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NUREG/CR-7131

Review of Probable Maximum Precipitation Procedures and Databases Used to Develop Hydrometeorological Reports

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Review of Probable Maximum Precipitation Procedures and Databases Used to Develop Hydrometeorological Reports

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ABSTRACT

This report presents a review of existing Probable Maximum Precipitation (PMP) methodologies, data bases, and estimates within the United States. The major focus is on a review of generalized PMP estimates in the southeastern United States, in order to subsequently assess the adequacy of existing PMP estimates and the need for potentially updating the PMP estimates in this region. The main objectives of the review were to: (1) review PMP procedures and databases used to develop Hydrometeorological Reports (HMRs); (2) examine storm databases in the Southeast and document the evolution in PMP methodologies and estimates over time; and (3); summarize extreme storm research and PMP work done since HMR 51 was published, that is germane to PMP estimates in the Southeast. Most of the review was limited to describing existing, generalized PMP reports (HMRs) and existing data related to those reports, including HMRs 51-53, and HMR 55A. Subsequent HMRs were reviewed for their treatment of PMP in orographic regions, and to summarize changes in methodologies. Comparisons were made between storm data and procedures used in HMR 33 and HMR 51 for the southeastern U.S. case study region. Studies related to PMP and recent research on extreme storm estimation were briefly reviewed and summarized.

Essentially, PMP methods as applied in the HMRs, are static and can be updated. A brief review of recent literature indicated some key areas for improvement. Research in several areas (e.g., incorporation of WSR-88D radar data into a PMP storm catalog; and studies for scientific understanding of extreme rainfalls, storm rainfall studies and extreme rainfall probabilities using numerical weather prediction models) has been completed by other organizations. Radar rainfall estimates can be very useful in extreme storm processing and PMP estimation. Several investigators have utilized advanced, 3-dimensional atmospheric models to replicate observed extreme storms, simulate them, and investigate the precipitation and other ingredients for extreme rainfalls and floods. Thus improvements to PMP and extreme storm estimation practice can be made by utilizing results of these investigations and associated methodologies. Most of this research has yet to be assimilated into operational estimates of PMP.

There are readily-available probabilistic alternatives to PMP for assessments and designs of critical infrastructure. Several methods, such as regional precipitation frequency with L-Moments, have been utilized in probabilistic assessments of major infrastructure. These methods should be considered, along with improvements on extreme storm rainfall estimation in lieu of or including PMP.

FOREWORD

This report (NUREG/CR-7131) documents work sponsored by the U.S. Nuclear Regulatory Commission (NRC) as part of the RES project “Research to Develop Guidance on Probable Maximum Precipitation (PMP) Estimates for the eastern United States”. The original objective of the project was to provide the NRC with data and analyses to assess whether PMP estimates for the eastern United States contained in Hydrometeorological Report 51 (HMR 51) published by the National Oceanic and Atmospheric Administration (NOAA) in 1978, could be exceeded if information on more recent storms is considered. However, due to limited resources, the research focused on a case study region in the Carolinas[1]. The work and recommendations presented in this report will be considered by the NRC as it revises Regulatory Guide 1.59, “Design Basis Floods for Nuclear Power Plants”, which was last updated in 1978.

NUREG/CR-7131 reviews the procedures and databases that NOAA used to develop the HMRs for nine regions of the continental U.S., emphasizing HMR 51 PMP estimates in the Carolinas. The review also compared HMR 51’s procedures and data with those used in HMR 33 (published in 1956), which HMR 51 superseded. The review found that the procedures for developing PMP estimates varied somewhat from one HMR to another, but that overall, PMP methods as applied in the HMRs have not kept pace with advances in methods for estimating extreme precipitation. A review of recent literature indicated some key areas for improvement. The review also identified probabilistic alternatives to PMP for assessments and designs of critical infrastructure. The review recommended that NRC consider probabilistic methods as an acceptable approach to developing PMP estimates[2].

This report provides useful information that NRC will consider as it revises Regulatory Guide 1.59. The report does not make detailed, site-specific recommendations or draw conclusions regarding PMP estimates used for licensing of specific power plants. It would not be appropriate to draw conclusions about the adequacy of flood protection for existing plants based on the work presented in this report, since precipitation is only one aspect of flood hazard assessment. It should be noted that, as part of its overall response to the March 2011 Fukushima accident, the NRC has issued a request for information to all power reactor licensees and holders of construction permits under 10 CFR Part 50 on March 12, 2012. The March 12, 2012 50.54(f) letter includes a request that respondents reevaluate flooding hazards at nuclear power plant sites using updated flooding hazard information and present-day regulatory guidance and methodologies.

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[1] Reducing the project scope to focus on the Carolinas case study region does not compromise the applicability of the study. The case study region has experienced several very large precipitation events in recent years. Analysis of these storms provides a sufficient basis for assessing the possibility that recent storms can challenge the existing PMP estimates for other regions provided in the HMRs.

[2] Current regulatory guidance does not include specific criteria for using probabilistic approaches for flood hazard estimation, noting (at the time the guidance was issued) the lack of widely accepted procedures for accurately and objectively defining the exceedance probabilities of significant rare events. Development of probabilistic approaches is encouraged as data and procedures improve, and it is noted that they may be acceptable or even preferable in certain cases at specific sites.

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EXECUTIVE SUMMARY

A review of PMP methods and databases was conducted. The main objectives of the review were to: (1) review PMP procedures and databases used to develop HMRs; (2) examine storm databases in the Southeast and document the evolution in PMP methodologies and estimates over time; and (3). summarize extreme storm research and PMP work done since HMR 51 was published, that is germane to PMP estimates in the Southeast. Most of the review was limited to describing existing, generalized PMP reports (HMRs) and existing data related to those reports, including HMRs 51-53. Subsequent HMRs were reviewed for their treatment of PMP in orographic regions, and to summarize changes in methodologies. Comparisons were made between storm data and procedures used in HMR 33 and HMR 51 for the southeastern U.S. case study region. Studies related to PMP and recent research on extreme storm estimation were briefly reviewed and summarized. Based on this review, we provide the following main conclusions.

The PMP DAD storm data base and related data bases are outdated. The USACE (1973) data base, the basis for HMR 51, is no longer maintained. Updates to extreme storm DAD data bases were made over time for individual HMRs (55A, 57 and 59). These data bases are also not being updated. There are relatively poor records and documentation in reports and files on individual extreme storms. Dewpoint climatology information is outdated and data sources for coastal areas have changed from land-based dewpoints (HMR 51) to SST estimates (HMRs 57 and 59). Precipitation frequency estimates, used for PMP comparisons (TP-40) and as base maps in orographic areas (NOAA Atlas 2), are outdated. These information sources are being updated with NOAA Atlas 14, with a much finer spatial resolution and improved methodology. Newer data sets, including radar-based precipitation estimates are available and the authors recommend that they be used in extreme storm processing and PMP estimation, thereby fulfilling the initial ideas presented in EPRI (1993b).

Generalized PMP reports in the eastern US, from HMR 23 to HMR 33 to HMR 51, were continually updated and improved. Updates in this region have since ceased. There was approximately a 30% increase in PMP for certain area sizes and durations in the Southeast over about a 30-year period (HMR 23 to HMR 51). The major change in PMP estimates from HMR 33 to HMR 51 was due to one storm (Yankeetown, 1950) and larger transposition regions. This one storm controls most PMP estimates in the Carolinas. A substantial amount of DAD data was gathered to expand and examine existing storms with centers in the Carolinas.

In terms of PMP methods, little has changed over the past 25 years since WMO (1986), as the recent WMO (2009) report includes the same base methodologies. As HMR 51 did not include orographic factors; limited PMP estimates were provided over the Appalachians and western parts of the region. Orographic methods, including storm separation, were developed in HMR 55A and subsequently documented in WMO (1986). These methods were used in HMR 57 and HMR 59, but the concept of storm separation has not been critically reviewed. There are several limitations noted in the western HMRs on providing space-time estimates of PMP, especially within orographic areas. Unlike the procedures in HMR 52, there are no methods for spatially and temporally distributing PMP over a watershed for locations other than the eastern United States.

Essentially, PMP methods as applied in the HMRs, are static and have not kept pace with the state of practice in meteorological observation and storm modeling. A brief review of recent literature indicated some key areas for improvement. The National Research Council (NRC 1994) recommended major research in several areas, including: incorporation of WSR-88D radar data into a PMP storm catalog; and studies for scientific understanding of extreme rainfalls, storm rainfall studies and extreme rainfall probabilities using numerical weather prediction models. Much research has been completed on these topics. As mentioned earlier, it is clear that radar rainfall estimates need to be used in extreme storm processing and PMP estimation. Several investigators have utilized advanced, 3D atmospheric models, including RAMS, MM5 and WRF, to replicate observed extreme storms, simulate them, and investigate the precipitation and other ingredients for extreme rainfalls and floods. Ready improvements to PMP and extreme storm estimation practice can be made by utilizing results of these investigations and associated methodologies. Most of this research has yet to be assimilated into operational estimates of PMP; thus there are a host of opportunities to make substantial improvements to existing PMP methods and data utilized. Key improvements based on numerical modeling, inclusion of uncertainties, finer spatial discretization, incorporation of local climate effects, use of climate variability/change information, and probabilistic estimates should be considered.

