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Considerations for Estimating Site-Specific Probable Maximum Precipitation at Nuclear Power Plants in the United States of America

Draft for Public Comment

Office of Nuclear Reactor Regulation

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ABSTRACT

As a result of advances in data and methodology, the U.S. Nuclear Regulatory Commission (NRC) has reviewed many studies pertaining to site-specific probable maximum precipitation (SSPMP) calculated at U.S. nuclear power plants. As described in NRC guidance and hazard assessment-related documents (e.g., Regulatory Guide 1.59[1]; NUREG-1800,[2] Section 2; NUREG/CR-7046[3]), the NRC guides its licensees to use the National Oceanic and Atmospheric Administration's hydrometeorological reports as an acceptable resource for the probable maximum precipitation estimates used to evaluate the design--basis flood for nuclear power plants. This NUREG/KM summarizes the knowledge the NRC staff has developed over the course of the reviews based on the similarities and differences between the methodologies.

The SSPMP estimates resulting from these studies were used as a critical hydrologic modeling input in multiple submittals by licensees, such as those responding to the NRC's letter of March 12, 2012, under Title 10 of the *Code of Federal Regulations* 50.54(f), requesting updated flooding hazard analyses for nuclear power plants. The estimates were also used in topical reports. Although the licensee's development and estimation of SSPMP studies generally followed processes similar to those described in the existing guidance, several different methods, data sources, assumptions, and procedures were used to obtain site-specific results other than those found using the NOAA hydrometeorological report methodology.

The purpose of this document is to help fulfill the NRC's goal of maintaining and preserving knowledge and deriving lessons learned from the recent flood hazard re-evaluations at nuclear power plant sites performed in connection with the Fukushima Dai-ichi accident. Specifically, this document (1) identifies terminologies, theories, methods, and lessons learned for SSPMP studies submitted to the NRC for review and (2) presents key considerations for developing and reviewing potential future SSPMP studies.

Although the NRC staff may suggest a course of action in this NUREG/KM publication, these suggestions are not legally binding, and the regulated community may use other approaches to satisfy regulatory requirements.

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[1] Regulatory Guide 1.59, "Design Basis Floods for Nuclear Power Plants" (Agencywide Documents Access and Management System (ADAMS) Accession No. ML003740388).

[2] NUREG-1800, "Standard Review Plan for Review of License Renewal Applications for Nuclear Power Plants—Final Report," Revision 2, issued December 2010 (ADAMS Accession No. ML103490036).

[3] NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," issued November 2011 (ADAMS Accession No. ML11321A195).

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ABBREVIATIONS AND ACRONYMS

ACWI	Advisory Committee on Water Information
ADAMS	Agencywide Documents Access and Management System
AEC	Atomic Energy Commission
AEP	annual exceedance probability
BAF	barrier adjustment factor
C	Celsius
CFR	*Code of Federal Regulations*
DAD	depth-area-duration
EPRI	Electric Power Research Institute
F	Fahrenheit
FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FHRR	flood hazard re-evaluation report
HMR	hydrometeorological report
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
IPMF	in-place maximization factor
KM	knowledge management
LIP	local intense precipitation
MCC	mesoscale convective complex
MTF	moisture transposition factor
NEXRAD	Next-Generation Radar
NOAA	National Oceanic and Atmospheric Administration
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
OTF	orographic transposition factor
PMP	probable maximum precipitation
POANHI	Process for the Ongoing Assessment of Natural Hazards Information
PW	precipitable water
SRep	storm representative dewpoint location
SSCs	structures, systems, and components
SSM	storm separation method
SSPMP	site-specific probable maximum precipitation
SST	sea surface temperature
TAF	total adjustment factor
TDL	Techniques Development Laboratory
TP	technical paper
TR	topical report
USACE	United States Army Corps of Engineers

USGCRP	United States Global Change Research Program
WMO	World Meteorological Organization
WS	watershed-scale

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The authors wish to acknowledge and extend sincere appreciation to the many individuals who contributed to the development of this document and to expanding the knowledge base of the U.S. Nuclear Regulatory Commission (NRC) staff concerning research development and review of site-specific probable maximum precipitation (SSPMP). The author team would also like to extend its gratitude to Kevin Griebenow and Kenneth Fearon of the Federal Energy Regulatory Commission (FERC) for introducing the NRC staff to the FERC Board of Consultants process, as well as for the lengthy discussions that furthered the team's understanding of SSPMP.

1 INTRODUCTION

This report summarizes methods, data sources, and procedures used in the development of site-specific probable maximum precipitation (SSPMP) estimates. To date, the U.S. Nuclear Regulatory Commission (NRC) staff, with assistance from Oak Ridge National Lab (ORNL) staff, has received and reviewed multiple submittals in response to the March 12, 2012, letter (Agencywide Documents Access and Management System (ADAMS) Accession No. ML12053A340) requesting, under Title 10 of the *Code of Federal Regulations* (10 CFR) 50.54(f), updated flooding hazard analyses for nuclear power plants (NPPs) and topical reports (TRs) that contain SSPMP evaluations. The objective of this document is to summarize the NRC staff's current understanding to support the development and review of SSPMP estimates for NRC-regulated NPPs in the United States for long-term knowledge management (KM).

Specifically, this document (1) identifies terminologies, theories, methods, and lessons learned for SSPMP studies submitted to the NRC for review and (2) suggests key considerations for the NRC staff when developing or reviewing any future SSPMP studies.

1.1 <u>Background</u>

The NRC has long recognized the importance of protecting NPPs against natural phenomena as a means to prevent reactor core damage, to ensure containment, and to preserve spent fuel pool integrity. The NRC established several requirements addressing natural phenomena in 1971, which are described in General Design Criterion (GDC) 2, "Design Bases for Protection Against Natural Phenomena," of Appendix A, "General Design Criteria for Nuclear Power Plants," under Title 10 of the *Code of Federal Regulations* (10 CFR) of Part 50, "Domestic Licensing of Production and Utilization Facilities." GDC 2 requires, in part, that structures, systems, and components (SSCs) important to safety be designed to withstand the effects of natural phenomena such as floods, tsunami, and seiches without loss of capability to perform their intended safety functions. GDC 2 also requires that design bases for these SSCs reflect (a) appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding region, with sufficient margin for the limited accuracy and quantity of the historical data and the period of time in which the data have been accumulated, (b) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, and (c) the importance of the safety functions to be performed.

On March 11, 2011, a 9.0-magnitude earthquake struck the Japanese mainland triggering a 14-meter (m) (45-foot (ft)) tsunami. The combination of events resulted in extensive damage to the Fukushima Dai-ichi NPP site overlooking the Pacific Ocean. (See ADAMS Accession No. ML112660383 for additional information about the accident).

In response to these events, the NRC developed a comprehensive set of recommendations (documented in the Near-Term Task Force report prepared by the staff entitled, "Recommendations for Enhancing Reactor Safety in the 21st Century," dated July 12, 2011

(ADAMS Accession No. ML111861807) and identified ensuing actions for current owners and operators (licensees) to consider and address. These actions were intended to allow the NRC staff to verify compliance against approved seismic and external flooding design bases, and to determine whether a plant's license should be suspended, revoked, or modified based on any additional safety enhancements needed. Specific to external flooding events, the NRC staff issued a request for information letter on March 12, 2012 under 10 CFR 50.54(f) (hereafter referred to as the "§50.54(f) letter") to all power reactor licensees and holders of construction permits in active or deferred status. Enclosure 2 of the §50.54(f) letter requested that licensees confirm the appropriateness of the re-evaluated beyond-design-basis flooding events assumed for their plants (and their ability to protect against them) using current guidance and methodologies. Those re-evaluations were also to rely on analytical approaches and methods consistent with current engineering practices. This information would allow the NRC staff to assess individual plant responses and determine if any additional regulatory actions were needed for a particular site.

The current guidance and methodologies mentioned in this NUREG/KM are the regulatory guidance and methodologies typically used for early site permit and combined license reviews including NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," Section 2.4.2, "Floods," issued March 2007 (ADAMS Accession No. ML070100647), and NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization of Nuclear Power Plants in the United States of America" issued November 2011.

In response to the 2012 §50.54(f) letter requesting updates of the flood hazard assessments, current owners and operators submitted 61 flood hazard re-evaluation reports (FHRRs) corresponding to the fleet of operating domestic nuclear power reactor sites. Many of the sites had re-evaluated hazards exceeding the design basis, particularly since the local intense precipitation (LIP) hazard was not part of the original design basis for several of the sites. For some licensees, changes in modeling data, assumptions, and techniques made during these re-evaluations resulted in various changes in flood estimates. The flood-causing mechanisms of interest that were the subject of the staff's 2012 information request included

- *Local Intense Precipitation (LIP)*, a measure of the anticipated extreme precipitation over a specific site location which is reported as a site characteristic.
- *Riverine Flooding,* associated with some stream or river considering the characteristics of the watershed, extreme rainfall and runoff on a regional basis and accounts for land cover, topography, flood control features and dams.
- *Dam Failure*, closely related to riverine flooding and considers the effect of seismic, overtopping and sunny day dam failures on the site location. Riverine flooding and dam failure analyses are addressed as one topic in this report.
- *Storm Surge,* associated with flooding that arises due to relatively large, intense (typically coastal) storm systems and includes the effects of tides, winds and storm characteristics (e.g., storm track, radius of maximum winds and meteorological pressure differentials).

- *Seiche,* associated with waves similar in motion to a seesaw and is a temporary disturbance in the water level of an enclosed (e.g., lake) or partially enclosed body of water which may be caused by changes in atmospheric pressure or ground motion.
- *Tsunamis*, typically caused by earthquakes, subaerial or submarine landslides or volcanic eruptions displacing large volumes of water.
- *Ice-Induced Flooding,* typically caused by the release of upstream ice dams or the formation of downstream ice dams on rivers.
- *Channel Diversions/Migrations* is associated with changing riverine channel flow paths.

Based on the analysis results provided in the FHRRs, the 2012 §50.54(f) respondents reported that most of the power plant sites had re-evaluated flood hazard elevations exceeding the design basis flood level elevations previously used in licensing. Most of the exceedances were associated with LIP, an external flooding hazard generally not explicitly considered as part of the original design basis for several of the sites. Computer modeling results performed by the respondents indicated that LIP, in concert with power plant grading, would likely lead to external flooding within the reactor power block at most operating reactor locations. Exceedances were also reported for some of the other external flood-causing mechanisms listed in the SRP for many of the power reactor sites. In many instances, improvements in modeling data and techniques, and changes in assumptions, made prior to the 2012 re-evaluations resulted in modifications to previous external flood estimates.

In the matter of the source of the precipitation values used in the LIP and riverine-based flood analyses, current NRC guidance for the evaluation of Early Site Permits and Combined Operating License Applications is to select the appropriate probable maximum precipitation (PMP) event reported in the National Weather Service's *Hydrometeorological Reports* (or HMRs) regionally-applicable to the power reactor site under review.

A common change among many of the FHRR submittals was the use of SSPMP estimates in place of conventional HMR PMP estimates. PMP estimates (discussed in detail in Section 1.4) serve as a critical hydrologic modeling input for assessing flood hazards, and the NRC's Standard Review Plan (SRP), NUREG-0800, Sections 2.4.2 and 2.4.3, "Probable Maximum Flood (PMF) on Streams and Rivers," issued March 2007 (ADAMS Accession No. ML070730405), identify the HMR PMP estimates for estimating LIP flooding and riverine flooding. Whereas SSPMP estimates employ a process similar to the HMRs, they ultimately use different methods, data sources, and procedures than those found in the HMRs. Because of these differences and uncertainties, the review may be more complex.

The NRC's SRP at the time of the re-evaluations did not describe SSPMP estimates, as they were a relatively recent approach to estimating extreme precipitation. For the re-evaluations, as is stated in NUREG-0800, Section 2.4.3, the SSPMP estimates required licensees to "evaluate how the proposed alternatives to the SRP acceptance criteria provide an acceptable method of complying with the NRC regulations."

The National Oceanic and Atmospheric Administration (NOAA) developed conventional PMP estimates and published them in a series of HMRs. In addition to the HMRs, NOAA provided PMP guidance through two technical memoranda (HYDRO 39, “Probable Maximum Precipitation for the Upper Deerfield River Drainage Massachusetts/Vermont” (Miller et al. 1984) and HYDRO 41, “Probable Maximum Precipitation Estimates for the Drainage above Dewey Dam, Johns Creek, Kentucky” (Fenn 1985), and two technical papers (TP No. 42, “Generalized Estimates of Probable Maximum Precipitation and Rainfall-Frequency Data for Puerto Rico and Virgin Islands” (U.S. Weather Bureau 1961), and TP No. 47, “Probable Maximum Precipitation and Rainfall-Frequency Data for Alaska” (Miller 1963)). Figure 1-1 illustrates the area of applicability associated with each NOAA HMR document.

Of the 61 FHRRs submitted, 26 included an evaluation of SSPMP for estimating LIP or riverine flooding. When it first received an SSPMP submittal, the NRC conducted an initial screening assessment to determine whether detailed review was required. Many of the submittals did not require an in-depth NRC examination because of small differences (generally less than 6 inches) in the resulting water surface elevation when comparing the SSPMP-driven simulation to the NOAA HMR PMP-driven simulation. For 12 sites where the relative water surface elevation changes were notable, the NRC and ORNL staff performed a detailed review of the SSPMP calculation and implementation. The remaining sites that used an SSPMP did not result in a notable difference in water surface elevation when compared against the NOAA HMRs. Figure 1-2 shows the geographic locations of the sites for which the NRC has reviewed detailed SSPMP information as part of a submittal. As indicated in Figure 1-2, all of these NPP sites are in the eastern United States, east of the Mississippi River, and within the regions covered by HMR No. 51/52/56 as shown in Figure 1-1.

To date, most of the SSPMP studies submitted to the NRC have been primarily used for evaluations in response to the §50.54(f) letter. With the exception of one study submitted as part of a TR, these evaluations were mostly completed outside of the framework of a quality assurance program. However, this methodology is also likely to be increasingly applied to licensing actions that should be completed under a quality assurance program in compliance with Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants,” to 10 CFR Part 50.

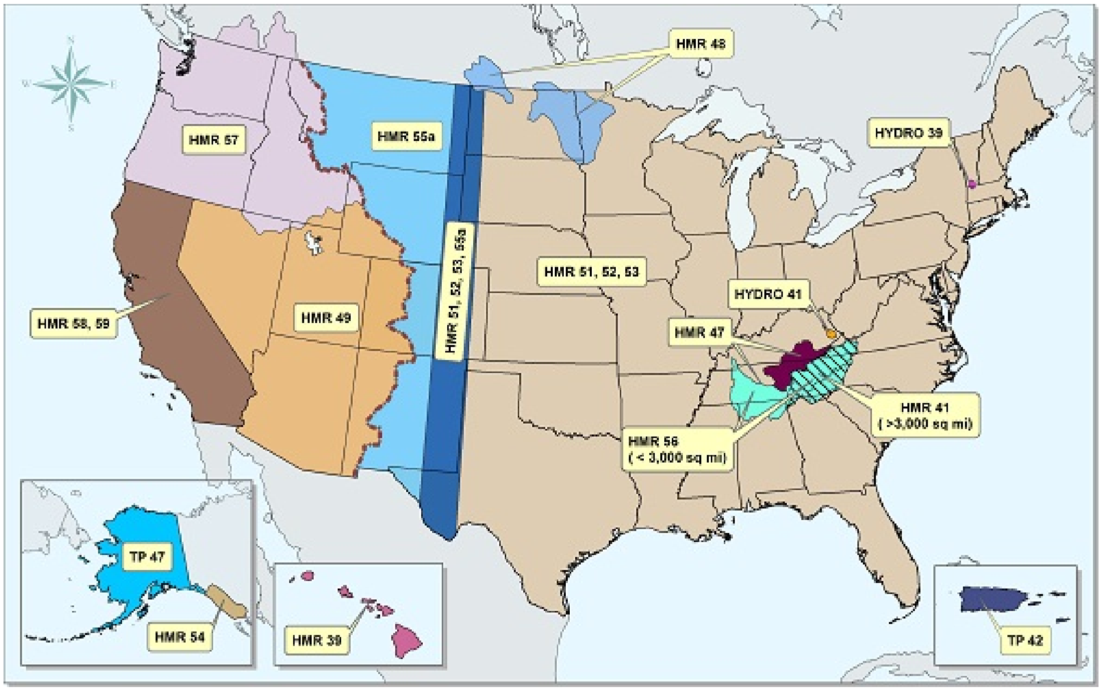

Figure 1-1 Map of Regions Covered by NOAA PMP Documents (as of 2015)[4]

[4] https://www.nws.noaa.gov/oh/hdsc/studies/images/pmp_figure.jpg

Figure 1-2 Map of NPP Locations for which the NRC Reviewed a Detailed SSPMP[5]

1.2 Purpose and Objective of this Document

The purpose of this document is to maintain and preserve the knowledge gained and document the lessons learned from the §50.54(f) FHRR reviews, specifically related to the development and review of SSPMP studies. Since its inception, the Atomic Energy Commission (AEC) and its successor, the NRC, have focused on preserving the decision-making record through the use of documents such as NUREGs, SECY papers, and regulatory guides. However, in 2006, the agency recognized that there was a need to engage in a more formal program of KM that also reflects the less tangible human capital aspect of the agency's knowledge base. This feature was considered to be particularly important as the agency enters its fifth decade of operation—a period characterized by the increasing number of retirements of long-serving NRC staff involved in many of the agency's early licensing programs.[6] Other aspects of the agency's KM program are described in SECY-06-0164, "The NRC Knowledge Management Program," dated July 25, 2006 (ADAMS Accession No. ML061550002).

