMP is separate and distinct from the various methods for PMP estimation. This modern definition reflects a deliberate focus on the physical quantity—precipitation depth—which is defined for a specific duration and location and applied over a particular spatial scale for application (Figure 5-2). The depth is defined for a particular duration that is relevant for a user application (see Chapter 2 section on Spatial and Temporal Scales for PMP Estimates) and may be a function of season; durations typically range from 1 hour to 96 hours. The term “areal extent” is the spatial scale specific to an application. For dam safety applications, spatial scales typically range from 1 to 10,000 mi^2 (Chapter 2). The 1 mi^2 scale is also used for pluvial flood hazards at nuclear reactor sites (Chapter 2).

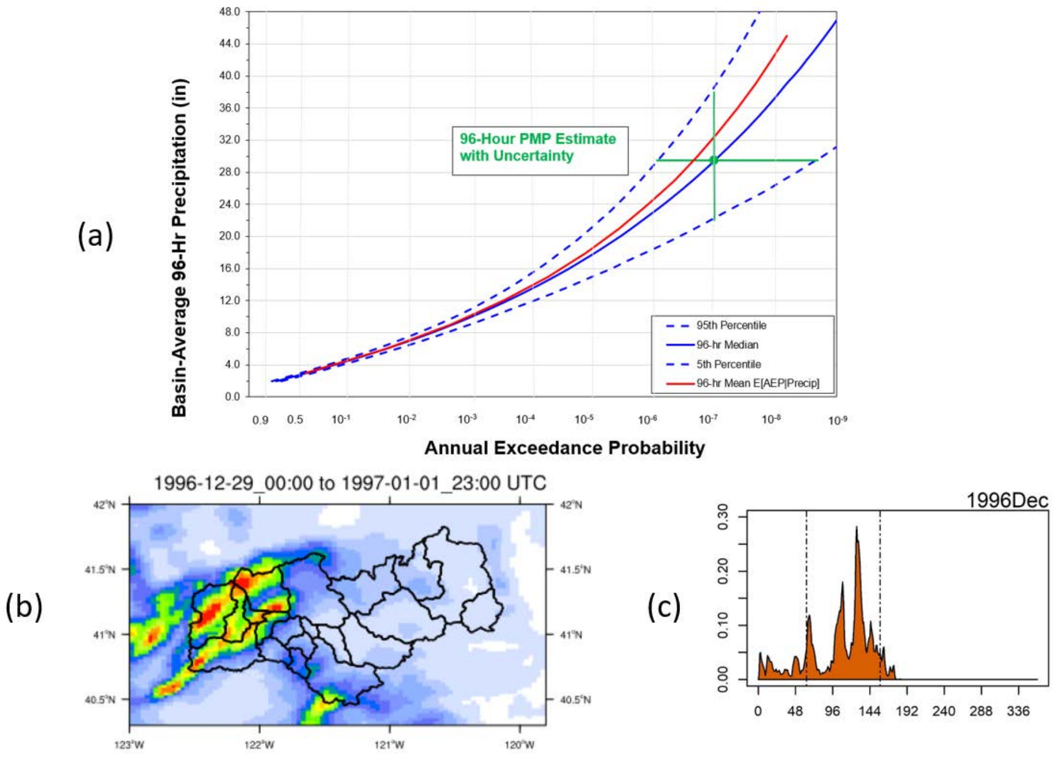


FIGURE 5-2 PMP precipitation depth that reflects the new definition. Components include PMP basin-average depth (a), spatial distribution over a watershed (b), and basin-average hyetograph (rain rates over time) (c) for a 96-hour duration event.

NOTES: The PMP basin-average depth is shown as a green dot in (a) with vertical and horizontal lines representing uncertainty in PMP depth and AEP, respectively. The spatial distribution of this 96-hour mean PMP depth over the watershed is shown in (b) with subbasins shown as black lines. Precipitation rates for each hour are shown in (c); vertical black lines are the start and end times for the 96-hour core precipitation period. The spatial distribution in (b) corresponds to the right vertical black line in (c).

SOURCE: Committee and Holman et al. (2019).

This precipitation depth is not an upper bound on rainfall but a depth with an extremely low annual probability of being exceeded (NRC, 1985, 1994). Extremely low annual probabilities have ranged from 10^{-4} to 10^{-7} for locations in the western United States (Box 4-2), which means that the depth referenced in the definition does not have a zero probability of exceedance. The extremely low AEP is not explicitly specified in the definition. Previous studies have suggested that the AEP of existing PMP estimates may vary by several orders of magnitude in the United States (Nathan and Weinmann, 2019; NRC, 1994; Schaefer, 1994) (see Box 4-2), at least for large watersheds and long durations. The selection of extremely low AEPs that define PMP can be achieved through guidance developed by the community.

Recommendation 5-4: Commensurate with the new definition, NOAA and the FEMA National Dam Safety Program, in partnership with federal agencies, states, and ASDSO, should develop guidance for specifying AEPs for PMP that are acceptable for infrastructure decisions and society.

The depth of precipitation that defines PMP is a quantile of the distribution (Box 3-2) of annual maximum precipitation corresponding with the specified AEP. This AEP will be extremely low. The choice of AEP can vary by location, duration, and areal extent. As noted above, the AEP of PMP estimates based on near-term enhancements can be assessed using model-based methods (details are provided in the Model-Based PMP Estimation Section below). These estimates, which can be developed as part of the transition from near-term enhancements to model-based PMP estimates, will provide useful information for specifying the appropriate AEP values for PMP. Risk-informed decision making (RIDM), nuclear reactor locations, and dam portfolios (Appendix C) are also important in selecting AEPs. The new PMP definition and model-based estimation process restore the physical basis behind PMP and enhance the utility of PMP estimates for assessing design floods (Figure 5-2). For the watershed shown in Figure 5-2, model fields are used to estimate the precipitation distribution and uncertainty. Model-based methods can provide PMP estimates for a specified duration and areal extent, as well as the capability for resolving additional aspects of rainfall variability that affect flood risk.

The depth of precipitation is defined for a specified climate period. This climate period is a duration of time (in years) and may represent the present climate or a future climate (see additional discussion in the Model-Based PMP Estimation Section below). By specifying a climate period for a specified year or set of years, the PMP depth is representative of that time period. Estimates can change over time and with selection of the climate period.

PMP estimation is based on assumptions, data, and models. As with current PMP estimates, PMP estimates under this definition are subject to change as knowledge of the physics of atmospheric processes improves (WMO, 1986), to reflect new information, newer and larger extreme storm datasets, and improved observation and model-based constraints on potential rainfall increases in a warming climate. PMP is estimated with uncertainty. The estimates can be described in a range with upper and lower limits that quantify (approximately) the uncertainty.

This definition applies to any specific location or spatial area (such as a watershed), any time of interest (including different seasons or climate periods), and any duration of interest, and is independent of storm type. Revised PMP estimation procedures are recommended to fulfill the intent of this modern definition of PMP and to meet user needs. The Advisory Committee for Water Information, Subcommittee on Hydrology, Extreme Storm Events Work Group (2018, p. 32) recognized that a revision to the current PMP definition may be needed as PMP methods and assumptions are revised. As with previous PMP definitions, this new definition can be adopted by NOAA in consultation with major federal agencies—U.S. Army Corps of Engineers (USACE), U.S. Bureau of Reclamation (USBR), Federal Energy Regulatory Commission (FERC), Tennessee Valley Authority (TVA), Nuclear Regulatory Commission, and ASDSO—and should replace the American Meteorological Association (AMS) Glossary definition.

NEAR-TERM ENHANCEMENTS TO PMP ESTIMATION

The long-term modeling framework will rigorously provide PMP estimates with robust scientific and statistical foundations. However, the full implementation of this framework may not be achieved in time to support some urgent needs. In the meantime, certain enhancements to present-day PMP estimation techniques are both needed and attainable. These enhancements will be based on improved data, expanded utilization of modeling, and the effective application of scientific understanding in implementing conventional PMP procedures.

Storm Catalog Data

> **Recommendation 5-5: USACE should make its existing storm catalog publicly available. NOAA should facilitate digitization and enhancement of the existing storm catalog of historical extreme storms used in PMP for the United States to contain gridded rainfall fields and moisture data for each event. NOAA should facilitate development of an expanded storm catalog including high-resolution radar rainfall fields and available surface rainfall measurements for the United States to improve near-term estimation of PMP.**

USACE, USBR, U.S. Geological Survey (USGS), and National Weather Service (NWS) have collaborated in various ways since the 1930s to collect and analyze storm rainfall data for PMP estimates (see example in Chapter 1 and summary in Chapter 3). The storm rainfall analyses, Depth-Area-Duration (DAD) data, and estimates of storm moisture for PMP have been used in the designs of most high-hazard dams in the United States. It is critically important to preserve the data from these "great storms" that represent the PMP-defining rainfall magnitudes in the United States. Preservation of data from these storms would facilitate comparisons of areal rainfall magnitudes from recent and future events, to assess increases over time and to quantify changes in PMP estimates.

These data are predominantly in paper and limited electronic formats from various Hydrometeorological Reports (HMRs), statewide and regional PMP studies, and some site-specific PMP studies. Full digital reproduction to gridded rainfall fields is recommended, with gathering, preserving, and archiving of surface observations and related data sufficient to reproduce the estimates. Individual storm rainfall centers, DAD summaries, moisture sources and influxes, and estimated transposition regions should be developed and archived for each event. The National Centers for Environmental Information (NCEI) would be an appropriate location for long-term storage, archiving, and maintenance of the extreme storm database (ACWI, 2018). The existing USACE extreme storm database (England et al., 2020) is a suitable prototype.

High-resolution rainfall datasets can be constructed from radar and surface rainfall observations to provide storm catalog data for the period from 1992 to the present (see Chapters 3 and 4 for discussion of key methodological details). Rainfall fields can be constructed with a spatial resolution of approximately 1 km and a temporal resolution of 5–15 minutes. The small spatial scale and short time resolution of rainfall fields are useful for addressing the ongoing challenge of PMP estimation for short durations and small areas (NRC, 1994). Although radar-based rainfall datasets will contribute to PMP estimation for all storm types, they will be most important in improving PMP estimates for convective storms, especially for time scales shorter than 12 hours and spatial scales smaller than 1,000 km^2. The radar reanalysis dataset (Recommendation 3-1) will provide an important resource for identifying candidate storms for inclusion in the storm catalog.

High-resolution radar rainfall fields during the NEXRAD era (from 1992 to the present) will be a principal component of storm catalogs and provide an important resource for near-term enhancements to PMP estimates. Because of phased deployment of radars during the 1990s and evolution of data archiving systems, near-complete records are not available prior to 2000. Radar coverage is also incomplete in some portions of the western United States, because of beam blockage in mountainous terrain (see additional discussion below).

For transparency in PMP estimation, methods used for computing rainfall from radar measurements and rain gauge observations should be standardized and documented. Procedures used for estimating rainfall from radar and rain gauges draw on a wide array of algorithms and assumptions, with quality control of both radar and surface rainfall measurements playing an important role (see Chapters 2 and 3). Documentation of methods used for development of high-resolution radar rainfall fields is critical for assuring that best practices are followed for transparency and accessibility of PMP estimates.

A time-consuming element of historical PMP studies has been the compilation of surface rainfall measurements (see Chapter 4). Surface rainfall measurements for storm catalog events should be a focus of data development activities, especially for the most extreme events that will control PMP estimates. Surface rainfall data should include conventional rain gauge measurements and all other measurements that can be obtained for a storm, including bucket survey measurements when available (e.g., Doesken and McKee, 1998). Similar attention should be paid to development of surface rainfall measurements for storm catalog events during the 1992–2024 period. Bucket surveys have not routinely been performed in recent years, but dense networks of gauges from the Community Collaborative Rain, Hail, and Snow network (CoCoRaHS) and other volunteer observing platforms provide detailed depictions of the spatial distribution of rainfall for durations of 1 day or longer.

Recommendation 5-6: NOAA should develop procedures for obtaining and validating surface rainfall measurements for PMP studies.

High-resolution radar rainfall fields during the period 2000–2024 can provide an important data resource for evaluating modeling systems developed for PMP estimation (see section on Model Evaluation Project below). The radar reanalysis dataset (see Chapter 3), which should be nearly complete for the period 2000–2024, provides observations that can be used to assess model simulations of current climate rainfall extremes across much of the United States. Intercomparisons between model simulations and high-resolution rainfall fields can be used to address the performance of models in simulating extreme rainfall for different storm types, especially for tropical cyclones (TCs) and convective storms. Intercomparisons can also contribute to regional assessments of model performance, especially for regions of complex terrain (mountainous regions, land-water boundaries, and urban environments).

Incomplete coverage by radar in mountainous terrain imposes geographic limitations on model assessments for mountainous regions. The "half-full glass" perspective on mountainous regions is that most radars in and adjacent to mountainous terrain can provide useful data for subsets of the radar coverage area. The Denver, Colorado, radar, for example, provides good coverage of portions of the Front Range, which has a complex history of PMP estimates (e.g., Friedrich et al., 2016).

For the polarimetric radar era (2013–present), high-resolution rainfall fields can be augmented by 3-D polarimetric fields for assessing model performance. These observations have proven especially useful in evaluating the capability of models to represent microphysical processes in extreme rain (Ryzhkov et al., 2020; Yang et al., 2019).

High-resolution radar rainfall fields can contribute to ongoing monitoring of rainfall extremes, including assessments of climate change impacts. Ongoing development of the radar rainfall datasets beyond 2024 will provide expanding observational resources for PMP analyses. Longer datasets will enhance the ability to assess performance of model simulations. They will also provide an observational base for assessing climate change impacts on rainfall extremes. NOAA will need to periodically evaluate the observed effects of climate change on rainfall extremes. The high-resolution rainfall fields will be especially useful for short-duration rainfall extremes, one of the biggest challenges for climate change assessments (Chapter 3).

Reconstruction of Rainfall Fields for Key Events in the Historical Storm Catalog Using Model Simulations

> **Recommendation 5-7: NOAA should facilitate model simulations of historical storm events that (1) may be added to the expanded storm catalog, (2) enhance scientific understanding of PMP-magnitude storms and their precipitation distributions, and (3) contribute to the MEP.**

Many of the storms that are currently used in PMP estimation occurred long before the advent of weather radar and other modern meteorological tools. As a result, the spatial and temporal distributions of precipitation in these events have been reconstructed, generally from sparsely located rain gauge measurements and "bucket surveys." The levels of confidence in these historical reconstructions vary, yet they represent the primary control on PMP in many regions. Retrospective analyses of these historical storms are not consistently accessible to the scientific community, because they have been developed by various agencies/companies and stored in a multitude of locations and formats.

In the 21st century, polarimetric weather radars and advanced algorithms to convert observed radar variables to rain accumulations have enabled much more detailed analyses of extreme rainstorms. Yet these methods also have uncertainties, especially in complex terrain where radar beams may be partially or fully blocked. Rain gauge coverage is generally greater now across the continental United States (CONUS) than in the past owing to efforts such as the CoCoRaHS network, yet gauge coverage is uneven, with highly populated areas having many more gauges than rural areas. Thus, consistently processed, publicly available simulations of historical PMP-magnitude storms are needed.

Model reconstructions of historical PMP-magnitude storms represent one method for enhancing storm catalogs in the near term, while also serving other purposes. Evaluations of model-simulated events that occurred during the radar era could be used to document existing strengths and weaknesses of numerical models for simulating PMP-type events. This task is the foundation of the MEP (see Model Evaluation Project section below), which represents one step in transitioning from near-term enhancements to PMP estimation to a fully model-based approach to PMP estimation. Simulated storm reconstructions will also be useful for supporting other near-term enhancements to PMP estimation (see further discussion in the following sections).

A promising approach for enhancing storm catalogs is to reconstruct each storm in the catalogs through the use of ensembles of high-resolution simulations with convection-permitting models, driven by global historical reanalyses, and produced by running multiple simulations with slightly different initial conditions or model configurations. Mahoney et al. (2022) demonstrated that this approach is possible for some PMP-controlling storms, most notably atmospheric river (AR) events with topographic focusing of extreme rainfall. For such simulations to be useful in near- and long-term efforts to enhance PMP estimation, simulations need to represent the general spatial distribution and magnitude of extreme rainfall in the region where it was observed, but they do not need to exactly replicate the location and timing of the event. Mahoney et al. (2022) noted that some historical events eluded successful simulation; short-duration, small-area rainfall extremes are especially challenging. So, while promising, expanding such model-based storm catalog information will require further research and development to improve models, determine whether data assimilation is needed/beneficial, and identify best practices for this approach.

Efforts to develop model-based entries to storm catalogs should begin with recent storms for which polarimetric radar data are available. The polarimetric data permit a comprehensive evaluation of simulations of these storms, enabling assessment and enhancement of the model configurations. Enhancements can contribute to reconstructions of historical storms that control or approach PMP, and for which high-quality detailed reconstructions are not currently available. These would include challenging events such as the Smethport, Pennsylvania (1942) and D'Hanis, Texas (1935) storms that control short-duration, small-area PMP estimates over large regions. These efforts should encompass a range of storm types that are known to produce PMP-magnitude precipitation accumulations, including ARs in the western United States and Alaska; "upslope" storms in the Rocky Mountains, Black Hills, and Appalachians; TCs in the southern and eastern United States and Hawaii; and mesoscale convective systems in the central and eastern United States. Strengths and limitations of existing reanalyses and models must be identified first, along with systematic approaches for reconstructing these events with numerical models. Besides the need to identify strengths and limitations, there is the need to improve initial conditions, forcing data, models, and experiment design beyond present-day best practices. As shown by Mahoney et al. (2022), current methods for generating model initial conditions may not be sufficient, especially for simulating short-term, localized storms.

Methods: Storm Types, Storm Transposition, Maximization and Transposition Factors, Envelopment

Recommendation 5-8: NOAA should include a summary of scientific principles in its national guidance for near-term PMP estimation. Near-term enhancements to storm transposition, moisture maximization, and transposition factors—especially for components involving subjective decisions—should be grounded in advances in scientific understanding, as detailed in this guidance.

Components of the conventional PMP methods can be highly subjective, are not transparent, and cannot be reproduced independently (Chapter 4). Therefore, near-term enhancements are needed to improve the clarity and objectivity of current PMP methodology.

Storm Types

The proposed model reconstruction dataset (see section on Reconstruction of Rainfall Fields above) can be exploited to make systematic connections between storm types and PMP-magnitude rain accumulations. The development of updated storm catalogs should include scientifically informed characterization of storm type. The combination of radar data and model output (including reconstructions of historic storms), along with machine learning (ML) classification techniques, should enable characterization to be done in a systematic way. ML can efficiently identify storm types when applied to this type of model output, and the spatial and temporal comprehensiveness of this dataset will make the results even more robust, compared to existing datasets that generally have gaps in space, time, or both. The findings of these studies can then be applied back to observational datasets as they are expanded and further developed.

Storm Transposition, Terrain and Orographic Adjustments

Sensitivity studies have illustrated the key role that storm transposition plays in determining PMP estimates (Micovic et al., 2015). The practice of storm transposition has centered on subjective decisions based on scientific reasoning applied by PMP practitioners (Chapter 4). Storm transposition is developed storm by storm and requires a deep understanding of the individual storms that are to be transposed and the meteorological circumstances in which they can occur. Determination of storm transposition regions also requires the ability to place the storm within the larger population of extreme storms in the region. Model reconstructions of storm catalog events, as detailed above, provide an important tool for developing the scientific understanding of individual storms needed for determining storm transposition regions.

For storm transposition, it is critical not only to define transposition regions, but also to understand how the moisture, terrain, and orographic adjustment should be applied during the transposition. The large number of reconstructed storms with detailed information of the storm characteristics and their environments can be used to analyze and categorize storms with similar drivers, and to summarize how the simulated rainfall depth may change across different terrain and orographic conditions. The information may be used to revise and simplify the conventional Storm Separation Method into a more reproducible topography adjustment procedure. The efforts should also include an assessment to determine how to utilize precipitation frequency estimates (e.g., NOAA Atlas 14 and 15) for orographic adjustment, either in terms of simple ratios or in other empirical equations. Additionally, a comprehensive understanding of their strengths and limitations is crucial.

Moisture Maximization

In terms of moisture estimates, the current methods based on surface dew point are highly subjective and difficult to reproduce. Although individual surface dew point observations can still be useful to estimate moisture for small-scale, short-duration storms, they may be insufficient for large-scale, long-duration storms in which the incoming moisture range can be extensive and dynamic. In such conditions, a more reasonable approach would be to estimate dew points or precipitable water (PW) over a large region, leveraging reanalysis datasets. Therefore, we envision modifications to the moisture calculations from two aspects. First, an enhanced dew point or PW selection procedure should be established. The procedure should provide clarity for independent verification, to enable easy confirmation of whether all selection criteria such as reasonable timing of moisture arrival are met.

Second, the calculation of moisture should account for storm type. For example, for continental convection (e.g., "local storms"), the use of surface dew point measurement may be most appropriate, because precipitation amounts are highly sensitive to the near-surface water vapor and there is often drier air aloft. In contrast, for TCs and ARs, where moisture transport over a deep layer is important to the intensity and distribution of rainfall, the vertically integrated water vapor (i.e., PW) provided by meteorological reanalysis datasets is likely a more appropriate variable to use in moisture maximization. While the direct measurements of PW are much less dense in space and time, modern data assimilation systems that combine model, satellite, and other information have enabled detailed reanalyses such as ERA5, which has global coverage and hourly time resolution. Although it is clear that the coarse resolution atmospheric reanalysis may be insufficient to represent local extreme rainfall processes (e.g., Zhang et al., 2023), it is expected that the storm environments, including the PW, are sufficiently well represented for use in moisture maximization calculations. Further research is needed to determine whether ERA5 is sufficiently accurate to be used to estimate PW for PMP calculation, and what specific processes and guidelines should be established for of its application to PMP.

Updated climatological information (i.e., frequency estimates) on surface dew point and PW should be used in modernized PMP estimation. When developing dew point climatology maps from point-based dew point observations, apart from including decades of additional measurement since the development of HMRs, best practices developed for extreme precipitation frequency analyses such as NOAA Atlas 14 should be followed. In addition to the final dew point climatology maps for applications, this effort should also provide verifiable information on data processing, computation, smoothing, and quality control. Development of a PW climatology should involve evaluation of various choices of reanalysis datasets and determination of the most appropriate ones for application. What frequency level should be used in the climatology calculation should also be clarified. As a reminder, the choice between a 100-year return level and $+2\sigma$ in the current practice seems inconsistent and arbitrary.

To date, the climatologies of dew point that have been used for PMP estimation in the United States have assumed that there is no underlying moisture trend. However, as the climate changes, expected extreme values of dew point or PW should change as well, partly because of the same thermodynamic relationship that leads to the expected increase in precipitation intensity with higher temperatures. Changes in extreme PW and dew points have indeed been observed across the United States (Kunkel et al., 2020; Lee et al., 2021; Scheff and Burroughs, 2023; Su and Smith, 2021). As a consequence, moisture maximization that is based on a stationary statistical analysis of historical dew point or PW tends to underestimate the maximum moisture that will likely be available to such a storm in the present, warmer climate.

So that PMP can be valid for the present-day climate, the dew point and PW climatologies should be created assuming nonstationarity, using estimates of the impacts of climate and land use change on dew point and PW. Moisture maximization of each storm would then be based on a suitable return period for moisture given present-day climatic and land use conditions. Such a practice would account for the bulk of the expected effects of climate change on PMP during the historical period.

Envelopment

Envelopment may be needed and should be used in the near-term enhancements approach to PMP estimation. Envelopment is particularly important to compensate for the limited number of near PMP-magnitude events in the storm catalog and sparse spatial coverage of storms, particularly in the western United States. Envelopment should be applied after transposition and maximization, with consideration of storm spatial and temporal scales. Sharp gradients and discontinuities that can occur at state or regional boundaries due to fixed transposition limits should be investigated and possibly removed with envelopment and regional smoothing.

Uncertainty Characterization

For the near-term enhancements approach, which is based on the current PMP practice of storm transposition and maximization, the committee sees no way to produce statistically sound uncertainty estimates.

In the near term, the committee recommends a combination of simple sensitivity analysis (e.g., varying one parameter at a time and quantifying variability in the result) and Monte Carlo-based sensitivity analysis. The simple sensitivity analysis is advantageous because it makes clear that the uncertainty derives from lack of certainty about key inputs. The Monte Carlo-based analysis is advantageous because it integrates the effects of lack of certainty about multiple inputs. However, neither approach has the standard statistical interpretation of statistical coverage (i.e., confidence), and presentations of uncertainty should emphasize that the uncertainty is driven by the variability quantified in the experts' input distributions.