There are readily-available probabilistic alternatives to PMP for assessments and designs of critical infrastructure. Several methods, including regional precipitation frequency with L-Moments, ARR concepts, and stochastic storm transposition, have been utilized in probabilistic assessments of major infrastructure. These methods can be considered, along with improvements on extreme storm rainfall estimation, in lieu of or including PMP.

ABBREVIATIONS AND ACRONYMS

AEP	Annual Exceedance Probability
ARR	Australian Rainfall-Runoff
COL	Combined Operating License
DAD	Depth Area Duration
EPRI	Electric Power Research Institute
ESP	Early Site Permit
FI	Flood Index
FRT	extratropical cyclone near a front
GCM	global climate model
GEV	Generalized Extreme Value
GHG	greenhouse gases
GISS	(NASA) Goddard Institute for Space Studies
HMR	Hydrometeorological Report
IPCC	Intergovernmental Panel on Climate Change
MCC	mesoscale convective complex
MCS	mesoscale convective system
MM5	Penn State Mesoscale Model
MMF	multiscale modeling framework
NA	North Atlantic
NARR	North American Regional Reanalysis
NAS	National Academy of Sciences
NASEM	National Academies of Science, Engineering, and Medicine
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NLCD	National Land Cover Database
NRC	U.S. Nuclear Regulatory Commission
NRC	National Research Council
NWS	National Weather Service
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
RAMS	Regional Atmospheric Modeling System
SA	South Atlantic
USACE	U.S. Army Corps of Engineers or Corps

1 INTRODUCTION

Probable Maximum Precipitation (PMP) is a widely-used concept in the design and assessment of critical infrastructure such as dams and nuclear facilities. This report presents a review of existing PMP methodologies, data bases, and estimates within the United States. The major focus is on a review of generalized PMP estimates in the southeastern United States, in order to assess the adequacy of existing PMP estimates and the potential need for updating the PMP estimates in this region.

1.1 Authorization

This work was completed by the Bureau of Reclamation (Reclamation) for the Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research (RES), via an Interagency Agreement. The work was performed under NRC Agreement RES-08-127, Job Code N6570. A case study region, including the states of North and South Carolina, was used. This report documents work from Task 1 of the NRC project, including a review of PMP methods and data bases. Caldwell et al. (2011a) present new storm data and analysis, as part of Task 2 of the agreement. Task 3 of the project, including a synthesis of new storm data, PMP results and uncertainties, is described in Caldwell et al. (2011b).

1.2 Background

The Nuclear Regulatory Commission (NRC) requested assistance in potentially improving estimates of PMP in the eastern United States. Probable Maximum Precipitation is the key factor in developing Probable Maximum Floods (PMFs). PMFs are needed for licensing and providing oversight of nuclear power plants.

NRC General Design Criterion 2, "*Design Bases for Protection Against Natural Phenomena*," of Appendix A, "*General Design Criteria for Nuclear Power Plants*," to 10 CFR Part 50, "*Domestic Licensing of Production and Utilization Facilities*," requires, in part, that structures, systems, and components 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 safety functions. Criterion 2 also requires that design bases for these structures, systems, and components reflect: (1) 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; (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena; and (3) the importance of the safety functions to be performed. Paragraphs 100.10(c) and 100.20 (c) of 10 CFR Part 100, "Factors to be considered when evaluating sites," require that physical characteristics of the site, including seismology, meteorology, geology, and hydrology, be taken into account in determining the acceptability of a site for a nuclear power reactor. Paragraph 100.20(c) (3) states that "The maximum probable flood along with the potential for seismically induced floods discussed in 100.23 (d) (3) must be estimated using historical data." Paragraph 100.23 (d) which focuses on "Geologic and seismic siting criteria" requires investigations and detailed study of seismically induced floods and water waves. Therefore, applicants for nuclear reactor Combined Licenses (COLs) must demonstrate the ability of their proposed facilities to withstand the Probable Maximum Flood, among other hazards. The demonstration is assessed by the NRC through internal technical reviews and a public licensing process. Some further details on NRC design criteria are described in NRC (1977) and Prasad et al. (2011).

A key input to the determination of the PMF for a particular reactor site is the PMP for the hydrologic unit within which the plant is to be located (Prasad et al., 2011). The National Oceanic and Atmospheric Administration's National Weather Service (NWS) has published a series of Hydrometeorological Reports (HMRs) (Table 1-1), that provide “generalized” PMP estimates over large regions of the United States (Figure 1-1). These HMRs are used by various Federal and State agencies, including the NRC, as a source to estimate PMP for locations of interest in the United States. The most recent HMR was completed in 1999 for estimating PMP in California (Table 1-1).

For those regions of the United States where most new reactors are expected to be located (east of 105 degrees west longitude), the data and information that form the technical basis for these reports (HMR 51) have not been updated for over thirty years (Table 1-1). The NRC licensing staff who are reviewing siting and design issues for Early Site Permits (ESP) and COLs need to review relevant historical data collected since publication of the HMRs, and the procedures for using these data to estimate the PMP for appropriate locations. The reviews contained in this report focus on a southeastern U.S. case study region consisting of North and South Carolina.

Table 1-1 Available NWS generalized HMR and HYDRO PMP reports*

Report No.	Title	Publication Date
HMR 23	Generalized Estimates of Maximum Possible Precipitation Over the United States East of the 105th Meridian for Areas from 10, 200 and 500 Square Miles	1947
HMR 33	Seasonal Variation the Probable Maximum Precipitation East of the 105th Meridian for Areas from 10 to 1000 Square Miles and Durations of 6, 12, 24 and 48 Hours.	1956
HMR 41	Probable Maximum and TVA Precipitation over the Tennessee River Basin above Chattanooga	1965
HMR 48	Probable Maximum Precipitation and Snowmelt Criteria For Red River of the North Above Pembina, and Souris River Above Minot, North Dakota	1973
HMR 49	Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages	1977
HMR 51	Probable Maximum Precipitation Estimates, United States East of the 105th Meridian	1978
HMR 52	Application of Probable Maximum Precipitation Estimates - United States East of the 105th Meridian	1982
HMR 53	Seasonal Variation of 10-Square-Mile Probable Maximum Precipitation Estimates, United States East of the 105th Meridian	1980
HMR 55A	Probable Maximum Precipitation Estimates - United States Between the Continental Divide and the 103rd Meridian	1988
HMR 56	Probable Maximum and TVA Precipitation Estimates With Areal Distribution for Tennessee River Drainages Less Than 3,000 Mi^2 in Area	1986

HMR 57	Probable Maximum Precipitation - Pacific Northwest States. Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages	1994
HMR 58	Probable Maximum Precipitation for California - Calculation Procedures	1998
HMR 59	Probable Maximum Precipitation for California	1999
HYDRO 39	Probable Maximum Precipitation for the Upper Deerfield River Drainage Massachusetts/Vermont	1984
HYDRO 41	Probable Maximum Precipitation Estimates for the Drainage Above Dewey Dam, Johns Creek, Kentucky	1985
*** Reports (pdf) are available at: http://www.weather.gov/oh/hdsc/studies/pmp.html#PMP_documents**		

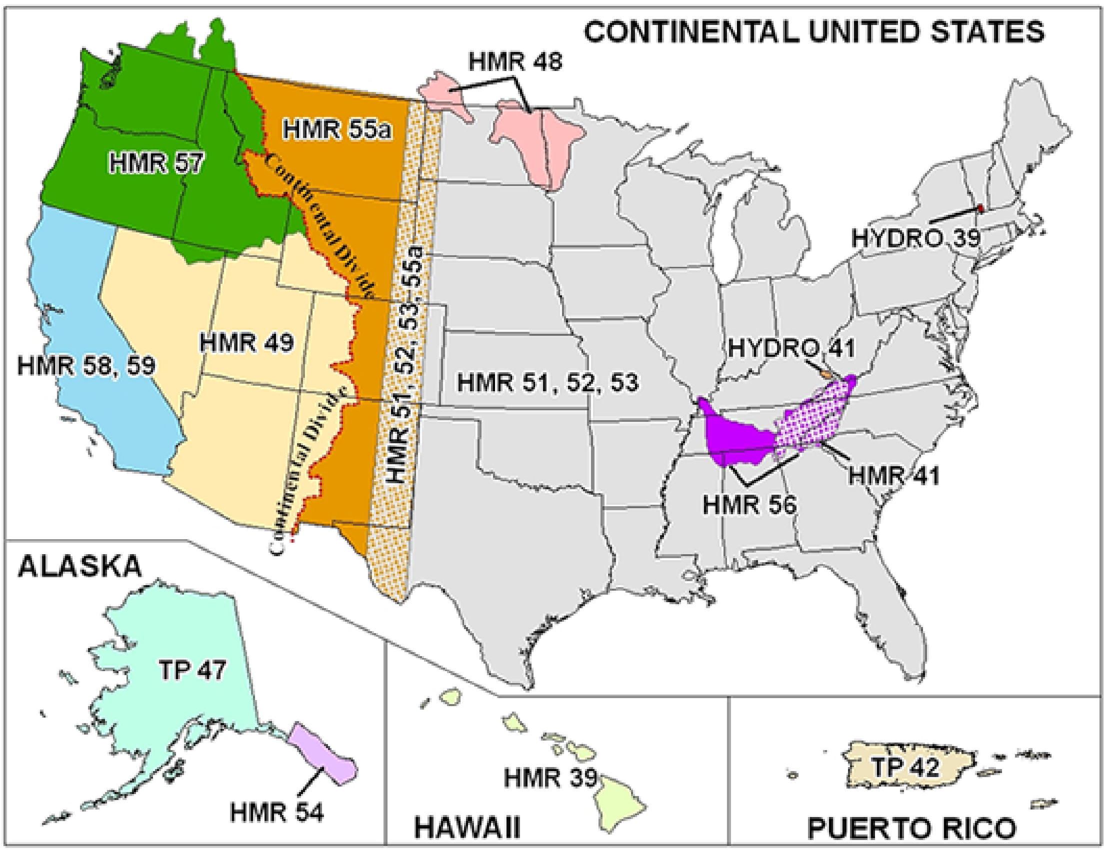


Figure 1-1 Regional coverages of generalized PMP reports (HMRs) in the United States (source: http://www.weather.gov/oh/hdsc/studies/pmp.html)

1.3 Objectives

The focus of this work is on investigating PMP estimates for the southeastern United States, with a specific emphasis limited to North Carolina and South Carolina. The major objectives of the work are as follows.