The NRC is enhancing its regulatory processes by developing and implementing a framework for ongoing assessment of natural hazards information, including information related to climate change, such as increased storm intensities. The NRC's enhancements to the existing regulatory processes are described in SECY-16-0144, "Proposed Resolution of Remaining Tier 2 and 3 Recommendations Resulting from the Fukushima Dai-ichi Accident," dated December 29, 2016 (ADAMS Accession No. ML16286A552), and are referred to as the Process

[5] Markers in Figure 1.2 indicate NPPs at Beaver Valley Power Station, Browns Ferry Nuclear Plant, Calvert Cliffs Nuclear Power Plant, Catawba Nuclear Station, Duane Arnold Energy Center, Indian Point Energy Center, Millstone Nuclear Station, Perry Nuclear Power Plant, Quad Cities Generating Station, R.E. Ginna Nuclear Power Plant, Sequoyah Nuclear Plant, and Watts Bar Nuclear Plant.

[6] NRC staff efforts to preserve this legacy of experience that describes historical events, facts, and research that were instrumental in shaping the NRC's regulatory programs can be found at http://www.nrc.gov/reading-rm/doc-collections/nuregs/knowledge/.

for the Ongoing Assessment of Natural Hazards Information (POANHI). The Commission approved this process, which uses a graded approach to proactively, routinely, and systematically seek, evaluate, and respond to new information on natural hazards, including climate change impacts on storm intensity, using the approved framework for the ongoing assessment of natural hazard information. This applies to all phases of a nuclear plant's operational timeline.

This document summarizes the terminologies, theories, general methods, data sources, and procedures used in SSPMP development. This document also identifies key considerations in developing and reviewing SSPMP estimates. Reports such as this are issued to describe, and make available to the public, methods acceptable to the NRC staff for submitting specific analyses to the NRC. This NUREG/KM is not a substitute for the regulations, and compliance with it is not required. Ultimately, this NUREG/KM aims to inform and support possible future estimates related to NPP SSPMP development and associated NRC review efforts.

1.3 Regulatory Context

Current NRC regulations for licenses, certifications, and regulatory approvals (Appendix A, General Design Criteria [GDC] 2, "Design Bases for Protection Against Natural Phenomena" of 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities") state, in part, the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated. 10 CFR Part 100, also states that factors to be considered when evaluating sites include the disposition and proximity of dams and other human-related hazards (10 CFR 100.20(b)) and the physical characteristics of the site, including the meteorology and hydrology (10 CFR 100.21(d)). In 10 CFR 50.54(f), the NRC states that a licensee shall at any time before expiration of its license, upon request of the Commission, submit written statements, signed under oath or affirmation, to enable the Commission to determine if the license should be modified, suspended, or revoked.

Attachment 1, Enclosure 2, to the §50.54(f) letter identified the flood-causing mechanisms that licensees were to address in their FHRRs. These flood-causing mechanisms correspond to major sections currently found in SRP Section 2.4.2, (ADAMS Accession No. ML070100647), for license applications to construct NPPs. Those flood hazard mechanisms include the following:

- LIP and associated drainage
- streams and rivers
- failure of dams and onsite water control and storage structures
- storm surge
- seiche
- tsunami
- ice-induced flooding
- channel migrations or diversions
- combined-effect flood

Under the current NRC regulatory guidance (Regulatory Guide 1.59, "Design-Basis Floods for Nuclear Power Plants," (ADAMS Accession No. ML003740388), and SRP Section 2.4.2 (ADAMS Accession No. ML070100647), PMP estimates are necessary inputs to evaluate LIP and stream and river flooding.

1.4 Probable Maximum Precipitation Definition and Existing Regulatory Guidance

The World Meteorological Organization (WMO) defines "probable maximum precipitation" as "the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular time of year" (WMO 2009). Operationally, when sufficient historical extreme rainfall observations are available, PMP is estimated based on a widely used method of combining storm moisture maximization, transposition (i.e., relocating patterns of storm precipitation to other areas), and envelopment (i.e., identifying maximum storm precipitation values) (Schreiner and Riedel 1978).

PMP has been used as input to simulate the probable maximum flood (PMF) which is a conservative design criterion for evaluating the safety for NPPs, according to Regulatory Guide 1.59 (ADAMS Accession No. ML003740388). The NRC staff considers conservative design criteria to satisfy the requirements of GDC 2, which states that applications for construction permits and operating licenses should consider "the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated." As the theoretical upper bound of rainfall depth that could occur under a series of severe hydrometeorological conditions, PMP is quantified in terms of a precipitation depth for a given duration and area. For example, a PMP for a particular location may be expressed as the 24-hour (h), 100-square-mile (mi^2) PMP, or the theoretical maximum amount of rainfall that would occur over a 24-h period for a 100-mi^2 area of interest.

Historically, PMP values for locations across the United States have been estimated primarily through a series of HMRs issued by NOAA and predecessor agencies. These estimates were based on data collected over decades and for a variety of extreme rainfall events. Sections 2.4.2 and 2.4.3 of the NRC's SRP document the use of the HMRs to estimate PMP when assessing LIP flooding and riverine flooding. However, NOAA stopped updating the HMRs in 1999, and the associated storm catalogs became dated. While some agencies analyze and develop depth-area-duration (DAD) curves, "there are no current procedures to update storm data sets" (U.S. Bureau of Reclamation 2011).

More recently, licensees, assisted by private entities (e.g., companies, contractors, and consultants), have conducted SSPMP studies using methods similar to those used by the HMRs, including SSPMP estimates for a number of NPPs in the United States. In response to the NRC's §50.54(f) letter, approximately 26 of the 61 FHRR submittals used SSPMP estimates provided by private entities.

Sections 1.5 and 1.6, of this report provide overviews of conventional PMP and SSPMP methods, respectively.

1.5 Summary of Conventional Probable Maximum Precipitation Methods

Fundamentally, PMP estimates can be classified as either theoretical or operational. Although the formal definition of PMP assumes a theoretical upper limit for precipitation, in practice, a theoretical PMP cannot be directly computed or verified. Instead, most conventional PMP estimates follow an operational approach in which historical data and subjective professional judgment may result in PMP estimates that are lower than the theoretical upper limit (Micovic et al. 2015).

Many NOAA HMRs have described the basic approach and detailed methods used in developing operational PMP estimates.[7] For example, HMR No. 51, “Probable Maximum Precipitation Estimates, United States East of the 105th Meridian” (Schreiner and Riedel 1978), provides generalized all-season PMP estimates for the United States east of the 105th meridian for drainage areas from 10 to 20,000 mi^2 and for durations of 6–72 hr. The NOAA HMRs identify two types of PMP estimates: generalized PMPs and individual drainage PMPs. The PMP estimates provided in most HMRs (e.g., HMR No. 51) are termed “generalized estimates.” With these HMRs, PMP isolines are overlain on a basin map to determine the basin-average PMP for a drainage basin. Typically, simplifying assumptions regarding the influence of topography and orographic processes were used in lieu of a detailed analysis. Other HMRs and studies produced by NOAA (e.g., HMR No. 41, “Probable Maximum and TVA Precipitation over the Tennessee River Basin above Chattanooga” (Schwarz 1965), HMR No. 46, “Probable Maximum Precipitation, Mekong River Basin” (U.S. Weather Bureau 1970), and HMR No. 56, “Probable Maximum and TVA Precipitation Estimates with Areal Distribution for Tennessee River Drainages Less Than 3,000 Mi^2 in Area” (Zurndorfer et al. 1986)) provide PMP estimates for individual drainage basins that are specifically adjusted for the area and physical influences of the drainage basin under consideration. Reasons for analyzing individual drainage basins include: (1) generalized PMP studies were not available, (2) the watershed was larger than those covered by available generalized PMP studies, or (3) detailed studies indicated that orographic effects would yield PMP estimates significantly different from those based on available generalized PMP charts (e.g., watersheds in the Appalachians).

To estimate PMP for a specific region, the HMR methods are initiated by identifying all historical extreme storms for the region (or for regions with similar meteorological settings that allow transposition of storms). This process is referred to as “storm selection.” For each storm, multiple rain gauge records are jointly analyzed to construct a rainfall DAD relationship; more recent PMP studies may use other precipitation products, such as radar-driven precipitation data to derive DAD. The total moisture air mass that supplied each storm (referred to as the “total storm precipitable water”) is estimated using representative surface dewpoint observations as a surrogate for atmospheric humidity readings. A measure of historical maximum dewpoint (often estimated from dewpoint climatology products, such as 100-year dewpoint maps) is used to estimate the climatically maximum total precipitable water (PW) that could occur during a similar annual timeframe and at the general location of the storm being analyzed. A ratio between observed and maximized PW is then calculated and multiplied with observed DAD to estimate the moisture-maximized DAD through a moisture maximization process. In practice, the identification and use of dewpoint values are selected as a proxy for PW content, which is computed following the pseudo-adiabatic assumption (Reitan 1963). Using similar calculation concepts, maximum dewpoint is analyzed at the PMP location of interest, with the storm’s rainfall depth further adjusted through a storm transposition process for moisture adjustment.

Other precipitation effects, such as barrier-induced moisture depletion or orographic enhancement, may be captured through further storm transposition calculations accounting for terrain adjustment. In the last step, envelopment (i.e., identifying maximum values) of all moisture-maximized storms across various durations and areas, a PMP DAD relationship is constructed. Proper spatial and temporal distributions are then used to disaggregate the derived total PMP depth for further modeling applications. To date, this data-driven storm moisture maximization, transposition, and envelopment method remains the most commonly used approach in engineering practice, though some new methods based on numerical weather

[7] http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html

simulation models have been proposed and developed in the past decade (e.g., Ohara et al. 2011, Ishida et al. 2014 and 2015, Rastogi et al. 2017).

Conventional PMP methods have been criticized on the basis of the validity of the method and concerns about the sufficiency of data to implement this deterministic approach (e.g., Papalexiou and Koutsoyiannis 2006), as well as the uncertainty associated with the PMP estimates (Micovic et al. 2015). An intrinsic assumption of the conventional PMP method is that the most significant storm that could lead to PMP (with maximized moisture) has occurred during the observation period. Such an assumption has never been tested and may even be invalid in a nonstationary climatic condition. From an engineering and regulatory perspective, perhaps the most concerning component of the PMP methodology is the significant "professional" judgment required at various steps during the development of conventional PMP estimates (e.g., determination of the storm-representative dewpoint). Such professional judgments could be specific to a particular site or expert and hence limit the reproducibility of PMP estimates by an independent third party. To gain acceptance by both the scientific and regulatory communities, the uncertainty and sensitivity involved in these professional judgments must be further understood to ensure the proper use of PMP for protecting critical infrastructure.

Highlighting the need for informed PMP estimation, the August 2017 landfall of Hurricane Harvey along the U.S. Gulf Coast produced historically high rainfall totals in the continental United States and approached HMR No. 51 PMP estimates. Using the radar-driven National Center for Environmental Prediction Stage IV Quantitative Precipitation Estimates (Lin 2011), Kao et al. (2019) reported that some Hurricane Harvey precipitation depths (72-h 5,000-mi^2 and 10,000-mi^2) exceeded HMR No. 51 values in the Houston, TX, area. This extreme event demonstrates the uncertainty associated with extreme precipitation given the limited historical record (for example, Hurricane Harvey exceeded Houston's previous 1-day rainfall observation by more than 50 percent) and emphasizes the importance of critical infrastructure management.

1.6 Summary of Methods Used in Licensee SSPMP Submittals

The SSPMP methods submitted by licensees to date largely follow the conventional HMR methods, but also include some updated procedures. In some cases, these updates are related to new meteorological knowledge and may require use of professional judgment. Deviations from HMR methods are reasonable when they are justified by advances in meteorological analysis techniques and data. Specific aspects of the SSPMP calculation process require varying levels of professional judgment, as described in the remainder of the report.

Fundamentally, HMRs and SSPMP estimates associated with the 2012 §50.54(f) information request followed a storm-based PMP approach, which is an approach to estimating PMP based on historical storm observations. The NOAA HMRs used a storm-based PMP approach.

As included in multiple SSPMP submittals to the NRC, PMP estimates can be provided either for a shorter duration local PMP (i.e., LIP-PMP) or for a longer duration watershed-scale PMP (i.e., WS-PMP). From an NPP perspective, LIP-PMP may drive flooding in the immediate vicinity of the powerblock and may affect onsite plant facilities, while WS-PMP may drive flooding in streams and rivers near NPPs as a result of heavy precipitation in the upstream watershed or flood-induced dam failure. NUREG/CR-7046 contains additional information on LIP-PMP and WS-PMP design-basis flood estimation (ADAMS Accession No. ML11321A195).

An LIP-PMP estimate is developed largely based on historical local storms, which WMO (2009) defines as follows:

> **Local storm**—A storm event that occurs over a small area in a short time period. Precipitation rarely exceeds 6 [h] in duration, and the area covered by precipitation is less than 1,300 km^2 [500 mi^2]. Frequently, local storms will last only 1 or 2 [h], and precipitation will occur over area sizes of up to 500 km^2 [193 mi^2]. Precipitation in local storms will be isolated from general-storm rainfall. However, the staff notes that for estimating the period of inundation, longer duration (up to 12 hours or more) regional storms may be used to develop a LIP-PMP estimate.

A WS-PMP estimate is developed largely based on historical general storms, which WMO (2009) defines as follows:

> **General storm**—A storm event that produces precipitation over areas in excess of around 1,300 km^2 [500 mi^2] and for durations longer than 6 [h] and is associated with a major synoptic [or large-scale] weather feature.

Depending on the watershed location, the WS-PMP may be controlled by general, synoptic storms, or by tropical storms, or by a combination of storm types. In addition, licensees have provided LIP-PMP and WS-PMP estimates in terms of all-season or cool-season bases, or both, to assess conservativeness and bounding scenarios, as described in NUREG/CR-7046 (ADAMS Accession No. ML11321A195). While an all-season PMP estimate considers all PMP storm types, regardless of when they occur throughout the year, a cool-season PMP estimate limits storm evaluation to historical storms that occurred during the cool season. Where the regional climate may support heavy rain-on-snow events with large snow melt and associated runoff, a separate cool-season PMP analysis is performed. The beginning and ending dates of a cool season differ depending on location.

To produce a SSPMP estimate for a given location, historical storm event data are collected and modified through a series of analytical procedures. Based on the NRC's participation in interagency research (ACWI 2018)[8] as well as NRC's flood hazard re-evaluation reviews, the NRC staff identified certain primary steps in the SSPMP estimate methodology. Those steps form the balance of this NUREG/KM and include the following actions:

- storm selection (Section 2)
- storm reconstruction (Section 3)
- storm transposition (Section 4)
- storm representative dewpoint selection and PW estimation (Section 5)
- dewpoint climatology, moisture maximization, and moisture transposition (Section 6)
- terrain adjustment (Section 7)
- PMP determination and envelopment (Section 8)
- applying SSPMP using spatial and temporal distributions (Section 9)

The steps outlined above are based on findings from the NRC staff's flood hazard re-evaluation reviews, a detailed TR review for a watershed, and experience gained from participating in or observing Board of Consultant reviews by the Federal Energy Regulatory Commission (FERC).

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8 The NRC actively participates in interagency research with the Advisory Committee on Water Information (ACWI) related to the evolving field of SSPMP study methodologies (ACWI 2018).

Depending on the objective and location of an SSPMP study, more or fewer steps than those described in Sections 2 through 9 of this NUREG/KM may be appropriate. Consequently, it is premature for the staff to issue guidance on this particular topic at this time as the state-of-the art continues to evolve. Thus, the SSPMP process steps identified in this NUREG/KM should be viewed as the staff's assessment of the state of science on this specific topic. Lastly, Section 10 presents an additional discussion of potential effects of long-term climatic change before the overall report summary in Section 11.

2 STORM SELECTION

This section of the Knowledge Management NUREG discusses the storm selection process that could be used in the development of SSPMP estimates, including descriptions of the terminology, general methodology, and key considerations. This chapter ends with a summary of lessons-learned from the recent reviews of the 2012 §50.54(f) FHRRs.