Comparisons between PMP estimates and maximum rainfall accumulations (as in Riedel and Schreiner, 1980), using data through 2024 (see additional discussion in Chapter 4), are also useful. Such comparisons can identify regions with relatively large apparent inconsistencies between the results of the two approaches.

Climate Change Adjustment Factors

The Chapter 3 section on Scientific Advances: Climate Change and Extreme Rainfall discussed how physical understanding, historical trends, and model simulations and projections all point to an increase in extreme precipitation with warming. Therefore, PMP is expected to increase in the future, because climate models project global warming to continue under all socioeconomic scenarios with increasing concentrations of greenhouse gases. Hence the near-term enhancements approach using conventional PMP methods should be augmented to account for the changes in PMP with future warming. By applying an adjustment factor to the PMP estimates of the present-day climate, the PMP in a future period can be estimated based on the nonlinear power law scaling of extreme precipitation with temperature as follows (Hardwick Jones et al., 2010).

$$\mathrm{PMP}_{\mathrm{future}} = \mathrm{PMP}_{\mathrm{present}}\,(1 + \mathrm{a})^{\mathrm{DT}}$$

Here, $PMP_{present}$ and PMP_{future} are the PMP estimates for the present-day and future climate, respectively, $(1 + a)^{DT}$ is the adjustment factor, DT is the change in surface air temperature (K) between the future and present-day periods, and a is the scaling of extreme precipitation with temperature (%/K). The adjustment factor can be calculated for a particular geographic area or region. With global mean surface temperature commonly being used in the scaling relationship (e.g., Figure 3-4), here for consistency in calculating the adjustment factor, DT can be estimated based on the global mean surface temperature simulated by global climate models. However, other temperature or thermodynamic variables, such as regional mean surface temperature and dew point temperature, have also been used to derive the scaling relationship. Although there is a need to further investigate the use of different variables and their spatial scales for the scaling relationship, the DT used in calculating the adjustment factor should be consistent with the temperature used in the scaling relationship.

Several mechanisms that influence the scaling relationship between extreme precipitation and temperature are important to consider in estimating a.

1. With no change in atmospheric circulation, storm dynamics, and relative humidity, extreme precipitation is expected to increase with warming at roughly the C-C rate (~7%/K) that dictates the increase in saturation vapor pressure with temperature.
2. As a result of the lapse rate effect reflected in larger warming at higher altitudes (Emanuel, 1994), the increase in atmospheric stability reduces precipitation intensity.
3. Increase in latent heat release due to increased moisture and condensation intensifies storms and extreme precipitation.
4. Reduced near surface relative humidity over land, a robust signature of global warming (Byrne and O'Gorman, 2016; Zhou et al., 2023), increases convective inhibition (CIN) that allows moist convective energy to build up over a longer period before it is released in more energized storms (Rasmussen et al., 2017).
5. Changes in precipitation efficiency with warming related, for example, to changes in cloud microphysical processes due to how efficient cloud condensates are converted to precipitation (Lutsko and Cronin, 2018).

While (1) is robust and influences storms in similar ways, the impacts of (2)–(5) on a would depend on the dynamical regimes and storm types (e.g., Muller, 2013), the duration of precipitation extremes (e.g., hourly vs. daily), and the extreme precipitation percentiles being analyzed. For extreme precipitation associated with convective storms, increase in latent heat release and CIN with warming will likely intensify the extreme precipitation beyond the C-C rate, particularly for the short duration and high percentile extreme precipitation (Berg et al., 2013; Haerter et al., 2010). For cold season orographic extreme precipitation related to ARs, the elevated warming with altitude may shift the extreme precipitation downwind for a larger fractional increase in extreme precipitation on the lee slope than on the windward slope of mountains (Siler and Roe, 2014). For PMP, the relevant scaling relationship a should be for events with extremely low probability of occurrence (e.g., < 0.001). Because theories and observational and modeling studies suggest that a increases with increasing precipitation percentile (Figure 3-4), using a spatially uniform value of a corresponding to the C-C scaling of 7%/K is likely a conservative starting point for the adjustment factor to account for the effect of global warming on PMP.

Given the various complex mechanisms that influence the scaling relationship, a may be more robustly estimated based on modeling to address both thermodynamic and dynamic changes, leveraging the convection-permitting model (CPM) capability that will be used for the reconstruction of historical PMP storms, as discussed above. To estimate a, the pseudo-global warming (PGW) approach (Schär et al., 1996) can be used to simulate the reconstructed historical storms under the future climate by adding perturbations to the initial and boundary conditions to account for the future changes in the environments as projected by global climate models. Changes in precipitation for the reconstructed storms in the historical and future environments and the change in the surface temperature can be used to provide an estimate of a for adjustment of the PMP for the future climate. Alternatively, long-term (decadal) CPM simulations can be performed using the PGW approach to determine the change in precipitation intensity for different probabilities of occurrence at each model grid cell. Using these simulations, a can be estimated based on the simulated precipitation intensity change for different percentiles and the change in surface temperature. The estimated a at each grid cell can also be averaged to provide an estimate of a for different climatic regions (e.g., Vergara-Temprado et al., 2021). While regional temperature has been used more often in regional modeling studies, using global mean surface temperature in estimating a offers a convenient way to calculate the adjustment factor for different socioeconomic scenarios and global warming levels because DT can be obtained from multi-model climate projections (e.g., from the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016)) for different socioeconomic scenarios or global warming levels, even if PGW simulations may be available for only a single scenario to estimate a. Although modeling has inherent biases and uncertainties, it can account for the various mechanisms that influence a and allow for sensitivity experiments to provide additional insights on a and its uncertainties (e.g., Lenderink et al., 2021).

> **Recommendation 5-9: For near-term enhancements to PMP estimation, NOAA should adopt climate change adjustment factors based on the model-based scaling relationship between extreme precipitation and temperature.**

MODEL-BASED PMP ESTIMATION

Advances in atmospheric and climate modeling and innovations in software engineering and computing infrastructure over the past decade (see Chapter 3 section on Numerical Modeling and Computing) have enabled the running of kilometer-scale climate simulations on high-performance computer architectures. Here kilometer-scale simulations refer to simulations produced at model grid spacing roughly between 1−5 km, often referred to as convection-permitting simulations. With demonstrated improvements in modeling various types of storms that could produce PMP compared to coarser-resolution models (e.g., Ban et al., 2014; Kendon et al., 2021; Mahoney et al., 2022; Prein et al., 2015; Rasmussen et al., 2023; Stevens et al., 2019), it is feasible in the longer term to modernize PMP estimation by using regional and global kilometer-scale models for PMP estimation.

Modeling offers several advantages over the conventional, largely data-driven approach outlined above for the near-term enhancements to PMP estimation, from several perspectives:

1. With sufficient length and ensemble size, model simulations provide a more complete record of PMP events that are not available from the limited observational record, especially in regions with complex terrain;
2. Simulations provide the full space-time fields, enabling estimation of PMP for any spatial area, location, and duration, as well as estimation of the spatial distribution of PMP;
3. With the plethora of data from the model simulations, PMP can be estimated using methods that are less reliant on expert judgement, such as approaches for storm transposition and orographic adjustment;
4. The calculation of uncertainty in the model-based PMP estimates becomes easier with ensemble simulations;
5. With models capturing the physical processes associated with PMP storms and their responses to climate change, modeling offers a more straightforward approach to PMP estimation under different climates; and
6. Through analysis of the model simulations and projections, model-based estimates of PMP and its future changes can be combined with narratives of the future scenarios and physical explanations of the underlying processes, potentially improving stakeholder communications regarding PMP estimation in a changing climate.

Based on assessment of the current and evolving state of modeling and computing, modeling approaches to PMP estimation in the present-day and future climates are discussed in the Long-Term, Model-Based PMP Estimation and Climate Change sections below. The committee recommends an MEP to rigorously evaluate, compare, and document different model-based approaches for estimating PMP to assess readiness to adopt model-based approaches (see section on Model Evaluation Project below). Such scientific evaluation should be complemented by a statistical assessment of the simulation length and ensemble size needed for model simulations and projections to provide a sufficiently complete record of PMP-magnitude events for PMP estimation (see sections on PMP Estimation: Extreme Value Methods and Power Analysis/Sample Size Determination below), as well as an assessment of the computational feasibility for performing those simulations and projections on the next-generation computational platforms.

Long-Term, Model-Based PMP Estimation

With a focus on the geographical region of the United States, both regional and global kilometer-scale models or CPMs can provide scientifically supported model-based estimates of PMP if found to be fit-for-purpose through the MEP. Regional modeling, an approach that is more generally known as dynamical downscaling, refers to the use of numerical weather and climate models to produce high-resolution simulations consistent with the large-scale conditions depicted by global reanalysis or simulated by lower-resolution GCMs. Both regional models (a.k.a. limited area models) and global models with regional refinement can be used for dynamical downscaling to produce kilometer-scale simulations for regions of interest (Gutowski et al., 2020). The latter has emerged in the past decade with methodological advances in generating unstructured meshes for computational modeling. In limited area models, large-scale constraints are provided through the lateral boundary conditions. In global variable-resolution models, large-scale circulations are downscaled to higher resolutions within the refined domain, but the finer-scale processes simulated therein have upscale impacts on the large-scale circulation outside the refined regions (Sakaguchi et al., 2015, 2016). Modeling processes across scales within the global variable-resolution modeling framework places a stronger requirement for the physics parameterizations to be scale aware.

Besides dynamical downscaling, it is now feasible to run kilometer-scale climate simulations using global CPMs on large supercomputers (Bolot et al., 2023; Stevens et al., 2019; Taylor et al., 2023). Global CPMs have the potential advantage of improving modeling of the large-scale circulations, which may improve simulations of precipitation within the United States, when compared to the use of regional refinement in which the large-scale circulations are largely governed by the lower-resolution simulations outside the refined domain.

To provide model-based estimation of PMP consistent with the updated definition, initial-condition large ensemble simulations (Deser et al., 2020) are needed to estimate the depth of precipitation with an extremely low AEP. By perturbing the initial conditions, which may be achieved by initializing the simulations on different dates or by adding small random noises to the initial conditions of the atmosphere, large ensemble simulations can be produced to account for uncertainty arising from natural variability and provide more robust estimation of precipitation events with very low probability of occurrence. For dynamical downscaling, limited-area models and global variable resolution models with regional refinement can be used to downscale GCM large ensemble simulations to provide the boundary conditions. For global CPM, large ensemble simulations can be produced using kilometer-scale atmosphere models coupled to eddy-resolving ocean models, or kilometer-scale atmosphere models driven by sea surface temperature and sea ice from lower-resolution coupled GCM simulations, depending on the readiness and computational feasibility of the former.

Although kilometer-scale coupled models hold great promise in transforming our ability to simulate the climate system with high fidelity and great details, running such simulations requires new strategies for model spin-up; the computational resources needed for the standard approach used by GCMs to run 500+ years of pre-industrial simulations from cold start for model spin-up are likely prohibitive for global CPM even with exascale computers. For global simulations, kilometer-scale atmosphere simulations driven by sea surface temperature and sea ice from lower-resolution coupled GCM simulations are more viable at the initial stage of adopting the long-term approach. To address multiple sources of uncertainty, multi-model initial-condition large ensemble kilometer-scale simulations are desired for quantifying uncertainty associated with both models and internal variability. As advances continue to be made in artificial intelligence (AI)/ML techniques and their trustworthiness, kilometer-scale modeling may be blended with AI/ML approaches to potentially improve model fidelity and computational efficiency. Such blending may include use of ML-enhanced parameterizations and numerical solvers in models, ML methods such as emulators for model calibration and uncertainty quantification, and ML emulation for ensemble boosting, which is particularly useful for augmenting the large ensemble kilometer-scale simulations. For example, an ML emulator of a low-resolution global atmosphere model was able to produce stable multi-year-long simulations (Watt-Meyer et al., 2024), hinting at the potential for ML techniques to be used in ensemble boosting. Trained using kilometer-scale simulations, the ML emulator can be used to increase ensemble size at much lower computational cost compared to kilometer-scale modeling, if the ML emulator is capable of simulating PMP-magnitude storms with appropriate frequency.

Climate Change

Model-based approaches are more amenable to directly estimating PMP under different climate conditions than current PMP estimation methods because models can produce simulations of PMP events consistent with the climates under different external forcings. This approach represents an improvement over the adjustment factor recommended for the near-term enhancement approach because surface temperatures do not uniquely determine precipitation characteristics. Different forcing agents, such as greenhouse gases and aerosols, are expected to have different effects on both weather patterns and on physical processes within storms (e.g., Fan et al., 2015; Yang et al., 2022) resulting in different mean and extreme precipitation trends (Rai et al., 2023; Risser et al., 2024). The large ensemble simulation approach for estimating PMP in the historical climate can be extended to produce large ensembles of kilometer-scale regional (downscaling from large ensembles of GCM projections for the future) and global simulations under different socioeconomic scenarios or global warming levels for PMP estimation under the future climates. Such simulations can naturally provide a large number of PMP-magnitude events to estimate the changes in PMP. Table 5-1 summarizes the historical and future simulations for model-based estimation of PMP for different climate periods. A potential constraint for this approach is the computational demand for running multi-model large ensembles of kilometer-scale simulations for multiple socioeconomic scenarios (e.g., SSP5-8.5 and SSP2-4.5 representing two contrasting socioeconomic pathways and different radiative forcing by 2100). However, similar to ensemble boosting for the present-day simulations, ML emulators can be trained using kilometer-scale simulations for the future climates to address the out-of-sample issue. Ensemble boosting using ML emulators is a computationally efficient way to augment large ensemble kilometer-scale simulations, providing enough samples of PMP events under both current and future climates for a potentially viable approach for estimating PMP with uncertainty and without storm transposition.

Although the recommended initial-condition large ensemble kilometer-scale simulations incur significant computational requirements, they are critical not only for modernizing PMP estimation but also for addressing a much broader set of questions related to extreme weather risk in a changing climate (PCAST Report, 2023). The grand challenge of producing such simulations calls for broad collaborations among government agencies and between the government, academia, and private sectors to accelerate progress that supports planning for a climate-resilient society.

> **Recommendation 5-10: In the long term, NOAA should adopt a model-based approach to PMP estimation that aligns with the revised PMP definition, consisting of multi-model large ensemble kilometer-scale or finer-resolution modeling to construct the probability distribution of precipitation for PMP estimation under different climates.**

PMP Estimation: Extreme Value Methods

With the large ensemble model runs discussed above, high frequency (sub-hourly to hourly) precipitation at kilometer-scale grid spacing will be available for a large ensemble of simulations covering at least 30 years for the historical period (e.g., 1981–2010) driven by historical forcings and the future periods (e.g., 2041–2070 for the mid-century) driven by various socioeconomic scenarios. Each member of the initial-condition large ensemble represents a plausible realization of transient climate consistent with the imposed time-dependent external forcings. Given sufficient precipitation data (for each climate period), one could directly estimate AEP depths for small, but not extremely small probabilities using empirical quantiles (e.g., for the 0.001 AEP depth, which is the value for which 0.1% of the annual maxima of the observations exceed the value). For more extreme PMP-relevant probabilities, extreme value methods are necessary because the number of years of modeled output is too short for direct estimation. In extreme value analysis (EVA), AEP depths depend solely on the parameters of the extreme value distribution and are driven particularly by the shape parameter. In fact, one can estimate the shape parameter with some precision even without massive amounts of data. We discuss the sample size required to achieve a specified precision below. This provides hope for estimating even fairly extreme quantiles (and for return periods much longer than the length of time the model has been run for) with moderate uncertainty. Of course, there is no free lunch; such estimation relies on the assumptions that justify use of extreme value distributions compared to approaches that do not rely on assuming a particular distribution.

> **Recommendation 5-11: For the long-term approach and in agreement with the recommended PMP definition, NOAA should use statistical approaches to estimate PMP (with associated uncertainty) as the precipitation depth corresponding to an extremely low AEP from the model-simulated precipitation distribution, with particular consideration of extreme value analysis based on threshold exceedance methods.**

When using model output one can directly estimate AEP depths at each grid point, or for each drainage basin or other area of interest, as well as for each duration of interest. Specifically, if a stakeholder is interested in estimation for a particular spatial area and duration, provided they have the full model output (or potentially model output limited to the occurrence of extremes, which can be used in threshold exceedance analysis) they can obtain the necessary extreme precipitation observations at the spatial/temporal domain of interest.

It is reasonable to assume that AEP depths should be relatively smooth in space and that the degree of smoothness will vary with topography. Individual grid cell estimates may not vary smoothly because of uncertainty associated with the parameter estimates arising from limited sample size. In particular, noisy estimates of the shape parameter can result in spatially noisy AEP depth estimates.

If estimates are not deemed to be sufficiently smooth in space (or perhaps with respect to duration), then the need arises for longer model runs or for analysis that borrows strength across locations (i.e., regionalization) to smooth the estimates, thereby reducing statistical uncertainty. Local likelihood, regional frequency analysis, or spatial statistics are potential methodological options to achieve smoother estimates. Alternatively, the estimates could be smoothed using simple non-statistical techniques, such as inverse distance weighting.

In regions of complex topography, how to do the smoothing is more troublesome, because it becomes more difficult to select comparable locations with similar climatology and therefore similar AEP depths. One possibility is to use data on less extreme precipitation to characterize areas that experience similar precipitation frequencies. This could then, for each location, provide a spatial area in which the practitioner is comfortable smoothing/borrowing strength.

Storm Types and Threshold Exceedance Estimation

Estimation of the extreme value parameters is affected by a statistical bias-variance tradeoff. As the block size or threshold is increased, the data is expected to be better approximated by an extreme value distribution, thus reducing bias, but with increased variance from the decrease in the number of observations.

With daily data, a sample size of 365 days in a block is generally considered sufficient for use of the generalized extreme value (GEV) distribution in many applications. The situation is more complicated with PMP-magnitude precipitation. Such precipitation may be driven by conditions that rarely occur, even over the course of an entire year. As discussed in Chapter 3, extreme precipitation in many locations and seasons is likely caused by a variety of storm types, and use of annual maxima could mix precipitation observations coming mostly from less extreme storm types with fewer observations from the type that generates the largest extremes. Inclusion of data arising from storm types with a lighter tail would bias estimation of the shape parameter associated with the storm types that lead to PMP-relevant events. Thus, for estimation of AEP depths for extremely small probabilities using model output, the threshold exceedance approach seems most appropriate, with the threshold chosen to exclude events that are not truly extreme—in particular those events from storm types not expected to produce precipitation amounts in the far tail of the distribution. Alternatively, given that the block maxima approach can be more straightforward (e.g., not requiring one to consider temporal declustering), a block size larger than a year could be selected. However, eliciting information from experts about the block size is less direct than eliciting information about magnitudes associated with different storm types for use in determining a threshold. Furthermore, threshold exceedance analysis lends itself to a data reduction strategy of only saving model output for days (or days and regions) in which extreme precipitation occurred somewhere in the United States.

> *Conclusion 5-2: Estimation of PMP using extreme value methods should employ the threshold exceedance approach, using a threshold sufficiently high to rely primarily on precipitation from events that produce the most extreme precipitation, in order to limit statistical bias.*

Once a threshold (or block size) is chosen, the statistical estimation strategy described above does not use information about storm types. However, in cases where multiple storm types could each produce PMP-magnitude precipitation, statistical consideration of mixtures of distributions corresponding to different storm types may be appropriate.

Climate Change

The proposed extreme value methods discussed above for PMP estimation are best suited for data that are assumed stationary. The specific analysis of simulations accounting for climate change will need to be tailored to the model data that are produced for PMP estimation. If long model runs are produced with a transitory climate, then the analysis will likely need to account for the nonstationary climate represented in the model output. The most straightforward statistical approach would be to include a linear trend in one or more of the three parameters of the extreme value distribution. A common approach attempts to account for nonstationarity by first building a trend into the location parameter, and then increasing model complexity if necessary by adding a trend to the scale parameter (or log scale because scale must be positive). However, with multiple replicates (an ensemble of runs), trends in all parameters could potentially be investigated. As a first-order approximation, a linear trend may be reasonable provided the time interval is not too long and/or the change in forcing not too strong. If climate change is instead addressed by producing ensemble model runs of shorter time periods under different climate scenarios, a stationary model could be fit to each scenario individually. There could still be statistical modeling choices to be made such as whether the shape parameter would be better estimated by assuming a common value for all scenarios or whether it should vary with climate. Such a choice is similar to whether the shape parameter is allowed to vary in a nonstationary model fitting.

Sample Size Determination

Intuitively, estimating an AEP depth for a small probability (a high quantile) will require a large sample size (many years of model output from a long model run or ensemble). Using standard likelihood-based statistical calculations (Coles, 2001), one can estimate the number of years of data needed to achieve a given level of precision in the estimated AEP depth under the assumptions underlying the use of extreme value methods (Chapter 3). This calculation relies on standard likelihood theory, using the relationship between the variance of the estimated AEP depth (which scales inversely with the sample size) and the estimated information matrix for the extreme value distribution parameters (see Box 3-2). Figure 5-3 presents the results of an example sample size analysis, indicating that the needed sample size increases with the shape parameter and with the use of more extreme probabilities. Estimation of an upper bound (where it exists) requires a much larger sample size than even very low probability AEP depths.

This sample size analysis assumes that using a block size of 1 year would produce yearly maxima that are representative of extreme precipitation and that could be treated as coming from a single extreme value distribution. As discussed above, for precipitation in some regions and seasons, that assumption is very likely to be violated, and the committee recommends use of the threshold exceedance approach. For a given location, season, and duration, it may be important to understand which storm type(s) produce PMP-magnitude precipitation to determine an appropriate threshold for use in a sample size analysis.

A sample size analysis for threshold exceedance modeling can be conducted as follows. If the threshold is taken to be the AEP depth for some (less extreme) probability, then it is straightforward to show that the sample size calculation for the GEV distribution is equivalent to the sample size calculation for the point process-based approach to the threshold exceedance model (see Chapter 7 in Coles, 2001 for details on the point process model), with the critical difference that instead of needing "x" years of data, one needs "x" exceedances (as indicated by the y-axis label of Figure 5-3) for a given desired precision. Thus, the number of years of data needed for a threshold exceedance analysis scales inversely with the probability of an exceedance in a given year. For example, if an exceedance occurs on average every 10 years (a 10% probability in a year), then 10 times as many years of data are needed as if yearly maxima were being used. This makes intuitive sense, because the information in the data scales with the sample size.

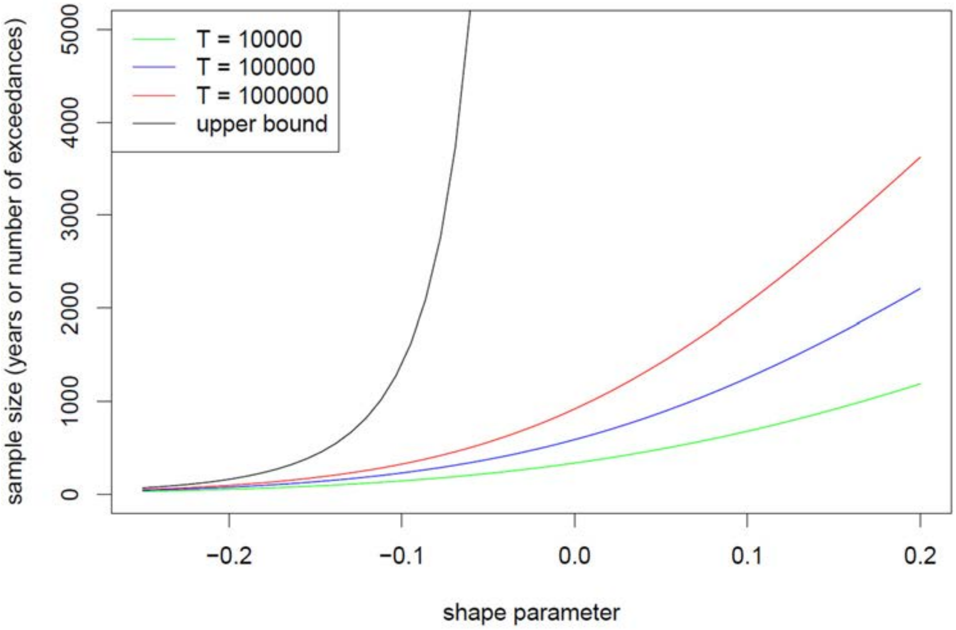


FIGURE 5-3 Sample size needed to achieve reasonable statistical uncertainty (in terms of the standard error) for an AEP depth or the upper bound as a function of the shape parameter value, under the assumptions of extreme value analysis.
NOTES: The sample size is the number of years if conducting a block maxima analysis and the number of exceedances if conducting a threshold exceedance analysis needed in order for the standard error of the estimated AEP depth (or upper bound) to be less than 12.5 percent of the value of the AEP depth. Results are shown for several different AEPs, corresponding to return periods of T = 10^4, 10^5, and 10^6 years (or upper bound). The constraint of 12.5 percent is equivalent to the length of a confidence interval being less than 50 percent of the estimated depth (or upper bound). This particular constraint is shown here for illustrative purposes; other constraints may be chosen in practice. The location and scale parameter values are based on a GEV fit to Global Historical Climatology Network (GHCN) data for Berkeley, California, but do not vary materially with the value of the location or scale parameters, as expected since the shape parameter controls the tail behavior.