1. Review PMP procedures and databases used to develop HMRs.

2. Examine storm databases in the Southeast and document the evolution in PMP methodologies and estimates over time.

3. Summarize extreme storm research and PMP work done since HMR 51 was published, that is germane to PMP estimates in the Southeast.

The emphasis is limited to existing, generalized PMP reports (HMRs) and existing data related to those reports. The primary HMRs that are reviewed include HMRs 51-53. HMR 55A and subsequent reports are reviewed for their treatment of PMP in orographic regions, as well as differences in methodologies.
Because the guidelines used by the NRC for the eastern United States (NRC, 1977) were originally developed using HMR 33, preliminary comparisons are made between procedures used in HMR 33 and HMRs 51-52 for the southeastern U.S. case study region. Examples of these include coverage area, transposition limits, orographic regions, treatment of areas smaller than 1,000 mi^2 as well as assumptions made about point vs. 1 mi^2 and 10 mi^2 precipitation.

Storm databases that are used in HMRs 33 and 51 for the areas that are applicable to the southeastern United States are examined and summarized. Possible database limitations on duration, area size, geographic distribution, and number of controlling storms (and locations), are also described.

1.4 Acknowledgments

Several individuals and agencies provided assistance in this work. Mr. Verne Leverson, Reclamation Meteorologist, partially contributed to this report prior to his retirement. Geoff Bonnin and Dr. Sanja Perica at the National Weather Service, Hydrometeorological Design Studies Center (NWS-HDSC) graciously shared storm data, provided access to NWS-HDSC files with background information on the HMRs, and provided web hosting of electronic files from HMR 51 that were generated as part of this work. Dr. Ed Tomlinson, Applied Weather Associates, provided fruitful and thought-provoking discussions on data, and supplied information from NWS-HDSC on individual storm transposition limits. Mr. Louis C. Schreiner, retired Reclamation Meteorologist/Group Manager and lead author of HMR 51, shared discussions and insights on PMP methods. Other individuals and collaborators that provided assistance are noted in the companion reports to this work (Caldwell et al., 2011a; Caldwell et al., 2011b).

2 EXISTING PMP METHODOLOGY

Current design criteria for nuclear power plants and dams require that the structures withstand and uphold their safety functionality during severe natural phenomena, including floods, earthquakes, and tsunamis. The Probable Maximum Flood is a deterministic, upper limit (maximum) flood estimate that is conventionally used as one design criterion (FEMA, 1998; Prasad et al., 2011). Regarding floods, the preeminent determinant in estimating the PMF for a watershed or drainage basin is the Probable Maximum Precipitation. PMP is defined as "theoretically the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year" (Hansen et al., 1982 p. 2). An operational definition may be that PMP is "the steps followed by hydrometeorologists in arriving at the answers supplied to engineers for hydrological design purposes" (WMO, 1973; WMO, 1986).

The concepts behind PMP in the United States date back to the late 1930s (Myers, 1967a; Stallings et al., 1986; Hansen, 1987). The term PMP was originally defined in the 1950s (NRC, 1983; NRC, 1985). Myers (1967a) and Hansen (1987) provide overviews of the evolution of PMP methods in the United States. Stallings et al. (1986) describe the cooperative Federal efforts on generalized PMP methods and reports. Overall, there have been modest changes to the definition and methodology of PMP since the mid 1960s, including a PMP applications manual for the eastern United States (Hansen et al., 1982) and orographic precipitation (storm separation concepts) in the western United States (Hansen et al., 1988). Hansen (1987) summarizes these advances in PMP that occurred through the mid-1980s. Since about 1988, there have been essentially no changes in generalized PMP methodology within the United States. Some details on the HMRs completed since 1988 and recent PMP-related research are presented in Sections 4 and 6, respectively.

The following subsections describe the main methodology that is currently used to estimate generalized PMP. Key concepts include: depth-area duration analysis of large storms; storm maximization; storm transposition; and envelopment. In-depth technical details of PMP concepts are presented in WMO (1986), Hansen et al. (1988) and WMO (2009). PMP-related concepts on generalized and site-specific PMP application scales, orographic areas, and spatial and temporal distributions are briefly described.

2.1 Depth-Area Duration Analysis

The initial step, prior to estimating PMP, is to perform a depth-area-duration (DAD) analysis of precipitation of the major storms of record within the region. The objective of a DAD analysis is to convert temporally and spatially discrete precipitation measurements to volumetric values through interpolation and integration over the storm area. This is typically completed in two phases: Part I consists of the compilation of basic data and the construction of mass curves of rainfall; and Part II consists of determining the depth-area-duration relationships. Full technical details on DAD analysis may be found in the 'Manual for Depth-Area-Duration Analysis of Storm Precipitation' (USWB, 1946), and in the follow-up manual of the same title (WMO, 1969a). The WMO DAD manual describes a "standard DAD method" that uses the same methods in USWB (1946), and a "computer method" that describes a computer implementation of DAD methods. Notably, there has been little change in DAD analysis techniques since the 1960s, other than some periodic computer implementations of DAD methods (e.g., Stodt, 1995) following USWB (1946) techniques.

The Part I phase typically involves field work. During this phase, the areal extent and duration of the storm is estimated by examining rainfall amounts reported in published records (e.g. Monthly Record of Observations provided by first-order stations, Monthly report of river rainfall stations, and Cooperative observers' meteorological records) and through bucket surveys, where bucket surveys are field investigations conducted to examine both recording and non-recording rain gauge data. During the bucket survey process, a meteorologist or hydrologist (historically from the Corps of Engineers, Bureau of Reclamation, or National Weather Service) typically would visit the storm-afflicted region to assess damage, converse with witnesses of the storm, collect information and evaluate the quality of the non-recording rain gauges. In most cases, 'non-recording rain gauges' refer to a variety of apparatuses in which the rain was collected, from horse troughs to assorted beverage containers to, not surprisingly, buckets. For example, the September 3-7, 1950 Hurricane Easy storm (SA 5-8) included a 45.2-inch maximum amount (Yankeetown No. 1, point 58) from an unofficial bucket-survey measurement from a case of empty Pepsi-Cola bottles (USACE, 1953).

Several authors clearly state the importance of bucket surveys (USWB, 1946; WMO, 1969a; Shipe and Riedel, 1976). Ho and Riedel (1980) acknowledge the importance of bucket surveys by stating that the probability is significantly low for the extreme amount of precipitation from a storm to fall exactly upon an official rain gauge; in fact, virtually all of the extreme precipitation measurements have emerged from the network of unofficial gauges. Ho and Riedel (1980) also warn that precautions should be taken (i.e. checks against the unofficial gauges to observations and weather patterns) to be sure that the measurements are indeed reasonable.

The product of the bucket surveys and other gage-based rainfall data are plots of the accumulated precipitation as a function of time for each rain gauge site, referred to as mass curves. As the rain gauge measurements are temporally discrete in nature, the mass curves provide the temporal interpolation between the measurements (i.e. display an estimated yet continuous history of the accumulated precipitation at a specific locale). Figure 2-1 shows an example of a mass curve plot. Technical details on mass curves used in DAD computations are presented in Shands and Brancato (1946).