2.1 Terminology, General Methodology, and Lessons Learned

Storm selection is the process of identifying and selecting historical storm events that are appropriate for inclusion in SSPMP development for a targeted site. To evaluate a SSPMP across various durations and areas following a storm-based approach, the storm selection process should incorporate into the SSPMP analysis all major historical storm events that can be collected and technically-justified. Example resources containing historical storm data include observations from the National Center for Environmental Information's (NCEI)[9] Cooperative Observer Program Network (COOP)[10] gauges, U.S. Geological Survey flood reports, journal articles, books, and Internet publications, as well as storm data from HMRs, U.S. Army Corps of Engineers (USACE) storm reports, previously submitted SSPMP studies, and other sources.

High-quality, reliable data on historical extreme precipitation events can be difficult to obtain, though several resources are available. In particular, the USACE Black Book (USACE 1973) provides a comprehensive collection of observed storm events, with data on over 550 historical storms occurring from 1875 to 1969 (see map in Figure 2-1). This database provides a valuable resource when reviewing SSPMP storm selection and should be leveraged during SSPMP development and review to ensure that storm selection reasonably considered major historical storms.

Once an initial list is assembled, the storms are further evaluated to determine which storms to examine in the full analysis. To begin, a storm search domain should be identified. A storm search domain represents the geographic region around a location of interest used to identify and select storms. Storms occurring within the storm search domain are assumed to have occurred because of regional hydrometeorological characteristics that are similar to (or could result in similar precipitation over) the location of interest. The storm search domain may include longitudinal (east–west) extents bounded by topography (e.g., the Appalachian or Rocky Mountains) or reasonable distance (e.g., a certain longitudinal extent away from the point of interest). Latitudinal (north–south) extents may be limited to approximately 6° north or south of the study area. This latitudinal constraint is applied because of changes in storm dynamics (e.g., vorticity) that occur across relatively large changes in latitude.

Seasonal and regional climatology and meteorology may also be considered to determine if a historical storm event could have occurred over the area of interest. A SSPMP study may provide both all-season and cool-season estimates. All-season estimates may occur at any time of the year and are typically applied as pure rainfall events. Cool-season estimates are intended to capture potential rain-on-snow events that may produce different flood hydrograph characteristics (e.g., snowmelt effects) than a rain-only event. The HMRs (e.g., Hansen et al. 1984; Corrigan et al. 1999) discussed cool-season PMP in general terms; however, cool-season

9 Formerly the National Climatic Data Center (NCDC) before dissolving in 2015.

10 https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/cooperative-observer-network-coop

PMP estimates were only provided for limited cases (e.g., HMR No. 53, "Seasonal Variation of 10-Square-Mile Probable Maximum Precipitation Estimates, United States East of the 105th Meridian" (Ho and Riedel 1980)) presented estimates for the 10-mi^2 PMP only).

The staff notes that the sufficiency of historical storms included in the catalog heavily influences the reliability of a SSPMP estimate. While no specific research exists to suggest a minimum number of required storms for SSPMP development, if there are sufficient samples to support the identification of a statistical maximum, removing any single sample should not result in a major change in the PMP estimate. If the intent is to derive SSPMP for applications across a wide range of areas and durations, a large collection of historical extreme storms with varying sizes and durations will be needed.

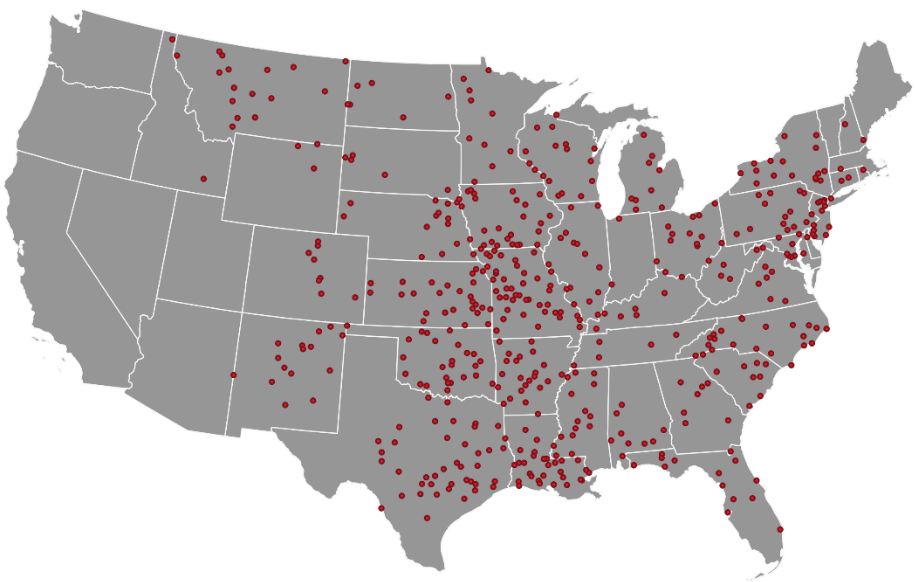


Figure 2-1 Map of USACE Black Book Storm Locations (Data from USACE 1973)

2.2 Key Considerations for SSPMP Development

Based on experience and knowledge gained through reviews of SSPMP estimates submitted in connection with the 2012 §50.54(f) FHRR submittals, the NRC staff identified several key considerations in the development of a SSPMP. These considerations build on the previously described terminology, general methodology, and lessons learned and highlight issues associated with some of the more subjective areas of SSPMP development. The NRC staff has identified the following key considerations related to storm selection:

- The comprehensive list of storms and their characteristics considered during the storm selection process should be clearly documented. If a major historical storm is purposely excluded during the storm selection process, justification should be provided for further review and evaluation.

- Extreme precipitation data that is both reliable and publicly available should be leveraged whenever possible. While publicly available storm data are available from the *USACE Black Book* (USACE 1973) and other data sources, there is currently no comprehensive inventory of major historical storms as well as a lack of public data on more recent storm events. In its 2018 *Extreme Rainfall Product Needs* proposal, the *Extreme Storm Events Working Group* (ACWI 2018) outlined its recommendation to create an archive of extreme precipitation events across the United States for use in developing PMP estimates. This archive would provide a digital repository of storm event data and be updated as new storm analyses are performed. If such an archive becomes publicly available, it should be considered for use in storm selection.

3 STORM RECONSTRUCTION

This section of the Knowledge Management NUREG discusses the storm reconstruction process that could be used in the development of SSPMP estimates, including descriptions of the terminology, general methodology, and key considerations. This chapter ends with a summary of lessons-learned from the recent reviews of the 2012 §50.54(f) FHRRs.

3.1 Terminology, General Methodology, and Lessons Learned

Storm reconstruction involves development of DAD curves, which summarize the highest observed rainfall depth at various combinations of storm areas and durations. During later phases of SSPMP calculation, the DAD of each storm is adjusted to estimate the theorized maximum precipitation of that storm under more critical meteorological conditions, and the collection of adjusted storm DAD values are enveloped to estimate PMP.

A DAD value is expressed as a maximum depth of precipitation occurring over a given area for a specified duration. For a single storm event, DAD values are computed by analyzing rain gauge or radar data over space and time. Historical DAD storm reconstruction by the USACE and NOAA involved manual calculation of mapped rain gauge data. Figure 3-1 provides an example precipitation map. Collectively, multiple DAD values form DAD curves and tables (Figure 3-2), which are used to summarize storm precipitation data. DAD curves for multiple storms may be compared and play a key role in PMP development through storm envelopment (Section 8). DAD curves require extensive data collection and processing efforts. General procedures for DAD analysis are provide in WMO (1969) and the U.S. Weather Bureau (1946).

With the advancement of automated rain gauges and improved radar rainfall estimates in recent years, extreme storm events are now measured with greater precision, resolution, and coverage compared with conventional methods used in past decades. To match improvements in data quality, improved analysis tools have also become available to quickly assess and quantify extreme storm events. Storms with existing DAD curves developed by NOAA, USACE, Environment Canada, and other organizations should be considered for inclusion, when available. Since some of these DAD curves were developed manually using undocumented information sources, it may be difficult to verify them. In these cases, SSPMP studies require professional, or engineering, judgment related to the potential use of the data.

For certain PMP applications (e.g., LIP-SSPMP or small basin WS-PMP studies for NPPs), subhourly PMP values are required to capture rapidly occurring peak flood effects. While some Next Generation Radar (NEXRAD) databases enable precipitation estimation for periods as short as 5 minutes, many storms are analyzed only in hourly increments. However, since many databases do not provide subhourly precipitation data, standard ratios available from the HMRs have been used in practice to convert hourly precipitation values to subhourly precipitation values (Section 9).

The accuracy of DAD values, which serve as the storm-specific baseline before adjustment to the study area, is a major consideration for SSPMP reviews. Variabilities and uncertainties in observed rainfall values are propagated throughout the PMP development process and can have significant impacts on the flood elevations estimated. Typically, for riverine flooding, long-duration and large-area DAD values will have the most impact on flood magnitude, since total precipitation volume will often drive riverine flood impacts. LIP evaluations are typically affected by short-duration DAD values because peak flooding conditions are most directly tied to peak rainfall intensity. However, for both riverine and LIP flooding assessments, a robust assessment of PMP scenarios and hydrologic response is warranted.

While the accuracy of DAD values mainly depends on the quality of input rainfall gauge data and the computational algorithm used to calculate DAD, other significant technical considerations are also involved. For instance, a major multiday and multicenter storm event may be analyzed as separate storm events (because of changing moisture sources and mechanisms) and characterized by DAD values). Such actions could reduce PMP values for larger areas (while having limited impacts on PMP values in smaller areas when considering the separate storm centers). As an example, the 1972 Hurricane Agnes storm event produced significant rainfall across the U.S. Atlantic coast and inland portions of the Appalachian range. During review of one SSPMP submittal, the NRC found that the licensee had split the precipitation event into multiple storm centers, thereby excluding the most intense portion of the precipitation event. This method resulted in a large decrease in the adjusted storm rainfall compared to a scenario in which the full storm is included. Given its significant impacts on larger area DAD values, decomposition of multicenter storm events should be avoided or, if used, accompanied by substantive justifications.

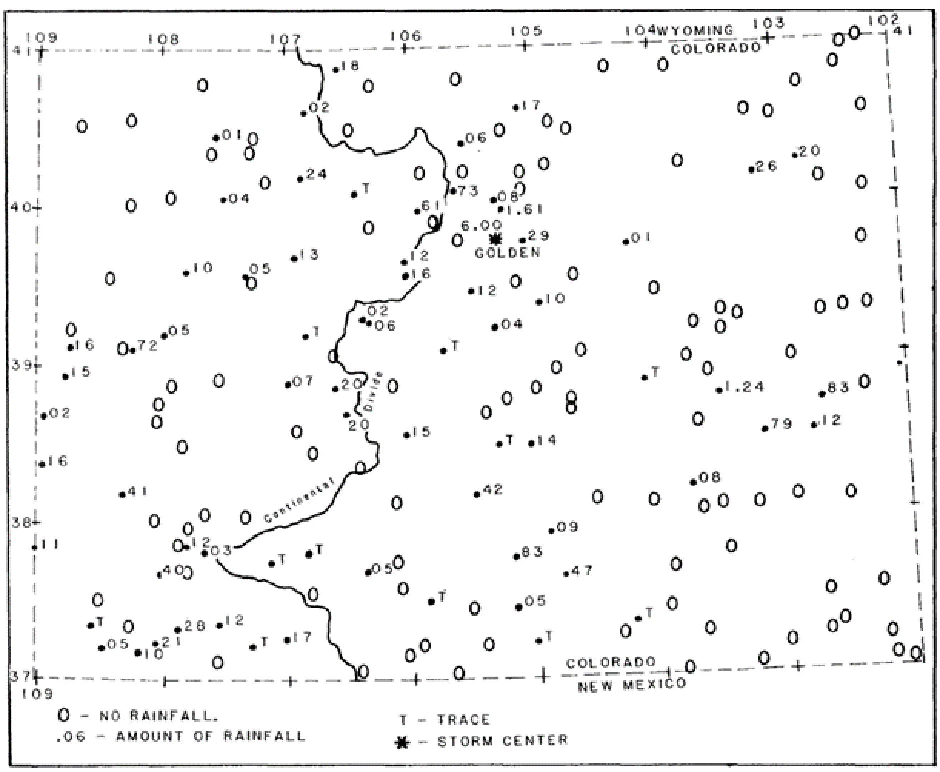


Figure 3-1 Map of Precipitation Gauge Data for June 1948 Golden, CO, Storm (from HMR No. 55A)

MAXIMUM AVERAGE DEPTH OF RAINFALL IN INCHES

AREA SQ.MI.	DURATION OF RAINFALL IN HOURS 6	12	18	24
10	24.7	26.7	28.7	29.2
100	16.4	19.4	21.8	22.4
200	13.1	16.8	19.3	19.9
1000	6.4	10.3	12.6	13.3

Figure 3-2 DAD Table for July 1942 Smethport, PA, Storm (from HMR No. 51)

3.2 Key Considerations for SSPMP Development

Based on experience and knowledge gained through reviews of SSPMP estimates submitted in connection with the 2012 §50.54(f) FHRR submittals, the NRC staff identified several key considerations in the development of a SSPMP. These considerations build on the previously described terminology, general methodology, and lessons learned and highlight issues associated with some of the more subjective areas of SSPMP development. The NRC staff identified the following key considerations related to storm reconstruction:

- The source(s) of all relevant data used in storm reconstruction should be documented and provided for the NRC staff's review, including data related to storm center location, elevation, observed DAD data/chart, cumulative mass curve(s), isohyetal precipitation maps, and any supporting information from historical analyses.

- Reliable, publicly available storm reconstruction data should be leveraged whenever possible. For DAD data, the USACE Black Book (USACE 1973) and other data sources provide information, but the USACE Black Book is outdated as it does not include storms since the 1970s. If the studies and databases proposed in the 2018 *Extreme Rainfall Product Needs* proposal (ACWI 2018) are developed, the corresponding information would provide a key additional source of storm reconstruction data.

- When subhourly precipitation estimates are not available for a particular storm but are needed for hydrologic modeling, standard HMR conversion ratios can be used.

- When available, DAD variations of a common storm analyzed due to different studies and software can be compared to evaluate potential differences and areas of uncertainty. When significant deviations exist among datasets (especially when lower DAD values are used), the selection should be justified.

- Documentation of the software used to derive DAD values and of the detailed analytical steps (i.e., algorithm) is relevant when reviewing SSPMP submittals associated with the 2012 §50.54(f) information request. The software's ability to reconstruct storm DAD relationships can be documented or demonstrated through controlled test cases. Any software used for NRC licensing actions for NPPs must meet the quality assurance (QA) requirements of 10 CFR Part 50, Appendix B. Licensee's that have submitted license amendment request or topical report applications to the NRC, and have included SSPMP have needed to justify the software under the QA/QC requirements of Appendix B.

- Decomposition of multicenter storm events involves significant professional judgment and is generally discouraged.

4 STORM TRANSPOSITION

This section of the Knowledge Management NUREG discusses storm transposition considerations that could be used in SSPMP development, including descriptions of the terminology, general methodology, and other key considerations. This chapter ends with a summary of lessons-learned from the recent reviews of the 2012 §50.54(f) FHRRs.

Subsequent precipitation adjustments are made to account for moisture and terrain differences when relocating storms via transposition. Sections 6 and 7, respectively, describe those moisture and terrain transposition adjustments.

4.1 Terminology, General Methodology, and Lessons Learned

The collection of historical extreme precipitation events that have occurred in or near the region of interest represents a very important aspect of storm-based PMP analysis. Given the limited historically-reported/instrumentally-recorded precipitation data available for use, PMP analyses typically require transfer of multiple storms and their associated precipitation characteristics to other regions where they could occur through a process known as storm transposition. As documented in HMR No. 51 (Schreiner and Riedel 1978), storm transposition is defined as "... relocating isohyetal patterns of storm precipitation within a region that is homogenous relative to terrain and meteorological features important to the particular storm rainfall under concern..." Section 2.5 of WMO (2009) gives details of this process, standard practice for traditional storm-based PMP methods.

Transposition limits have been defined as "... the outer boundaries of the region where a particular storm could occur..." (Hansen et al. 1988) Figure 4-1 shows an example of an HMR-analyzed storm transposition limit map. Affected by the storm features (e.g., location, duration, seasonality), the transposition limit can be unique for each storm.

When considering an SSPMP site of interest, the transposition limits and whether a storm can be transpositioned to the location need to be evaluated. To inform these decisions, professional judgment is used in assessing precipitation location, moisture source location, storm dynamics, seasonal influences, orographic effects, and other considerations. In some cases, these judgments can be fairly subjective and the basis for selection should be described. Therefore, whether a critical storm can be allowed to be transpositioned to a specific SSPMP site is usually the main focus during the development and review of SSPMP.

Storm transposition determination involves considerable professional judgment, and the resulting application of transposition limits can greatly influence PMP values. Common transposition limit criteria (NRC, 2015) applied include the following:

- Storms should not be transpositioned across significant barriers (e.g., the Appalachian and Rocky Mountain ranges).
- Storms should not be transpositioned more than 5° or 6° of latitude (Hansen et al. 1994) owing to changes in storm dynamics (e.g., vorticity).
- Storms should not be transpositioned over unreasonable distances from moisture sources, and the closest quality data should be used (e.g., storms associated with coastal hurricane flooding may be restricted from inland transpositioning).