Uncertainty Estimation

In contrast to the difficulty in quantifying uncertainty with current PMP methodology, quantifying sampling uncertainty in EVA-based AEP depth estimates can be done using well-established statistical methods, particularly when the analysis is done location by location and duration by duration without any borrowing of strength. The simplest approach is to use standard likelihood-based confidence intervals (see Box 3-2) or confidence intervals based on the profile likelihood (Obeysekera and Salas, 2014, 2016; Zhang and Shaby, 2022). Other approaches are also possible, for example, bootstrapping in conjunction with any estimation method (e.g., likelihood or L-moments) or Bayesian approaches. The amount of uncertainty will be driven by the sample size (i.e., the number of years of model output or number of exceedances, from one or more model runs) and can be decreased if needed by additional model simulations. Estimation of uncertainty when using procedures that borrow strength across locations would need to account for spatial dependence in the data arising from the fact that multiple locations see the same storm. Full accounting of this dependence in extreme value modeling is presently challenging and an area of research, but storm dependence could be accounted for with bootstrap approaches.

Bias caused by the use of models of the real world and sensitivity to choices made in the numerical modeling processing are much more difficult to characterize. However, sensitivity across an ensemble of models can be assessed, as is done in model inter-comparison projects.

Although this report offers suggestions for possible statistical approaches to achieve the goals of AEP-based PMP estimation and associated uncertainty, the committee envisions that statisticians will be integrally involved in the discussions of how best to use the model output to obtain an official PMP estimate.

MODEL EVALUATION PROJECT

> **Recommendation 5-12: NOAA should embark on a Model Evaluation Project to assess model skill, identify strengths and limitations relevant to PMP estimation in current and future climate states, and achieve fitness for purpose, which is necessary for community confidence in models for estimating PMP.**

The committee recommends that NOAA facilitate a rigorous MEP. The MEP represents an appraisal effort during which NOAA and the broader scientific/operations communities determine when model-based methods are deemed sufficiently good for estimating PMP and thus suitable for transitioning to a model-based approach to PMP estimation. The MEP aims to assess model skill, identify limitations of and methods for improving storm resolving models, demonstrate scientifically supported methods for quantifying impacts of climate change on PMP-type storms, and ultimately achieve fitness for purpose. The MEP will likely take the form of an iterative process that occurs between near-term enhancements (expected within the next 6 years) and the long-term effort (expected within 10 to 15 years). The MEP is also expected to occur between future updates to PMP estimates.

The committee recommends that NOAA structure the MEP as a series of simulation categories that successively build toward the long-term goal of using model simulations to estimate PMP. These simulations are described here and summarized in Table 5-1. The first type of model simulations recommended is event-based reconstructions of historical PMP-magnitude storms. Evaluation of simulation output should focus on storm and precipitation characteristics, such as system size, propagation speed and direction, spatial structure and temporal distribution of precipitation, and event total precipitation. Additional model evaluation should emphasize relevant physical processes associated with the simulated storms, such as generation mechanism, moisture source(s), orographic forcing, and microphysics, among others.

Precipitation data used for comparison with event-based simulations will come principally from the enhanced storm catalog data used for near-term PMP estimation. The temporal and spatial scales of these observations mesh with the scales needed for comparison with model-based reconstructions of precipitation for PMP-magnitude storms. As noted in the Storm Catalog Data section above, high-resolution precipitation fields (approximately 1 km spatial scale and 15-minute time scale) will be constructed for the NEXRAD era and digitized storm catalog data will be available for the pre-radar era. Both can prove useful in comparisons with model simulations. The 3-D polarimetric radar fields are especially important for assessing model performance in accurately representing microphysical processes (Ryzhkov et al., 2020). They can also contribute more broadly to assessments of physical/dynamical processes associated with extreme precipitation. Collectively, these simulations are intended to contribute to storm catalog updates, document model skill, and inform moisture maximization, transposition, and orographic adjustments recommended in the near-term enhancements.

The second type of model simulations recommended includes continuous, historical, kilometer-scale simulations with configurations similar to those recommended for use in the long-term approach to estimating PMP, only shorter in duration (such as multi-year to decadal), to enable evaluation of seasonal-to-interannual variability simulated by the models. These simulations can be further categorized by simulated domain, including limited-area and global. Emerging examples of continuous, historical, kilometer-scale simulations with limited-area models include work by Rahimi et al. (2022) and Rasmussen et al. (2023). Examples of continuous, historical, kilometer-scale simulations with global domains include work by Stevens et al. (2019) and Taylor et al. (2023). The spatial and temporal resolution of simulation output of these kilometer-scale simulations will enable comparisons of storm and precipitation characteristics, large-scale storm environments (i.e., intensities, frequencies, locations), and quantile-based statistical comparisons of distributions of precipitation at various temporal and spatial aggregations, by storm type as appropriate. The continuous rainfall reanalysis dataset extending from 2000 to 2024 (and beyond; see discussion in Chapter 3 and in the Storm Catalog Data section above) provides precipitation observations for comparison with simulated precipitation fields from the continuous model simulations at comparable grid resolutions.

A natural question to ask when performing these simulations is, when will models be fit-for-purpose to estimate PMP? Required criteria for assessing fitness for purpose include adequately simulating the climatology of extreme events by storm type, including short-duration, high-intensity events (including those over complex terrain) and accurately simulating extreme precipitation events for the correct physical reasons. Beyond model requirements, NOAA should collaborate with stakeholder groups to achieve community acceptance of modeling and analysis plans.

The MEP should be coordinated by NOAA, with participation from the scientific and operational communities. Public dissemination of model results, limitations, improvements, and findings will enhance community knowledge through time. Furthermore, output from successful model simulations used in the MEP may also serve to support community interests beyond use for PMP, and even beyond the climate and hydrology sectors. The community will transition to the long-term estimation approach when models have been deemed fit-for-purpose.

BRIDGING NEAR-TERM AND LONG-TERM STRATEGIES

Transitioning to the long-term model-based approach for PMP estimation poses some risks and challenges. Foremost among the challenges for the 10-year vision are (1) the length of time until models are deemed fit-for-purpose for modeling PMP-magnitude storms and precipitation on climate timescales and (2) the computational requirements for producing the large ensemble kilometer-scale simulations. The first challenge relates to the larger challenge in modeling PMP-magnitude precipitation events in continuous climate simulations, which require skillful simulations of both the large-scale environments that support the PMP storms as well as the PMP-magnitude precipitation. The second challenge includes not only the availability and cost of high-performance computing resources to run a large ensemble of simulations in parallel on different computers, but also the model performance on the computational systems that determines the simulation throughput and hence the wall clock time needed to complete a multidecadal simulation covering the historical and future periods. Strategies that may be helpful in addressing these challenges are discussed below.

Kilometer-scale simulations can be used for near-term enhancements to PMP estimation once the models are deemed fit-for-purpose based on the model skill, but computational resources may be temporarily insufficient for full implementation of model-based methods that require very large ensemble simulations for estimating PMP and its uncertainty. Small- to medium-size ensemble kilometer-scale simulations can contribute to implementation of moisture maximization procedures, computation of orographic transposition factors, and development of scientifically based geographic transposition factors (especially for near-coastal regions). As noted in Chapter 4 and the Near-Term Enhancements to PMP Estimation section above, poor spatial and temporal sampling of rainfall and water vapor pose major challenges to implementing moisture maximization and computing transposition factors. Simulations can advance the computing of the climatological quantities needed for implementing PMP procedures (such as the 100-year rainfall frequency products used for computing transposition factors), especially for estimating sub-daily PMP in mountainous terrain and near-coastal regions. More generally, kilometer-scale simulations will stimulate advances in scientific understanding of extreme rainfall, a key component of near-term enhancements to PMP estimation.

As models approach fitness for purpose, there may be a stage in which model deficiencies can be well characterized using existing observations. If that is the case, it may be possible to apply bias corrections to model output such that modeled return values align with observed return values at locations where such return values are suitably constrained by observations. Such an approach would be particularly valuable in places such as the intermountain west where spatial coverage of observations is limited and transposition is challenging. In general, stakeholders may well consider such “calibrated” model output as being preferred for PMP estimation even when known model errors become small.

Also during the transition period, downscaling approaches can be developed for PMP estimation consistent with the new PMP definition, especially for storms producing large-area rainfall extremes, including ARs and TCs. In this approach, large-scale circulation and thermodynamic conditions from lower-resolution GCM large ensemble simulations conducive to PMP events are selected for downscaling of the specific storm events using regional modeling, similar to the modeling approach used in the storm reconstruction. This approach, which can be applied to both the present-day and future climates, takes advantage of lower-resolution GCM large ensemble simulations to estimate the probability of occurrence of the PMP events and runs CPM simulations for specific storm cases to produce a very large number of PMP-magnitude events. This approach thus decomposes the PMP estimation by using large ensemble GCMs and kilometer-scale simulations of storm cases selected from the GCM simulations to estimate the PMP probability and intensity separately.

As climate change may alter the thermodynamic and dynamical environments to produce black swan and gray swan events not observed in the past, it is important to account for such events in PMP estimates for the future climate. The downscaling approach is amenable to modeling changes in both frequency and intensity of PMP and unprecedented events because it selects large-scale circulations conducive to PMP events from large ensembles of GCM simulations, which are available for the present-day and future climates. By sampling a wide range of initial conditions, large ensemble simulations encompass a range of possible climate futures consistent with the external forcing, enabling simulation of unprecedented events with no historical analogs.

TABLE 5-1 Summary of Model Simulation Types, Characteristics, and Purpose to Support the Recommended Approach (Near-Term Enhancements, Model Evaluation Project, and Long-Term Approach)

Type	Time Period	Boundary Condition	Ensemble Method	Recommended Phase(s)	Purpose
Storm reconstructions (short simulations)	Historical	Reanalysis	Perturb initial conditions and/or model configurations	Near-term Enhancements MEP[a]	Storm catalogs Storm transposition MEP for weather simulations
PGW[b] storm reconstructions (short simulations)	Future	Reanalysis + climate change perturbations		Near-term Enhancements	Climate change adjustment factor
Long-term km-scale limited-area climate simulations	Historical	Reanalysis	NA	MEP	MEP for climate simulations
Long-term km-scale global climate simulations	Historical	Observed SST[c] and sea ice	NA	MEP	
Large ensemble long-term km-scale limited-area climate simulations	Historical	GCM simulations	Initial-condition large ensemble GCM simulations	Long-term Approach	PMP estimation for historical period using extreme value theory
Large ensemble long-term km-scale global climate simulations	Historical	Observed SST and sea ice	Perturb initial conditions	Long-term Approach	
Large ensemble long-term km-scale limited-area climate simulations	Future	GCM[d] projections	Initial-condition large ensemble GCM projections	Long-term Approach	PMP estimation for future period using extreme value theory
Large ensemble long-term km-scale global climate simulations	Future	Observed SST and sea ice + their changes projected by GCMs	Perturb initial conditions	Long-term Approach	

[a] Model Evaluation Project
[b] Pseudo-Global Warming
[c] Sea Surface Temperatures
[d] Global Climate Model

USER NEEDS

PMP Products

PMP estimates from the recommended model-based approach can be provided at relevant spatial and temporal scales needed for hydrologic/hydraulic modelers and decision makers. It is envisioned that key products would include gridded PMP estimates (at kilometer scale) for various durations; basin-wide PMP estimates for watersheds of interest across the United States (such as at dam locations); and full space-time fields for PMP estimation at any area, location, and duration of interest. Examples of some potential types of kilometer-scale products are shown in Figure 5-4. A key characteristic is to provide seamless, national coverage of PMP for the CONUS, analogous to existing coverage of non-extreme precipitation estimates illustrated in Figure 5-4(a). PMP estimates over Alaska, Hawaii, Puerto Rico, and other territories (not shown) can also be provided in a seamless fashion. Individual storm-scale events for user-specified durations, such as a 24-hour accumulation for the 23 June 2016 storm over West Virginia as shown in Figure 5-4(b), can be provided. Storm-scale products would have consistent and broad-scale spatial coverage, with sub-hourly (nominally 15-minute) temporal coverage. Maximum precipitation depths at each grid cell for durations of interest can be provided, as shown in Figure 5-4(c). Ensemble simulations would be used to provide uncertainty estimates. Estimates for user-specified watersheds, as illustrated in Figure 5-4(d), can be provided, with distributions such as shown in Figure 5-2(a). The products can be tailored to meet the needs of traditional standards-based decisions and RIDM.

> **Recommendation 5-13: NOAA should facilitate the availability of the high-resolution model fields from model simulations. These high-resolution fields expand the value and applicability of the simulations for hydrologic and broader climatological applications.**

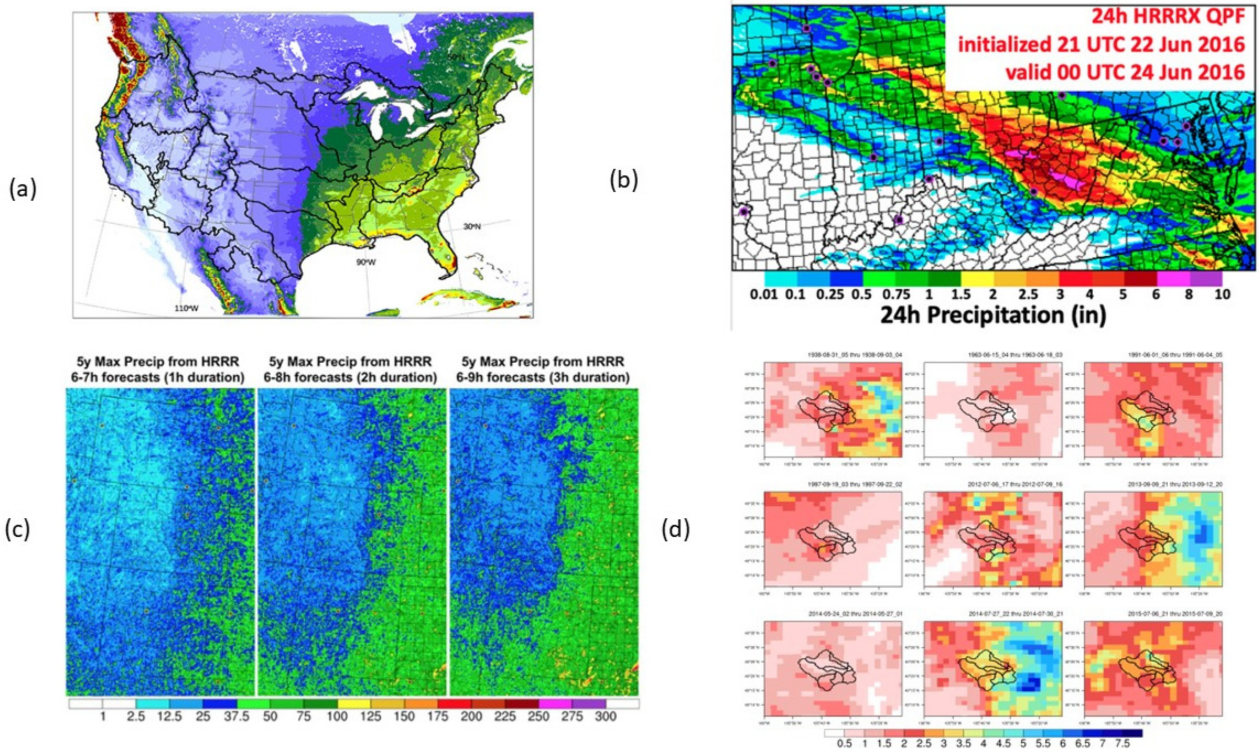


FIGURE 5-4 Example spatial and temporal scales desired for PMP products at kilometer-scale resolution: (a) mean annual precipitation for a specified climate period over CONUS (4 km), illustrating the scale and coverage desired for PMP estimates; (b) event-scale (24-hour accumulation) spatial distribution of an extreme storm (3 km); (c) maximum precipitation in each grid cell (3 km) at 1-, 2-, and 3-hour durations over New Mexico, Colorado, and Wyoming; and (d) spatial distributions of event precipitation over a watershed (shown as black lines) for a 72-hour accumulation (3 km).
NOTE: HRRRX, High-Resolution Rapid Refresh Experimental.
SOURCE: (a) Rasmussen et al. (2023), © American Meteorological Society; (b) Dowell et al. (2022), © American Meteorological Society. Used with permission.; (c) NOAA (2018); (d) Holman and Keeney (2020).

CRITERIA FOR VALID/USEFUL PMP ESTIMATES AND ESTIMATION PROCESS

As presented in Chapter 4, the committee established criteria for a modernized PMP estimation process and robust PMP estimates. As described in Chapter 4, these criteria were applied to current methods now employed to estimate PMP with the result that the current process and the PMP estimates that they yield fail most of the criteria, including those the committee holds essential for a modernized PMP, in particular the assignment of appropriate AEP depths and uncertainty measures to future PMP estimates.

Other sections of this report have detailed the circumstances limiting past advancement of PMP methodologies, explored opportunities that new technology and understanding affords PMP science and application, and identified recommended near-term enhancements and a long-term program that, based on a redefinition of PMP, will facilitate PMP advancement and development of vastly more robust and reliable PMP estimates. This chapter concludes with reapplication of the criteria established in Chapter 4 against the recommended program and the results the committee believes the recommended program will yield. The assessment is detailed in Appendix D, columns 3 (near-term recommended program) and 4 (long-term recommended approach).

Beginning from the top of the Appendix D, column 3, the recommended near-term approach contrasts most strongly with current methods in that it will meet or exceed many more of the criteria associated with data collection, development, and presentation. The approach emphasizes digitization of storm data, expansion of the storm catalogs, and systematic employment of radar data to extend and densify, in both time and space, existing storm catalogs such that they encompass observations of the extreme storm precipitations recorded over the past two decades and that are generally absent from existing storm catalogs. It retains reliance on maximization and transposition concepts, but employs modern modeling techniques, and thus, can be expected to better meet criteria associated with those concepts. Because the approach is based on systematic review and reanalysis of radar data, including new incoming observations, it should meet criteria associated with the currency of PMP information. Finally, if the near-term approach is well implemented, it should meet 12 criteria and partially meet 9, while failing 2 (those associated with estimation of AEP depths and uncertainty).

Assessment of the expected performance of the recommended long-term approach is challenging. The feasibility and success of the long-term approach hinges on the results of the MEP. The approach will fulfill the committee’s vision that high-resolution climate models can accurately simulate the dynamics of extreme storms and their associated extreme precipitation. Assuming that this premise holds, the approach will meet, or render nonapplicable, every criterion that the committee identified and assessed. Critically, the approach incorporates the redefinition of PMP and repositions PMP analysis to estimate AEP depths and their associated uncertainty. These elements are essential to rational incorporation of PMP results into the RIDM philosophy and techniques that currently dominate federal dam design and safety assessments, and which are increasingly being used by state and local dam owners and regulators, as well as those of the private sector. If properly implemented, the long-term approach will meet or exceed criteria related to transparency, accessibility, objectivity, and reproducibility.

SUMMARY

In this chapter, we present the core recommendations of the committee, including a revised definition of PMP and a phased approach to modernizing PMP estimation, whereby near-term enhancements to current PMP methods based on observations will transition to the long-term model-based approach. The long-term model-based approach facilitates the effective treatment of climate change effects on extreme precipitation and characterization of uncertainty of PMP estimates. The committee's recommendations are grounded in the vision that ***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 revised definition addresses the two most critical weaknesses of current PMP methods—the assumption that rainfall is bounded and the absence of an explicit reference to the effects of climate change. The assumption that rainfall is bounded does not provide a tenable foundation for PMP estimation. Climate change has resulted in historical changes in extreme rainfall and the likelihood that greater changes will occur over the coming decades. The two changes to the definition are essential for developing scientifically grounded methods for estimating PMP.

The path toward implementation of model-based PMP estimation is impeded by significant challenges, leading to our recommendation for a phased approach. An important component of this proposed process is the MEP, which will provide scientific grounding for model-based PMP estimation, inform development of the necessary modeling infrastructure, and provide the foundation for determining when the transition should occur. Results from the MEP will also provide key tools for enhancing PMP estimation in the near term.

Near-term enhancements to PMP will be grounded in improved data for storm catalogs, integration of model-based analyses of PMP-magnitude storms into PMP procedures, and synthesis of advances in scientific understanding of extreme rainfall into the approaches used to implement storm transposition, moisture maximization, and transposition factors. Improved rainfall data 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. Reconstructions of major historical storms also inform development of model-based PMP estimation procedures and are an important component of the MEP. For near-term PMP estimation, the effects of climate change can be incorporated through climate change adjustment factors developed from model-based temperature scaling relationships.

Long-term model-based estimation of PMP can occur through use of kilometer-scale climate models capable of resolving PMP storms and producing PMP-magnitude precipitation. To estimate the depth of precipitation with an extremely low AEP over a particular duration and areal extent, initial-condition large ensemble simulations are needed to construct the probability density function of precipitation for different durations and areal extents. Large ensemble simulations driven by different external forcings will provide precipitation data for estimating PMP for the present-day and for the future under different socioeconomic scenarios or global warming levels. By capturing natural variability, large ensemble simulations will also enable statistical quantification of the uncertainty of the PMP estimates. Furthermore, high-resolution space-time fields provide value for other hydrologic and climatological applications.

The recommended approach for modernizing PMP estimation 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 ability to assess precipitation extremes in a warming climate. Significant research is needed to achieve the vision of model-based PMP estimation, requiring scientific and modeling advances that should engage researchers across a broad array of disciplines, as well as synergistic collaborations between federal agencies, states, academia, and the private sector. Scientific and modeling advances along this front will contribute not only to achieving the goals for PMP estimation, but also more broadly to addressing the societal challenges linked to the changes in extreme storms and precipitation in a warming climate, a critical step for the safety of our infrastructure and society.

Accurate high-resolution simulations of storms and precipitation in the current and future climates will enable a rigorous assessment of how space-time patterns of precipitation for extreme storms will change at different spatial and temporal scales, from sub-hourly and kilometer scales to the scales of large basins upstream of high-hazard dams. This information is essential for modeling extreme floods for planning and water management decisions, and for vulnerability assessment of communities and critical infrastructure to extremes. The kilometer-scale simulations will also provide critically needed information for assessing future changes in hazards that are often coupled with extreme rainfall, including coastal storm surge and compound flooding.

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Appendix A
Committee Member and Staff Biographical Sketches

James A. Smith (*Chair*) is Research Scientist and Professor Emeritus in the Department of Civil and Environmental Engineering at Princeton University. He joined Princeton University in 1990 after working in the Radar Hydrometeorology program at the National Oceanic and Atmospheric Administration. His research has focused on the hydrometeorology and hydrology of extreme floods. Research interests have centered on measurement and analysis of extreme rainfall and on estimating the upper tails of flood frequency distributions. Urban environments have been a special interest in studies of extreme rainfall and flooding. Smith is a Fellow of the American Meteorological Society (AMS) and American Geophysical Union. He received the AMS Hydrologic Sciences Medal in 2019. He received his Ph.D. in environmental engineering and an M.S.E. in mathematical sciences, both from Johns Hopkins University. Smith served on the National Academies of Sciences, Engineering, and Medicine's Committee on Meteorological Analysis, Prediction, and Research.

Daniel Cooley is Professor and Graduate Director in the Department of Statistics at Colorado State University (CSU). He has been a faculty member at CSU since 2007, and prior to that was a postdoctoral researcher both in CSU's Statistics Department and at the National Center for Atmospheric Research (NCAR). Cooley's research is in methodological development for and application of extreme value statistics. Much of his research aims to understand and model tail dependence, which is essential for understanding risk associated with extreme events arising from multiple variables. His research is largely motivated by problems from atmospheric and climate science, and he has collaborated with atmospheric scientists from places such as NCAR and Lawrence Berkeley National Laboratory. Cooley is a member of the American Statistical Association (ASA), the ASA's Section on Statistics and the Environment, the International Environmetrics Society, and the Institute for Mathematical Statistics. He was a Professor Laureate of CSU's College of Natural Sciences from 2017 to 2019. Cooley received his Ph.D. in applied mathematics from the University of Colorado at Boulder. He served on the National Academies of Sciences, Engineering, and Medicine's Committee on Anthropogenic Methane Emissions in the United States.