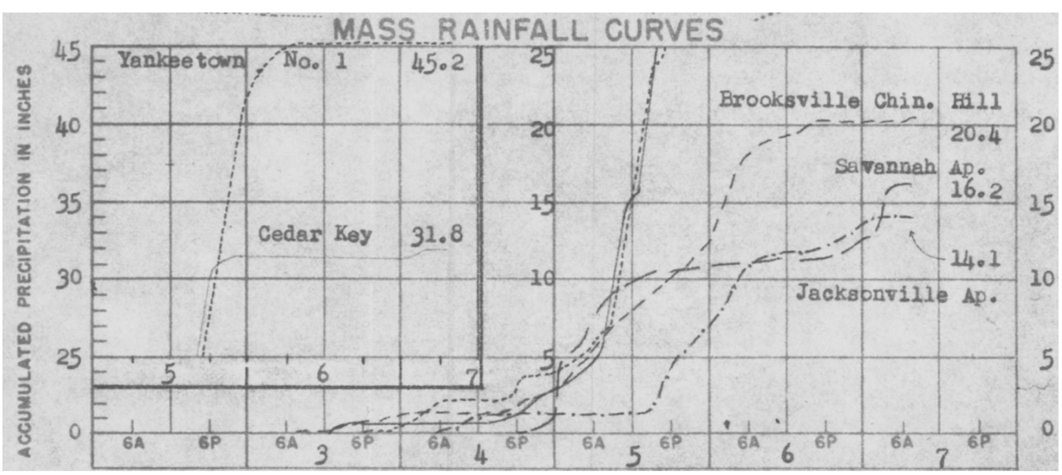


Figure 2-1 Example of a final (Part II) mass curve plot for the September 3-7, 1950 (Hurricane Easy) storm (SA 5-8)

In Part II of the DAD analysis, the above collected data is assembled together in an isohyetal map, plot of the average mass curves, and a maximum depth-area-duration table. Isohyets are lines of equal amounts of precipitation, thus the isohyetal map depicts contours of the final precipitation amounts associated with the storm in question (i.e. the depth-area interpolation portion of the study, see Figure 2-2 for an example of an isohyetal map). The map is constructed for the storm total period; Thiessen polygons are used to spatially interpolate rainfall from mass curves (USWB, 1946). From this map, various rainfall centers or “zones” may be identified or constructed. Periodically, multiple rainfall centers are observed, and the storm area may be split into zones to conform to the multiple centers for easier investigation. Usually, these divisions are created for mere convenience, but occasionally a large storm region, though producing contemporaneous precipitation, does not have similar topographical or meteorological influences throughout its entire domain and, as such, is partitioned. In this situation, it is desirable to preserve the division of the storm region and to consider each zone independently for the remainder of the analysis. A plot of the average mass curve for the entire extent of the storm area is next produced; to accomplish this, the divisions are combined, unless the split is determined to be significant, as described above. With the depth-area (isohyetal map) and depth-duration (mass curves) interpolations complete, a final DAD table is generated.

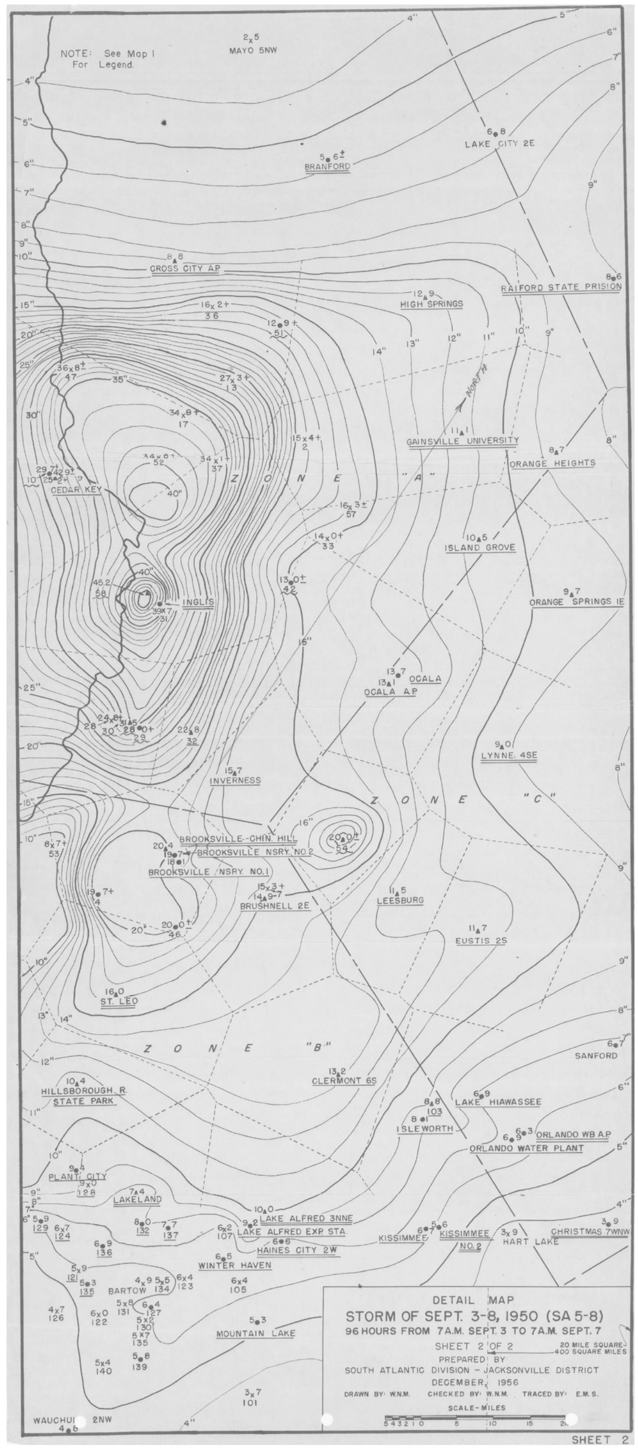
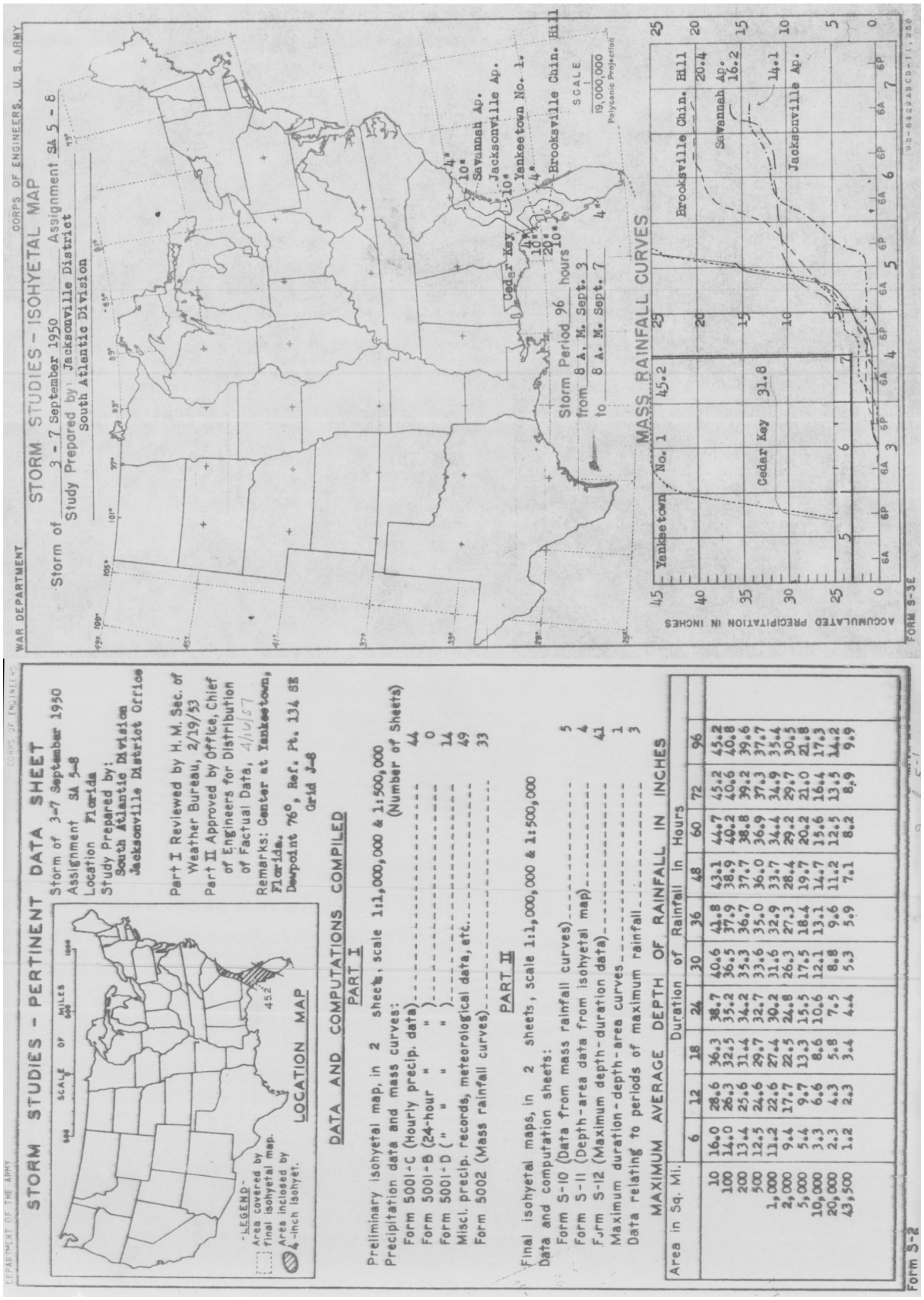


Figure 2-2 Example of a final (Part II) isohyetal map for the September 3-7, 1950 Hurricane Easy storm (SA 5-8), showing the detail within Zones A-C. Mass curves were estimated at stations with underlined names; double-underlined station names indicate recording stations. Bucket survey amounts indicated by dots or triangles, underlain by '~', with Yankeetown No. 1 (45.2 in) shown as point 58. Thiessen polygons are shown as thin dashed lines.

The final result of the DAD analysis may typically be found on ‘storm studies - pertinent data sheets’ from the U.S. Army Corps of Engineers on forms S-2 and S-3E. An example is shown in Figure 2-3. This front and back sheet summarizes the Part I and Part II studies, presents the DAD table, mass rainfall curves, and the isohyetal map. The DAD table typically presents information for 6-hour duration accumulations for fixed area sizes, ranging from 10 mi^2 to over 20,000 mi^2, depending on storm area. For the most recent HMRs, DAD information for some storms included 1 hour, 1 mi^2 amounts (Hansen et al., 1994; Corrigan et al., 1999).