- Storm types that would not occur in the area of interest may not be applicable (e.g., an extreme rainfall event occurring in March in the South-Central plain states may not be appropriate for consideration in the Upper Midwest).

Another common transposition limit consideration is the elevation difference between an original storm center and the study area. This consideration may exclude storms that occurred at elevations more than about 300 meters (m) (1,000 feet (ft)) above or below the study area elevation because of potential differences in moisture availability and other meteorological factors.

In addition to considering whether a single storm event is transpositionable to a location of interest, SSPMP development may involve storm center separation in which individual storm centers resulting from the same storm may be justifiably separated into separate sets of DAD data, each with potentially unique transposition limits. When and how to separate storms into multiple storm centers involves considerable professional judgment and can result in significant changes to PMP results.

As mentioned in the prior sections, the reliability of SSPMP estimates is heavily influenced by the sufficiency of the included historically-reported storms, while storm transposition is a necessary method to increase the number of selected storms for SSPMP development (i.e., given the limited historical observations). With enough historic observations for any given site, an objective is to avoid storm transposition or use strict transposition criteria for a more meteorologically rigorous analysis. However, if the historical storm observations are limited for an SSPMP site, then more general transposition criteria must be used to avoid underestimates due to insufficient sampling. Each SSPMP study should clearly justify and evaluate the tradeoff between sample sufficiency and allowable storm transpositionability.

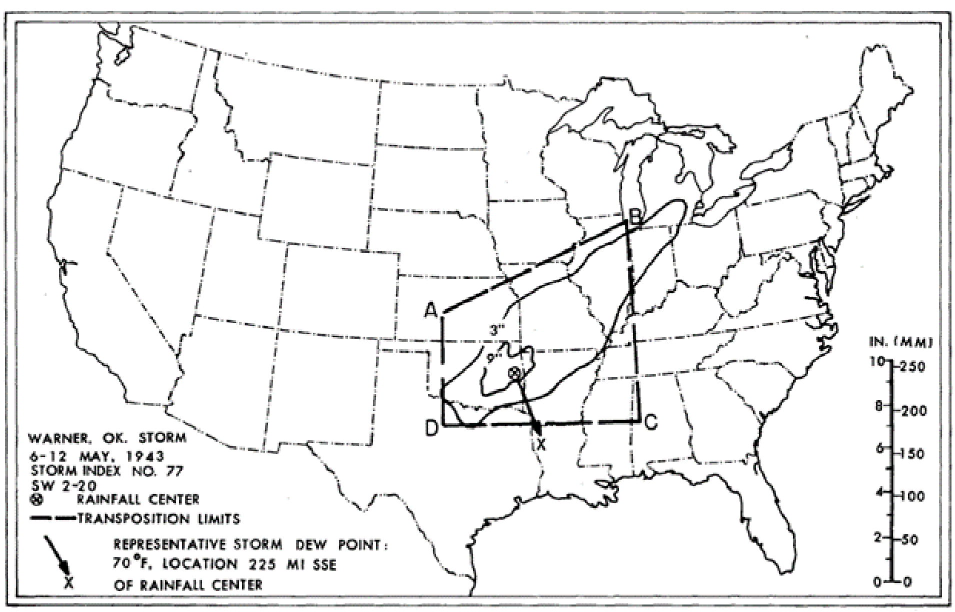


Figure 4-1 HMR Transposition Limit Map for May 1943 Warner, OK, Storm (from HMR No. 51)

4.2 Key Considerations for SSPMP Development

Based on experience and knowledge gained through reviews of SSPMP estimates submitted in connection with the 2012 §50.54(f) FHRR submittals, the NRC staff identified several key considerations in the development of a SSPMP. These considerations build on the previously described terminology, general methodology, and lessons learned and highlight issues associated with some of the more subjective areas of SSPMP development. Related to storm transposition, the NRC staff identified the following key considerations:

- When defining transposition limits, clear justification and supporting evidence should be provided. Documents should adequately explain where the analyzed storms were transpositioned to within the study domain.

- For studies that include dynamic transposition zones in which some storms are transpositioned to only part of the basin or region of interest, summary information should be provided to document which storms are analyzed in each zone. This helps identify regions where a small number of storms may be used for SSPMP development.

- Since some major historical storms tend to control SSPMP wherever they are transpositioned, DAD curves (or data) showing individual storm DAD and the SSPMP within each sub-region should be provided to help identify cases where a single storm event may greatly affect SSPMP results or where the PMP relies on a small number of storms.

5 STORM REPRESENTATIVE DEWPOINT SELECTION AND PRECIPITABLE WATER ESTIMATION

This section of the Knowledge Management NUREG discusses considerations in the storm representative dewpoint selection and storm PW estimation processes used in SSPMP development, including descriptions of the terminology, general methodology, and other key considerations. This chapter ends with a summary of lessons-learned from the recent reviews of the 2012 §50.54(f) FHRRs.

5.1 Terminology, General Methodology, and Lessons Learned

As with storm selection, reconstruction, and transposition, the identification of storm representative dewpoint is a significant step in the PMP development process. Conventionally, based on the pseudo-adiabatic assumption, surface dewpoint observation is used as a surrogate to estimate the theoretical moisture air mass supply (i.e., PW) for each storm. Used for the calculation of moisture maximization (Section 6), storm representative dewpoint selection requires evaluation of observed windspeed, dewpoint, and other meteorological information to identify the most representative moisture air mass that supplies each selected storm. This determination often involves significant professional judgment.

5.1.1 Moisture Source Identification

To identify the moisture air mass trajectory of a storm, some modern storm assessments use NOAA's Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)[11] in conjunction with daily weather maps (Figure 5-1) to analyze a storm's moisture travel path based on a selected windspeed dataset. HYSPLIT returns a trajectory shapefile that can be overlapped with dewpoint observation data to identify an approximate moisture source location (or source region) and set of suitable weather stations from which storm representative dewpoint is analyzed. While the variable-height HYSPLIT trajectories are useful in determining moisture inflow paths, some historical storm events may suffer from large uncertainties with respect to moisture source timing and location. In such cases, professional, or engineering, judgment may be required to determine appropriate locations of the storm representative dewpoint. In general, storm representative dewpoint timing is selected for a period before the rainfall event begins. Section 5.1.2 presents additional information on the storm representative dewpoint location and timing.

Despite some limitations, the use of HYSPLIT is a significant improvement over the conventional manual approach to identifying storm moisture source. The trajectories calculated by HYSPLIT can increase the clarity of moisture inflow and help reduce the subjectivity in the conventional approach. Nevertheless, determining the most suitable storm representative location based on HYSPLIT trajectories still requires careful judgment from experienced analysts and careful examination during the SSPMP review.

When the main moisture mass is judged to come from a lake or ocean, sea surface temperature (SST) data are used instead. SST data measurements are mainly taken from ships and, consequently, have coarser temporal resolution (reported daily instead of hourly), spatially sparse and nonstationary coverage, and higher data uncertainty. Therefore, when available, land-based dewpoint measurements are preferred to SST measurements to determine

11 http://ready.arl.noaa.gov/HYSPLIT.php

atmospheric moisture. Given the poorer temporal and spatial coverage and uncertainty, significant differences between land-based dewpoint and SST measurements can be seen in many SSPMP studies. Nevertheless, SST is still considered an acceptable surrogate measure of moisture over the ocean.

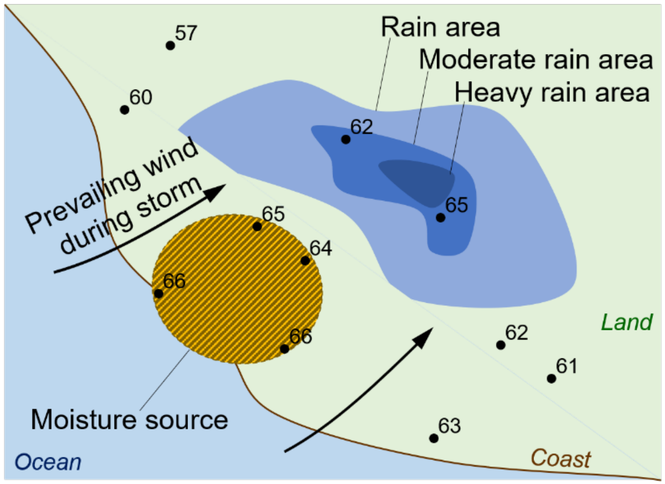


Figure 5-1 Example Weather Map Showing Moisture Inflow and Dewpoint Observations (Adapted from WMO 2009)

5.1.2 Storm Representative Dewpoint Data and Selection

While various sources of data have been used in submittals to the NRC, the surface dewpoint data were mainly collected from the NOAA Techniques Development Laboratory[12] (TDL) U.S. and Canada Surface Hourly Observations dataset.[13] However, the recommended dataset to collect and process hourly dewpoint observations is the National Climatic Data Center (NCDC)[14] TD3505 Integrated Surface Hourly Data released by NOAA. Both TD3505 and TDL[13] datasets are official NCDC/NCEI data products; the TDL dataset is a collection of as-recorded weather station observations, whereas the TD3505 is subjected to additional quality control (QC) and processing by NOAA. Although the two datasets are largely similar, differences do exist that could affect the storm representative dewpoint and subsequent adjustment of dewpoint values.

The representative dewpoint values for storms used in analysis should be obtained from HMRs and based on the highest persisting 12-h dewpoint. In contrast, SSPMP studies have often used maximum 6-, 12-, or 24-h average dewpoints to define the storm representative dewpoint. The use of multiple durations is intended to improve the representativeness of the analysis to more closely match the observed storm duration. Local storms, which typically produce intense precipitation over short durations, are typically analyzed using 6- or 12-h durations, while larger scale general or tropical storms are analyzed using 12- or 24-h durations. The selection of a maximum average dewpoint is consistent with the hypothesis that extreme precipitation events require high moisture supply for extended periods.

12 Now named the Meteorological Development Laboratory (MDL): http://www.nws.noaa.gov/mdl/
13 ds472.0, http://rda.ucar.edu/data sets/ds472.0/#!description
14 Now named the National Centers for Environmental Information (NCEI): https://www.ncdc.noaa.gov/

Based on the type of storm (e.g., shorter duration mesoscale convective or longer duration frontal), licensees calculated the maximum 6-,12-, or 24-h average dewpoint of each station and determined the region with the highest moisture mass (dewpoint) in HYSPLIT's trajectory zones. To determine the maximum 6-, 12-, or 24-h average dewpoint, time series of dewpoint data must be collected. A series of 6-, 12-, or 24-h average dewpoint values is computed (typically using instantaneous, hourly measurements, though less frequent measurements may be available), and the maximum average value is selected.

To illustrate the differences between the maximum average dewpoint and the conventional 12-h persisting dewpoint (used in HMRs) approaches, Figure 5-2 provides a comparison. The histogram depicted as the background in Figure 5-2 show the hourly dewpoint observations, and the thick black line represents the running 24-h average dewpoint with a maximum of 74.6 degrees Fahrenheit (F) (as the representative dewpoint). Such running maximum average dewpoint can be calculated only when hourly (or every 3-h) observations are available. However, when the conventional 12-h persisting dewpoints were derived for HMRs, most dewpoint observations were often made only at three fixed times per day (e.g., at 0700, 1200, and 1900 hours local time). Following a similar HMR process and assuming the same data limitation, the 12-h persisting dewpoint values, with a maximum of 74.5 degrees F, are also provided in Figure 5-2 for comparison. In this particular example, both approaches may yield similar storm representative dewpoints. Nevertheless, the maximum average dewpoint approach can leverage more dewpoint observations and should be more reliable than the conventional approach.

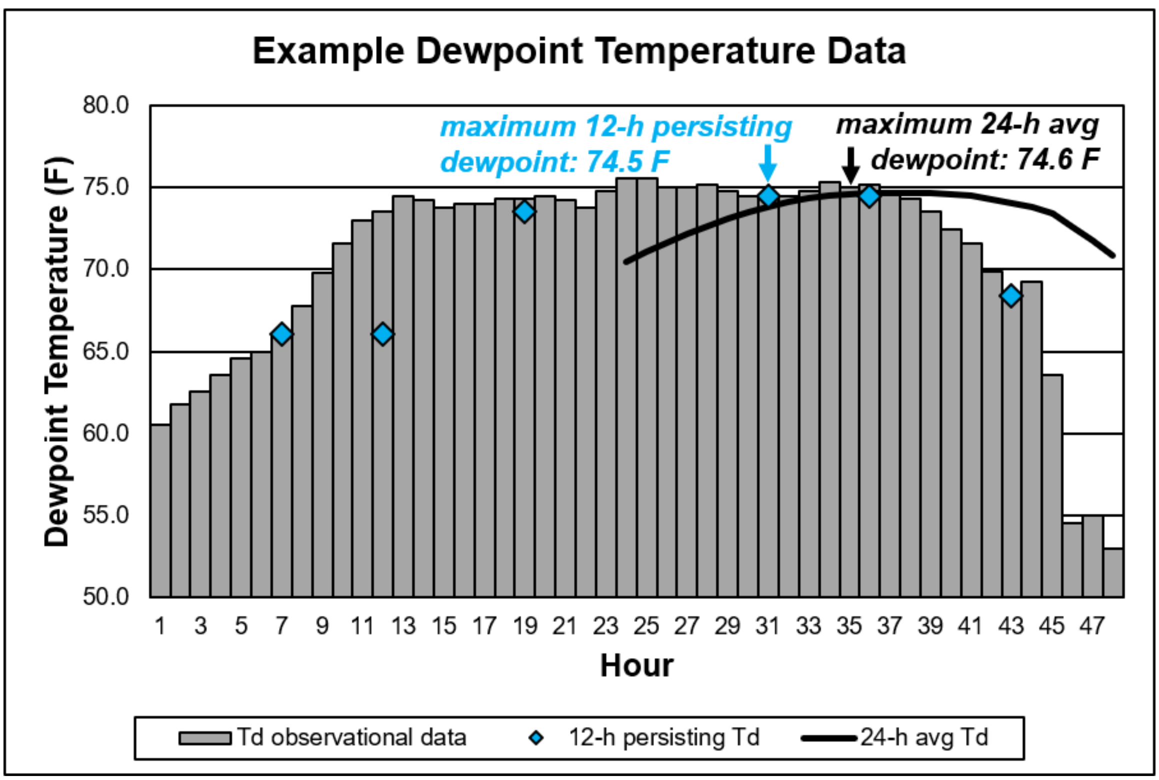


Figure 5-2 Example Dewpoint Temperature Data with the Maximum 24-h Average Dewpoint and Maximum 12-h Persisting Dewpoint Values Identified

Section 5.2 of HMR No. 55A, "Probable Maximum Precipitation Estimates—United States between the Continental Divide and the 103rd Meridian" (Hansen et al. 1988), provides recommended criteria for selecting storm representative dewpoints. In general, these same criteria are considered applicable to SSPMP studies, though the use of maximum average dewpoint temperatures is also considered reasonable. In particular, HMR No. 55A requires the use of data from at least two stations located along the inflow trajectory but outside the rain area for a timeframe "that generally allows transport of the moisture to the precipitation site during a reasonable interval compatible with observed winds in the storm." (Hanson et al. 1998)

The timing of storm representative dewpoint selection was identified as a common area of concern during several SSPMP reviews. Figure 5-3 illustrates data for an example storm and shows that the dewpoint selection timeframe used to compute the storm representative dewpoint did not adequately represent the rainfall event. Since dewpoint observations used for this step of the SSPMP calculation are typically located hundreds of miles away from the precipitation location, it would be inconsistent to use dewpoint data that could not have influenced the precipitation observations based on meteorological conditions. As shown by the red arrow in the figure, a travel time is required for the moisture (denoted as "PW" for precipitable water and described in more detail in Section 5.1.4) to move from the moisture source location (the timing of which is represented by the gray box) to the storm center location (the timing of which is represented by the red box). For this example, the theoretical moisture arrival at the storm center location coincides with a timeframe after most rainfall had already occurred; therefore, the dewpoint has been improperly selected.