John England is a Lead Civil Engineer with the U.S. Army Corps of Engineers Risk Management Center. From 1997 to 2015 he conducted flood hazard, storm rainfall, and dam safety risk studies at the U.S. Bureau of Reclamation (Reclamation) and was the flood hydrology technical specialist. He previously conducted extreme storm rainfall and flood research at the U.S. Geological Survey and Colorado Climate Center. His work centers on extreme storm rainfall, precipitation frequency, paleoflood hydrology, and flood hazards to assess risks and designs for dams and critical infrastructure. England performed research on extreme storm rainfall and probable maximum precipitation changes for the Nuclear Regulatory Commission and reviewed extreme precipitation studies for Colorado and New Mexico. He was awarded the Reclamation Engineer of the Year in 2008 and was the lead author of Bulletin 17C – Federal guidelines for determining flood flow frequency. He is a registered professional hydrologist, a registered professional engineer, and a board-certified water resources engineer. He is a fellow of the American Society of Civil Engineers and serves on the American Academy of Water Resources Engineers Board of Directors. England received his M.S. and Ph.D. in hydrology and water resources from Colorado State University.

Efi Foufoula-Georgiou is a Distinguished Professor and the Samueli Endowed Chair in Civil and Environmental Engineering and Earth System Science at the University of California, Irvine. From 1989 to 2016 she was a McKnight Distinguished Professor at the University of Minnesota, Director of the St. Anthony Falls Laboratory, and of the National Center for Earth-surface Dynamics. Foufoula-Georgiou studies hydrology and geomorphology with an emphasis on understanding the space-time organization and multiscale structure of precipitation and landforms for improving modeling and prediction. She has served the community in several capacities including member of the National Science Foundation Advisory Council for Geosciences, NASA Earth Sciences Subcommittee, and the Nuclear Waste Technical Review Board. She also served as President of the American Geophysical Union's (AGU) Hydrology Section. She is the recipient of the European Geophysical Union John Dalton Medal, American Meteorological Society (AMS) Hydrologic Sciences Medal, AGU Robert Horton Medal, and the International Water Prize, Dooge Medal. She is a fellow of AGU, AMS, and AAAS and member of the European Academy of Sciences and the American Academy of Arts and Sciences. She received a diploma in civil engineering from the National Technical University of Athens, Greece, and a Ph.D. (1985) in environmental engineering from the University of Florida, Gainesville. She is a member of the National Academy of Engineering and the National Academies of Sciences, Engineering, and Medicine's Board on Atmospheric Sciences and Climate and a former member of the Water Science and Technology Board.

Kathleen (Katie) Holman is an atmospheric scientist working at the U.S. Bureau of Reclamation (USBR) Technical Service Center in Denver, Colorado. Her professional expertise falls within two primary categories: hydrologic hazard analyses for dam safety and water resources planning studies. Holman often leads one component of the complex hydrologic hazard analyses to support risk analyses, which are completed as part of the Safety of Dams program in the USBR Dam Safety Office. The water resources planning studies are often driven by local and regional questions and needs, including trying to better quantify and understand reservoir evaporation. Her graduate research focused on understanding extreme precipitation events in a changing climate and connections between large-scale atmospheric circulation patterns and regional precipitation in the Midwest. Holman is a member of the American Meteorological Society and American Geophysical Union. Prior to joining USBR, she earned a B.S. in mathematics from Lake Superior State University and a M.S. and Ph.D. in atmospheric and oceanic sciences from the University of Wisconsin, Madison.

Shih-Chieh Kao is a Senior Research Staff and Group Leader of the Water Resource Science and Engineering Group within the Environmental Science Division at Oak Ridge National Laboratory (ORNL). He also serves as the Program Manager of the ORNL Water Power Program that oversees dozens of research projects supported by the Department of Energy Water Power Technologies Office (WPTO). His areas of research include hydrologic modeling, flood simulation, hydro-climate impact assessment, high-performance computing, and hydropower resource evaluation. He has been the principal investigator of the WPTO "Effects of Climate

Change on Federal Hydropower – SECURE Water Act Section 9505 Assessment" project since 2011. Kao supported the Nuclear Regulatory Commission on the review of multiple site-specific probable maximum precipitation studies. He received the 2008 Purdue Civil Engineering Best Dissertation Award, 2009 Journal of Hydrologic Engineering Outstanding Reviewer Award, 2013 ICSH Statistical Hydrology Best Paper Award, and 2020 Platform for Advanced Scientific Computing Best Paper Award. Kao received a Ph.D. from Purdue University in hydraulic and hydrologic engineering.

L. Ruby Leung is a Battelle Fellow at Pacific Northwest National Laboratory. She is the Chief Scientist of the Department of Energy (DOE) Energy Exascale Earth System Model (E3SM), a major effort to develop state-of-the-art capabilities for modeling human-Earth system processes on DOE's high performance computers. Her research cuts across multiple areas in modeling and analysis of climate and water cycle including orographic precipitation, monsoon climate, extreme events, land surface processes, land-atmosphere interactions, and aerosol-cloud interactions. Leung is an advisory board member of the National Center for Atmospheric Research's Mesoscale and Microscale Meteorology Laboratory Division and a council member of the American Meteorological Society. She is an elected member of the National Academy of Engineering and Washington State Academy of Sciences and a fellow of the American Meteorological Society (AMS), American Association for the Advancement of Science, and American Geophysical Union (AGU). She is the recipient of the AGU Global Environmental Change Bert Bolin Award and Lecture in 2019, the AGU Atmospheric Science Jacob Bjerknes Lecture in 2020, and the AMS Hydrologic Sciences Medal in 2022, and she was awarded the DOE Distinguished Scientist Fellow in 2021. Leung received an M.S. and Ph.D. in atmospheric sciences from Texas A&M University.

Robert Mason was the Extreme Hydrologic Events Coordinator and Senior Science Advisor for Surface Water in the U.S. Geological Survey (USGS) until his retirement in December 2022. In the recent past, Mason served as the Chief, USGS Office of Surface Water and as Delaware River Master. He chaired the former Advisory Committee on Water Information, Subcommittee on Hydrology from 2014 until 2016 and was one of the authors of "Bulletin 17C," the federal guidelines for flood-frequency analysis. He served on various other federal councils and interagency committees that have made recommendations related to probable maximum precipitation, including the Federal Emergency Management Agency's Technical Mapping Advisory Council (2014–2022). He has a professional passion for statistical hydrology, flood-frequency analysis, and streamflow data-collection techniques and records uncertainty. Mason received a B.S. and M.S. in civil engineering from North Carolina State University and is a registered professional engineer.

John Nielsen-Gammon is the Texas State Climatologist, Director of the Southern Regional Climate Center, and Regents Professor in the Department of Atmospheric Sciences, Texas A&M University, where he joined the faculty in 1991 after a postdoctoral research position at the State University of New York at Albany. He is President of the American Association of State Climatologists until June 2024 and has served as President of the International Commission for Dynamical Meteorology and Chair of the American Meteorological Society's (AMS) Board on Higher Education. After being appointed Texas State Climatologist in 2000, Nielsen-Gammon has focused his attention on weather and climate issues affecting the state, with particular emphasis on droughts, heavy rainfall, and implications of climate change. His research interests also include sea breezes and air pollution, computer modeling, and improving the value of climate information. He was named a Presidential Faculty Fellow by the National Science Foundation and the White House in 1996 and became a fellow of the AMS in 2011 and a Fellow of the American Association for the Advancement of Science in 2024. He received an S.B. in earth and planetary Sciences, and S.M. and Ph.D. degrees in meteorology from the Massachusetts Institute of Technology.

Jayantha Obeysekera is a Research Professor and the Director of the Sea Level Solutions Center in the Institute of Environment at Florida International University. He has national and international experience in the planning and management of water resources systems, with particular emphasis on both deterministic and stochastic modeling in hydrology, and implications of climate change and sea level rise. His current research interest is in the development of nonstationary approaches for infrastructure design, projections of extreme rainfall and sea levels associated with climate change, and understanding uncertainties of climate models. He served as a member of the federal advisory committee associated with the 2014 National Climate Assessment and is a recipient of the national 2015 Norman Medal of the American Society of Civil Engineers. Recently he was appointed to the California Bay-Delta Independent Science Board. He holds a B.S. in civil engineering from the University of Sri Lanka, an M. Eng. from the University of Roorkee, India, and a Ph.D. in civil engineering from Colorado State University. He served on the National Academies of Sciences, Engineering, and Medicine's Committee on Sustainable Water and Environmental Management in California Bay-Delta and the Committee to Review the Edwards Aquifer Habitat Conservation Program.

Christopher Paciorek is an Adjunct Professor, as well as a research computing consultant, in the Department of Statistics at the University of California, Berkeley. Before joining to Berkeley, he was an Assistant Professor in the Biostatistics Department at the Harvard School of Public Health. His statistical expertise is in the areas of Bayesian statistics and spatial statistics, with primary application to environmental and public health research. Paciorek's work in recent years has focused on methodology and applied work in a variety of areas, in particular quantifying trends in extreme weather, quantifying millennial-scale changes in vegetation using paleoecological data, and developing computational software for hierarchical modeling (the NIMBLE project). He has also worked on measurement error issues in air pollution epidemiology, Bayesian methods for global health monitoring with a focus on combining disparate sources of information, and spatio-temporal modeling of air pollution. He received a B.A. in biology from Carleton College, an M.S. in ecology from Duke University, and a Ph.D. in statistics from Carnegie Mellon University.

Russ Schumacher is Professor of Atmospheric Science at Colorado State University and serves as the Colorado State Climatologist and Director of the Colorado Climate Center. He was Assistant Professor at Texas A&M University from 2009 to 2011 before joining the faculty at Colorado State. Along with serving as the state climate office, the Colorado Climate Center operates and manages two weather data networks that are part of the National Mesonet Program: the Community Collaborative Rain, Hail, and Snow (CoCoRaHS) network, an international citizen science initiative, and the Colorado Agricultural Meteorological network (CoAgMET), a statewide network of automated weather stations. Since 2016, Schumacher has served as an editor for the journal *Monthly Weather Review*. His research and teaching focuses on understanding and predicting high-impact weather systems, especially those that produce extreme precipitation. He received the CAREER award from the National Science Foundation in 2010 and was selected as Outstanding Professor of the Year by the students of the department in 2012. He received the Clarence Leroy Meisinger Award for early-career research from the American Meteorological Society in 2021. Schumacher received his Ph.D. in atmospheric science from Colorado State University. Schumacher served on a project review board for a regional extreme precipitation study, and publicly supported updates to state policy consistent with the recommendations of that report.

Staff

Kyle Aldridge was a Senior Program Assistant with the Board on Atmospheric Sciences and Climate and the Polar Research Board. He has a B.A. in earth science from James Madison University.

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Hugh Walpole is an Associate Program Officer with the Board on Atmospheric Sciences and Climate and the Polar Research Board. He has an M.S. and Ph.D. in environmental social science from The Ohio State University.

Appendix B
History of PMP

This Appendix provides historical context for conceptual models that informed the development of PMP in the United States, and for the development and evolution of PMP definitions, expanding on the overview given in Chapter 2.

CONCEPTUAL MODELS FOR EXTREME RAINFALL AND PMP

Conceptual models have played a central role in providing a basis for a 'theory' of physical limits to rainfall (PMP) and the associated evolution of PMP definitions. The conceptual model for PMP over areas unaffected by terrain influence (Figure B-1) was based on an idealized model of a convective cell (thunderstorm model), which is described and illustrated in numerous publications from the 1940s (Bernard, 1944; Paulhus and Gilman, 1953; Showalter and Solot, 1942; USWB, 1943c, 1947). This conceptual model (Figure B-1) assumes that the convective cell is the most efficient at producing precipitation and that there is a physical limit to the depth of precipitable water in the column. Critical variables are the depth of the inflow column, the height to which this column is lifted (nearly the tropopause), and the difference in moisture between the inflow and outflow columns (Showalter and Solot, 1942). Other physical "limits" in this model were the rate at which wind can transport water vapor over a basin and the fraction of water vapor that can be converted to surface precipitation (NRC, 1994). Notably, the roots of this model were also used for application to forecasting using mass storage and vertical velocity equations described in Showalter (1944a, b). At that time, there was a tight connection between personnel developing PMP concepts and models for forecasting precipitation magnitudes. This convective cell conceptual model was later investigated in Hydrometeorological Report (HMR) 23 for possible refinement using three vertical layers (USWB, 1947b), but no changes were made. This model was used to provide generalized PMP estimates in the eastern United States (HMRs 23, 33, and 51) through 1978. It was also used, and continues to be used, in many statewide and regional PMP studies with no modification.

Since its development in the early 1940s, no changes have been made to this conceptual PMP model that is still used in practice today (WMO, 2009). The connection between developers of PMP models and methods, and those from the forecasting community, generally ceased in the early 1970s. The basic equation to estimate PMP from an observed storm rainfall depth using moisture maximization (described in the Moisture Maximization sections in Chapters 2 and 4) has not changed since the 1940s. This model does not reflect modern atmospheric science knowledge in convection (e.g., Houze, 2004; Schumacher and Rasmussen, 2020), 50 years of advances in forecasting precipitation, and current practices in understanding and estimating extreme rainfall magnitudes that are described in Chapter 3.

Orographic Precipitation

In regions with prominent orography (most of the western United States), conceptual PMP models were developed in the early 1940s to account for orographic precipitation in

California. These models were based on ideas from Bjerknes on dynamics of air currents ascending over a mountain barrier (USWB, 1943b). Various models were developed, applied, and refined to estimate PMP over the Sacramento River basin (HMR 3; USWB, 1943b), Los Angeles River Basin (HMR 21B; USWB, 1945), and San Joaquin (HMR 24; USWB, 1947c). As shown in Figure B-2, these 2D models included wind, pressure, and moisture flow over a ridge.

These orographic precipitation models were further developed and improved over time in the 1950s and 1960s for generalized PMP estimates over California and the Pacific Northwest with pressure layers shown in Figure B-3 (USWB, 1966). In the 1970s and 1980s, conceptual orographic models for PMP were further developed for the Southwest (HMR 49) and the Rocky Mountains, summarized by Hansen (1987).

Investigations stagnated in 1980s on exploring, researching, and testing numerical weather prediction (NWP) models for use in estimating PMP, especially in orographic areas, to replace the models used in HMR 36 and HMR 43. Attempts were made in the early 1980s using a steady-state orographic model (Rhea, 1978), but that approach could not reproduce the June 1964 Gibson Dam storm (Hansen et al., 1988). The Storm Separation Method (SSM) was a conceptual model that separated convergence and orographic rainfall to estimate PMP (Hansen et al., 1988). A key model assumption in the SSM was that "non-orographic precipitation is directly proportional to the effectiveness of atmospheric forcing and inversely proportional to the effectiveness of the orographic forcing mechanisms" and that this precipitation can be transposed in the domain (Hansen et al., 1988). The SSM was later used (1990–1999) to revise generalized PMP estimates in the Pacific Northwest (HMR 57) and California (HMR 59), with little to no improvement to the orographic methods.

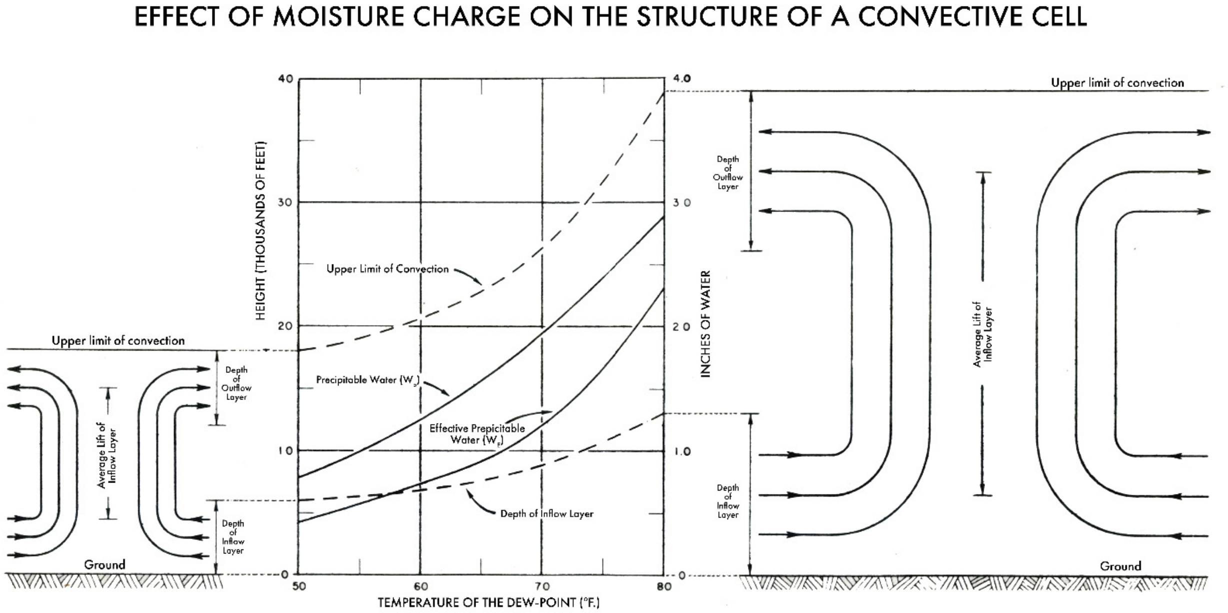

FIGURE B-1 Conceptual model for PMP based on a convective cell.
SOURCE: USWB (1947a), HMR 5, Figure 22.

COMPARATIVE INFLOW AND OUTFLOW VELOCITIES

FIGURE I - VERTICAL STRETCHING DUE TO DECELERATION

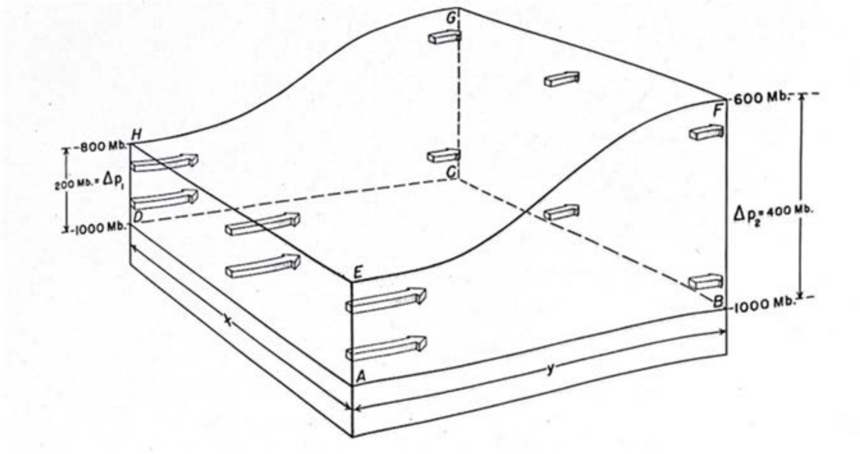

FIGURE 2- FLOW OVER AN IDEALIZED BARRIER

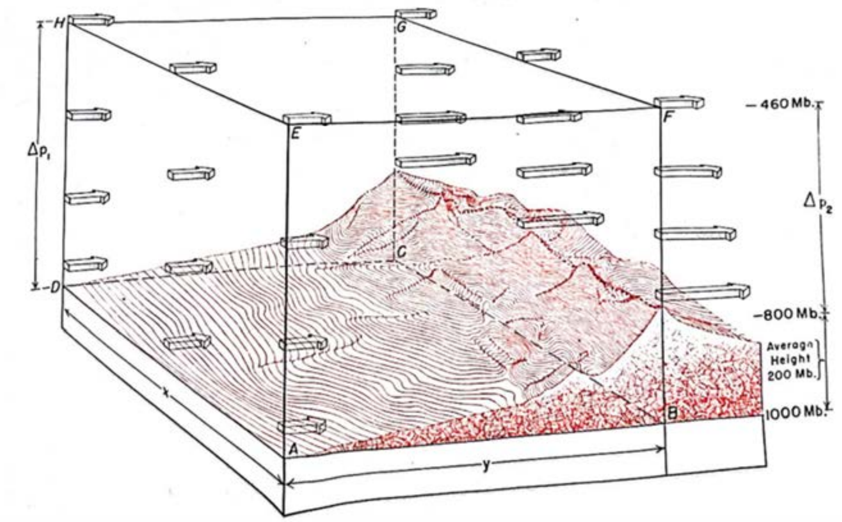

FIGURE B-2 Conceptual orographic model for PMP based flow over a ridge.
SOURCE: HMR 21B (USWB, 1945), Figures 1 and 2.

Uncertainty of PMP Estimates and Changes over Time

The current PMP definitions convey a concept of "exact" physical (deterministic) magnitude and do not clearly convey that these quantities are estimated with uncertainty, or the fact that PMP estimates change over time (can increase or decrease) (Salas et al., 2020). In fact, significant changes in PMP estimates over time have occurred.

WMO (1986) discusses accuracy and confidence limits, invoking the use of meteorological judgment:

There is no objective way of assessing the accuracy of the magnitude of PMP estimates derived by the procedures described here or by any other known procedures, Judgement of meteorologists, based on meteorological principles and storm experience, is most important.

The delineation of lower and upper limits to PMP estimates is somewhat analogous to the confidence bands used in statistics. It would be convenient if a confidence band could be placed about a PMP estimate in an objective manner, similar to the standard statistical method, but this is not possible because PMP is not estimated by formal statistical procedures. This limitation, however, does not invalidate the concept of a confidence band about the estimate, but it means that such limits must be based in considerable measure on judgement, as is the PMP estimate itself.

WMO (2009) briefly discusses accuracy, as follows:

The accuracy of PMP/PMF estimation rests on the quantity and quality of data on extraordinary storms and floods and the depth of analysis and study. Nonetheless, it is impossible to give precise values for PMP and PMF. As yet, there are no methods to quantitatively assess the accuracy of PMP and PMF. Presently, it is most important to analyze, compare and harmonize results of PMP/PMF from multiple perspectives.

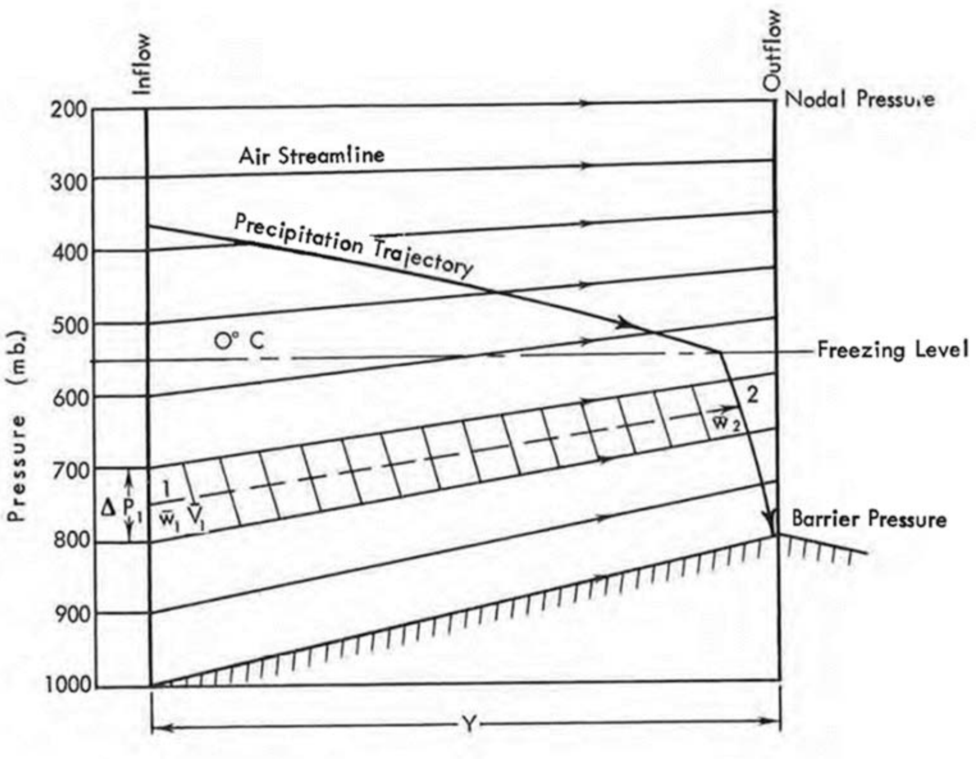

FIGURE 4-1. Orographic precipitation model (schematic)

FIGURE B-3 Conceptual orographic model for PMP based flow over a ridge with discretized pressure layers.
SOURCE: USWB (1966), HMR 43, Figure 4-1.

This statement is essentially the same as WMO (1986).