The pertinent data sheets from many of the major storms of record within the United States have been assembled into a single catalog, the U.S. Army Corps of Engineers Storm Catalog (USACE, 1973), for easy reference. The catalog contains storms from about 1889 through 1972 in the eastern U.S. The original bound presentations of the Part I and Part II analyses are stored within various government agencies including the U.S. Army Corps of Engineers District offices, the National Weather Service Hydrometeorological Design Studies Center in Silver Spring, MD, and the Bureau of Reclamation, Denver, CO. However, these files are inconsistent, incomplete, in deteriorating condition, and only available in paper format.

The DAD methods in USWB (1946) have been used in HMRs 51, 55A, 57 and 59 to process selected individual storms rainfall amounts. Computer implementations of DAD methods started with HMR 55A (Hansen et al., 1988), culminating in a “Ministorm” set of programs (Stodt, 1995) used to process storms for HMR 57 (Hansen et al., 1994). The NWS subsequently used GRASS GIS methods and other programs to estimate DAD for storms in California for HMR 59 (Corrigan et al., 1999). Importantly, DAD methods utilized to date for the HMRs have not kept pace with advances in gridded (radar) data, spatial interpolation methods, improvements in temporal and spatial statistics, or advances in GIS software. Advances in extreme storm analysis methods that have been made outside the HMR process are described in Section 6, including numerical modeling and radar studies.



STORM STUDIES - PERTINENT DATA SHEET

Storm of 3-7 September 1950
Assignment SA 5-8
Location Florida
Study Prepared by:
South Atlantic Division
Jacksonville District Office

Part I Reviewed by H. M. Sec. of Weather Bureau, 2/19/53
Part II Approved by Office, Chief of Engineers for Distribution of Factual Data, 4/16/57
Remarks: Center at Yankeetown, Florida.
Dewpoint 76°, Ref. Pt. 134 SE Grid J-8

LOCATION MAP

-LEGEND-
Area covered by final isohyetal map.
Area inclosed by 4-inch isohyet.

DATA AND COMPUTATIONS COMPILED

PART I

Preliminary isohyetal map, in 2 sheets, scale 1:1,000,000 & 1:500,000
Precipitation data and mass curves: (Number of Sheets)
Form 5001-C (Hourly precip. data) 44
Form 5001-B (24-hour " ") 0
Form 5001-D (" " ") 14
Miscl. precip. records, meteorological data, etc. 49
Form 5002 (Mass rainfall curves) 33

PART II

Final isohyetal maps, in 2 sheets, scale 1:1,000,000 & 1:500,000
Data and computation sheets:
Form S-10 (Data from mass rainfall curves) 5
Form S-11 (Depth-area data from isohyetal map) 4
Form S-12 (Maximum depth-duration data) 41
Maximum duration-depth-area curves 1
Data relating to periods of maximum rainfall 3

MAXIMUM AVERAGE DEPTH OF RAINFALL IN INCHES

Area in Sq. Mi.	Duration of Rainfall in Hours									
	6	12	18	24	30	36	48	60	72	96
10	16.0	28.6	36.3	38.7	40.6	41.8	43.1	44.7	45.2	45.2
100	14.0	26.3	32.5	35.2	36.5	37.9	38.9	40.2	40.6	40.8
200	13.4	25.6	31.4	34.2	35.3	36.7	37.7	38.8	39.2	39.6
500	12.5	24.6	29.7	32.7	33.6	35.0	36.0	36.9	37.3	37.7
1,000	11.2	22.6	27.4	30.2	31.6	32.9	33.7	34.4	34.9	35.4
2,000	9.4	17.7	22.5	24.8	26.3	27.3	28.4	29.2	29.7	30.5
5,000	5.4	9.7	13.3	15.5	17.5	18.4	19.7	20.2	21.0	21.8
10,000	3.3	6.6	8.6	10.6	12.1	13.1	14.7	15.6	16.4	17.3
20,000	2.3	4.3	5.8	7.5	8.8	9.6	11.2	12.5	13.5	14.2
43,500	1.2	2.3	3.4	4.4	5.3	5.9	7.1	8.2	8.9	9.9

Form 5-2

STORM STUDIES - ISOHYETAL MAP

Storm of 3 - 7 September 1950 Assignment SA 5 - 8
Study Prepared by: Jacksonville District
South Atlantic Division

Storm Period 96 hours
from 8 A. M. Sept. 3
to 8 A. M. Sept. 7

Figure 2-3 Example pertinent data sheet for the September 3-7, 1950 Hurricane Easy storm (SA 5-8)

2.2 Storm Maximization

The DAD analysis is only an examination of an observed storm; there are additional steps before estimating PMP for an area or region, including maximization of the observed storms. Moisture maximization is increasing storm rainfall depths for the location and season, for higher atmospheric moisture than was available in the actual storm (Ho and Riedel, 1980). It is theorized that the amount of precipitation produced by a storm is controlled by the quantity of moisture that is available and the atmospheric process that initiates the storm convection, where the processes to initiate convection could be any of the following: atmospheric convergence, orographic lifting, frontal systems, and free convection (WMO, 1986; WMO, 2009). It is always assumed that the initiating process be at its greatest potential. The available moisture, however, may be increased to match the maximum moisture conditions observed for the storm region. To accomplish this, the following expression is used:

$$P_a = P_o \frac{W_{p,a}}{W_{p,o}} \qquad (1)$$

where P_a is the precipitation with maximized moisture, P_o is the observed precipitation, $W_{p,a}$ is the maximum precipitable water for the storm reference location (in place), and $W_{p,o}$ is the observed precipitable water. From this equation, it is apparent that the moisture within the atmosphere is expressed in terms of precipitable water. As this variable cannot be physically measured, it is calculated from a measurable parameter, surface dewpoint temperature. Thus to calculate $W_{p,o}$, a representative dewpoint value is selected in the area of moisture inflow for the storm, adjusted pseudoadiabatically to 1000 mb with moisture supplied so as to keep the parcel saturated, and assumed to correspond to a saturated atmosphere. The moisture profile can next be integrated to compute the representative precipitable water value. To compute the maximum precipitable water amount, $W_{p,a}$, the greatest 12-hour persisting dewpoint, at the same location as the storm representative dewpoint and at 15 days into the warm season (for a higher dewpoint), is found (WMO, 1986; WMO, 2009). Other representative dewpoints such as 6-hour persisting or 12-hour, 100-year have sometimes been used (EPRI, 1993a). Selecting the dewpoint temperature that persisted for 12 hours reduces the possibility of an incorrect hourly observation. Following, this maximum dewpoint value, like the storm representative dewpoint temperature, is adjusted pseudoadiabatically to 1000 mb and assumed to correspond to a saturated atmosphere. The maximum precipitable water is found by integrating over the subsequent moisture profile. The resultant precipitation, P_a, is the initial PMP estimate for the storm area at that location. The estimate is then adjusted as needed for elevation or intervening barriers (WMO, 2009). In certain cases, storm total maximization adjustments may be constrained to some upper limit, such as 150 percent of observed precipitation (Schreiner and Riedel, 1978).

Such moisture maximization analyses as described above are confined to the areal extent of the observed storms; there are great expanses between storms that lack such studies and therefore lack PMP values. To remedy this, storm transposition and envelopment techniques are employed. The PMP estimates for several storms within a region are then combined and modified by transposition and envelopment.

2.3 Storm Transposition

Storm transposition means relocating isohyetal patterns of storm precipitation within a region that is homogeneous relative to terrain and meteorological factors important to the particular storm rainfall under concern (Schreiner and Riedel, 1978). Transposition is performed under the assumption that the major storms of record could have occurred anywhere within an area of homogeneous meteorology and topography. This postulation thus allows for the relocation of observed storm events to any place within a homogeneous region and for the computation of PMP for that region using the observed storm data. Mathematically, storm transposition is described as (Cudworth, 1989):

$$P_{a,t} = P_o \left(\frac{W_{p,a}}{W_{p,o}} \right) \left(\frac{W_{p,t}}{W_{p,a}} \right) \qquad (2)$$

where $P_{a,t}$ is the adjusted, moisture-maximized precipitation amount in the transposed location, P_o is the observed precipitation, $W_{p,t}$ is the value of maximum precipitable water in the transposed location (region), $W_{p,a}$ is the maximum precipitable water for the storm reference location (in place), and $W_{p,o}$ is the maximum precipitable water in the region where the storm was observed. This is the equation for moisture adjustment (1) multiplied by the ratio of maximum precipitable water in the region of transposition to the maximum value for precipitable water in the observed storm region. It may be reduced to:

$$P_{a,t} = P_o \left(\frac{W_{p,t}}{W_{p,o}} \right) \qquad (3)$$

This process is typically referred to as explicit transposition. Each individual storm is examined, and transposition limits are estimated. Explicit transposition limits are the outer boundaries of a region where a storm may be transposed with relatively minor adjustments to observed rainfall amounts (WMO, 1986). An example transposition limit estimate is shown in Figure 2-4 for a tropical storm. A standard convention is to apply distance from coast transposition adjustments for tropical storm rainfall (Schreiner and Riedel, 1978). From the above equations, it is apparent that the only adjustment made to the observed storm during transposition is to the available moisture. If the transposition is such that the storm is moved closer to the source of moisture, the calculation will result in increased precipitation, or a decreased amount if moved further from the moisture source. Furthermore, any effects due to a change in elevation are accounted for as the moisture is adjusted to the maximum of the region of transposition (i.e. to the maximum precipitation associated with the different elevation) (WMO, 1986).