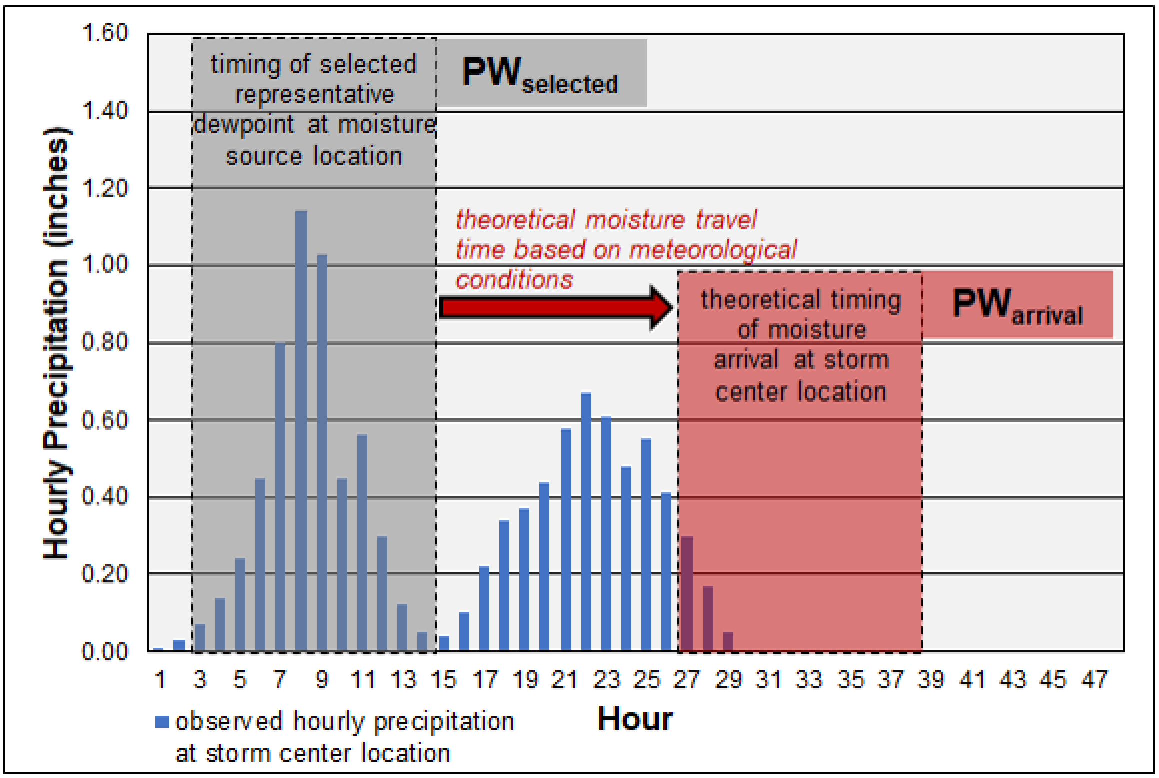


Figure 5-3 Example of Improper Representative Dewpoint Timing Selection Based on Theoretical Moisture Travel Time for Precipitation Event

5.1.3 Historical Dewpoint Conversion

While evaluations of dewpoint climatology and precipitation recurrence intervals typically benefit from the fact that adequate periods of record exist and, therefore, are generally reliable, observed dewpoint values for historical storms depend heavily on station-specific or local observations. Though improvements in technology have enabled higher measurement frequency and density, much historical meteorological data suffer from less frequent, sparser measurements. Consequently, a direct re-evaluation of older storms is often not possible. In fact, many of the 12-h persisting dewpoint values documented by NOAA relied on data measurements taken 2–3 times daily rather than the hourly observations available for more recent storms.

Since many historical HMR and USACE storm analyses produced maximum 12-h persisting dewpoint values for which supporting data are not available, the Electric Power Research Institute (EPRI)-sponsored PMP study for Wisconsin and Michigan (EPRI 1993) developed an approach for converting maximum 12-h persisting dewpoints to maximum average dewpoints. To quantify the conversion factors, the EPRI study analyzed seven historical storms occurring in the Midwest. These storms were analyzed as a part of the PMP study in Michigan and Wisconsin for which sufficient data were available to compute and directly compare the 6-, 12-, and 24-h average dewpoint values with the 12-h persisting dewpoint value. Of these seven storms, three were classified as mesoscale convective complexes (MCCs; i.e., local storms) and four were classified as synoptic systems (i.e., general storms).

For the three MCC (local) storms analyzed in EPRI (1993), the maximum 6-h average dewpoint was found to be 7 to 8 °F higher than the maximum 12-h persisting dewpoint. To provide a more conservative adjustment (lower storm representative dewpoint values are more conservative), the EPRI study recommended a conversion factor of +5 °F (i.e., maximum average dewpoint = maximum 12-h persisting dewpoint + 5 °F). However, subsequent evaluations by licensees resulted in modification of this recommendation to a value of +7 °F for MCC storms. For the four synoptic (general) storms analyzed in EPRI (1993), the maximum 24-h average dewpoint was found to be 2 to 3 °F higher than the maximum 12-h persisting dewpoint. The EPRI study recommended a conversion factor of +2 ° F for synoptic (general) storms. These EPRI conversion factors are used throughout recent SSPMP studies when converting maximum 12-h persisting dewpoint values to maximum 6-, 12-, or 24-h average dewpoint values.

To support SSPMP review and evaluate the EPRI conversion factors, ORNL staff conducted limited independent analysis using multiple storms from SSPMP submittals associated with the 2012 §§50.54(f) information request in the Midwest (see Figure 5-4). Results demonstrate that some large differences exist, and alternative conversion factors may be reasonably estimated as +3 to +4 °F for local storms and +1 to +2 °F for general storms. The differences found between the EPRI study and the ORNL staff's independent assessment demonstrate the need to closely evaluate historical storms to which the conversion factors were applied, especially considering the proximity of the original EPRI storms to those analyzed.

To summarize, based on limited independent analysis of multiple storms used in licensee SSPMP submittals associated with the 2012 §50.54(f) information request, the following recommendations are made:

- an alternative conversion factor for MCC (local) storms of +3 to +4 °F (i.e., increase the 12-h persisting dewpoint by 4 ° F)

- an alternative conversion factor for synoptic (general) storms of +1 to +2 °F (i.e., increase the 12-h persisting dewpoint by 2 °F)

Since these alternative conversion factors were developed based on storms occurring exclusively in the Midwest, they may not apply in other regions. Future analyses in other regions should be conducted to better assess the reliability of the results presented here and evaluate whether alternative conversion factors are needed for storms in other regions.

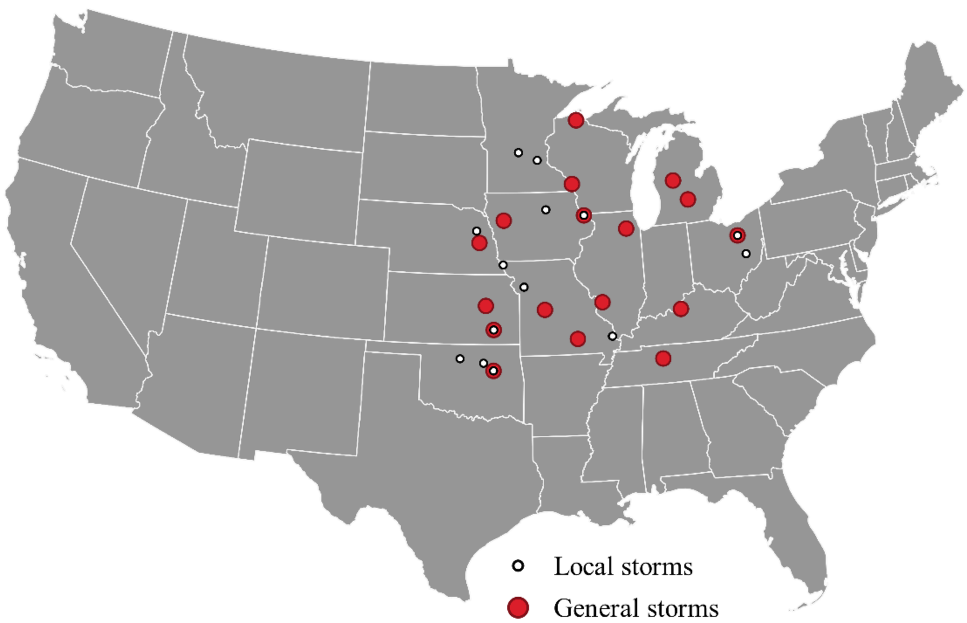


Figure 5-4 Map of Storms Used to Evaluate Alternative Storm Representative Dewpoint Conversion Factors

5.1.4 Precipitable Water Estimation

To numerically estimate storm precipitable water (PW_{Storm}) through the entire vertical atmospheric column, based on the surface observed dewpoint, a lookup table published in Appendix C to HMR No. 55A (Hansen et al. 1988) and based on pseudo-adiabatic assumption may be used. For instance, for a 22-degree Celsius (°C) (71- °F) surface dewpoint, the total PW from sea level to the top of the atmosphere (i.e., 0–9,150 m (0–30,000 ft)) is estimated to be 6 centimeters (2.36 in.). Overall, the PW_{Storm} value is considered to be one of the most significant variables affecting the calculation of SSPMP. Although the three-dimensional PW values are now available in modern meteorological reanalysis datasets, all current SSPMP studies to date have used the conventional way to estimate PW by surface dewpoint.

In reality, the value of PW_{Storm} would also change dynamically as the storm progressed, but the current approach provides only a snapshot of total PW right before a storm occurs. In addition, the current moisture maximization process assumes that the amount of PW is linearly proportional to rainfall depth. This critical assumption has yet to be examined as part of the previously reviewed PMP calculations.

In terms of sensitivity, a lower storm representative dewpoint will lead to a more conservative PMP estimate. In general, a 1-°F difference in dewpoint contributes to an approximate 4 to 5 percent difference in PMP. This sensitivity stems from the moisture maximization process in which moisture availability is estimated based on the relationship between dewpoint and PW provided in the HMR No. 55A PW tables (Hansen et al. 1988). Various storm-specific factors, including dewpoint temperature and elevation, affect the calculation of moisture availability.

5.2 Key Considerations for SSPMP Development

Based on experience and knowledge gained through reviews of SSPMP estimates submitted in connection with the 2012 §50.54(f) FHRR submittals, the NRC staff identified several key considerations in the development of a SSPMP. These considerations build on the terminology, general methodology, and lessons learned described previously and highlight issues associated with some of the more subjective areas of SSPMP development. The NRC and ORNL staffs identified the following key considerations related to storm representative dewpoint selection and PW estimation:

- For storms that require conversion of persisting dewpoint temperature data to maximum averaged dewpoint temperature, the adjustment should be carefully considered. Several licensee submittals have used adjustment values that have been shown to be potentially nonconservative based on limited independent ORNL staff sensitivity analysis.

- All relevant data used in storm representative dewpoint selection should be used for storm representative dewpoint analysis at the moisture source location. These data may include the storm moisture inflow maps (e.g., HYSPLIT trajectory maps, weather maps, etc.) and the observed in-place dewpoint temperature data and maps (or SST data and maps). For storms for which hourly dewpoint data were unavailable or not used, the relevant data or source information used to determine the storm representative dewpoint should be documented and provided.

- If the selection of the storm representative dewpoint location deviated significantly from the HYSPLIT trajectories, detailed meteorological reasoning should be documented and provided.

- The selection of the storm representative dewpoint timeline should be clearly compatible with moisture transport characteristics (i.e., the location, timing, and travel time of dewpoint observations relative to the precipitation location and timing). If the compatibility is not clear, detailed meteorological reasoning should be documented and provided.

- PW estimation involves high uncertainty given the typical lack of robust analysis. While the conventional HMR procedures for estimating PW (i.e., using surface dewpoint before the storm occurs) remain an acceptable approach, modern meteorological tools and products that can yield more methodologically defensible PW estimates are highly encouraged.

6 DEWPOINT CLIMATOLOGY, MOISTURE MAXIMIZATION, AND MOISTURE TRANSPOSITION

This section of the Knowledge Management NUREG discusses considerations in the dewpoint climatology, moisture maximization, and moisture transposition selection processes used in SSPMP development, including descriptions of the terminology, general methodology, and other key considerations. This chapter ends with a summary of lessons-learned from the recent reviews of the 2012 §50.54(f) FHRRs.

6.1 Terminology, General Methodology, and Lessons Learned

After a storm representative dewpoint and the corresponding PW_{Storm} are identified for each selected storm (Section 5), the next step in SSPMP development is to estimate the probable maximum total precipitable water (PW_{Max}) for moisture maximization, which WMO (2009) defines as "the process of adjusting observed precipitation amounts upward based on the hypothesis of increased moisture inflow to the storm."

To estimate PW_{Max}, a maximum dewpoint is determined using dewpoint climatology maps derived from historical dewpoint observations. The resulting ratio (i.e., adjustment factor) between the PW_{Max} and PW_{Storm} is then used to rescale the observed storm rainfall depth to calculate SSPMP with the assumption that PW_{Max} sufficiently estimates the theoretical maximum water content that could have been available to the storm. This process of identifying a storm representative dewpoint and performing moisture maximization using dewpoint climatology is consistent with the process employed in the HMRs, with some methodological nuances as described in the sections below.

6.1.1 Dewpoint Climatology

To estimate the PW_{Max}, HMR No. 51 used "the highest dewpoints observed for a given location and time of year" from the *Climatic Atlas of the United States* (EDS 1968). In particular, it used 12-h persisting dewpoint, defined as "the dewpoint value at a station that has been equaled or exceeded throughout a period of 12 consecutive hours" (WMO 2009). The use of the 12-h persisting dewpoint partially reflected the state of dewpoint observations in the 1960s when instantaneous dewpoint measurements were generally made only twice a day (e.g., 7 a.m./7 p.m. or 8 a.m./8 p.m.) and could not provide temporal resolution finer than 12-h. With only morning and evening observations available for many locations, calculations of persisting dewpoint could not capture the intermediate changes in dewpoint temperatures occurring throughout the day. The maximum 12-h persisting dewpoint maps (Figure 6-1) in the *Climatic Atlas of the United States* were constructed by summarizing all available dewpoint observations and directly constructing contour maps covering the entire United States for each calendar month.

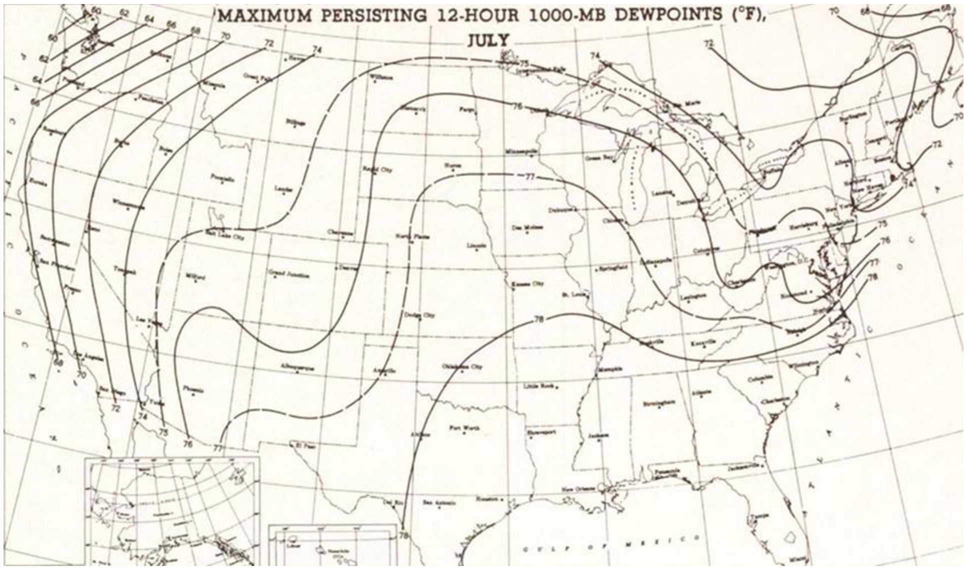


Figure 6-1 Example Maximum 12-h Persisting Dewpoint Map for July (EDS 1968)

Perhaps the most significant difference between the HMRs and SSPMP study methods submitted by licensees in response to the 2012 §50.54(f) information request is the use of different dewpoint climatology values. Instead of using 12-h persisting dewpoints for all storm types, SSPMP studies used maximum 6-, 12-, or 24-h average dewpoints for different storm types (in general, 6-h for mesoscale convective systems and 24-h for large-scale frontal systems). This refinement has become possible through the increased availability of hourly (and 3-h) dewpoint observations since the publication of the *Climatic Atlas of the United States* in 1968. Nevertheless, because climatology maps using maximum 6-, 12-, or 24-h average dewpoints were not otherwise available, SSPMP studies have relied on proprietary, privately developed dewpoint climatology datasets. SSPMP submittals have used the 100-year return period dewpoint climatology with the assumption that a 1-percent annual exceedance probability (AEP) represents a reasonable “maximum” moisture level for moisture maximization.

As mentioned in Section 5.1.2, many SSPMP estimates associated with the 2012 §50.54(f) information request submittals included storm representative dew point estimates and dew point climatology datasets developed using land-based surface dewpoint data from the NOAA TDL dataset rather than the higher quality-controlled TD3505 dataset. This lower quality-controlled TDL dataset has been used for both storm representative dewpoint temperature determination and dewpoint climatology estimation. Although the two datasets are largely similar, differences in the annual maximum dewpoint values caused by the presence of missing or erroneous values in the TDL dataset may result in different annual maximum series fitting results and dewpoint climatology estimates as compared to a TD3505-based analysis. Differences in dewpoint climatology estimates can lead to differences in moisture maximization and moisture transposition adjustments, as described in Sections 6.1.2 and 6.1.3, thereby affecting SSPMP estimates.