Generalized PMP estimates in the eastern United States have increased by 10 to 30 percent from 1947 to 1978 (England et al., 2011; NRC, 1985, pp. 47–48). In contrast, generalized PMP estimates in the Rocky Mountain region decreased by 10 to greater than 40 percent at high elevations from HMR 55 to HMR 55A (Figure B-4 below; Hansen et al., 1988); other recent statewide studies show similar decreases compared to HMR 51 estimates. Likewise, recent PMP estimates for the states of Colorado and New Mexico decreased by up to 62 percent from HMR 55A (Table B-1 below; AWA, 2018). PMP revised estimates in HMRs 57 and 59 are highly variable for individual watersheds, ranging from –63 percent to +63 percent for watersheds in the Pacific Northwest (Table B-2; Hansen et al., 1994) and California (Table B-3; Corrigan et al., 1999). Understanding and quantifying this variability and changes over time (potential increases and decreases) should be reflected in a modern definition of PMP.

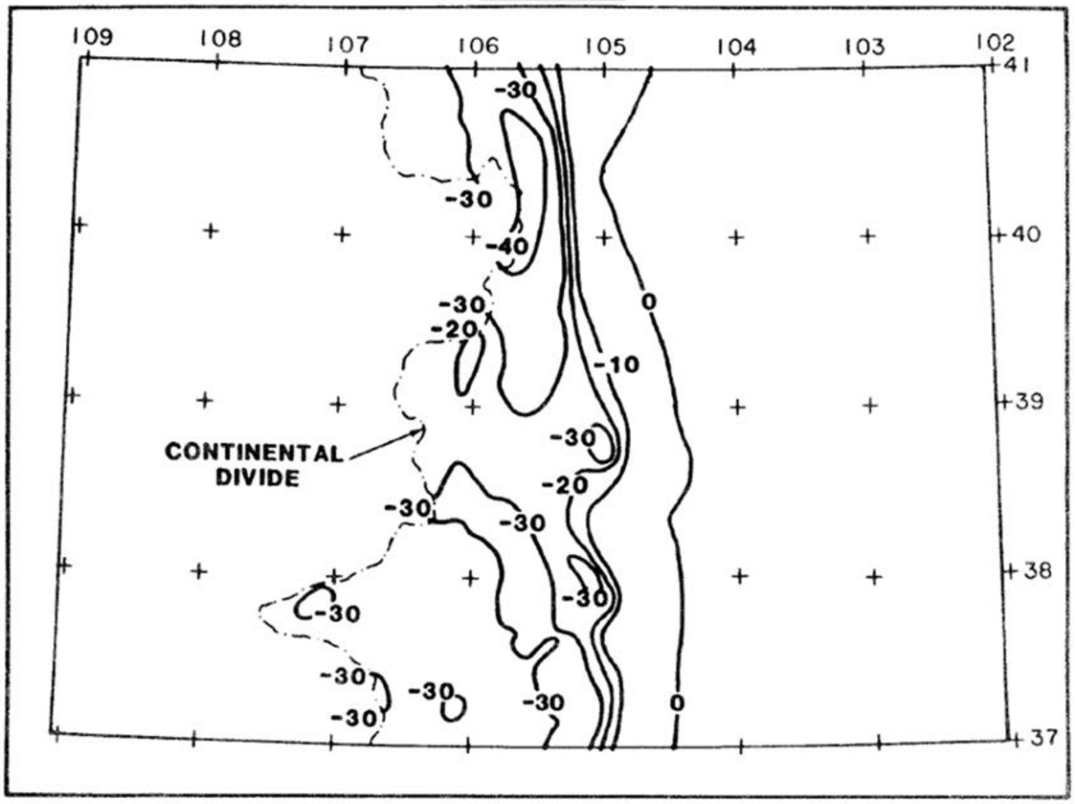

Figure 10.1.--Example of percentage change in 1-hr 10-mi^2 general-storm PMP index map for current study relative to that given in HMR No. 55 (1984), for Colorado. Considerable smoothing applied to example over detailed analysis.

FIGURE B-4 Percent change in 1-hour, 10 mi^2 PMP from HMR 55 to HMR 55A at high elevations. SOURCE: Hansen et al. (1988).

TABLE B-1 Average Percent Change in 10 mi^2 PMP from HMR 55A over Colorado and New Mexico for Various Locations and Durations

Transposition Zone	**1-hour**	**6-hour**	**24-hour**	**72-hour**
Colorado Plains	–39.2%	–31.4%	–41.3%	–45.5%
New Mexico Plains	–33.3%	–24.8%	–41.9%	–41.6%
Front Range Transposition Zone	–46.4%	–26.2%	–26.5%	–44.1%
Sacramento Mountains	–27.5%	–28.5%	–47.5%	–45.1%
Colorado Rockies North	21.6%	–26.4%	–52.0%	–33.6%
Colorado Rockies South	26.7%	–0.7%	–42.4%	–39.7%
San Luis Valley	3.4%	–21.3%	–43.6%	–40.5%
Rio Grande	–0.7%	–13.8%	–40.6%	–43.0%
North Park	11.5%	–30.6%	–61.8%	–59.8%

SOURCE: AWA (2018) Table 8.

TABLE B-2 Summary of Percent Changes in PMP Estimates at 47 Watersheds from HMR 43 to HMR 57

Month		**1-hour**	**6-hour**	**24-hour**	**48-hour**	**72-hour**
June	Range	–63 to 4	–52 to 44	–52 to 48	–51 to 58	–52 to 61
	Mean	–28	–7	–13	–13	–14
December	Range	–42 to 98	–32 to 96	–50 to 68	–54 to 66	–55 to 63
	Mean	4	16	–5	–9	–11

SOURCE: HMR 57.

TABLE B-3 Summary of Percent Changes in PMP Estimates at 38 Watersheds from HMR 36 to HMR 59

	1-hour	**6-hour**	**12-hour**	**24-hour**	**48-hour**	**72-hour**
Range of %	–25 to 29	–23 to 43	–23 to 48	–32 to 41	–30 to 53	–31 to 53
Mean %	2	9	10	0	4	4

SOURCE: HMR 59.

PMP DEFINITIONS

The U.S. Weather Bureau developed PMP definitions in the late 1930s and early 1940s, building on concepts and procedures introduced by the Miami Conservancy (Showalter and Solot, 1942; see also Myers, 1967 and Chapter 2). The U.S. Weather Bureau (USWB), U.S. Army Corps of Engineers (USACE), and U.S. Bureau of Reclamation (USBR) collaborated in development of PMP concepts, definitions, and estimation procedures, which played a central role in design and construction of large dams in the United States by USACE (Hathaway, 1939a, b) and USBR (Billington et al., 2005; USWB, 1947b). These concepts and definitions were later adopted by other federal agencies and states for use in dam design, construction, and safety programs (e.g., Leopold and Maddock, 1954; USWB, 1960) and for use in designing nuclear facilities (USNRC, 1977).

Evolving challenges and perspectives on risk, uncertainty, and physical limits to extreme rainfall informed and are reflected in PMP definitions. An important part of this history is that the definition of PMP changed over time, but the concept of upper bounds on rainfall have been a fundamental element of the evolving definitions from the 1930s to the present.

Hydrometeorologists from the USWB (and later the National Weather Service [NWS]) subsequently refined both PMP definitions and concepts as they conducted studies for specific watersheds and dams (e.g., USWB, 1939) and then developed generalized PMP estimates to cover large areas (USWB, 1947b). The NWS hydrometeorologists later wrote PMP definitions and methods in guidance documents for the world through the World Meteorological Organization (WMO; 1973, 1986). PMP definitions were also published by the American Meteorological Society (AMS, 1959, 2022). The PMP definition and methods in the WMO guidance document were updated in 2009 to reflect experience and practices in China (WMO, 2009).

Current PMP Definitions

Three PMP definitions are in current use as reflected in PMP reports, textbooks, manuals, and guidance documents: HMR 52 (Hansen et al., 1982), WMO (1986), and WMO (2009). In the United States, PMP definitions are from NWS HMRs. The WMO definitions are presented and reviewed here to encompass an international perspective.

HMR 52 (Hansen et al., 1982)

The most widely used definition of PMP is from HMR 52 (Hansen et al., 1982):

> Probable Maximum Precipitation (PMP). Theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year.

Hansen et al. (1982, p. 2) note the following regarding this definition: “This definition is a 1982 revision to that used previously (American Meteorological Society [AMS] 1959) and results from mutual agreement among the National Weather Service, the U.S. Army Corps of Engineers, and the Bureau of Reclamation.” The definition of PMP was revised in HMR 52 to focus on the fact that PMP should reflect storm area rather than watershed area, which reflected the practice of providing generalized PMP estimates (e.g., Schreiner and Riedel, 1978). They also defined three important and related terms: “PMP storm pattern,” “storm-centered area-averaged PMP,” and “drainage-averaged PMP” based on the computation methods in HMR 52. Notably, this definition of PMP is used in both WMO (1986) and AMS (2022).

WMO (1986)

WMO (1986) provides the following definition of PMP:

> Precipitation associated with the uppermost limits is known as the probable maximum precipitation (PMP), which is currently defined (Hansen et al.,1982) as theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year. Such is the conceptual definition of PMP. This definition is a description of the upper limit of precipitation potential that is storm centred,

> i.e., related to the center of the precipitation pattern of the storm irrespective of the configuration of the boundaries of a particular basin.

WMO (1986) was an update and revision to WMO (1973) (see Historical PMP Definitions section below for details on WMO [1973]). The principal author J.F. Miller worked extensively on precipitation frequency and PMP at NWS. WMO (1986) provided conceptual and operational definitions of PMP, with important terms and concepts on probable maximum storm, accuracy, and confidence limits. The definitions were nearly the same as those in WMO (1973), but with two important changes; (1) the use of the HMR 52 PMP definition, noting that it is "currently defined as" and (2) the critical operational definition was revised to include "with virtually no risk of being exceeded."

Along with the definition, WMO (1986) included statements that PMP values may change with new knowledge, and that climate trends are not considered, as follows. "The values derived as PMP under these definitions are subject to change as knowledge of the physics of atmospheric processes increases. They are also subject to change with long-term climatic variations, such as would result from changes in solar radiation intensity. Climatic trends, however, progress so slowly that their influence on PMP is small compared to other uncertainties in estimating these extreme values. Climatic trends are therefore, not considered when preparing PMP estimates."

WMO (1986) also provided an "operational definition" of PMP:

> In addition to the conceptual definition of PMP, an operational definition may be considered as consisting of the steps followed by hydrometeorologists in arriving at the answers supplied to engineers or hydrologists for hydrological design purposes. Whatever the philosophical objections to the concept, the operational definition leads to answers that have been examined thoroughly by competent meteorologists, engineers, and hydrologists and judged as meeting the requirements of a design criterion with virtually no risk of being exceeded.

WMO (1986) also defined **probable maximum storm**:

> The term probable maximum storm (PMS), has been used to refer to any maximized, observed or hypothetical storm that is equal to PMP for durations and area sizes critical for developing the probable maximum flood (PMF) for a basin. The term has also been applied to a hypothetical storm that would produce PMP for all durations at the total basin area and somewhat lesser values for smaller areas within the basin. … PMP for various durations and sizes of area within a specific basin is usually determined by several types of storms.

This definition conflates the definition of PMP (storm area) with that of the watershed area, and what is a maximum.

WMO (2009)

WMO (2009) provides three definitions of PMP with slight variations:

> Summary page xxiii:
>
> Probable maximum precipitation (PMP) is defined as the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends.
>
> Section 1.1:
>
> PMP is the theoretical maximum precipitation for a given duration under modern meteorological conditions. Such a precipitation is likely to happen over a design watershed, or a storm area of a given size, at a certain time of year.
>
> Glossary, p. 243:
>
> Probable Maximum Precipitation (PMP) Theoretically, the greatest precipitation for a given duration that is physically possible over a given watershed area or size of storm area at a particular geographic location at a certain time of year, under modern meteorological conditions.

The slight variations between the three WMO (2009) definitions can lead to some confusion. The first explicitly excludes climate trends, whereas the second and third state "under modern meteorological conditions" without defining what that means. The second includes the concept of "theoretical maximum" whereas the first and third refer to the greatest precipitation meteorologically or physically possible. The first and third definitions imply that a PMP value is intrinsic to an individual watershed or storm area, whereas the second is vague about the spatial extent of PMP values. Although they were likely thought to be conceptually identical when written, these subtle differences could have large consequences in interpretation. In general, the first definition is the most often quoted.

WMO (2009) updated and revised WMO (1986) to reflect experience since 1986 in the United States, Australia, and India, with a focus on direct watershed estimates of PMP in China. The PMP definition was changed to indicate that PMP could represent a storm area or a design watershed. This version recognizes that PMP is an estimate of a physical upper limit and makes simple statements about its accuracy. The operational PMP and probable maximum storm definitions, and discussion on confidence bands in WMO (1986) were eliminated.

Historical PMP Definitions

This section provides details on the history of and philosophy behind PMP definitions, obtained and summarized from various sources including NWS (USWB) PMP reports, WMO manuals, federal agencies and industry guidelines, AMS definitions, hydrology and hydrometeorology textbooks, and statewide PMP reports. A survey and review of PMP definitions from the 1930s through 2023 illustrates the evolution and changes to PMP definitions, and differing perspectives on risk, uncertainty, and physical limits to extreme rainfall.

These definitions also contain context and discussion that surrounds each definition, limited to relevant points and ideas for related history and criticisms of PMP current practices that may be useful in Chapter 4, to build the case (after Chapter 3) for the new approach. See, for example, the definition and discussion below by Shuttleworth (2012), and the discussion by Gilman (1964) on “advantages of the procedure” (methods), which were conceived in the 1930s and are still in use today.

NWS (USWB) PMP Reports

HMRs 1, 2, 3, and 5

Maximum Possible Precipitation (MPP) is not defined specifically in the early HMRs (1–3). These first reports were focused on specific watersheds in Vermont, Pennsylvania, and California, and were published retroactively. HMR 2 (USWB, 1943a) provides the theoretical basis for maximum precipitation in the first two chapters, as illustrated by chapter titles. Chapter I is “Adjustments and Extrapolation of Storms to Physical Upper Limits,” and Chapter II is “Theoretical Computation of Rainfall and the Influence of Seasonal Variations in Hydrometeorological Factors.” These concepts appear in Showalter and Solot (1942), who outline the concepts behind a maximum possible storm and utilize results from HMRs 1–3 to illustrate the computation. HMR 3 is the first hydrometeorological report that contains a glossary; however, a specific definition/term for MPP/PMP is not included. HMR 5 (USWB, 1947a) also contains a glossary but does not provide a definition for MPP. The conceptual model for PMP was based on an idealized model of a convective cell (thunderstorm model), which is described and illustrated in HMR 3 (Figure 17), HMR 5 (Figure B-2), Showalter and Solot (1942), Bernard (1944), and Paulhus and Gilman (1953). This conceptual model was slightly refined as discussed in HMR 23.

HMR 10

The first concise definition of “maximum precipitation” was presented in the foreword to HMR 10 (USWB, 1939, p. 1) where it stated the following (emphasis added):

> It is believed timely to review and restate the philosophic premise upon which these studies are based. **In general it can be stated that the objective is to determine the maximum or limiting storm – the depth-area pattern of rainfall which cannot under any combination of meteorological factors be exceeded.** This objective is accomplished through:
>
> a) The exhaustive treatment of all available data.
> b) The application, by especially qualified technicians, of a rapidly improving technique based upon modern meteorological conceptions.
> c) The rational extrapolation to physical upper limits, as the result of the composite judgment of the technical group analyzing the storms.”

The authors also note that "the technique of storm analysis is based upon the modern conception of synoptic and dynamic meteorology, which includes air mass analysis and the utilization of upper air data."

HMR 23

The first HMR that provided generalized PMP estimates for the eastern United States defined MPP as follows (USWB, 1947b, p. 2; emphasis added):

> **The maximum possible precipitation for a given area and duration is defined as the depth of precipitation which can be reached but not exceeded under known meteorological circumstances.** In this, as in all hydrometeorological reports, it is an estimate because the laws limiting precipitation rates are not completely known. Like any estimate, it implies a range of tolerance, the extent of which will depend on deficiencies in data, limitations of technical knowledge, and degree of thoroughness of the analysis. The values derived are considered to be the maximum possible, since they have been derived, within the limits of current theory and available data, from the most effective combination of the factors controlling rainfall intensity.

HMR 33

HMR 33 (Riedel et al., 1956) was published to build upon the results of HMR 23 and to establish seasonal PMP estimates for the domain east of the 105th meridian from the generalized estimates of PMP given in HMR 23 (see England et al., 2011 for a summary). HMR 33 provided the following definition (Riedel et al., 1956, p. 1, emphasis added), which was the first to use the term "probable maximum precipitation" and include a seasonal component:

> **The probable maximum precipitation represents the critical depth-duration-area rainfall relations for a particular area during various seasons of the year that would result if conditions during an actual storm in the region were increased to represent the most critical meteorological conditions that are considered probable of occurrence.** The critical meteorological conditions are based on an analysis of air-mass properties (effective precipitable water, depth of inflow layer, temperatures, winds, etc.), synoptic situations prevailing during the recorded storms in the region, topographical features, season of occurrence, and location of the respective areas involved. The rainfall values thus derived are designated as the probable maximum precipitation since they are determined within the limitations of current meteorological theory and available data and are based on the most effective combination of factors controlling precipitation intensity. The term "maximum possible precipitation" used in previous reports is synonymous with "probable maximum precipitation", however, it is believed the term "probable maximum precipitation" is a more descriptive one.

Technical Paper 38

The first generalized PMP estimates for the western United States were presented in Technical Paper No. 38 (USWB, 1960), primarily for use by the Soil Conservation Service. The report did not provide a new definition of PMP. It did describe in Chapter 4 some philosophy and context of the estimates, including that various storm types contribute to PMP over an area, as illustrated in the paragraphs below.

> 4.1.1 There is no doubt that there is a physical upper limit to the amount of precipitation that can fall over a specific area in a given time. Referring to floods, Horton [19] once wrote: "A small stream cannot produce a major Mississippi River flood for much the same reason that an ordinary barnyard fowl cannot lay an egg a yard in diameter; it would transcend nature's capabilities under the circumstances." The same reasoning applies to precipitation. The physical upper limit of precipitation has come to be known as probable maximum precipitation, or PMP.
>
> 4.1.2 At one time the concept of PMP was expressed in terms of the words "maximum possible." However, in considering the limitations of data and understanding implicit in an estimate of "maximum possible" precipitation, it seemed that there was sufficient uncertainty to substitute for the expression "maximum possible" the more realistic one, "probable maximum." This was done with no intention or implication of making the values any different. "Probable maximum" simply seemed to be more descriptive and more realistic.
>
> 4.1.3 The use of meteorology for determining limiting precipitation values was initiated in the middle 1930's. The probable maximum, or maximum possible, storm evaluated in studies prior to about 1945 was understood to be a fictitious, or synthetic, storm that could produce the heaviest, meteorologically-possible precipitation over a specific area for all durations within a storm. A distinction between precipitation and storm is now generally recognized. The probable maximum precipitation, or PMP, as now generally known, for a specific area for various durations is usually determined by several types of storms. For example, the PMP for an area under 100 sq. mi. and for durations less than 6 hours is very likely to be realized from thunderstorms, but general storms are more likely to provide the limiting precipitation values for longer durations.

HMR 43

HMR 43 (USWB, 1966) provided generalized PMP estimates for the Pacific Northwest. Notably, PMP estimates were made as the sum of convergence precipitation and orographic precipitation. An orographic precipitation model was used following HMR 36. A definition of PMP is stated in Chapter 1 as follows, noting "rainfall that approaches the upper limit." There are several important statements on PMP estimation that follow the definition, including wind, how much to maximize, and the use of judgments (emphasis added).

> **PMP over a watershed is the depth of rainfall that approaches the upper limit of what the atmosphere can produce.** In mountainous regions it is derived in part by physical methods, in that maximum winds and moisture are input to an orographic storage equation that makes use of several principles of airflow to compute precipitation due to lift by mountain slopes. Involved in the procedure is maximizing storms of record for moisture and indirectly for wind. How much and which storms to maximize is all-important to the upper limit. Much of this report is devoted to answering these questions. It is easily shown that if storm transposition were unlimited and if maximum values of winds, moisture and other variables of storms were combined, the results would be unrealistic. Limited transposition and combination of near maximum values of a variable with high but not necessarily highest values of other variables require making judgments at several steps in the procedure. Such judgments are influenced through study of record storms. Additional guidelines come from results of other PMP studies and statistical analyses of extremes in observed variables.

HMR 51

HMR 51 (Schreiner and Riedel, 1978) provided updates to generalized PMP estimates for the eastern United States, along with estimates for larger drainage areas. HMR 51 provided two definitions of PMP from AMS (1959) and WMO (1973), with notes about estimation and judgment, as follows (emphasis added).

> **PMP is defined as the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year (AMS, 1959).** In consideration of our limited knowledge of the complicated processes and interrelationships in storms, PMP values are identified as estimates.
>
> Another definition of PMP more operational in concept is ‘the steps followed by hydrometeorologists in arriving at the answers supplied to engineers for hydrological design purposes’ (WMO, 1973). This definition leads to answers deemed adequate by competent meteorologists and engineers and judged as meeting the requirements of a design criterion.

HMR 52

HMR 52 (Hansen et al., 1982) was created as a supplement to HMR 51. The report established procedures to apply PMP estimates found in HMR 51 to watersheds. The definition of PMP was revised in HMR 52 to focus on the fact that PMP reflects storm area rather than watershed area. This revised definition is listed below, along with definitions for storm pattern and area averages (emphasis added).

> Probable Maximum Precipitation (PMP). **Theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year.**

> (This definition is a 1982 revision to that used previously (American Meteorological Society 1959) and results from mutual agreement among the National Weather Service, the U.S. Army Corps of Engineers, and the Bureau of Reclamation.)
>
> PMP Storm Pattern. The isohyetal pattern that encloses the PMP area plus the isohyets of residual precipitation outside the PMP portion of the pattern.
>
> Storm-centered area-averaged PMP. The values obtained from HMR No. 51 corresponding to the area of the PMP portion of the PMP storm pattern. In this report all references to PMP estimates or to incremental PMP infer storm-area averaged PMP.
>
> Drainage-averaged PMP. After the PMP storm pattern has been distributed across a specific drainage and the computational procedure of this report applied, we obtain drainage-averaged PMP estimates. These values include that portion of the PMP storm pattern that occur over the drainage, both PMP and residual.

HMR 55A

HMR 55A provided generalized PMP estimates for an area between the 103rd meridian and the Continental Divide. It retained the PMP definition from HMR 52 and provided definitions for generalized and individualized estimates.

> Generalized. When used as an adjective to modify names such as PMP or estimates or charts, is to be taken in the sense of "comprehensive," i.e., pertaining to all things belonging to a group or category. Thus, a generalized PMP map for a specific area and duration defines PMP for all points in the region; no location is excluded.
>
> Individualized. As applied to drainage estimates, indicates studies for specific drainages that include considerations for possible local influences. In the sense of applications to specific basins, it is commonly implied that information obtained from a generalized study will be processed and result in specific drainage-averaged values.

HMR 57

HMR 57 (Hansen et al., 1994) provided updated generalized PMP estimates from HMR 43. It retained the PMP definition from HMR 52. Some relevant definitions and philosophy for the estimates are as follows, from HMR 57 section 1.2.

> The definition of PMP was changed in 1982 (Hansen et al., 1988) to read, “theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year.” This change to the definition used previously (American Meteorological Society, 1959), and in HMR 43, resulted from mutual

agreement among the NWS, the U. S. Army Corps of Engineers (COE), and the Bureau of Reclamation (USBR) among others. The new definition stresses the independence of atmospheric control over precipitation from that relative to a particular drainage area mentioned in the earlier definition.

The foundation of PMP estimation lies in observations of rainfall amounts as observed in major storms. PMP studies deal with the potential rainfall that may be produced from the coincidence of an optimum set of atmospheric conditions and circumstances. It is important to realize that the PMP is a theoretical value that represents a limiting precipitation amount for a particular duration and area, and as such is not a quantity that is expected to be observed. Because of this concept, the PMP in this report as others should always be regarded as an estimate. Recent NWS PMP reports (Schreiner and Riedel, 1978; Hansen et al., 1988) have described the procedures used to derive PMP estimates, based on observed storm rainfall maxima and atmospheric knowledge.

Two important atmospheric conditions that are considered in most PMP studies are the moisture content and the efficiency with which a storm converts moisture into precipitation. A procedure known as moisture maximization is used to approximate the highest moisture potential in storms. It is also recognized that records of observed storm rainfalls are relatively short, generally less than 100 years. One means to improve the adequacy of the storm sample has been to apply a procedure of storm transposition. By increasing the storm sample at a location through transposition, it is assumed that at least one storm in the sample has contained maximum efficiency. This assumption is necessary because not all aspects of the physical processes resulting in the most extreme rainfall are known. PMP estimates are the result of envelopment and smoothing of a number of moisture maximized, transposed storm rainfall amounts. This report will discuss these procedures as applied to Pacific Northwest storms.