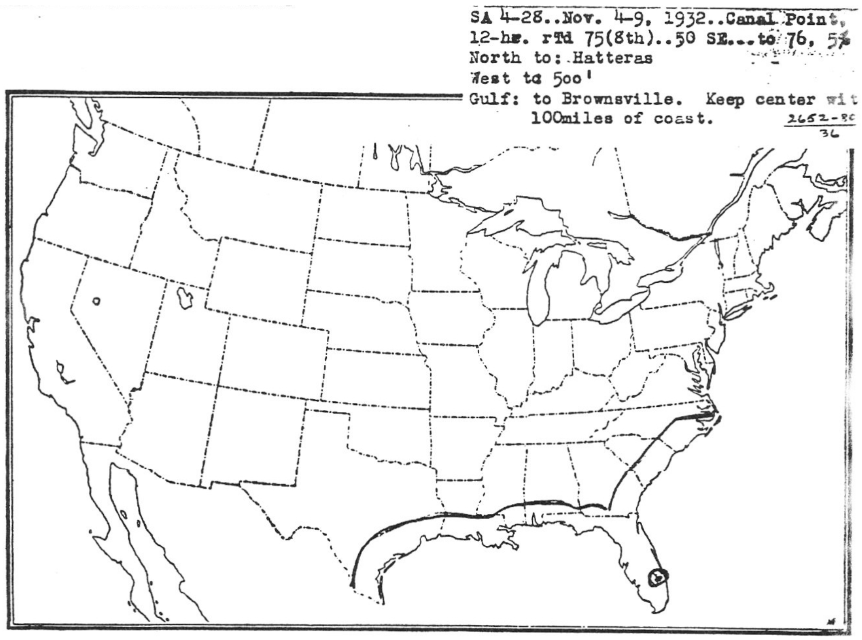


Figure 2-4 Example transposition limit estimate for the November 4-9, 1932 Canal Point, Florida storm (SA 4-28). Storm center is shown as a dot; transposition region is shown as solid line. (source: NWS HDSC files)

Since the above procedure, known as explicit transposition, may only be applied to areas homogeneous to the observed storm region, there may exist pockets between and among the homogeneous areas that do not qualify for the above transposition calculations. Yet, as atmospheric discontinuities do not exist in nature, these pockets need to be considered. Usually, the pockets can be explained by meteorological influences or the topography of the area, and thus adjusted accordingly, but in some instances, the rationale for the discontinuity is ambiguous. To address these cases, implicit transposition, a method of extrapolation and extension between the explicit transposition zones, is applied (Schreiner and Riedel, 1978; WMO, 1986). Additional details on storm transposition concepts and examples are in Myers (1966), WMO (1969b) and WMO (1986).

2.4 <u>Envelopment</u>

Envelopment continues the theme of applying PMP calculations outside of the random and erratic areal extents of observed storms; there are regions that persist without a PMP value in spite of utilizing maximization and transposition techniques. Maximization and transposition of major storms typically set the very lowest value PMP at each grid point (Ho and Riedel, 1980). Envelopment is a smoothing tool that encapsulates the areas without PMP values by connecting regions of like PMP to one another, and selecting the largest values from any data set (WMO, 1986). Envelopment establishes consistency throughout the area of study and alleviates anomalies (Cudworth, 1989), so that the effects of limited number of storms can be reduced. Envelopment is typically performed within various durations, to account for regional effects, and seasonal estimates (Ho and Riedel, 1980; WMO, 1986; Corrigan et al., 1999), so that generalized PMP estimates are consistent throughout the region. An example of depth-area envelopment is shown in Figure 2-5; other examples are given in WMO (1986).

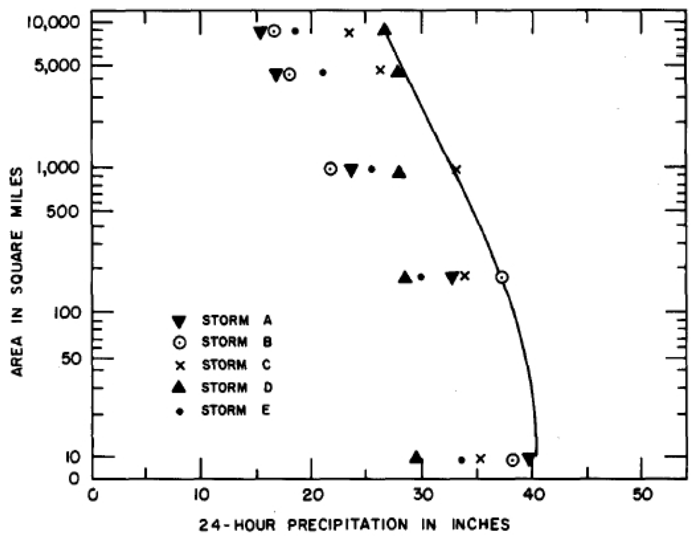


Figure 2-5 Example depth-area envelope of transposed, maximized 24-hour precipitation (Cudworth, 1989)

2.5 Additional PMP Concepts

In addition to maximization, transposition, and envelopment, there are several other PMP concepts that are important. These include PMP estimate scales, orographics, and applications to watersheds.

2.5.1 Generalized, Regional and Site-Specific PMP Scales

PMP estimates are made at three typical area scales: generalized, regional and site-specific scales. Generalized estimates typically refer to PMP over very large regions. In the United States, generalized PMP estimates are provided for the following areas (Figure 1-1; Table 1-1): eastern U.S. (HMR 51); Rocky Mountains east of the continental divide (HMR 55A); Great Basin and southwest – Colorado River basin (HMR 49); Pacific Northwest (HMR 57); and California (HMR 59). Generalized PMP estimates are provided as sets of isolines or maps (e.g., Figure 2-6) for various area size and duration combinations (Schreiner and Riedel, 1978) or index maps for a particular area and duration such as 24 hour, 10 mi^2 (Corrigan et al., 1999). Regional estimates are similar to generalized estimates, but are typically prepared at a somewhat smaller scale, such as a river basin or state. Some examples include the Red River of the North (Riedel, 1973), the Tennessee River basin (Zurndorfer et al., 1986), Michigan/Wisconsin (EPRI, 1993a) and Nebraska (AWA, 2008a).

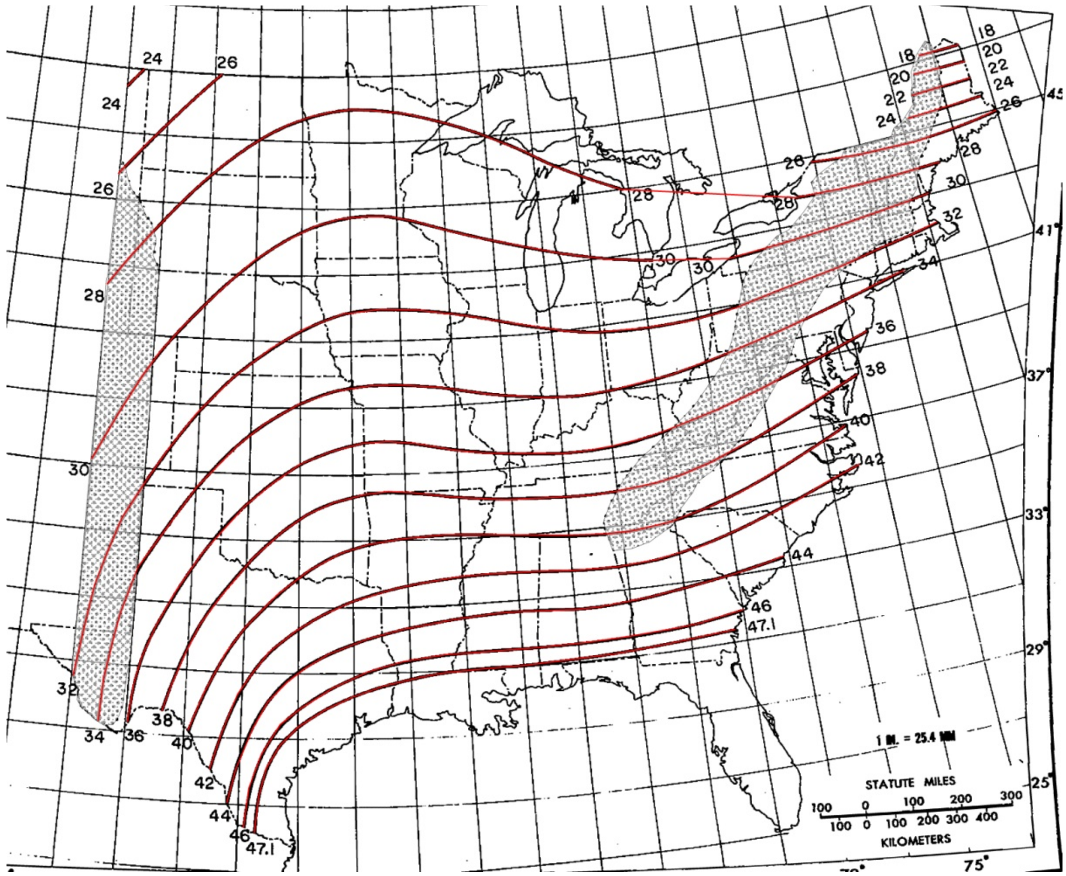


Figure 2-6 Example of a generalized PMP estimate for the eastern U.S. for 24 hr, 10 mi^2 precipitation depth (inches) PMP from HMR 51 with stippled region

Some advantages of generalized and regional estimates are (WMO, 1986 p. 109): (1) maximum use is made of all data in a region; (2) consistent smoothing is done for durations and areas within the region; (3) consistency is maintained between basin estimates in the region; and (4) best estimates for individual basins can be made easily and accurately. The main limitations of generalized estimates are: the time required to complete the large-area study is long; terrain and orographic effects are not fully taken into account (Schreiner and Riedel, 1978); estimates can be overly smoothed (envelopment) resulting in large values; and individual drainage basin characteristics such as local shielding, moisture depletions and local increases are neglected (WMO, 1969b). In some cases regional, statewide PMP estimates are lower than generalized estimates (EPRI, 1993a; AWA, 2008a). Generalized PMP estimates are determined by higher values for all points in a region, even though at specific points within the region topographic features would lead to smaller PMP values from a site-specific analysis (NRC, 1994).