These independently created dewpoint climatology maps have been used when the storm moisture mass is located on land. When the moisture mass is located over the ocean, SSPMP studies have used an approach similar to what is used in the HMRs. As a surrogate for the land-based dewpoint, an SST value that is two standard deviations (i.e., +2σ) warmer than the mean SST (approximately equivalent to a 40-year return level (AEP: 2.3 percent) based on a normal distribution) is used. Licensees have used the 1981–2010 NOAA Optimum Interpolation Sea Surface Temperature Analysis[15] to generate the +2σ maps for each calendar month. Given the inconsistencies in return periods (i.e., 100 years versus approximately 40 years), as well as the very different data types (i.e., land-based gauge dewpoint measurement versus ocean-based gridded SST product), significant discontinuity of dewpoint climatology can be seen in the land and ocean interface in multiple SSPMP studies. Section 6.2 presents additional information on how this discontinuity should be addressed.

6.1.2 Moisture Maximization

After a land-based 100-year dewpoint value (or a sea-based +2σ SST) is identified, it is converted to a corresponding PW_{Max} value, and an in-place maximization factor (IPMF) is calculated using Equation (1), as explained below. The IPMF adjustment attempts to maximize a historical storm event by increasing the event's PW content to a historical maximum value through use of a ratio (i.e., adjustment factor):

$$IPMF = \frac{PW_{Max,Srep,SE}}{PW_{Storm,Srep,SE}}, \quad (1)$$

where

$PW_{Max,Srep,SE}$ = the PW calculated using the 100-year dewpoint (or +2σ SST) at the storm representative dewpoint location from the storm elevation to the top of atmosphere.

$PW_{Storm,Srep,SE}$ = the PW calculated using the storm representative dewpoint at the storm representative dewpoint location from the storm elevation to the top of atmosphere

To avoid over-adjustment and unreasonable PMP estimation, HMR authors suggested an upper bound of 1.5 in computing this factor (i.e., if it is calculated to be above 1.5, the IPMF value is set to 1.5). The IPMF adjustment factor is then multiplied with two additional adjustment factors. The justification for limiting the IPMF to a value of 1.5 remains unclear. A recent study based on the numerical weather simulation model suggested that the change of PMP depth can be even larger than the change of PW during moisture maximization (Rastogi et al. 2017).

6.1.3 Moisture Transposition Adjustment

For a historical storm event considered transpositionable to a study area, the moisture transposition process accounts for differences in maximum available moisture (i.e., PW) associated with relocating the storm to the study area. To determine the PW available under the original and transpositioned scenarios, the calculation relies on various data, including the maximum dewpoint value (e.g., from dewpoint climatology) and elevation associated with the storm representative dewpoint location and the transpositioned location. This same general procedure for converting from dewpoint to PW (i.e., using Appendix C to HMR No. 55A) may be used.

15 http://www.emc.ncep.noaa.gov/research/cmb/sst_analysis/

Once the PW depths are identified, the ratio between the transpositioned location's maximum PW and the original location's maximum called PW (the moisture transposition factor (MTF)) can be computed by Equation (2):

$$MTF = \frac{PW_{Max,ST,SE}}{PW_{Max,SRep,SE}} \quad (2)$$

where

$PW_{Max,ST,SE}$ = the PW calculated using the 100-year dewpoint (or +2σ SST) at the storm transposition location from the storm elevation to the top of atmosphere

$PW_{Max,SRep,SE}$ = the PW calculated using the 100-year dewpoint (or +2σ SST) at the storm representative dewpoint location from the storm elevation to the top of atmosphere

To estimate $PW_{Max,ST,SE}$ and $PW_{Max,SRep,SE}$, the PW associated with the maximum dewpoint is identified for the surface elevation of interest (i.e., the PW that would otherwise occur between the surface elevation and sea level) and subtracted from the total PW available above sea level. The resulting difference provides the amount of PW available at the location of interest.

6.2 Key Considerations for SSPMP Development

Based on experience and knowledge gained through reviews of SSPMP estimates submitted in connection with the 2012 §50.54(f) FHRR submittals, the NRC staff identified several key considerations in the development of a SSPMP These considerations build on the previously described terminology, general methodology, and lessons learned and highlight issues associated with some of the more subjective areas of SSPMP development. NRC and ORNL staff identified the following key considerations related to dewpoint climatology, moisture maximization, and moisture transposition:

- If not publicly available, all relevant data used to develop dewpoint climatology datasets should be documented and provided, including the station-based annual maximum series data used for fitting, the monthly 100-year dewpoint climatology values at each station, and the monthly 100-year dewpoint climatology maps. The 100-year threshold used for moisture maximization and transposition is only an example threshold, and other approaches could reasonably be used with adequate justification.

- When performing storm moisture maximization, the type of data used to estimate observed moisture and maximum moisture should be compatible. For instance, if SST data are used to estimate observed storm moisture, SST data (and not dewpoint temperature data) should be used to estimate maximum moisture. In addition, the use of analysis technique (e.g., persisting dewpoint temperatures versus maximum average temperatures) should be consistent.

- The maximum thresholds used to analyze land-based dewpoint temperature data and ocean-based SST are different (100-year dewpoint versus +2σ SST, respectively). Whereas land-based thresholds are associated with an AEP of 1 percent, ocean-based thresholds are associated with a less extreme value with an approximate AEP of 2.3 percent. This difference can impart high sensitivity depending on which data source is used and affect SSPMP estimates for both coastal regions and noncoastal regions that include storms with ocean moisture sources (i.e., near-coast storms). Since near-coast storms are often transpositioned inland for SSPMP development, land/ocean data differences may affect SSPMP estimates across a large region and not only affect coastal NPP sites. Given the potentially high sensitivity between land- and ocean-based PW estimation and moisture adjustments for near-coast storms and in coastal regions,the NRC staff recommends using the approach that provides a more conservative SSPMP value.

- As mentioned in Section 5, PW estimation involves high uncertainty given the typical lack of robust analysis. Further research should be conducted to examine the reasonableness of the PMP maximization factor (i.e., assuming the change of total PW is linear to the change of rainfall depth). Previous studies (Rastogi et al. 2017; Abbs 1999) have questioned the reasonableness of the linear relationship assumed when applying PW adjustments for PMP maximization.

- During the development of dewpoint climatology, annual maximum dewpoint data should be tested for potential long-term trends through commonly used trend detection methods (e.g., Mann-Kendall test). If a significant trend is found, then a nonstationary statistical fitting method should be used to avoid biased dewpoint climatology estimation. Maximum moisture levels are currently assumed to be stationary, without consideration of historical data trends (e.g., changing 100-year dewpoint temperature estimates). Based on published literature, this assumption is questionable and potentially nonconservative in a changing climate. See Section 10 for more discussion of the potential effects of climate change.

7 TERRAIN ADJUSTMENT

This section of the Knowledge Management NUREG discusses considerations in the terrain adjustment processes used in SSPMP development, including descriptions of the terminology, general methodology, and other key considerations for SSPMP development. This chapter ends with a summary of lessons-learned from the recent reviews of the 2012 §50.54(f) FHRRs are also discussed.

7.1 Terminology, General Methodology, and Lessons Learned

Historically, simplifying assumptions regarding the influence of topography and orographic processes were used in lieu of a detailed analysis of PMP estimates. However, when a storm event is being transpositioned from its original location to an SSPMP study area with dissimilar underlying topographic features, the influences of new terrain should be considered. For instance, elevated terrain located between the moisture source and the study area may present physical barriers to moisture inflow and decrease the amount of rainfall that can occur in the study area. On the other hand, terrain-induced lifting could increase the amount of rainfall. In the conventional HMR framework, the terrain-related adjustments are introduced as another adjustment multiplier after the steps of storm in-place moisture maximization and transposition (discussed in Section 6). To account for the impacts of terrain on moisture reduction, one of two different approaches have been used: a barrier adjustment factor (BAF) or an orographic transposition factor (OTF).

These approaches differ from previous terrain adjustment methods used in the HMRs, including the storm separation method (SSM). The research community has not developed a physically based alternative to replace the SSM, which has not been used in recent SSPMP studies because of its complexity and subjectivity. SSMs have been described in the literature, including Hansen et al. (1994).

The SSM, BAF, and OTF can be categorized as types of terrain adjustment factors. In general, for enhancement of storms due to changing topography (e.g., terrain-induced lifting), a terrain adjustment factor of greater than 1.0 is needed, whereas for reduction of storms due to moisture blockage, a terrain adjustment of less than 1.0 is needed.

7.1.1 Barrier Adjustment Factor

Various licensee SSPMP submittals have simulated the reduction of moisture using a BAF. One BAF calculation approach involves using digital elevation data (e.g., National Elevation Dataset (NED[16])) or Global Multi-resolution Terrain Elevation Data (GMTED2010[17])) to identify barriers for each storm based on the inflow direction. Using the study area location as a starting point, a vector is plotted upwind for each inflow direction considered, and a cone of influence (a triangle with a length 1.5 times the base) is extended beyond the most significant barrier. The cone of influence is then repositioned to encompass the entire basin, and the maximum upwind barrier across the width of the cone base is identified. The average barrier height is then determined. An "effective" barrier height may also be computed to account for irregularities in the maximum barrier profile through which more or less moisture may pass. This effective barrier height adjustment is made on a storm-by-storm basis and can be subjective, though the sensitivity is usually minor. HMR No. 55A, Section 3.3 (Hansen et al. 1988), documents a similar approach to

16 https://catalog.data.gov/dataset/usgs-national-elevation-dataset-ned
17 https://www.usgs.gov/land-resources/eros/coastal-changes-and-impacts/gmted2010

account for orographic blockage of storm moisture inflow; however, the development of geographic information system methods has greatly enhanced SSPMP practitioners' ability to identify and quantify barriers. The BAF is also similar to various procedures described in WMO (2009).

A consideration in the BAF method that neither licensee- nor HMR-based barrier analyses account for is whether the original storm track crossed physical barriers that resulted in less total PW downwind of the barrier because of moisture depletion. While moisture depletion due to a physical barrier is considered explicitly for the transpositioned storm track when the BAF method is applied, moisture depletion that may have occurred when the original storm crossed a barrier is not considered. For example, for the original storm track, if a moisture center moves over a barrier and results in rainfall on the downwind side of the barrier, the available moisture would (theoretically) be reduced through the same mechanisms that reduce PW content that are applied to the transpositioned storm track via the BAF method. However, under previously discussed methodologies, no accommodation is made for moisture depletion that reduced the observed rainfall because of BAF effects. The potential result is reduced conservatism in transpositioning storms that moved over a barrier.

7.1.2 Orographic Transposition Factor

Various licensee SSPMP submittals have used another terrain adjustment approach, the OTF, in place of the BAF. The OTF is a grid-based adjustment factor computed using precipitation frequency data (e.g., NOAA Atlas 14[18]) and is calculated as the ratio of a climatological precipitation parameter at a target location (i.e., any grid point within the target basin) to the same parameter at the storm source location. To use this terrain adjustment approach, licensees assume that spatial variation in climatological precipitation depth (e.g., 100-year rainfall) can be used to predict spatial rainfall patterns for extreme events. Typically, this approach has used a 24-h duration for synoptic storms (i.e., general and tropical storms) and a 6-h duration for convective storms (i.e., local storms). The OTF calculation approach represents a significant departure from conventional HMR approaches. The OTF was originally developed to quantify the effects of topography on rainfall in mountainous terrain. However, in more recent submittals, licensees have applied the OTF procedure throughout regions where reliable precipitation frequency data are available, regardless of terrain. Therefore, the OTF procedure has been used to quantify the effects of topography and elevation differences between any two locations. Given the large adjustment that OTF can bring in non-orographic regions and its large deviation from HMR methods, the use of OTF in non-orographic regions is discouraged, unless it results in no significant difference compared to the more conventional BAF approach.

In some licensee studies, the terrain adjustments are computed following a linear best-fit approach. Following this approach, NOAA Atlas 14 precipitation frequency depths with recurrence intervals of 10 to 1,000 years are collected for the storm center and target locations. The identified values are fit into a linear regression line, shown in Equation (3), to estimate *m* and *b*:

$$P_{Atlas14,Site} = m * P_{Atlas14,SC} + b \tag{3}$$

18 http://hdsc.nws.noaa.gov/hdsc/pfds/

where

$P_{Atlas14,Site}$ = target grid point rainfall frequency depth (in inches (in.)) across various selected durations and return periods from Atlas 14

$P_{Atlas14,SC}$ = storm center grid point rainfall frequency depth (in.) across various selected durations and return periods from Atlas 14

m = slope

b = intercept (in.)

The linear relationship determined through the target-source regression fit above is then used to determine the orographically adjusted rainfall for all grid points based on the in-place rainfall using Equation. Eq. (4):

$$P_{Site} = m^{*}P_{SC}+b \tag{4}$$

where

P_{Site} = orographically adjusted rainfall (in.) at the targeted grid point

P_{SC} = in-place rainfall (in.)

m = slope from Equation (3)

b = intercept (in.) from Equation (3)

Rearranging Equation (4) yields the OTF, as shown in Equation (5):

$$OTF = \frac{P_{Site}}{P_{SC}} = m + \frac{b}{P_{SC}} \tag{5}$$

In more recent SSPMP studies, terrain adjustments have been computed using different calculation methodologies. Rather than using the linear best-fit approach, the adjustment can also be computed by using the ratio between the 100-year precipitation frequency depths at two locations. Ratios using alternative recurrence intervals (e.g., 1,000 years) may also be used; however, licensees have suggested that the NOAA Atlas 14 100-year precipitation frequency depths offer a preferred balance between the rarity and uncertainty of the estimate. Eq. (6) shows the adjustment calculation using the 100-year ratio:

$$OTF = \frac{P_{Atlas14,100\text{-}y,Site}}{P_{Atlas14,100\text{-}y,SC}} \tag{6}$$

7.1.2.1 Calculation methodology for orographic transposition factor

Preliminary comparison between Equations (5) and (6) has shown nonnegligible differences resulting from the use of these two equations. While both equations are conceptually similar, the staff has noticed more stable and intuitive results from Equation (6). From an end-use standpoint, calculating the OTF using the ratio of the 100-year precipitation frequencies may offer a more sound approach, since the spatial variation in OTF values is consistent with the spatial variation in NOAA Atlas 14 precipitation frequencies. Use of a linear best-fit approach introduces variability in OTF values without clear justification. Therefore, using a 100-year ratio approach, rather than the linear best fit, is preferred when calculating the OTF.

7.1.2.2 Orographic transposition factor lower and upper limits

When applying the OTF, licensees have typically enforced an upper limit (usually 1.50) but no lower limit. While the selection of an upper and lower limit for terrain or geographic adjustment values is subjective, when terrain or geographic adjustment limits are used, the NRC staff recommends that the bounds should be inversely related (i.e., an upper limit of 1.50 should be used with a lower limit of 0.67, or 1/1.50). This ensures consistency in applying this methodology between two locations, regardless of the source and target locations. Consequently, any studies that use terrain or geographic adjustment should include consistent lower limits or provide a defensible rationale for not doing so.

7.1.2.3 Use of orographic transposition factor in non-orographic regions

The OTF was originally developed to capture the orographic effects that drive extreme precipitation production in complex terrain with the assumption that such effects may be represented in precipitation frequency estimates. However, some licensees have subsequently extended OTF to non-orographic regions where precipitation frequency data are available. In some cases in which OTF was used in non-orographic regions, the NRC staff found that OTF use may result in significant precipitation reductions that do not have a clear physical explanation. Hence, using OTF in non-orographic regions represents a relatively large deviation from the conventional HMR-based PMP approach. As stated previously, the use of OTF in non-orographic regions is generally discouraged. However, when the OTF is used in non-orographic regions, detailed NRC staff review is justified to ensure that the SSPMP adjustments are reasonable; more conventional BAF-based adjustments could provide reasonable comparison.

7.1.2.4 Uncertainty and use of NOAA Atlas 14 to compute orographic transposition factor

While statistical parameters are used for other PMP-related calculations (e.g., the use of 100-year dewpoint climatology for moisture maximization), the use of NOAA Atlas 14 to calculate terrain adjustments diverges from standard PMP calculation practices. The lack of clear evidence that precipitation-producing processes are appropriately captured in NOAA Atlas 14 and unexpected spatial variations in precipitation frequency depths have been raised as important indicators of sensitivity and uncertainty. The ORNL staff has observed the following:

- NOAA Atlas 14 has been developed in stages, and multiple volumes have been produced. Each volume provides precipitation frequency data for specific regions that are considered meteorologically similar. Different regional probability distributions may exist for each region and can contribute to large differences across regions.

- NOAA Atlas 14 precipitation frequencies are computed based on annual maximum precipitation and do not distinguish among various storm types. Therefore, storm type mixing presents an issue when precipitation frequencies are applied in a storm-based PMP approach.

- Since NOAA Atlas 14 precipitation depths are derived based on point precipitation observations, it is unlikely that the spatial patterns and magnitude of variation are representative of precipitation frequencies for large-area storms. Since there are multiple areas of uncertainty and a lack of a clear physical basis associated with the OTF calculations, future PMP reviews should carefully examine the use of this or similar methodologies.