The concept of PMP as an upper limit often evokes concerns that the procedure combines maximized quantities to reach a level that cannot reasonably be expected to occur. It will be noted in this study, as in past NWS studies, that this is not the case. While moisture is indeed maximized, numerous other factors are involved at a lesser level to effectively control unreasonable compounding of extremes.

Terrain plays an important role in precipitation and can act both to enhance as well as reduce (shelter) observed rainfall. It is well known that storms that move slowly or become stalled, or reoccur over a specific location result in more precipitation falling in a particular rain gage than do rapidly moving storms. Thus, orographic effects from storm-terrain interactions to the extent that they trigger moisture release or block storm movement, play an important role in PMP studies. The Pacific Northwest has some of the most complex terrain features in the country and makes this region a difficult, although interesting, challenge for study.

HMR 59

HMR 59 (Corrigan et al., 1999) provided updated generalized PMP estimates from HMR 36. It retained the PMP definition from HMR 52 (as did HMR 55A). Some relevant definitions and philosophy for the estimates are as follows, from HMR 59 section 1.3.

> The PMP definition used for this report was given in HMR 55A (1988) as 'theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year.' This is slightly different from the previous definition (American Meteorological Society 1959), which was used in HMR 36. The HMR 36 definition stressed that the estimate was for a particular drainage area. The current definition is more generalized, and emphasizes the control the atmosphere has over a broad geographic region. At the same time, the techniques from this report provide estimates of PMP for specific basins.
>
> The PMP storm for a region is considered the upper limit of precipitation. Moisture maximization, storm transposition, and envelopment are tools that provide estimates of the upper limits of precipitation for a region from intense storms. However, the remaining procedures used to develop a PMP design storm do not maximize the other factors involved in the estimation of these potential storms. Moisture is maximized, but other factors are allowed to act in a lesser manner, so that an unreasonable compounding of extremes does not occur. These procedures produce a PMP design storm. For orographic regions, only that portion of the precipitation that can be considered non-orographic is transposed. No attempt is made to transpose the orographic components of a storm.

World Meteorological Organization Manuals

WMO first produced a manual for estimating PMP in 1973. It was revised in 1986 and 2009 with slight changes in definitions. The 1973 and 1986 manuals were written by current or recent employees of the NWS Office of Hydrology, implying endorsement by NWS.

WMO 1973

WMO (1973) provided conceptual and operational definitions of PMP as listed below. The conceptual definition is from AMS (1959). Important terms and concepts on probable maximum storm, accuracy, and confidence limits are also provided (emphasis added).

> Conceptual Definition
>
> The use of meteorological knowledge to derive limiting precipitation values for hydrological design purposes began to gain favour in the middle 1930's. There are varying degrees of limiting design values depending on the purpose for which they are required. **Precipitation associated with the uppermost limits is known as the probable maximum precipitation (PMP), which is defined [1] as the**

theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a particular time of year. Such is the conceptual definition of PMP. The values derived as PMP under this definition are subject to change as knowledge of the physics of atmospheric processes increases. They are also subject to change with long-term climatic variations, such as would result from changes in solar radiation intensity. Climatic trends, however, progress so slowly that their influence on PMP is small compared to other uncertainties in estimating these extreme values. Climatic trends are therefore ignored.

Operational Definition

In addition to the conceptual definition of PMP, an operational definition may be considered as consisting of the steps followed by hydrometeorologists in arriving at the answers supplied to engineers for hydrological design purposes. Whatever the philosophical objections to the concept, the operational definition leads to answers that have been examined thoroughly by competent meteorologists and engineers and judged as meeting the requirements of a design criterion. The result of applying the operational definition over an entire region is to approach uniformity in design, safety and cost.

Maximum possible precipitation

Probable maximum precipitation (PMP) was once known as maximum possible precipitation (MPP), and this latter term is found in most reports on estimates of extreme precipitation mode prior to about 1950. The chief reason for the name change to PMP was that MPP carried a stronger implication of physical upper limit of precipitation than does PMP, which is preferred because of the uncertainty surrounding any estimate of maximum precipitation. Procedures for estimating PMP, whether meteorological or statistical, are admittedly inexact, and the results are approximations. Different, but equally valid, approaches may yield different estimates of PMP. For this reason various levels of PMP may be considered, as discussed in section 1.2.

Probable maximum storm (PMS)

PMP for all durations and sizes of area in a specific basin is usually determined by several types of storms. For example, thunderstorms are very likely to provide PMP over an area smaller than about 1000 km^2 for durations shorter than 6 hours, but controlling values for longer durations and larger areas will be derived almost invariably from general storms. For short durations, thunderstorms can produce heavier rainfall than can general storms, but they are relatively short-lived, and individual storms cover relatively small areas. General storms, although they often include thunderstorms, produce less intense rainfall on the average, but their longer life and greater areal coverage result in greater rainfall amounts for durations of about 6 hours and longer, and for large areas.

Normally, it would appear illogical to assume that PMP for all durations and sizes of area could be realized from one storm, but this is not necessarily so. PMP for small basins may be, and is often assumed to be, obtainable from a single storm. In such cases, PMP and PMS are synonymous, but this is not always so. PMP values for all ranges of duration and sizes of area in a basin are always understood to represent limiting rainfall amounts without regard to storm type. In other words, PMP values envelop the probable maximum amounts that might be realized from any type of storm that could produce heavy precipitation over the basin. PMS, on the other hand, may refer to any maximized observed or hypothetical storm that is equal to PMP for at least one duration and size of area. The term has been applied also to a hypothetical storm that would produce PMP for all durations at the total basin area and somewhat lesser values for smaller areas within the basin.

Accuracy of PMP estimates

That the procedures described here for deriving estimates of PMP yield results to the nearest millimeter or tenth of an inch should not be taken as an indication of the degree of accuracy of the estimates. There is no objective way of assessing the general level of PMP estimates derived by the procedures described here or by any other known procedures. Judgment based on meteorology and experience is most important. Obviously, estimates subsequently exceeded by observed storm rainfall were too low. There is no way, however, that an estimate can be labelled with certainty as being too low or too high at the time it is mode. Their accuracy may be assessed, however, by consideration of the following factors: (1) excess of estimated PMP over the maximum observed rainfall values for the project basin and surrounding region; (2) number and severity of record storms; (3) limitations on storm transposition in the region; (4) number, character, and interrelationship of maximizing steps; (5) reliability of any model used for relating rainfall to other meteorological variables; and (6) probability of occurrence of the individual meteorological variables used in such models, with care being taken to avoid excessive compounding of probabilities of rare events.

Subsequent chapters show that various steps in the procedures require meteorological judgment. Consequently, the resulting estimates can be conservative or liberal depending on decisions affecting the degree of maximization used in their derivation. Thus, in effect, lower and upper limits to PMP can be estimated, although only one set of values is usually derived.

Confidence bands

The delineation of lower and upper limits to PMP is somewhat analogous to the confidence bands used in statistical work. It would be nice if a confidence band could be placed about a PMP estimate in an objective manner, similar to the standard statistical method, but this is not possible because PMP is not estimated by formal statistical methods. This limitation, however, does not invalidate the concept of a confidence band, but it means that its limits must be based in

> considerable measure on judgment, as is the PMP estimate itself. Factors influencing such judgment are the same as those for assessing the general level of PMP listed in the preceding paragraph.

WMO 2009

WMO (2009) was an update and revision to WMO (1986), with revisions that reflect experience since 1986 in the United States, Australia, and India, with a focus on direct watershed estimates of PMP in China. The PMP definition was changed to indicate that PMP could represent a storm area or a design watershed, and eliminates the operational PMP definition. This version recognizes PMP is an estimate of a physical upper limit and makes simple statements about its accuracy. The discussion on confidence bands in WMO (1986) was eliminated. WMO (2009) provides three slightly different definitions of PMP. The first one includes “meteorologically possible” and a statement about climate trends; the second one includes the “theoretical maximum” concept and “modern meteorological conditions,” without mentioning climate trends. The second definition is close to the third definition that is listed in the glossary. The term “modern meteorological conditions” is not specifically defined.

> Definition of PMP (Summary page xxiii)
>
> Probable maximum precipitation (PMP) is defined as the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends.
>
> Definition of PMP (Section 1.1)
>
> PMP is the theoretical maximum precipitation for a given duration under modern meteorological conditions. Such a precipitation is likely to happen over a design watershed, or a storm area of a given size, at a certain time of year. Under disadvantageous conditions, PMP could be converted into PMF – the theoretical maximum flood. This is necessary information for the design of a given project in the targeted watershed.
>
> Definition of PMP (Glossary, p. 243)
>
> Probable Maximum Precipitation (PMP) Theoretically, the greatest precipitation for a given duration that is physically possible over a given watershed area or size of storm area at a particular geographic location at a certain time of year, under modern meteorological conditions.
>
> 1.4.1 Basic knowledge
>
> Storms, and their associated floods, have physical upper limits, which are referred to as PMP and PMF. It should be noted that due to the physical complexity of the phenomena and limitations in data and the meteorological and hydrological

> sciences, only approximations are currently available for the upper limits of storms and their associated floods.
>
> 1.6 ACCURACY OF PMP/PMF ESTIMATION
>
> The accuracy of PMP/PMF estimation rests on the quantity and quality of data on extraordinary storms and floods and the depth of analysis and study. Nonetheless, it is impossible to give precise values for PMP and PMF. As yet, there are no methods to quantitatively assess the accuracy of PMP and PMF. Presently, it is most important to analyse, compare and harmonize results of PMP/PMF from multiple perspectives. This task is called a consistency check in the United States (Hydrometeorological Reports 55A, 57 and 59: Hansen and others, 1988; Hansen and others, 1994; and Corrigan and others, 1998) and is termed a rationality check in China (section 7.2.7 of the manual). Results are quality controlled through such a comparison. When evaluating various PMP estimates, there are some other aspects to consider:
>
> (a) the amount by which the estimated PMP exceeds the maximum observed rainfall values for the surrounding meteorologically homogeneous region;
> (b) the frequency and severity of recorded storms that have occurred in the region;
> (c) limitations on storm transposition in the region;
> (d) the number of times and character of maximization, and correlations between them;
> (e) the reliability of relations between rainfalls and other meteorological variables in the model;
> (f) occurrence probabilities of individual meteorological variables in the model, though excessive combination of rare occurrences should be avoided.
> Although the procedures described here produce PMP estimates to the nearest millimetre or tenth of an inch, this should not be used to indicate the degree of accuracy.

Federal Agency and Industry Guidelines

NRC 1985 Safety of Dams Flood and Earthquake Criteria

NRC (1985, pp. 56-57) contained the following finding relevant to modernizing PMP and definitions:

> The committee has found general agreement in the following observations regarding current spillway capacity criteria:
>
> - Interpretations of data from past storms and storm model concepts are required to make estimates of PMP.
> - As shown by past experience, PMP estimates can change as more data become available; thus, the PMP estimate cannot be regarded as a fixed

> criterion, but confidence in the estimates should rise with successive PMP estimates for a given locality.
>
> - The probability that a rainfall will equal or exceed current PMP estimates is indeterminate but probably not uniform for projects in different parts of the country.
> - In order that judgments can be made on appropriate allocation of resources, it would be desirable to be able to express spillway design flood criteria in terms of annual probabilities.
> - Each existing large, high-hazard dam having a spillway that fails to meet current PMF criteria should be considered separately. It does not seem appropriate to adopt fixed rules for such situations. Each study should consider how deficient the project is under current criteria and the relationship of the allocated spillway capacity to other flood criteria. If a deficiency relates to change in safety evaluation criteria (such as an increase in PMP estimates), the reason for such change and their relationship to the project in question should be critically examined.

NRC 1994

NRC (1994) used the WMO (1986) PMP definition.

ASCE 1988 Evaluation Procedures for the Hydrologic Safety of Dams

ASCE (1988, pp. 66–67) included the following statements relevant to modernizing PMP and definitions.

> In recent years, the National Weather Service has prepared Hydrometeorological Reports which provide estimates of PMP for the United States. Use of these reports to define PMP should help reduce variations in PMF estimates.
>
> There are a number of sources of uncertainty in making PMP estimates. Estimates of PMP are based upon observed storm experience and maximum observed dewpoints. As the length of record increases and new storms are experienced, estimates of PMP are likely to change, particularly in regions where storm data are currently sparse. This introduces uncertainty in the PMF determination.

USBR 1989, 2006

Cudworth (1989, p. 25) utilizes the PMP definition from HMR 52 and states the following regarding severe storm knowledge.

> As hydrometeorologists expand their knowledge of severe storm meteorology, future revisions to present PMP estimates can be expected. However, at least for the conterminous United States, only minimum modification to current values of PMP is expected in the foreseeable future because knowledge of severe storm phenomena has reached a plateau.

Swain et al. (2006) restate the PMP definition from HMR 52 and note PMP estimates from the HMRs are used:

> The PMP, as defined by these three agencies at that time, is "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year." PMP must always be termed as an estimate because there is no direct means of computing and evaluating the accuracy of the results. Since the mid-1980s, Reclamation has considered that the series of HMRs prepared and updated by the National Weather Service provide the best estimates of PMP potential within the limits of each report.

USACE 1991 Engineering Regulation 1110-8-2 Inflow Design Floods for Dams and Reservoirs

The USACE (1991) regulation utilizes the PMP definition from HMR 52.

NRC NUREG/CR-7046 and ANSI/ANS 2.8-2019

Prasad et al. (2011) summarized the design flood estimation at nuclear power plants for the Nuclear Regulatory Commission; they cite the WMO (1986) PMP definition in the glossary of their report. Prasad et al. (2011) acknowledge the idea of risk for design purposes as follows.

> In the past, NRC [U.S. Nuclear Regulatory Commission] adopted the concept of a "probable maximum event," for estimating design bases. The probable maximum event, which is determined by accounting for the physical limits of the natural phenomenon, is the event that is considered to be the most severe reasonably possible at the location of interest and is thought to exceed the severity of all historically observed events. For example, a probable maximum flood (PMF) is the hypothetical flood generated in the drainage area by a probable maximum precipitation (PMP) event. … The PMP is assumed to be a theoretical maximum and its estimation uses no associated probability distribution. In standard practice, estimating the PMF from the PMP involves some subjectivity and also uses no probabilistic basis.
>
> More recently, probabilistic methods have also gained acceptance for determining design-basis events. The advantage of probabilistic methods is that an estimate of the probability-of exceedance of the selected design basis can be made. This capability enables clear articulation of the level of risk that an SSC important to safety encounters during its operation. The emphasis, therefore, is not on determining the worst-case scenario as a basis for design, but to state the level of risk a chosen design would face.

The American Nuclear Society (ANS, 2019) in its revision to ANSI/ANS 2.8 rescinded the use of PMP and Probable Maximum Flood (PMF) as a design flood standard, replacing it with a probabilistic flood hazard evaluation. Relevant excerpts for modernizing PMP are as follows.

> This standard differs from its predecessor in the following areas:
>
> - The applicability of the standard extends to all nuclear facilities, not just power reactors.
> - Probabilistic assessment: This standard replaces the prescriptive "probable maximum" approach for establishing design flood hazards with a probabilistic approach for analyzing the frequency and magnitude of flood hazards. Thus, this standard focuses on the performance of a probabilistic flood hazard assessment and development of site probabilistic hazard frequency curves. An integral part of this process is the treatment of uncertainty.

UK PMP/PMF Improvements 2021 Draft

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

American Meteorological Society

AMS first provided a definition of PMP (AMS, 1959) that is based principally on HMR 33. A subsequent revision (AMS, 2022) reflects the HMR 52 theoretical definition that focuses on storm area. Both are shown below.

> Probable maximum precipitation - (Also called maximum possible precipitation.) The theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year. In practice, this is derived over flat terrain by storm transposition and moisture adjustment to observed storm patterns. (AMS, 1959)
>
> Probable maximum precipitation - [Also called maximum probable precipitation, maximum possible precipitation (rare).] Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year. (AMS, 2022)

Hydrology Texts and Statewide PMP Reports

Handbook of Applied Hydrology – 1964

> From Gilman (1964, pp. 9-62 to 9-64)
>
> … For these reasons, design engineers have asked meteorologists for estimates of the probable maximum precipitation as the basis for design of such spillways.

The estimates represent the best judgment of the meteorologists of the realistic upper limit of precipitation that can occur. Many meteorologists have thought that there is no upper limit on precipitation amount - that any given amount can conceivably occur. Such a view is not realistic mathematically or physically speaking, since it is certainly possible to put an upper bound on the precipitation that can occur. And if it is possible to fix an upper bound, there must exits a least upper bound, which might be called the possible maximum, or probable maximum, precipitation (PMP).

Advantages of the procedure are several. It provides empirical or statistical controls. The values are directly related to the largest that have occurred. The experience of a basin is extended through transposition. The use of actual storms for patterns ensures realism in that nature's integrations are used rather than hard-to-justify synthetic ones. The overcompounding of probabilities is minimized.

Several features of the results obtained are worthy of note. The highest estimates of PMP often exceed the greatest value of observed precipitation in certain basins by only a small percent. In other basins they may be several times as great as the maximum observed. The greatest maximizing process for a given basin is storm transposition. If a precipitation value several times as large as any over a given problem basin has been observed over a nearby basin, then it is considered that the observed isohyets in the actual storm can be transferred, or transposed, so as to indicate the maximum amount over the problem basin. … The principal place this difficulty appears is in the rugged mountainous areas such as the West Coast of the United States. The estimation of PMP in mountainous areas is usually considered to be much more uncertain than in large homogeneous areas.

Wiesner 1970

From Wiesner (1970, p. 186)

Definition of probable maximum precipitation, PMP. It is recognized that there is a physical upper limit to the amount of precipitation that can fall over a specified area in a given time (Bernard, 1944). This upper limit has become known as the Probable Maximum precipitation, PMP, and is more precisely defined as, that depth of precipitation, which, for a given area and duration, can be reached, but not exceeded under known meteorological conditions.

Chow Maidment Mays 1988

From Chow et al. (1988, p. 418)

The concept of an estimated limiting value is implicit in the commonly used probable maximum precipitation (PMP) and the corresponding probable maximum flood (PMF). The probable maximum precipitation is defined by the WMO (1983)

> as a “quantity of precipitation that is close to the physical upper limit for a given duration over a particular basin.

Viessman et al. 1989 Introduction to Hydrology, 3rd Edition

Viessman et al. (1989, p. 372) provide an unusual PMP definition; it includes the term “reasonable” and notes a low probability of occurrence.

> The PMP is defined as the reasonable maximization of the meteorological factors that operate to produce a maximum storm. The PMP has a low, but unknown, probability of occurrence. It is neither the maximum observed depth at the design location or region nor a value that is completely immune to exceedance.

McCuen 1989 Hydrologic Analysis and Design

McCuen (1989, p. 600) cites the PMP definition from HMR 52.

Handbook of Hydrology—Maidment 1993

Smith (1993, p. 3.33) utilized the PMP definition from WMO (1986) (same as HMR 52). He notes the following, relevant for modernizing PMP, including the concept of “very low risk of exceedance.”

> For design of high-hazard structures such as spillways on large dams it is necessary to use precipitation values with very low risk of exceedance. Ideally a hydrologist would like to choose design storms for which there is no risk of exceedance. A theoretical problem that has plagued the search for such a storm is determining whether there is indeed an upper limit on rainfall amount. The conclusion of Gilman in 1964 that the existence of an upper limit on rainfall amount is both mathematically and physically realistic remains valid. The spatial and temporal context of the upper bound on rainfall amount is incorporated into the definition of *probable maximum precipitation* (PMP) which is defined by the World Meteorological Organization as ‘theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of year.’ A more troublesome problem than ascertaining whether an upper bound exists is determining what it is.

Viessman and Lewis 2002 Introduction to Hydrology, 5th Edition

Viessman and Lewis (2002, pp. 551–552) present a definition that retains the “reasonable” term and provide two other definitions, including one with the notion of a “low probability of occurrence.”

> The PMP is generally defined as the reasonable maximization of the meteorological factors that operate to produce a maximum storm for any given duration and areal extent. Other definitions have been proposed, including:

1. The PMP is the maximum amount and duration of precipitation that can be expected to occur in a drainage basin.
2. The PMP is the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region. The PMP has a low, but unknown, probability of occurrence. It is neither the maximum observed depth at the design location or region nor a value that is completely immune to exceedance.

Shuttleworth 2012

Shuttleworth (2012, pp. 207–208) provided a definition of PMP along with relevant discussion (emphasis added).

> A further measure of extreme precipitation for a region that might be helpful in infrastructure design is the concept of probable maximum precipitation (PMP). Although the name implies PMP is a statistical measure, it is largely a physical estimate of what might be the greatest possible precipitation given a certain set of extreme atmospheric conditions. **PMP is a hypothetical concept which is defined as "the analytically estimated greatest possible depth of precipitation that is physically possible and reasonably characteristic over a geographical region at a certain time of year"**. PMP is usually defined with respect to a given area, often a drainage basin, and includes estimates of the inflow of moisture over the basin and the maximum likely amount of that moisture which could be precipitated. The name total precipitable water (W) is inaccurate because not all of the water in the atmosphere can be precipitated by any known mechanism. Consequently, in addition to depending on W, the calculation of PMP needs to recognize and make allowance for realistic restrictions on the rate of convergence of water vapor towards a storm and the maximum effect of vertical motion within a storm. One approach used to estimate PMP is to adopt (and if necessary transpose from elsewhere) models of real extreme storms to estimate these additional restrictions, but then to index these to local extreme values of W. However, the assumptions and generalizations made when adopting the storm model approach are such that a sometimes preferred technique involves the use of actual storm occurrences, which are then 'maximized' to become an extreme storm for the area using the highest observed surface dew points and most extreme morphological conditions. … In regions with topography the estimation of PMP is much more difficult.

Bedient 2019

From Bedient (2019, p. 191):

> When it is not possible to reduce the risk to a desired level by designing for a high (but hypothetical) return period event, an alternative is to design for the probable maximum flood, which is the flood that results from the probable maximum precipitation (PMP) event. The PMP is the highest precipitation likely to occur

> under known meteorological conditions (Smith, 1993; Mays, 2001) and has been computed for most areas by the National Weather Service Hydrometeorological Design Studies Center.

Handbook of Applied Hydrology Singh 2017

Mukhopadhyay and Kappel (2017) rely on the HMR 52 PMP definition; they also include brief statements on estimation, probability, and climate change.

> Probable Maximum Precipitation (PMP) is defined as the theoretically greatest depth of precipitation for a given duration that is physically possible over a given size storm area and reasonably characteristic over a given geographic location at a certain time of the year (Hansen et al., 1982; Hansen, 1987). PMP is only an analytical estimate representing a theoretical upper limit and therefore cannot be exact. Generally, the probability of occurrence of a PMP is not given in its estimation. Furthermore, due to the large uncertainty in regards to the effects of climate change, any potential effect of climate change on the estimation of a PMP is generally not evaluated (WMO, 2009).

Statewide PMP Studies

Statewide PMP studies, such as for Nebraska (Tomlinson et al., 2008), Texas (Kappel et al., 2016), and North Dakota (AWA, 2021), generally use the HMR 52 PMP definition.

Appendix C
Dam Characteristics

Dam safety regulations, the agencies who regulate dam safety, and the needs of those agencies differ depending on where the dams are located, who owns them, and how they were constructed. This Appendix explains the committee's use of the National Inventory of Dams (NID) to illustrate the locations and pertinent data for high-hazard dams across the 50 states and Puerto Rico. This information underscores the breadth and scope of facilities, communities, and levels of government potentially impacted by needed changes to PMP estimation.

The NID is a publicly accessible database maintained by the U.S. Army Corps of Engineers (USACE) in collaboration with other federal agencies and state dam safety programs. It serves as a central repository of information on dams located throughout the United States. The NID captures extensive data about dams, including their location, purpose, size, ownership, construction materials, and associated hydraulic infrastructure.

The primary objective of the NID is to provide a standardized and up-to-date inventory of dams across the country. By compiling information on dam characteristics and associated attributes, the NID enables a comprehensive understanding of the nation's dam inventory. This knowledge supports decision-making processes regarding dam safety, risk assessment, maintenance, and regulatory compliance. Furthermore, the NID serves as a valuable resource for researchers, engineers, policymakers, and the general public to access information on dams and their potential impacts.

SOURCE DATA AND DATA NOTES

Data are from the National Inventory of Dams (https://nid.sec.usace.army.mil/), accessed 6 July 2023 and, for Figure C-5, 20 September 2023. The NID summary data (csv and GIS formats) were obtained from the NID website to initiate the committee's analysis. At the time of access, the NID contained data on 91,750 dams with 80 fields of information. Most of the information is provided by the dam owners supplemented by information from the various dam safety agencies. There are inconsistencies, typos, and missing data fields within the NID. Basic error handling was done to filter out filler values in some fields.