In contrast to generalized and regional estimates, site-specific PMP estimates are made for individual watersheds or to provide design and assessment information for specific dams or nuclear reactor facilities. These studies typically focus on: smaller, individual drainages so that local effects are taken into account; or estimate PMP for larger area sizes or durations not provided by generalized PMP reports (HMRs). One distinction between site-specific (or regional) and generalized PMP estimates is that generalized PMP estimates typically include an additional smoothing step in the objective analysis procedure used to map local PMP estimates onto national or regional maps (NRC, 1994 p. 13). Some site-specific examples include the 207 mi^2 Johns Creek drainage basin (with orographics) above Dewey Dam (Fenn, 1985), and the 167,000 mi^2 Colorado River basin above Hoover Dam (M-K Engineers, 1990). Many other site-specific PMP studies have been completed for projects regulated by the Federal Energy Regulatory Commission (e.g. AWA, 2008b), and for other states.

2.5.2 Orographic Areas

The PMP procedures summarized above (principally DAD, maximization, and transposition) are modified for applications in mountainous areas. Terrain can significantly influence extreme precipitation magnitudes and distributions, resulting in (for example) increases on windward slopes and decreases on lee areas. PMP estimates in orographic areas typically are based on two components: (1) orographic precipitation, resulting from orographic influences; and (2) convergence precipitation, which results from atmospheric processes presumably independent of orographic influences (WMO, 1986). Some generalized PMP estimates, principally HMR 51, do not account for detailed terrain effects in the estimates. These areas that may be affected by orographics are shown as “stippled” regions along the Appalachian Mountains and between the 103rd and 105th meridians (Schreiner and Riedel, 1978). Current generalized PMP methods (WMO, 1986; Hansen et al., 1988; WMO, 2009) use orographic separation techniques to account for terrain. Some details on these methods are presented in Section 4.

2.5.3 Probable Maximum Storm Spatial and Temporal Distributions

In order to apply PMP amounts to a watershed, spatial and temporal distributions of storm rainfall are needed. For the eastern U.S., an application manual (HMR 52) provides idealized spatial and temporal patterns for applying HMR 51 PMP estimates to a watershed (Hansen et al., 1982). A spatial pattern in the form of an ellipse is specified, and temporal patterns are based on 6-hour sequencing within three 24-hour periods. It is recommended that HMR 52 spatial and temporal patterns apply for the eastern U.S. up to the 105th meridian (Figure 1-1). For other areas in the U.S. with generalized PMP estimates, such as HMR 49, 55A, 57 and 59, there are no specific spatial and temporal applications guides. Some general approaches are described in WMO (1986), and in hydrology manuals by various Federal agencies. For example, for PMP applications in the western U.S., Reclamation uses a simple spatial approach called “successive subtraction” and a 2/3 alternating block temporal pattern for general storms (Cudworth, 1989; Swain et al., 2006).

3 EXISTING PMP STORM DATA BASE

The basis for extreme storm rainfall estimates and PMP in the United States is depth-area duration studies of notable extreme storms (e.g., USACE, 1973). For at least the past 60 years, the U.S. Army Corps of Engineers, Bureau of Reclamation, and National Weather Service (and others) have jointly collaborated in collecting and analyzing storm rainfall data and publishing DAD data. Stallings et al. (1986) describe how the cooperative agency studies evolved. These agencies have also collaborated in developing and improving PMP techniques. Hansen (1987) provides a review and summary of the PMP methods that are commonly used today.

The main data bases used to estimate generalized PMP within the HMRs include: (1) DAD estimates for individual storms; (2) individual storm dewpoints and climatologies; and (3) precipitation frequency estimates. These existing data sets are summarized, along with their current status.

3.1 USACE Storm Catalog

The United States Army Corps of Engineers (USACE) Storm Catalog (USACE, 1973), the result of a nationwide investigation established in 1937 to study all notable extreme storms, was initially published in 1945. The purpose of the catalog was to provide a DAD storm data base "with the purpose of accumulating comprehensive rainfall data necessary for evaluating flood potentialities of drainage basins that would affect the design and operation of flood control, navigation, and multiple-purpose projects" (USACE, 1973). This catalog was then used as the data base to estimate PMP for HMR 23 (USWB, 1947), HMR 33 (Riedel et. al., 1956), and HMR 51 (Schreiner and Riedel, 1978). Updates were made to this catalog in 1958, 1962, and 1973, such that the final product is pertinent data sheets (e.g.,Figure 2-3), Part I and Part II analyses (described in Section 2) containing the storm isohyetal map, mass curves, and DAD table for most major storms occurring between 1875 and about 1972. This translates into data for about 539 storms (USACE 1973; Shipe and Riedel, 1976). The catalog is organized by geographical area, where the United States is divided into 11 regions (Figure 3-1). The storms are classified by their location of occurrence and then given a name consisting of the region's identifying abbreviation, such as 'SA' for South Atlantic (Figure 3-1), plus a number (e.g., SA 5-8; Figure 2-3). Most of the storms within this catalog are located in the U.S., east of the 105th meridian (Shipe and Riedel, 1976; NRC, 1988). Storms from the South Atlantic (SA) and North Atlantic (NA) Divisions are the focus of this present study for the Nuclear Regulatory Commission.

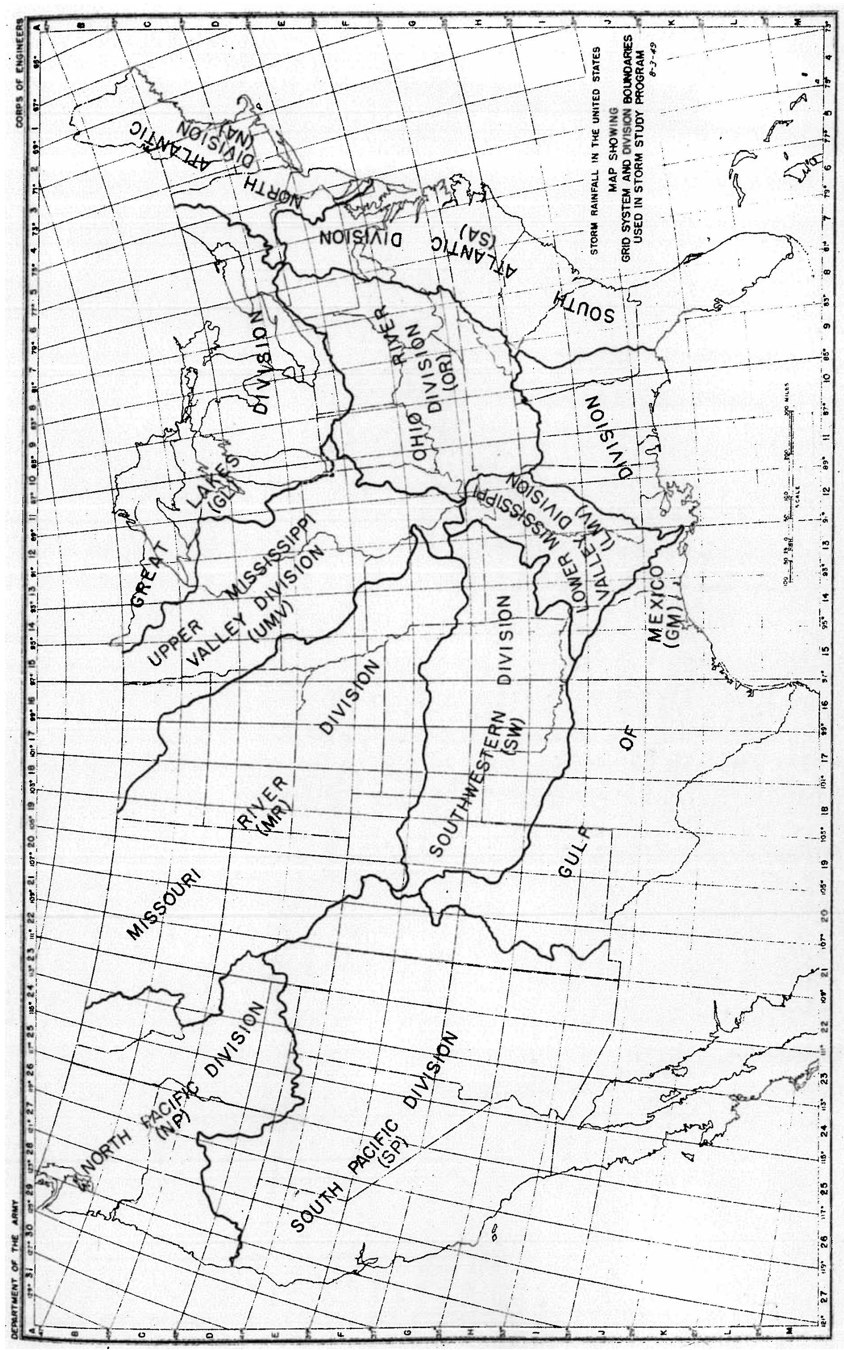


Figure 3-1 US Army Corps of Engineers Storm Catalog geographic division map showing the 11 divisions and their associated abbreviations