7.1.2.5 *Double counting of orographic transposition factor and moisture transposition factor*

When using a terrain adjustment method (e.g., the OTF method), the potential exists for double counting of moisture adjustment, since the influence of climatology is retained when precipitation frequency analysis is used. SSPMP developers should evaluate and discuss terrain adjustments and MTF since the degree to which the atmospheric component of the MTF is also accounted for in the OTF is unknown. Until the relationship between terrain adjustments and MTF is determined, the MTF adjustment should continue to be used regardless of whether the OTF is used.

The NRC staff notes that while MTF values have a clear physical basis, OTF values do not and introduce high uncertainty in the SSPMP calculation. Therefore, the reasonableness and conservativeness of OTF for controlling and near-controlling storms should be carefully evaluated when assessing SSPMP estimates and consequential flood hazard determinations.

7.2 Key Considerations for SSPMP Development

Based on experience and knowledge gained through the earlier reviews of SSPMP submittals associated with the 2012 §50.54(f) information request, the NRC staff has identified several key considerations for SSPMP development. These considerations build on the previously described terminology, general methodology, and lessons learned and highlight issues associated with some of the more subjective areas of SSPMP development.

The staff identified the following key considerations related to terrain adjustment using the BAF:

- All relevant data used to develop terrain adjustment should be provided, including barrier profile elevation and effective barrier height data.
- While the BAF has known limitations and does not capture orographic enhancement effects, its use can be physically justified in regions with high terrain influence. Where alternative methods are being considered, preference should be given to the more conservative and physically justifiable approach to improve the reasonableness of the flood hazard assessment.
- When calculated average barrier heights are adjusted to effective barrier heights, clear justification should be provided and explained. The ORNL staff has found that the sensitivity associated with this adjustment is usually minor.
- When using the BAF, analysts should consider an observed precipitation event’s potential loss of moisture over high terrain based on the original storm track.

Related to terrain adjustment using the OTF, the staff identified the following key considerations:

- All relevant data used to develop terrain adjustment should be provided, including all precipitation frequency data used for OTF calculation across the study area.
- The OTF should be used with caution, with application limited to regions where orographic influences are clear drivers of extreme precipitation. Geographic patterns in OTF values derived from NOAA Atlas 14 do not have a clear physical basis, and some of the characteristics may introduce double-counting effects overlapping with the MTF.

At a more fundamental level, subject matter experts or academic peer review has not thoroughly vetted the assumption that variation in NOAA Atlas 14 point-based precipitation frequency depths provides a reasonable approximation of PMP-scale precipitation. The use of point-based precipitation frequency depths for OTF calculation may also be problematic when used to estimate precipitation over large areas, although datasets for areal precipitation frequency depth are not currently publicly available. Where alternative methods are being considered, preference should be given to the more conservative approach to improve the reasonableness of the flood hazard assessment (e.g., PMF estimate).

- When used, the OTF should be calculated based on the best available techniques. For example, calculating the OTF using a ratio of precipitation depths of the same return period is considered superior to using regression techniques which exhibit high uncertainty and can bias results.

- A reasonable lower limit should be used for the OTF method.

- Given the large adjustment that OTF can bring in non-orographic regions and its large deviation from HMR methods, the use of OTF in non-orographic regions is discouraged, unless its use results in no significant difference compared to the more conventional BAF approach.

8 ENVELOPMENT AND PROBABLE MAXIMUM PRECIPITATION DETERMINATION

This section of this Knowledge Management NUREG discusses considerations in the PMP determination and envelopment processes used in SSPMP development, including descriptions of the terminology, general methodology, and other key considerations. This chapter ends with a summary of lessons-learned from the recent reviews of the 2012 §50.54(f) FHRRs.

8.1 Terminology, General Methodology, and Lessons Learned

Once all adjustment factors (i.e., IPMF, MTF, and OTF or BAF) have been determined for a storm, the total adjustment factor (TAF) can be determined. Since both the OTF and BAF provide a means of capturing terrain adjustment, only one of the two factors may be used for any given storm. Note that when using the OTF instead of the BAF, licensees have typically modified the MTF calculation to exclude elevation adjustment (i.e., the calculation in Equation (2) is modified). Equation (7) shows the calculation of TAF:

$$TAF = IPMF \times MTF \times BAF$$

or

$$TAF = IPMF \times MTF \times OTF \tag{7}$$

where

TAF = the total adjustment factor

IPMF = the in-place maximization factor

MTF = the moisture transposition factor

OTF = the orographic transposition factor

BAF = the barrier adjustment factor

Once all selected storms have been analyzed and subjected to TAF adjustment, the final adjusted DAD values used to determine PMP values are determined using envelopment. As documented in HMR No. 51 (Schreiner and Riedel 1978), envelopment is defined as "smoothly interpolating between the maxima from a group of values for different durations and/or areas." Envelopment represents the final step in the SSPMP development process and uses the maximized, transpositioned DAD values computed using the methods described in Sections 5-7.

Since most LIP-PMP evaluations for SSPMP submittals associated with the 2012 §50.54(f) information request relied on a 6-h, 10-mi^2 PMP value or a 1-h, 1-mi^2 PMP value (ADAMS Accession No. ML11321A195), the maximum final adjusted DAD value among all storms is selected. This same approach is used for all area-duration combinations required for a study; however, storm-specific DAD curves are typically plotted for a particular duration to produce an appropriately smoothed envelopment curve. Since most WS-PMP evaluations for licensee submittals use a 72-h precipitation hyetograph, WS-PMP studies typically plot area versus depth for 6-, 12-, 24-, 48-, and 72-h durations. The resulting smoothed envelopment curve provides the final PMP values used for simulating flooding hazards.

Figure 8-1 provides an example of an envelopment curve, where the curve equals or exceeds the maximum depth among all storms for each area size. For some areas (e.g., 2,000 mi^2), the example envelopment curve exceeds the maximum value by a larger margin owing to the desire to produce a smoothed curve. Professional judgment is also used to ensure that the envelopment curves across all durations exhibit similar patterns, and further smoothing may be performed as needed. As stated in HMR No. 51, Section 2.1 (Schreiner and Riedel 1978), "such smoothing compensates for the random occurrence of large rainfalls, in that a drainage may not have experienced equally efficient precipitation mechanisms for all pertinent durations and sizes of areas."

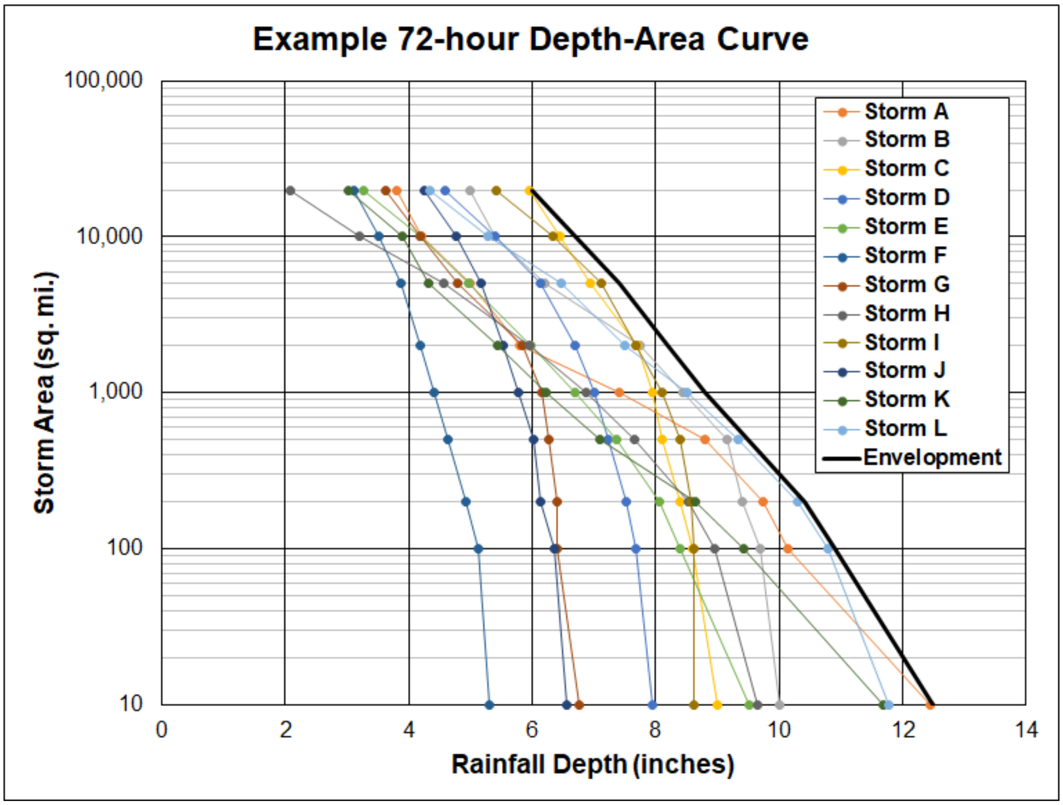


Figure 8-1 Example DAD Curves (Including Envelopment) for a 72-h PMP (Note: Values Do Not Represent Actual Storms or PMPs)

8.2 Key Considerations for SSPMP Development

Based on experience and knowledge gained through reviews of SSPMP submittals associated with the 2012 §50.54(f) information request, the NRC staff has identified several key considerations for SSPMP development. These considerations build on the previously described terminology, general methodology, and lessons learned and highlight issues associated with some of the more subjective areas of SSPMP development. The staff identified the following key considerations related to temporal and spatial envelopment:

- All relevant data used in PMP determination and storm envelopment should be provided, including all storm-based adjustment factors, adjusted storm DAD data, and final PMP data.

- SSPMP estimates should ensure that all DAD values are properly enveloped to ensure no loss of PMP values for the simulated flooding hazard.

- During the envelopment process, a developer should verify that sufficient storms have been captured in each combination of durations and areas. While further research is needed to quantify a minimum number of storms to support the SSPMP development, a preliminary suggestion is that at least the 10 largest moisture-maximized storms (after exclusion considering transpositionability) should be included in the envelopment of SSPMP at each duration, area, and subarea. Multiple storms are needed since no single historic storm should (theoretically) control PMP values across all durations and areas simultaneously. If a minimum storm count cannot be reasonably identified, the storm transposition limit criteria should be revisited to increase the representativeness of the storms.

9 SPATIAL AND TEMPORAL DISTRIBUTIONS FOR SSPMP APPLICATIONS

This section of this Knowledge Management NUREG discusses considerations in the use of spatial and temporal distributions for SSPMP applications, including descriptions of the terminology, general methodology, and lessons learned, as well as other key considerations. This chapter ends with a summary of lessons-learned from the recent reviews of the 2012 §50.54(f) FHRRs.

9.1 Terminology, General Methodology, and Lessons Learned

While PMP values are provided in terms of a DAD relationship, that relationship lacks specificity as to where, when, and how the precipitation is distributed. For hydrologic and hydraulic modeling applications, the concentration of precipitation in space and time is determined by using spatial and temporal distributions (defined below). The spatial and temporal distributions can impart significant changes to a basin's hydrologic response to PMP. As with the development of SSPMP, the application of spatial and temporal distributions can be highly subjective and require careful review.

Spatial distribution is defined as "the geographic distribution of precipitation over a drainage [basin] according to an idealized pattern storm of the PMP for the storm area" (WMO 2009). Temporal distribution is defined as "the time order in which incremental PMP amounts are arranged within the PMP storm" (WMO 2009).

Conventional PMP documentation found in the HMRs specify procedures for determining and applying spatial and temporal distributions. For example, HMR No. 52, "Application of Probable Maximum Precipitation Estimates—United States East of the 105th Meridian" (Hansen et al. 1982), documents a procedure for temporally and spatially distributing the PMP values found in HMR No. 51 (Schreiner and Riedel 1978). The procedure is stepwise and involves several key steps, including identifying a suitable temporal distribution, isohyetal pattern, and isohyetal orientation. To simplify the implementation of HMR No. 52 procedures, the USACE developed the computer program HMR52 (USACE 1984). Procedures vary among HMRs, and some SSPMP submittals associated with the 2012 §50.54(f) information request used alternative approaches.

The SSPMP submittals generally excluded consideration of spatial and temporal distribution. Instead, many submittals include the SSPMP application of both spatial and temporal distribution as a part of the drainage basin hydrologic modeling analysis rather than as a part of the meteorological precipitation analysis, with many applications simply applying standard HMR procedures. Both HMR and SSPMP methods are discussed below.

9.1.1 Spatial Distribution

Precipitation intensity is often visualized spatially in the form of an isohyetal map, which shows equivalent precipitation depths in a storm (similar to how an elevation contour map shows lines of equal elevation across an area). Conventional HMR procedures for developing a spatial distribution rely on standard, idealized isohyetal patterns. Figure 9-1 (left) shows an example standard isohyetal map from HMR No. 52 (Hansen et al. 1982) in which an elliptical pattern is used with a major axis 2.5 times longer than the minor axis (a generalized pattern which was informed by analyzing actual storm patterns). The total area and average rainfall within each layer of isohyetal would correspond to the same storm area and PMP depth summarized in the

DAD table. Through this approach, the spatial distribution can capture PMP across various storm areas to help effectively identify the most critical peak flow condition. In more complex terrain, precipitation tends to display less symmetric spatial patterns; thus, alternative isohyetal maps have been used in highly topographic regions. For example, the map shown in Figure 9-1 (right) represents a PMP spatial distribution from HMR No. 41 (Schwarz 1965) intended to provide a reasonably conservative PMP spatial pattern over the upper portion of the Tennessee Valley Authority (TVA) watershed. HMR No. 41 also provides other spatial distributions, including a topographically adjusted pattern to concentrate precipitation over the lower watershed and an elliptical pattern similar to the one found in HMR No. 52.

While HMR No. 52 recommends using a single-centered isohyetal pattern, it notes that multicentered rainfall patterns occur and tend to be more common for large-area events. Such multicentered analyses can produce less conservative stream flow estimates since, as noted in HMR No. 52, “all else being equal, the more centers used, the lower the peak discharge” (Hansen et al. 1982). The report states that when using custom patterns, the “arrangement should not violate the basic elliptical shape of the total isohyetal pattern.” HMR No. 52 discusses this further.

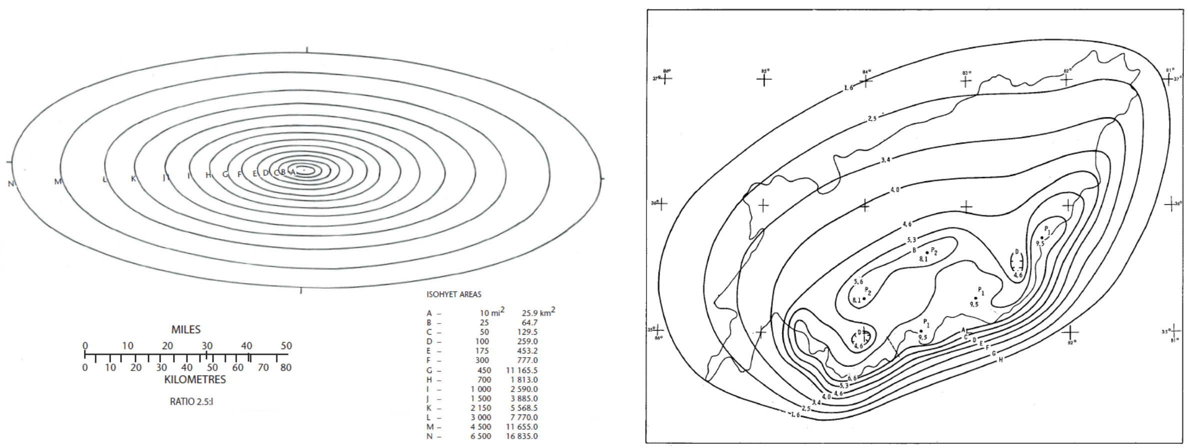


Figure 9-1 Standard Isohyetal Spatial Distribution Pattern Recommended in HMR No. 52 (left; Hansen et al. 1982 as Included in WMO 2009) and Example Probable Maximum March Isohyets Provided in HMR No. 41 (right; Schwarz 1965)

Following HMR No. 52 (Hansen et al. 1982) procedures, once a standard isohyetal pattern is developed, its placement and orientation over the drainage basin are determined with a goal of maximizing precipitation volume over the basin and thereby maximizing peak stream flow. The volume will vary based on the pattern centering, basin shape, and area of PMP distributed over the basin. Given this complexity, HMR No. 52 employs a series of trials and provides suggestions. Note that where patterns have been adjusted to account for topographic influences or, per HMR No. 52, “major storm patterns that have been observed on the drainage,” reorientation may not be needed.

Among the considerations for storm orientation is whether a particular orientation is of typical significance in the region or is constrained by terrain or other factors. HMR No. 52 (Hansen et al. 1982) documents its analysis of precipitation storm orientations and develops a procedure for quantifying geographically varying preferred orientations and adjustments when an orientation is notably different (e.g., larger than 40 degrees).