The NID provides data on the three standard hazard potential classification categories (FEMA, 2004): low, significant, and high. The data field can also include undetermined and not available entries. High-hazard potential dams are an obvious priority for continued monitoring and assessment. The physical properties and hydrologic settings of these dams should inform the focus and range of parameters that a modernized PMP estimation process should serve, particularly storm duration and area resolution. Thus, our analysis focused on dams identified as high-hazard potential. Dams that were identified as undetermined hazard were not included in the analysis beyond the total count of dams (Figure C-1).

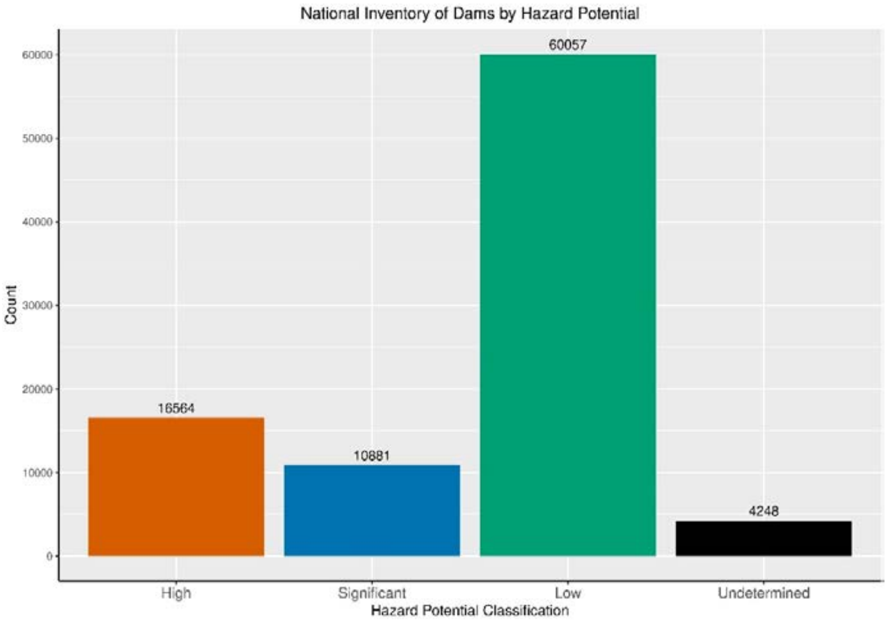

FIGURE C-1 Number of dams listed within each hazard potential classification.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

DAM LOCATION

Figure C-2 shows the number of high-hazard potential dams in each state. Figure 2-6 shows the location of each high-hazard potential dam.

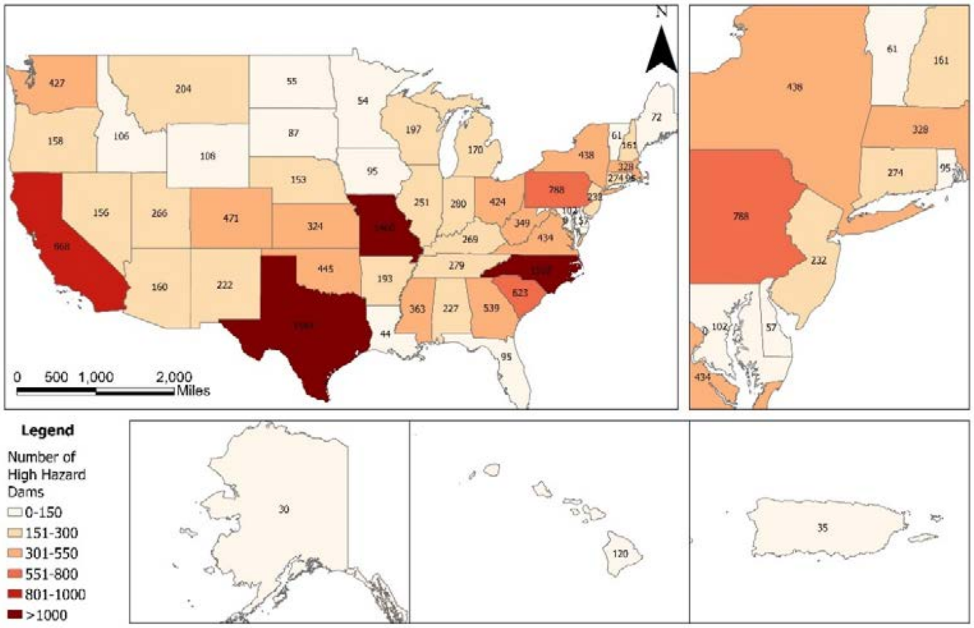

FIGURE C-2 Number of high-hazard potential dams within each state.
SOURCE: McGraw (2023), using data from National Inventory of Dams (https://nid.sec.usace.army.mil).

DAM OWNERSHIP AND REGULATORS

The NID lists seven ownership classes; the vast majority of dams are listed as privately owned or owned by local government (Figure C-3). When dams have multiple owners listed, the Primary Owner Type field was assumed to be the owner responsible for dam operation and maintenance.

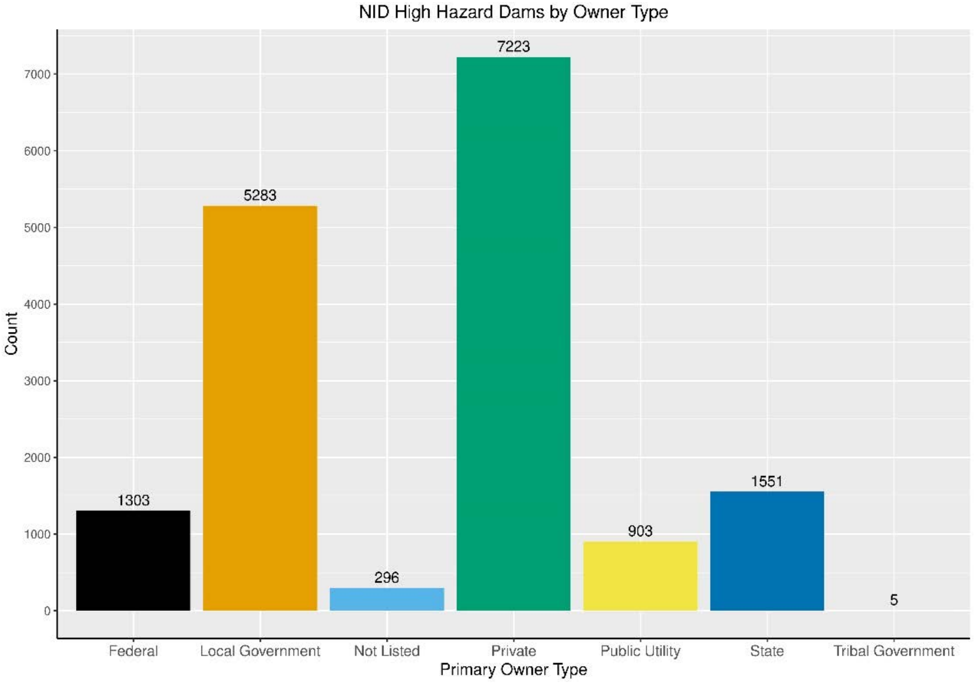

FIGURE C-3 High-hazard potential dams by owner type.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

There are both federal and state regulators of dams in the United States. Federal regulators generally focus on privately owned dams in the hydropower and mining industries, respectively. The primary regulators of high-hazard dams are listed in the NID as federal, state, and federal-state combinations. In some cases, the regulator is unknown. The numbers of high-hazard potential dams regulated by each of these groupings are shown in Figure C-4. About 12,686 dams (76.6% of the total) are regulated by state agencies.

DAM CHARACTERISTICS

Drainage Area

Drainage area distributions for all dams, separated by hazard class, are shown in Figure C-5. High-hazard dams are located on watersheds with larger drainage areas than significant and low-hazard dams (red line). Median drainage area estimates for each state are shown in Figure C-6; the median drainage of most states is less than 100 mi^2 with many less than 20 mi^2. Density estimates by owner type and dam height are shown in Figures C-7 and C-8; double peaks illustrate high number of dams with small drainage areas (1 to 10 mi^2) and secondary peaks at moderate scales (100 mi^2) that reflect the river network and watersheds where dams were built.

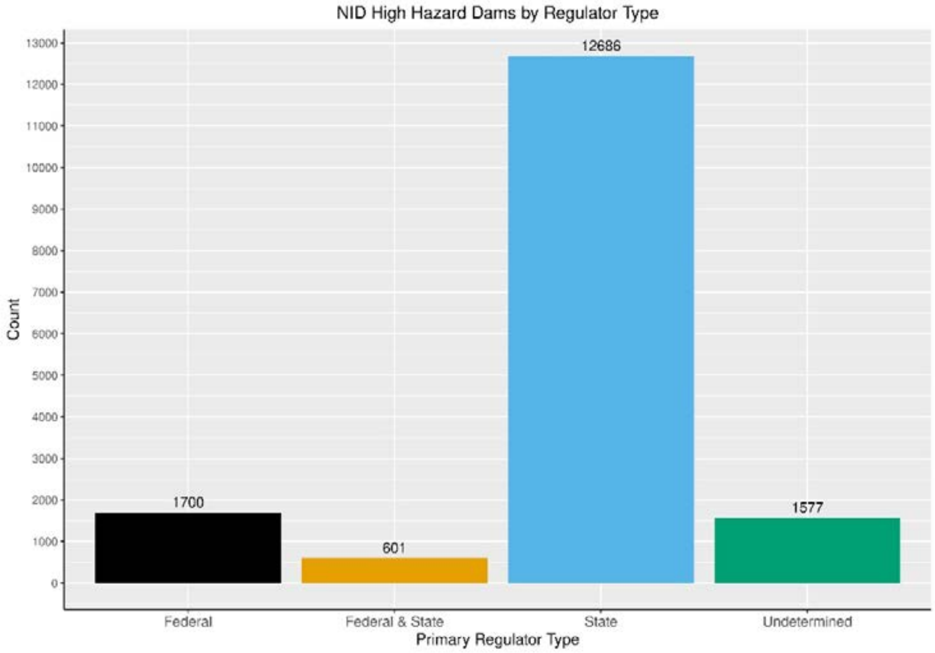

FIGURE C-4 Regulators of high-hazard potential dams.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

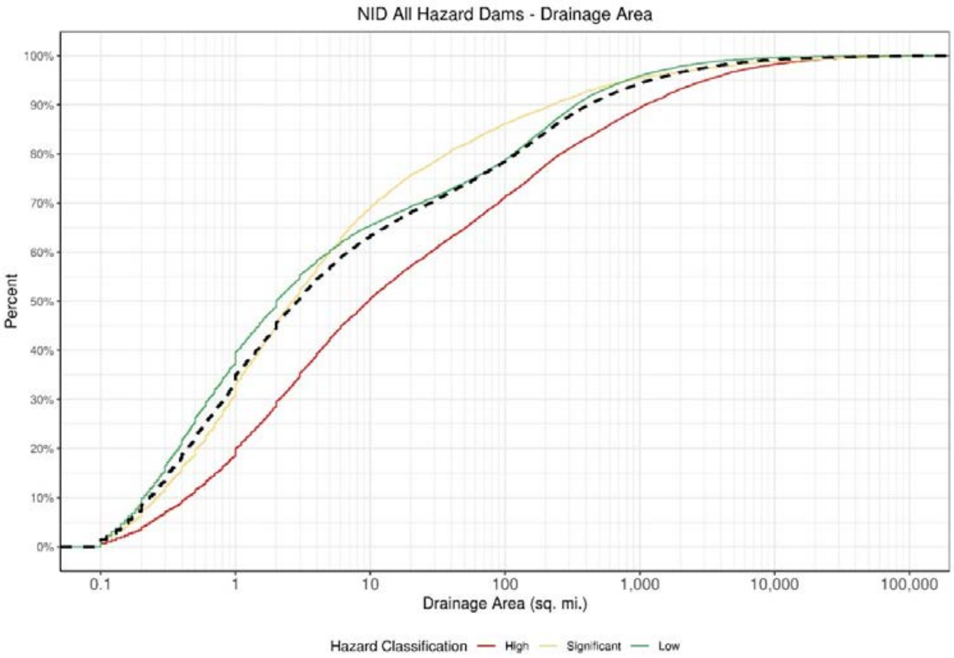

FIGURE C-5 Empirical cumulative distributions of drainage areas, shown by hazard classification. The distribution for all dams is shown by the thick black dashed line.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

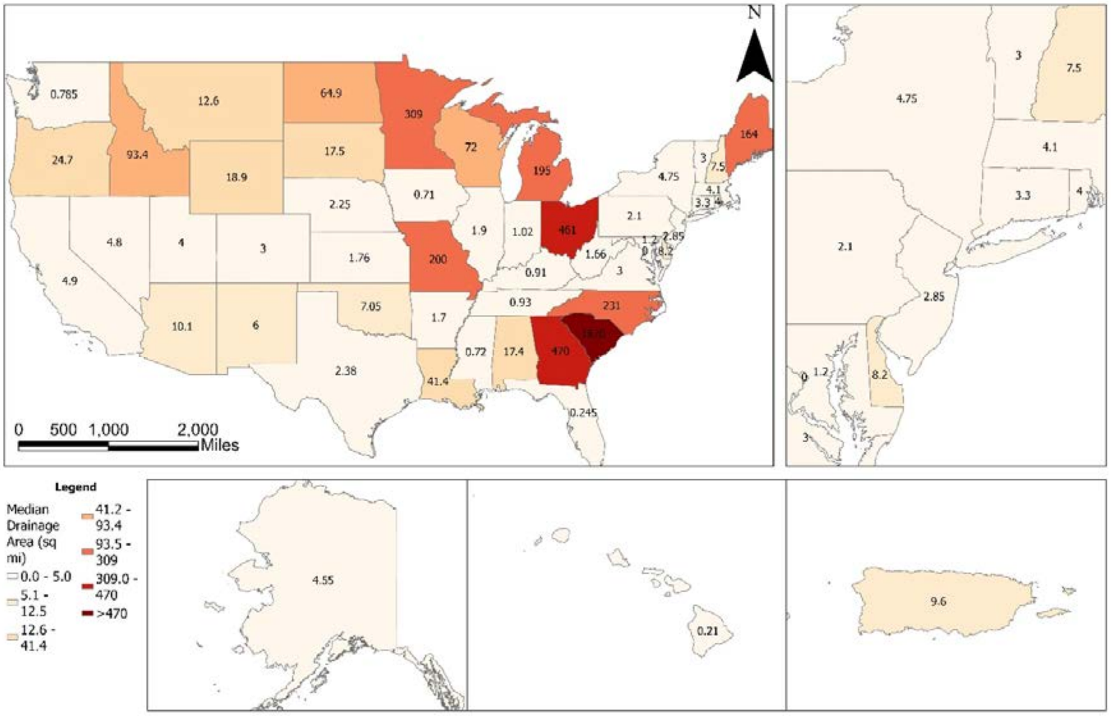

FIGURE C-6 Median drainage area of high-hazard potential dams for each state.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

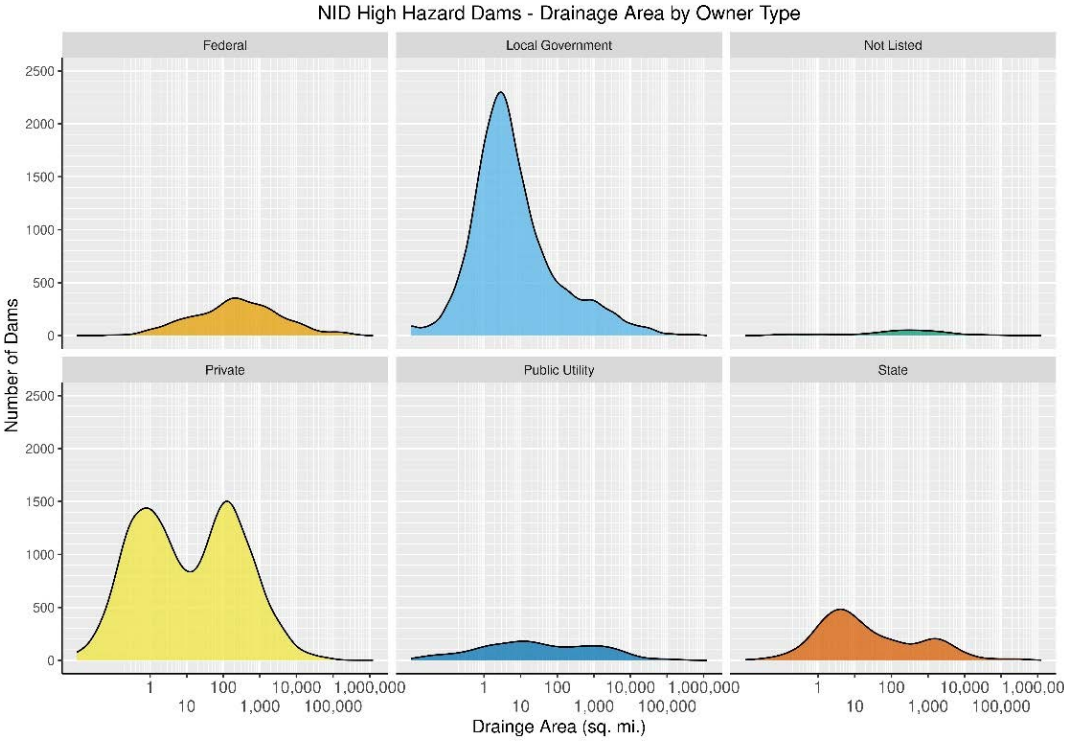

FIGURE C-7 Smoothed density estimates of drainage areas, shown by primary owner type, for high-hazard potential dams.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

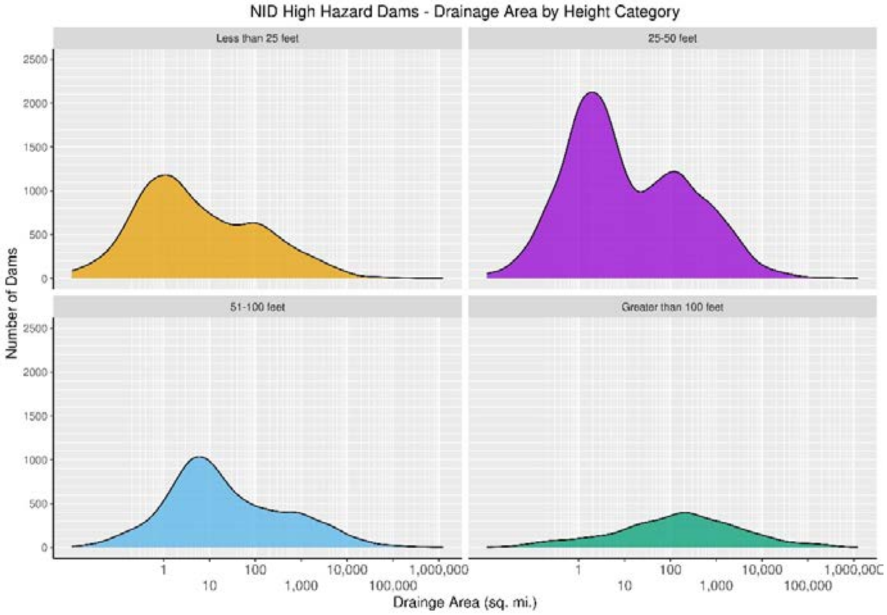

FIGURE C-8 Drainage areas for four classes of dam heights—high-hazard potential dams.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

Material

The NID contains information indicating the primary dam type, indicated by thirteen categories. For high-hazard potential dams, the most common dam type is earthen embankment (Figure C-9).

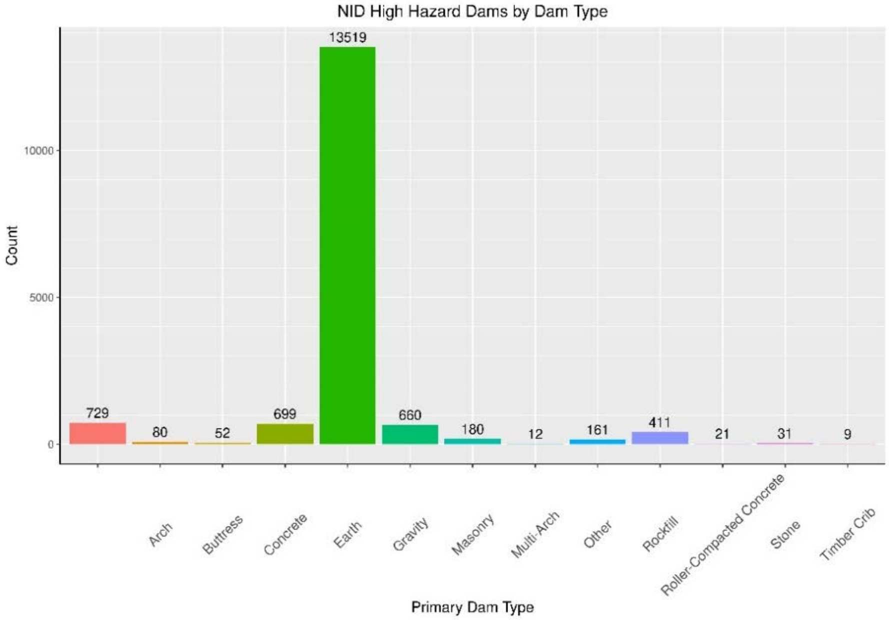

FIGURE C-9 Primary dam type of high-hazard potential dams. There are 729 high-hazard dams in the NID that do not have a dam type designated (far left bar).
SOURCE: McGraw (2023), using data from National Inventory of Dams (https://nid.sec.usace.army.mil).

Height

Median dam heights by state are generally less than 50 feet (Figure C-10). Dam height and storage relations are shown by owner type in Figure C-11 and by construction material in Figure C-12.

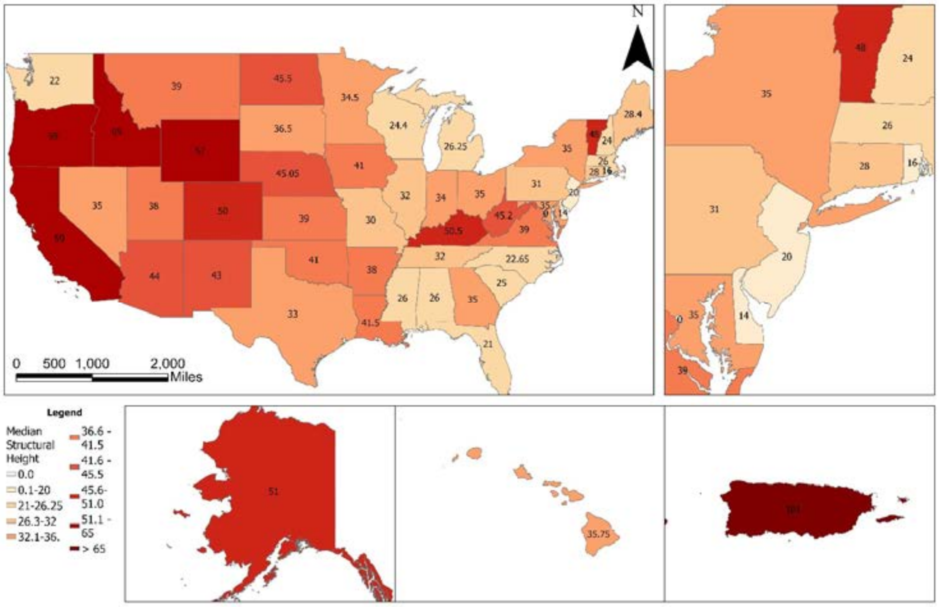

FIGURE C-10 Median height of high-hazard potential dams in each state.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

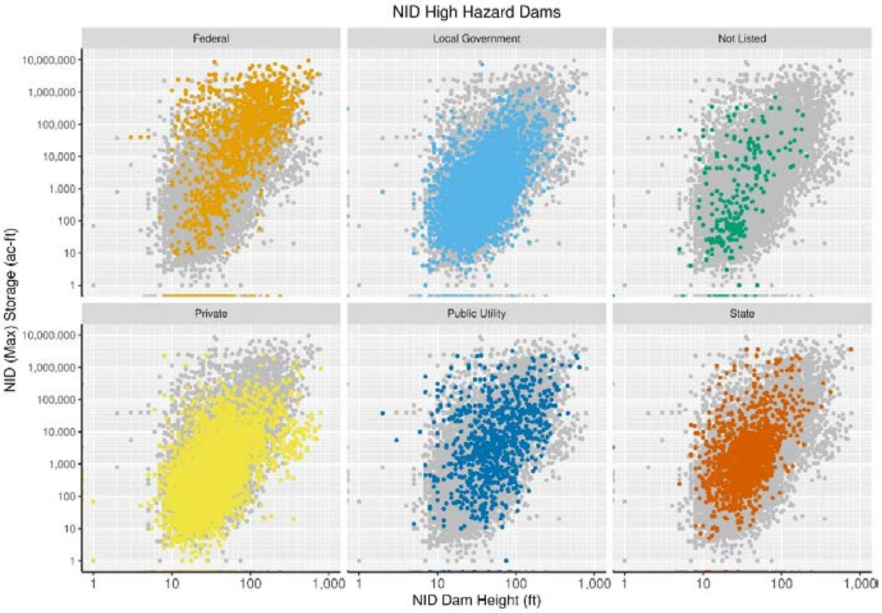

FIGURE C-11 Dam height and storage relations, shown by primary owner type, for high-hazard potential dams.
SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

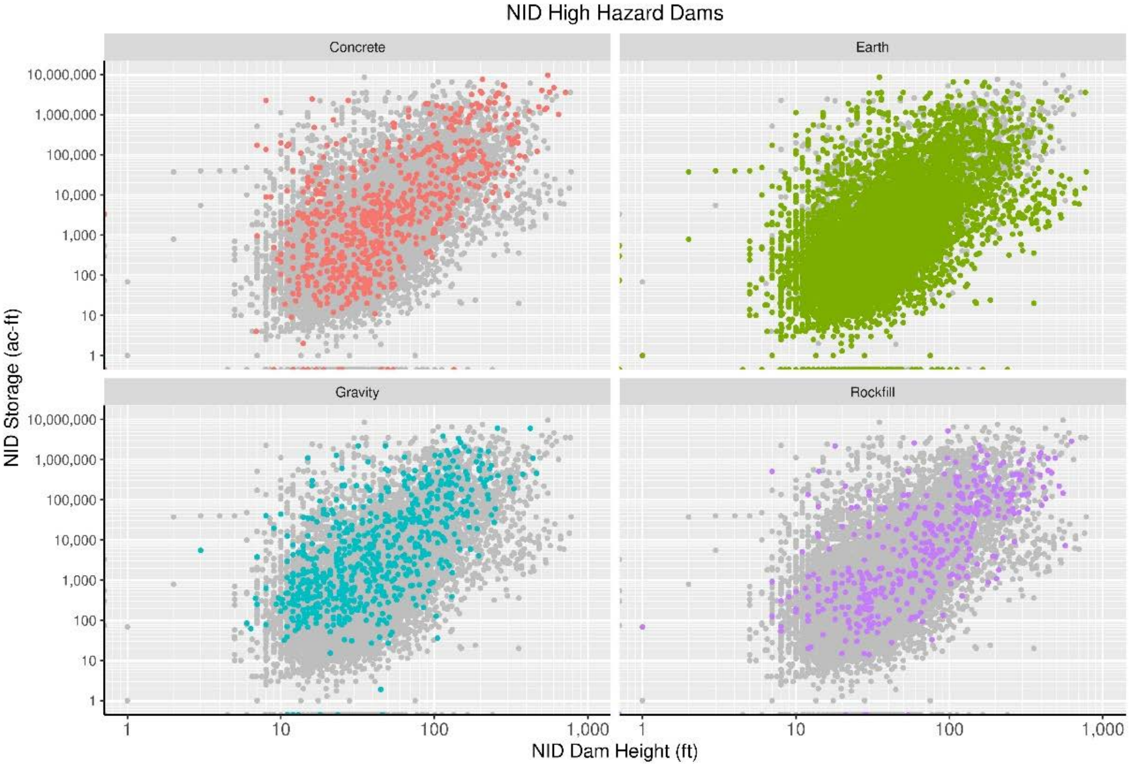

FIGURE C-12 Dam height and storage relations, shown by primary dam type, for high-hazard potential dams.

SOURCE: McGraw (2023), using data from the NID (https://nid.sec.usace.army.mil).

Appendix D
Criteria for a Modern PMP Estimation Process

This appendix summarizes the evaluation criteria developed by the committee for use in assessing the current and recommended approaches for estimating PMP. Table D-1 was introduced in Chapter 2, where the committee assessed the current PMP estimation process, demonstrating that the current process fails 20 of 23 criterion while partially meeting 3 necessary for producing objective, transparent, reproduceable, and accessible PMP estimates, as well as key rarity (Annual Exceedance Probability [AEP]) and uncertainty characterizations. In Chapter 5, the committee assessed the proposed near-term approach as meeting 12 criterion, partially meeting 9, and failing criterion related to AEP and uncertainty characterization, and the long-term approach as meeting 17 criterion including those for AEP estimation and uncertainty criterion, while rendering 6 as nonapplicable.

TABLE D-1 User Criteria for Valid/Useful PMP Estimates and Estimation Process

	Committee Assessment of		
Criteria	**Current Estimation Process**	**Recommended Near-term Process**	**Recommended Long-term Process**
Data collection, characterization, and availability			
Storm observations			
Ongoing and systematically collected and geospatially- and temporally dense storm rainfall observations are employed	Fails: Most HMRs and more recent state-level PMPs are based on irregular and sparse observations of extreme precipitation. HMR 51, for example, though covering most of the Nation east of the 105th meridian, was based on 55 storms that occurred from 1878 to 1972. Characterization of extreme precipitation during these storms and those used for state-level PMPs was based on sparse surface rain gauge networks greatly supplemented by "bucket surveys" following major storms.	Meets: The near-term recommended process includes use of conventional rain gauge and all other measurements that can be obtained for a storm, including bucket survey measurements when available, but relies principally on use of modern radar with a spatial resolution of approximately 1 km and a temporal resolution of 5-15 minutes.	Meets: The long-term recommended process incorporates data from reanalysis of historic storms and ongoing radar-based observations but relies mainly on large ensemble kilometer-scale modeling to supply storm data with which to construct PMP probability distributions.
Storm catalogs			
Storm catalog is centralized, up-to-date, and publicly accessible	Fails: Some agencies and private sector entities have compiled storm catalogs, but maintenance and updates are irregular and driven by individual agency project or regulatory needs. Public accessibility various greatly.	Meets: The near-term recommended process includes digitization of existing (2023) PMP-scale storm data and construction of a National, centralized, and publicly accessible PMP storm catalog.	Not applicable: The long-term recommended process will substitute model simulations of extreme precipitation events for each gridded cell and watershed.
New storm observations are systematically included	Fails: Storm catalog updates are irregular and often do not include recent storms.	Meets: The near-term recommended process envisions ongoing reanalysis and characterization of recent storms captured by radar observations.	Meets: The long-term recommended process envisions ongoing reanalysis and characterization of recent storms captured by radar observations.

Catalog routinely includes digitized rainfall fields to document and characterize temporal and geospatial intensity rainfall distributions	Fails: Most storms included in current storm catalogs include depth-area-duration curves but lack gridded information.	Meets: The near-term recommended process envisions ongoing digitization of recent storms captured by radar observations.	Meets: The long-term recommended process envisions ongoing digitization of recent storms captured by radar observations.
Modeling process (screening, adjustment, simulation, and statistical characterization to produce a PMP estimate)			
Storm maximization			
Maximization of observed or transposed storms is objective and reproduceable	Fails: Storm and long-term precipitable water estimates were based on surface dew point observations and empirical vertical moisture distribution models requiring subjective estimates of model parameters.	Partially meets: Process-based storm models are now available that could provide storm maximized precipitation and simulated temporal histories at high geospatial resolutions without resort to empirical techniques. The recommended near-term actions include development of a model validation project to identify and test promising model approaches.	Not applicable: The long-term recommended process recommends numerical simulations that include storms covering a broad range of extreme-precipitation events that will not require traditional individual storm maximization techniques. However, realizing this recommendation will require substantial and sustained model development and evaluation.
Maximization takes into account known interactions between major dynamical and thermodynamical processes	Fails: Current estimates of PMP are based on empirical models that inaccurately assume the independence of dynamical and thermodynamical process that has not withstood critical examination.	Partially meets: Process-based storm models are now available that could provide storm maximized precipitation and simulated temporal histories at high geospatial resolutions without resort to empirical techniques. The recommended near-term actions include development of a model validation project to identify and test promising model approaches.	Not applicable: The long-term recommended process recommends numerical simulations that include storms covering a broad range of extreme-precipitation events that will not require traditional individual storm maximization techniques. However, realizing this recommendation will require substantial and sustained model development and evaluation.
Storm transposition			
Transposition regions are developed and defined objectively	Fails: HMR PMP estimates often employ transposition regions that are based on subjective meteorological judgments and driven by use of singularly unique historic storms within sparse datasets.	Partially meets: The recommended near-term program includes development of transposition guidelines and tools and a model development and evaluation program to improve transposition tools and techniques.	Not applicable: The long-term recommended process recommends numerical simulations that include storms for every cell and watershed in a high-resolution grid that will not require traditional storm-transposition. However, realizing this recommendation will require substantial and sustained model development and evaluation.
Transposition adjustments are objectively determined	Fails: HMR PMP estimates are often based on correction factors that have little theoretical bases.	Partially meets: The recommended near-term program includes development of transposition guidelines and tools and a model development and evaluation program to improve transposition tools and techniques.	Not applicable: The long-term recommended process recommends numerical simulations that include storms for every cell and watershed in a high-resolution grid that will not require traditional storm-transposition. However, realizing this recommendation will require substantial and sustained model development and evaluation.

continued

TABLE D-1 *continued*

Criteria	Committee Assessment of Current Estimation Process	Recommended Near-term Process	Recommended Long-term Process
Storm envelopment			
State of science analytical procedures are employed	Partially meets: The HMRs employed smooth enveloping isohyets drawn to transposed observed and maximized storm precipitation values for various durations and area extents. The positioning and spacing of the isohyets were refined through consideration of regional information.	Partially meets: The recommended near-term program includes development of transposition guidelines and tools.	Not applicable: The long-term recommended process recommends numerical simulations that include storms for every cell and watershed in a high-resolution grid that will not require traditional storm-transposition. However, realizing this recommendation will require substantial and sustained model development and evaluation.
Model fidelity *(for this evaluation: the degree to which a model or simulation reproduces a state or behavior of a natural process)*			
Strong correlation with natural extreme rainfall generation processes through physically based analogs and algorithms	Fails: Past PMP estimation was based on empirical methods that estimated reasonable upper limits of maximized observed and transposed storm data with limited correlation to natural processes.	Partially meets: The recommended near-term program includes a model evaluation project to identify and integrate appropriate model algorithms for simulation of extreme storm events and their maximization, transposition, and envelopment pending transition to the recommended long-term process.	Meets: The recommended long-term program envisions the use of selected, data-driven, process-verified model algorithms and ongoing research to improve these models and apply them to varying storm types and climatic conditions.
Modern modeling *(for this evaluation: use of physically based algorithms that accurately simulate long ensembles of extreme rainfall events across most storm-types of concern and applicable climates relevant to PMP estimation and capable of outputting gridded results)*			
Use of up-to-date climate and weather models capable of accurately simulating long ensembles of extreme precipitation events of varying storm types and climatic conditions	Fails: Past PMP estimation was based on empirical methods that estimated reasonable upper limits of maximized observed and transposed storm data with limited correlation to natural processes.	Partially meets: The recommended near-term program includes a model evaluation project to identify and integrate appropriate model algorithms for simulation of extreme storm events and their maximization, transposition, and envelopment pending transition to the recommended long-term process.	Meets: The recommended long-term program envisions the use of selected, data-driven, process-verified model algorithms to simulate large-ensemble, high-resolution extreme storm rainfall events with which to construct PMP distributions.
Character of PMP and related products			
High-resolution, grid-based products			
GIS datasets depicting high-resolution (1-km spatial and 60-minute temporal) gridded PMP rainfalls for selected durations	Partially meets: Early PMP studies provided paper and then digitalized maps of PMP totals for selected storm durations. More recent, private-sector based studies have provided geospatial estimates for selected storm-durations together with storm catalog information.	Partially meets: The near-term recommended process includes digitization of existing (2023) PMP-scale storm data and identification and digitization of subsequent storms based on radar information.	Meets: The long-term recommended process includes numerical simulations of simulated storms that can be delivered as grid-based products.

Probability estimates			
AEP estimates of PMP for selected durations	Fails: The current PMP definition does not permit development of formal AEP estimates, thus no PMP study has provided AEP estimates.	Fails: The near-term recommended program will continue to operate based on the historic definition and will not produce AEP estimates.	Meets: The adoption of the recommended PMP definition will permit the association of PMP events with AEPs through long-term simulations that produce large numbers (100,000s) of precipitation events, including PMP-scale precipitation events, that will be analyzed statistically to estimate depths associated with and lead to PMP-magnitude AEPs.
Uncertainty			
Reliable uncertainty estimates	Fails: Subjective assessments have been provided by some PMP studies.	Fails: The current PMP definition does not permit development of formal uncertainty estimates.	Meets: The adoption of the recommended PMP definition will permit the characterization of uncertainty in PMP estimates.
Update frequency			
Every 10 years or as often as underlying conditions change significantly. (Provide process for quality-assuring and incorporating user-agency updates when resources for national updates are not available)	Fails: HMRs and more recent state-based updates have been irregular and ad-hoc as they are largely funded through state agencies.	Partially Meets: The recommended near-term process envisions ongoing capture of extreme events using radar-based observations and near-continuous reanalysis of these storms as the data are made available. Recommended approach facilitates updates needed to accommodate new data or climate change.	Meets: The recommended long-term process envisions ongoing capture of extreme events using radar-based observations and near-continuous reanalysis of these storms as the data are made available. Recommended approach would facilitate updates needed to accommodate new data or climate change.
Applicability of PMP Products			
Geospatial extent of covered area			
National extent without state-line or regional faults	Fails: HMRs and state-based products applied to discrete regions to cover most of continental U.S. for varying time periods.	Meets: The recommended near-term program includes requirements to meet this criterion.	Meets: The recommended long-term program includes requirements to meet this criterion.
Spatial resolution			
1 to 10,000 square miles	Fails: HMRs generally provided estimates for 10–20,000 square miles. State-based products differ in resolution.	Meets: The recommended near-term program includes requirements to meet this criterion	Meets: The recommended long-term program includes requirements to meet this criterion.
Storm duration			
1-hour to 7 days	Fails: HMRs generally provided estimates for 6–72 hours duration.	Meets: The recommended near-term program includes requirements to meet this criterion	Meets: The recommended long-term program includes requirements to meet this criterion.
Public Accountability and the PMP Estimation Process			
Transparency *(for this evaluation: the ease with which citizens can access governmental information and assess agency adherence to established timelines, rules, procedures, protocols, and standards of practice and care in governmental decision making)*			
Consistent and planned process disclosed prior to study with follow-on adherence to the plan timelines and	Fails: Early studies driven by varied agency needs and resources and conducted with little public input. Source data and models are often not well documented or	Meets: The near-term recommended program includes establishment of tracked timelines and written procedures to guide selection	Meets: The long-term recommended program includes establishment of tracked timelines and written procedures to guide selection of data input,

continued

TABLE D-1 *continued*

Criteria	Committee Assessment of		
	Current Estimation Process	**Recommended Near-term Process**	**Recommended Long-term Process**
Transparency *(for this evaluation: the ease with which citizens can access governmental information and assess agency adherence to established timelines, rules, procedures, protocols, and standards of practice and care in governmental decision making)*			
established procedures disclosing data sources, input and output data, technical assumptions, computer scripts and parameters, and ancillary information	easily accessed. Recent state-level studies have involved greater transparency and significant state-level interagency oversight.	of data input, computational processes, and software, and publish interim and final results and the use of periodic public notices through NOAA publications, the Federal Register, and other official means to document progress, explain delays or new directions, and to seek public comment.	computational processes, and software, and publish interim and final results and the use of periodic public notices through NOAA publications, the Federal Register, and other official means to document progress, explain delays or new directions, and to seek public comment.
Objectivity			
Minimize procedural reliance on subjective judgment in the selection of source data and methods and in the absence of clearly objective measures channel selections with decision support matrices	Fails: Manual review and selection of storms, maximization techniques, transposition extent and other inputs and procedures were often based on subjective assessments.	Meets: The near-term recommended program envisions written procedural guidance and decision support matrices to proscribe and limit subjective influences.	Meets: The long-term recommended program envisions written procedural guidance and decision support matrices to proscribe and limit subjective influences.
Accessibility			
Access to data, computer scripts, and interim and final results, is provided through public websites and open publications	Partially meets: The various HMRs and state-based PMP products vary in providing public access to source data or codes some of which are proprietary.	Meets: The near-term recommended program envisions the establishment of public webpages to supply data, computer scripts, and other inputs and outputs used in estimation of PMPs.	Meets: The long-term recommended program envisions the establishment of webpages to supply data, computer scripts, and other inputs and outputs.
Reproducibility			
PMP estimates are fully reproduceable using the same inputs, tools, parameters, and settings. PMP estimates obtained by independent practitioners are consistent	Fails: Generally consistent high-level process but with varying data quantity and quality due to reliance on opportunistic data collection and haphazard documentation, somewhat subjective storm selection criteria, and varying adjustments for topographic effects.	Meets: The near-term recommended program envisions written procedural guidance and decision support matrices to proscribe and limit subjective influences and the release of all input data and tools and publication of model parameters and settings.	Meets: The near-term recommended program envisions written procedural guidance and decision support matrices to proscribe and limit subjective influences and the release of all input data and tools and publication of model parameters and settings.
Collaboration			
Development of procedures and production of PMP estimates are produced through sustained collaboration to the extent possible	Fails: Past development of PMP estimates were conducted largely within the confines of agency structures with little public input. Recent state-level PMP estimates have been vetted with external expert panels, but without upfront participation of private sector or environmental interest representatives.	Meets: The near-term recommended program envisions ongoing engagement of the scientific and practitioner communities.	Meets: The long-term recommended program envisions ongoing engagement of the scientific and practitioner communities.

Appendix E
R Code used in Report Figures 3-5 and 5-3

R CODE FOR FIGURE 3-5

```
## Code to reproduce Figure 3-5.
## Author: Christopher Paciorek (UC Berkeley)

## R version: 4.3.2
library(evd)    # Version 2.3-6.1

## Location and scale parameter estimates from GEV fit to GHCN daily
## precipitation data for for Berkeley, California, but qualitative
## results are similar for parameters from GEV fits for other US locations.
location <- 4.5  # in centimeters
scale <- 1.5     # in centimeters

## Generate grid of shape parameter values for plotting.
shape_grid <- c(seq(-0.25, 0, length = 30),
                        seq(0, 0.2, length = 20))
bounded_shape_grid <- shape_grid[shape_grid < 0]

## Calculate return values as quantiles of GEV distribution.
rv_0.0001 <- sapply(shape_grid, function(shape) qgev(1-1/1e4, location,
scale, shape))
rv_0.00001 <- sapply(shape_grid, function(shape) qgev(1-1/1e5, location,
scale, shape))
rv_0.000001 <- sapply(shape_grid, function(shape) qgev(1-1/1e6, location,
scale, shape))
## Calculate upper bounds for negative shape parameter values.
ub <- sapply(bounded_shape_grid, function(shape) location-scale/shape)

png('plot-shape-rv.png', height = 500, width = 600)
plot(shape_grid, rv_0.000001, type = 'l', col = 'red',
     xlab = 'shape parameter', ylab = 'AEP level or upper bound (cm)', ylim =
c(0,120))
lines(shape_grid, rv_0.00001, col = 'blue')
lines(shape_grid, rv_0.0001, col = 'green')
lines(bounded_shape_grid, ub, col = 'black')
legend('topleft', legend = c('p = 0.0001', 'p = 0.00001', 'p = 0.000001',
'upper bound'),
       col = c('green', 'blue','red','black'), lty = rep(1,4), bty='n')
text(x = .1, y = 0, "no upper bound")
text(x = -.1, y = 0, "upper bound present")
dev.off()
```

R CODE FOR SAMPLE SIZE CALCULATION (FIGURE 5-3)

```
## R version: 4.3.2
library(evd)    # Version 2.3-6.1
```

```
library(pracma) # Version 2.4.4

calc_sample_size <- function(location = 0, scale = 1, shape = .1,
                             return_period = 100, se_proportion = 0.125,
                             upper_bound = FALSE, verbose = FALSE) {
    ## Calculates sample size needed to limit the standard error of the
estimated
    ## return value (or upper bound) to `se_proportion` of the estimate,
using
    ## the expected information matrix for the GEV distribution and the delta
method
    ## to approximate the variance of the estimate as a function of the
estimated
    ## parameters.

    ## If the `se_proportion` is 0.125, that corresponds to a confidence
interval
    ## whose length is half (50% = 0.125*4) the magnitude of the return value
(or upper bound).

    ## Arguments:
    ## location: location parameter of GEV model.
    ## scale: scale parameter of GEV model.
    ## shape: shape parameter of GEV model.
    ## return_period: desired return period (years); not used if upper_bound
is TRUE.
    ## se_proportion: desired magnitude of standard error of return value (or
upper bound)
    ##   as a proportion of the return value (or upper bound) estimate.
    ## upper_bound: determine sample size for the upper bound rather than
return value.

    ## Output: estimate of the sample size (in years for GEV block-maxima
estimation and
    ## number of exceedances for threshold exceedance-based estimation).

    ## Authors: Daniel Cooley (Colorado State University) and Christopher
Paciorek (UC Berkeley).

    if(shape >= 1/2){
        stop("Method not supported if variance is infinite (shape >= 1/2)")
    }
    if(upper_bound & shape >= 0){
        stop("Cannot have upper bound if shape >= 0")
    }

    ## Calculate the expected information matrix.

    ## Set up grid of observation values based on quantiles.
    y_low <- qgev(1e-5, loc = location, scale = scale, shape = shape)
    y_high <- qgev(1 - 1e-5, loc = location, scale = scale, shape = shape)
    y_len <- 2000
    y <- seq(y_low, y_high, length.out = y_len)

    ## Evaluate density.
    dens_values <- dgev(y, loc = location, scale = scale, shape = shape)
    dens_array <- array(dens_values, dim = c(y_len,3,3))
```

```
    ## Use numerical differentiation to obtain Hessian.
    param_vec <- c(location, scale, shape)
    hess_array <- array(dim = c(y_len,3,3))

    loglik <- function(par, y){  # Wrapper providing param vec as first
argument.
        return(dgev(y, loc = par[1], scale = par[2], shape = par[3], log =
T))
    }

    for(i in seq(1, y_len)){
        hess_array[i,,] <- hessian(loglik, param_vec, y = y[i])
    }
    ## Alternative to avoid the loop:
    ## tmp <- sapply(y, function(val) hessian(loglik, param_vec, y =val))
    ## hess_array <- array(t(tmp), c(2000,3,3))

    ## Use trapezoidal rule to estimate integral over the density.
    integrand_array <- -hess_array * dens_array
    diff_array <- array(diff(y), dim = c((y_len-1),3,3))
    trapezoids <- (integrand_array[-1,,] + integrand_array[-y_len,,])/2 *
diff_array
    exp_info_mtx <- apply(trapezoids, c(2,3), sum)
    cov_mtx <- solve(exp_info_mtx)  # Asymptotic var-cov matrix of parameter
estimates.

    ## Use the information matrix to estimate the sample size.

    if(upper_bound) {
        ub_fun <- function(par) {
            return(par[1]-par[2]/par[3])
        }
        ub <- ub_fun(c(location,scale,shape))
        se <- se_proportion * ub
      if(verbose) print(paste("upper bound is",
ub_fun(c(location,scale,shape))))
      grad_vec <- grad(ub_fun, param_vec)

    } else {
      prob <- 1-1/return_period
      qTile <- qgev(prob, loc = location, scale = scale, shape = shape)
        se <- se_proportion * qTile
      if(verbose) print(paste(prob, "quantile is", round(qTile, 2)))
      qTileFn <- function(par, p){
            return(qgev(p, loc = par[1], scale = par[2], shape = par[3]))
      }
      grad_vec <- grad(qTileFn, param_vec, p = prob)
    }

    ## Calculate variance of return value based on delta method.
    delta_var <- t(grad_vec) %*% cov_mtx %*% grad_vec
    ## Invert to determine sample size.
    n <- ceiling(delta_var/se^2)

    return(n)
```

```
}

## Example usage.

## Sample size for depth corresponding to annual exceedance probability for
p=0.0001.
location <-  4.5
scale <- 1.5
shape <- 0
calc_sample_size(location, scale, shape, return_period = 10000, se_proportion
= 0.125)

## Sample size for estimating upper bound.
location <-  4.5
scale <- 1.5
shape <- -0.1
calc_sample_size(location, scale, shape, upper_bound = TRUE, se_proportion =
0.125)
```