While the HMR No. 52 procedures focus on an idealized elliptical pattern, later HMRs (e.g., HMR No. 57, "Probable Maximum Precipitation—Pacific Northwest States: Columbia River (Including Portions of Canada), Snake River and Pacific Coastal Drainages" (Hansen et al. 1994), and HMR No. 59, "Probable Maximum Precipitation for California" (Corrigan et al. 1999)) use spatial distributions based on 100-year precipitation frequency climatology from NOAA Atlas 2 (Miller et al. 1973), the predecessor of NOAA Atlas 14. The authors of those reports found that NOAA Atlas 2 correlated well with underlying topography, which was useful for evaluation in complex terrain, and noted that "actual storms may have quite different spatial distributions" (Hansen et al. 1995). The HMR No. 57 authors suggest another approach of using an observed storm's pattern to develop an isopercental distribution; however, they note that data for such storms are limited, and ultimately, no specific spatial distribution procedures are provided.

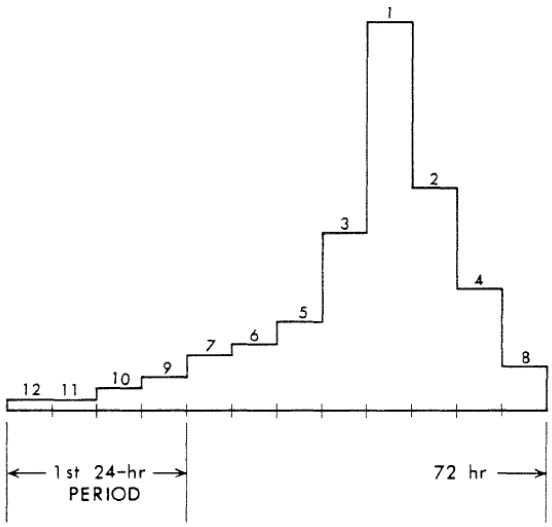
The SSPMP submittals to the NRC have generally excluded consideration of spatial distribution. Instead, many submittals include the SSPMP application of both spatial and temporal distribution as a part of the drainage basin hydrologic modeling analysis, with many applications simply applying standard HMR procedures. However, few SSPMP submittals included spatial distribution analysis. To date, such analyses have been based on storm-specific analysis of multiple major precipitation events that occurred over the watershed, similar to the suggested isopercental approach described in HMR No. 57. Instead of using a synthetic structure, such as shown in Figure 9-1, to spatially distribute SSPMP depths across different storm areas to each layer of the isohyetal, selected historic extreme rainfall events were rescaled to meet the SSPMP depth respective to the watershed size, and then to support the hydrologic and hydraulic modeling. In other words, while the average rainfall depth for the entire watershed is the same in both approaches, the alternative approach uses the historically-observed rainfall records to spatially distribute the total rainfall depth within the watershed and leads to different storm structures.

An important factor in this storm-based spatial distribution approach is whether the selected spatial distributions (historical storms) are sufficiently different and produce a conservative result. As mentioned previously, the HMR No. 52 trial-based approach seeks to maximize precipitation volume over the basin as a way of maximizing peak stream flow. By using multiple storm-based spatial distributions of sufficient variability, a similar effect can be achieved. It is also worth noting that such storm-based distributions may exhibit multicenter characteristics as artifacts of the original event. In some cases, the most intensive portion of the constructed storm can be even larger than the smaller area SSPMP depth in the DAD table. These potential issues need to be considered when selecting and applying the spatial distributions.

9.1.2 Temporal Distribution

Precipitation intensity may be visualized temporally in the form of a hyetograph, defined by WMO (2009) as "a graph displaying the intensity of precipitation versus time." For watershed-scale PMP application, the HMR No. 52 (Hansen et al. 1982) procedure for hyetograph development involves dissecting PMP values into 6-h increments and arranging them in a sequence to form a 72-h event. The sequencing suggested in HMR No. 52 involves ranking the 6-h precipitation increments, positioning the peak 6-h incremental precipitation, and arranging progressively decreasing 6-h increments on either side of the peak; Figure 9-2 (left) provides an example. The authors of that report note that based on study of major storms, maximum rainfall rarely occurs at the beginning of an event sequence; hence, the gradual increase exemplified in Figure 9-2 (left).

For local-scale PMP application, while HMR No. 52 does not provide explicit hyetograph examples, maps are provided for converting 1-h PMP values to subhourly PMP values (5-, 15-, and 30-minutes) using ratios that vary geographically. These maps were produced using maximum annual precipitation values for each duration since none of the available storm studies contained subhourly precipitation data and were suggested for use for areas of 517 square kilometers (200 mi^2) or less. In contrast, HMR No. 57 (Hansen et al. 1994) illustrates representative front- and middle-loaded hyetograph curves based on storm analyses; Figure 9-2 (right) provides an example for middle-loaded storms. The authors do not provide curves for end-loaded storms because of their rarity in the Pacific Northwest region covered by HMR No. 57.



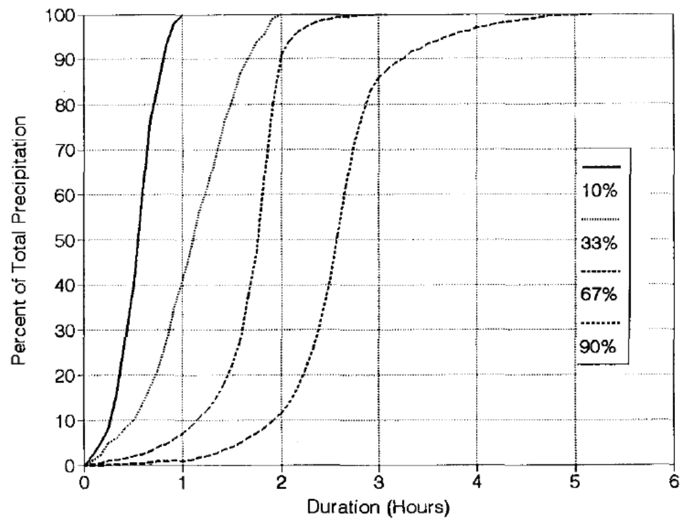


Figure 9-2 Example Temporal Distribution for a Watershed-Scale 72-h PMP Event Provided in HMR No. 52 (Left; Hansen et al. 1982) and Example Temporal Distributions for Middle-Loaded Local-Scale Storms Provided in HMR No. 57 (Right; Hansen et al. 1994)

Various studies in the literature suggest that temporal rainfall characteristics vary regionally based on the prevalence of assorted driving factors (e.g., convective storm patterns, climate, topography).

As described in WMO (2009), another temporal distribution method involves simulating observed temporal storm patterns. Regardless of the method selected, WMO (2009) notes that "it is the responsibility of the meteorologist and hydrologist to determine which arrangement is appropriate for a particular region and will result in the critical design storm for a basin."

Given its goal of providing generalized PMP estimates, the HMR No. 52 procedure recommends using the same isohyetal spatial distribution and orientation throughout the PMP event (i.e., fixed spatial pattern), though the report acknowledges that "it is meteorologically reasonable for the rainfall center to travel across the drainage with time during the storm" (Hansen et al. 1982). This consideration may be especially important for application over large drainage basins, and application of a moving storm "could result in a higher peak if the direction and speed of movement coincides with downstream progression of the flood crest" (Hansen et al. 1982).

Given the important role of PMP application in dam safety, a review of relevant dam safety literature offers additional insight into the application of PMP temporal distribution practices. According to the Federal Emergency Management Agency (FEMA), 57 percent of States do not provide temporal distribution guidance, with about half of the existing guidance indicating that the HMRs should be used (FEMA 2012). Other approaches mentioned include distributions developed by the Natural Resources Conservation Service and those developed by the States for regional or custom applications.

It is also important to note that while the HMRs address PMP durations for up to 72 h, longer precipitation events have been observed and have contributed to major flood events historically. Evaluation of precipitation events exceeding 72 h may be warranted. FEMA (2012) indicates that 37 percent of States do not specify design storm duration in their hydrologic design guidelines; the 63 percent that do provide guidance typically base the design duration on a watershed's time of concentration, with durations ranging from 6–72 h.

9.2 Key Considerations for SSPMP Development

Based on experience and knowledge gained through reviews of SSPMP submittals associated with the 2012 §50.54(f) information request, the NRC staff has identified several key considerations for SSPMP development. These considerations build on the previously described terminology, general methodology, and lessons learned and highlight issues associated with some of the more subjective areas of SSPMP development.

The staff identified the following key considerations related to the SSPMP application using spatial distributions:

- One main objective of spatial distribution (following the conventional HMR No. 52 approach) is to apply the SSPMP DAD information using a spatial pattern that produces the hydrologically most critical runoff scenario. Since no single distribution is likely to maximize flooding across different storm sizes, this process requires that alternative distributions (e.g., historical rainfall events or different isohyetal patterns) be considered to assess hydrologic impacts. The set of alternative distributions should contain multiple distinct spatial patterns to identify the most critical scenario for flood risk evaluation.

- All relevant data used to develop spatial distribution, such as precipitation hyetograph shapefiles or spatially gridded precipitation event data, are needed for review and evaluation.

Related to PMP application using temporal distributions, the ORNL staff identified the following key consideration:

- The timing of peak precipitation intensity within a temporal distribution can significantly affect the resulting flood hydrograph. Analysis using alternative temporal distributions can provide insight into the relative sensitivity of using different timing.

10 POTENTIAL EFFECTS OF LONG-TERM CLIMATIC CHANGE

None of the SSPMP studies submitted by owners and operators in response to the staff's 2012 §50.54(f) information request captured or addressed the potential effects of long-term climatic change. In the context of climate change, the issue is whether deterministic PMP values will demonstrate a trend or will remain unchanged under the projected future climatic conditions. Until now, the magnitude of extreme storms relevant to PMP development has been considered stationary, meaning that the mechanism producing PMP-relevant storms will not change significantly in the future. If there are significant changes and climate variability, it is assumed that these changes would be captured when integrating recent storm events into the analysis, such that the impacts of gradual climate change on PMP will be addressed, at least in part, by incorporating storm lists that are sufficiently detailed and up to date to represent the impacts of climate change on PMP.

Over the last few decades, studies have produced evidence that the climate at global to local scales has become nonstationary with the climate signals clearly showing an increase in ambient temperature. The U.S. Global Climate Change Research Program (USGCRP) *Climate Science Special Report* (USGCRP 2017) stated the following:

> The global, long-term, and unambiguous warming trend has continued during recent years. Since the last National Climate Assessment was published, 2014 became the warmest year on record globally; 2015 surpassed 2014 by a wide margin; and 2016 surpassed 2015. Sixteen of the warmest years on record for the globe occurred in the last 17 years.

Increasing air temperature has a direct implication for the air moisture holding capacity and the occurrence of extreme precipitation events. The USGCRP report stated that "extreme precipitation events are generally observed to increase in intensity by about 6% to 7% for each degree Celsius of temperature, as dictated by the Clausius-Clapeyron relation." The USGCRP report also stated that "[t]he frequency and intensity of heavy precipitation events are projected to continue to increase over the 21st century (*high confidence*)." The findings remained unchanged in the fourth National Climate Assessment (USGCRP 2018) that "based on evidence from climate model simulations and our fundamental understanding of the relationship of water vapor to temperature, *confidence is high* that extreme precipitation will increase in all regions of the United States," and "extreme precipitation events are projected to increase in a warming climate and may lead to more severe floods and greater risk of infrastructure failure in some regions."

The WMO defines PMP as being calculated "under modern meteorological conditions" and "with no allowance made for long-term climatic trends" (WMO 2009). Nevertheless, Chapter 1.8 of WMO (2009) indicated that extreme rainfall events would likely increase in the 21st century (owing to the overall increase in available moisture in a warming climate) and highlighted the need for careful examination of potential climate change effects on major PMP driving mechanisms such as moisture availability, depth-area curves, storm types, storm efficiency, and generalized rainfall depths.

The conventional PMP theory used in the HMRs and in SSPMP studies depends on the physical relationship between the amount of moisture in the atmosphere available to a storm and the efficiency of the storm to turn that moisture into rainfall. It stands to reason that a warming atmosphere may lead to increased moisture (PW). Through numerical modeling, some recent studies suggest the likely change of PMP in the future climatic conditions (e.g., Kunkel et al. 2013; Stratz and Hossain 2014; Klein et al. 2016; Rastogi et al. 2017). Statistically significant increasing trends were also found in some surface dewpoint observations (e.g., Kao et al. 2019) that would gradually change the estimate of dewpoint climatology and directly affect SSPMP estimation.

As suggested by various studies and evidence, future SSPMP studies should account for the effects of climate change, especially in the consideration of PW. Studies should provide details of how the effects of climate change are incorporated into the study, or alternatively, provide a justification as to why this information is not necessary for a specific site or watershed. In view of the long lifespan of NPPs and other critical infrastructure (including dams) and the current use of PMP in establishing design criteria, future SSPMP studies should address PMP changes related to projected climate change.

The NRC is enhancing its regulatory processes by developing and implementing a framework for ongoing assessment of natural hazards information, including information related to climate change, such as increased storm intensities. SECY-16-0144 describes the NRC's enhancements to the existing regulatory processes; these enhancements are referred to as the Process for the Ongoing Assessment of Natural Hazards Information (POANHI). The Commission approved this process, which uses a graded approach to proactively, routinely, and systematically seek, evaluate, and respond to new information on natural hazards, including climate change impacts on storm intensity, using the approved framework for the ongoing assessment of natural hazard information.

11 SUMMARY

This NUREG/KM report presents the NRC's lessons learned from the recent flood hazard re-evaluations at NPP sites performed in connection with the 2012 §50.54(f) reviews and a recent TR review. Specifically, this Knowledge Management NUREG identifies and explains the terminologies, theories, methods, and data sources used in historical and modern PMP studies. It also includes key considerations for developing and reviewing potential future SSPMP studies.

Since the development of the NOAA HMR-based PMP estimates from the 1950s to 1990s, technological advances have enabled more efficient data collection and processing, while improved meteorological understanding has refined how such data are used. While the HMRs periodically introduced new methods or procedures, much of the framework remained unchanged. SSPMP studies have maintained the use of a similar framework though introduction of some new data sources, calculation procedures, and methods. This report documents the current state of practice in SSPMP studies and the NRC staff knowledge gained through review. The approaches and methods described will continue to evolve in the future as technological and meteorological advances are made. Consequently, professional judgment will continue playing a key role in SSPMP development.

As noted in this report, several areas of the SSPMP development process involve considerable uncertainty and require some subjective professional judgment. The most significant areas of uncertainty include the following:

- storm DAD data and multicenter storm analysis
- storm transposition limit determination
- PW estimation and maximization based on dewpoint temperature
- terrain adjustment

While not discussed in detail in this report, precipitation measurement data are also subject to error and uncertainty. With precipitation measurement representing the base input used for SSPMP estimation, any error and uncertainty in such data propagate throughout the calculation process and directly affect SSPMP estimates. In addition, the observation longevity for storm-based PMP studies presents a key uncertainty because historical rainfall records are limited to approximately 150 years or (in many cases) less. The storm transposition, moisture maximization, and envelopment processes attempt to overcome this challenge, yet uncertainty remains as to how accurately SSPMP estimates meet the definition of a theoretical upper precipitation limit. In short, the SSPMP estimation process involves considerable uncertainty, yet the methods, data sources, and procedures used provide a defined framework for quantifying SSPMP.

For the purpose of long-term KM, the objective of this report is to summarize the NRC staff's current understanding of SSPMP estimation. By documenting this information and identifying key considerations, this NUREG/KM report aims to support the development and review of SSPMP estimates for NRC-regulated NPPs in the United States. This Knowledge Management NUREG report does not constitute guidance or invalidate any prior guidance documents or the studies conducted in accordance with the prior guidance.

While the NRC's SSPMP reviews to date have excluded NPP license amendment requests, SSPMP studies are likely to be included as a part of such licensing actions in the future. Consequently, this report may inform future NRC guidance regarding SSPMP development.

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Scott DeNeale, Shih-Chieh Kao, and David Watson (retired) are all employees at Oak Ridge National Laboratory

11. ABSTRACT (200 words or less)

The U.S. NRC reviewed many studies pertaining to site-specific probable maximum precipitation (SSPMP) calculated at U.S. nuclear power plants. As described in NRC guidance and hazard assessment-related documents, the NRC guides its licensees to use the NOAA hydrometeorological reports as an acceptable resource for estimating PMP for use in design-basis flood evelation. This NUREG/KM summarizes knowledge the NRC staff has developed over the course of the reviews based on the similarities and differences between the methodologies.

The SSPMP estimates were used as critical hydrologic modeling input in multiple submittals by licensees, such as those responding to the NRC's letter of March 12, 2012, under 10 CFR 50.54(f), requesting updated flooding hazard analyses and topical reports. Although the licensee's development and estimation of SSPMP studies generally followed processes similar to those in existing guidance, several different methods, data sources, assumptions, and procedures were used to obtain site-specific results.

This document helps the NRC maintain and preserve knowledge and derive lessons learned from the recent flood hazard re-evaluations. Specifically, this document (1) identifies terminologies, theories, methods, and lessons learned for SSPMP studies submitted to the NRC for review and (2) presents key considerations for developing and reviewing potential future SSPMP studies.

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