The USACE Storm Catalog is somewhat thorough for the storms included in its database within the eastern United States. Unfortunately, the catalog does not include any storm after the June 19-23, 1972 Tropical Storm Agnes (NA 2-24A), and has not been updated since 1973. Thus, there is a deficiency of nearly 40 years of more up-to-date storm data that the catalog lacks. Some more recent storm DAD data collection efforts are described in the next section. Lastly, it should be noted that the catalog is only available in paper format; the full Part I and Part II studies have yet to be converted to complete electronic form. Some of the information from pertinent data sheets within the catalog (e.g., DAD tables) has been converted to electronic format. Availability of specific storm information in electronic format for the USACE SA and NA Divisions is discussed below.

3.2 Other Federal Agencies Storm DAD Data

The main Federal agencies that have collaborated on developing storm DAD data are the U.S. Army Corps of Engineers, National Weather Service and Bureau of Reclamation (Stallings et al., 1986). In addition to the USACE storm catalog, NWS and Reclamation have significant repositories of storm DAD data that have been used to estimate maximum areal rainfalls across the U.S. (Shipe and Riedel, 1976) and to provide storm data for the HMRs (e.g., Hansen et al., 1988). Storm DAD data through January, 1976, that were used to assess areal rainfalls, were from three sources: USACE (539 storms); NWS (221 storms); and Reclamation (93 storms).

The main source and basic repository of DAD data, since USACE (1973), are the individual HMRs that have been completed after HMR 51. These include HMR 55A (Hansen et al., 1988), HMR 57 (Hansen et al., 1994) and HMR 59 (Corrigan et al., 1994). Individual storm DAD tables are contained within the appendix of each HMR. The number of storm DAD data used in each HMR, latest storm used, and other characteristics are summarized in Table 3-1. The original files for the DAD computations are located at the NWS HDSC for HMR 55A and HMR 59, and at the Bureau of Reclamation for HMR 57. The DAD computations, completed as part of the HMRs, generally followed USWB (1946) and WMO (1969a) methods. However, the computations were not fully documented as Part I and Part II individual files, and were not archived in any way. The implication is that these analyses and data sets are not preserved for widespread and subsequent use, other than the summary DAD tables preserved in HMR Appendices.

There is limited DAD information and other extreme storm-related data sources at the NWS HDSC, the Bureau of Reclamation in Denver, and various USACE District offices. Most of these files are in paper format, and data have been developed for individual projects or analyses. For example, Reclamation has some older storms from the 1940s through 1960s analyzed for individual, specific structures in the western U.S. These data sets, sources and analyses are (in most cases) scattered, inconsistent, incomplete, and poorly documented compared to the Part I and Part II storm documentation procedures. There are some exceptions to this, such as the storm studies and documents completed for Hoover Dam (M-K Engineers, 1990).

Table 3-1 Storm DAD status summary of generalized Hydrometeorological Reports

HMR No.	Publication Date	Number of Critical/ Major U.S. Storms with DAD	Latest Storm Used	Comments
49	1977	None (used alternate methods)	Sept. 3-7, 1970	See HMR 50 (Hansen and Schwarz, 1981) for storm information. The

				1983 Prescott, AZ storm exceeds PMP (Leverson, 1986).
51	June 1978	55	June 19-23, 1972	USACE (1973) used as DAD source. Replaced HMR 33 (1956)
55A	June 1988	43	Aug. 1-4, 1978	Replaced HMR 55 (1985) and TP 38 (1960)
57	October 1994	28	Dec. 24-26, 1980 (general) Aug. 16, 1990 (local)	Replaced HMR 43 (Nov. 1966)
59	February 1999	31	Feb. 14-19, 1986	Includes 7 DAD analyses from HMR 57. Replaced HMR 36 (Oct. 1961)

Since the last HMR was updated (Corrigan, 1999), other state and local agencies and consultants have been documenting extreme storms and developing some storm catalogs. The Colorado Climate Center developed an index of extreme storms for Colorado (McKee and Doesken, 1997). Recognizing the importance of bucket surveys (e.g., Ho and Riedel, 1980 p. 3), Doesken and McKee (1998) documented the July 1997 Fort Collins storm and the July 1997 Pawnee storm (Doesken, 1998). AWA (2008a p. 47) documented and analyzed nine new storms in the Midwest as part of the Nebraska statewide PMP study. These studies, as well as many others published in the literature (e.g. Smith et al., 1996) have yet to be synthesized into a comprehensive extreme storm data base, with DAD data and other information needed for PMP estimation.

3.3 Storm Dewpoints and Climatologies

Individual storm dewpoint estimates and maximum persisting dewpoint climatology information are a critical data source needed for PMP estimates (Section 2.2). The basic data used for maximum persisting dewpoint climatologies within each HMR has changed over time, as have data sources for individual storm dewpoints. National maps for 12-hour, maximum persisting dewpoints (EDS, 1968) were used in HMR 51. An example dewpoint map is shown in Figure 3-2; these maps were based on data from selected U.S. Weather Bureau first-order stations for the approximate period 1900 through 1946. In HMR 51, individual storm reference dewpoints were obtained from HMR 33 and principally from surface (land-based) stations.

The persisting dewpoint national maps (EDS, 1968) were partially and periodically updated for the geographic areas within HMR 55A, 57 and 59. In HMR 55A, monthly dewpoint maps were revised for the western U.S. The data from 81 stations were used, adding 31 years for the period 1948-1978 (Hansen et al., 1988 p. 70). Data from surface (land-based) stations were used to estimate storm dewpoints. The monthly persisting dewpoint climatology maps were again revised specifically for the region within HMR 57, using surface (land-based) data through 1983 (Hansen et al., 1994). Because many critical storms in HMR 57 had moisture sources in the Pacific, sea-surface temperatures (SSTs) were used as a proxy for individual storm dewpoint temperatures. Data for these storm-based estimates were obtained from U.S. Navy

(1981). The dewpoint climatology and storm dewpoint methods used in HMR 59 followed that of HMR 57. The dewpoint climatology maps from HMR 57 were used and examined for exceedances; new monthly maps were made for California (Corrigan et al., 1999). Storm dewpoints were based on SSTs from U.S. Navy (1981) and trajectory analysis.

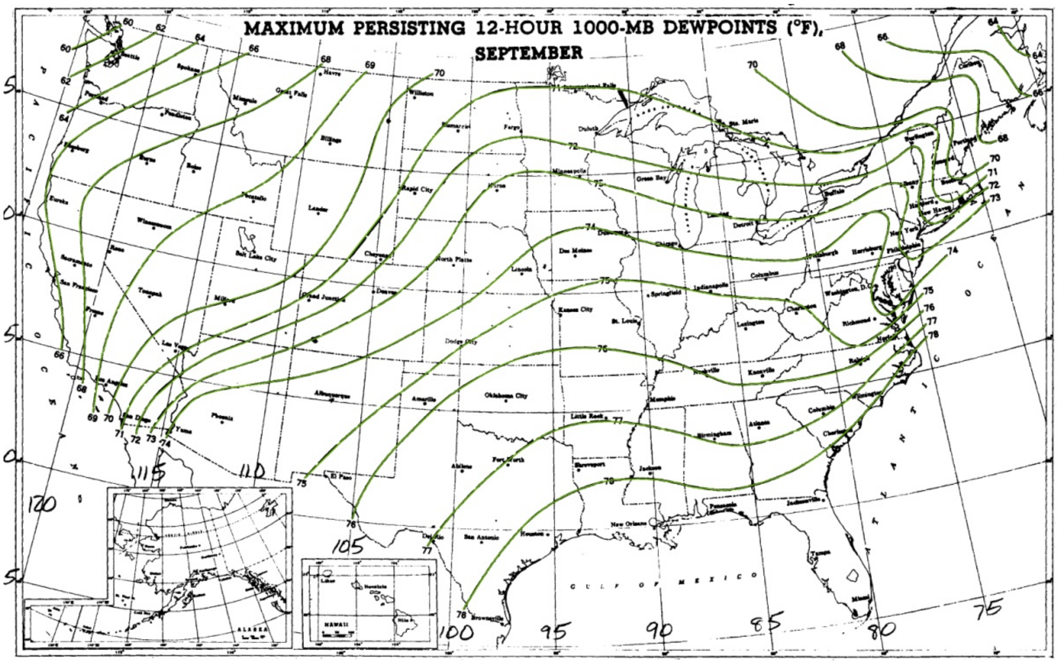


Figure 3-2 Maximum 12-hour persisting dewpoints for September, from EDS (1968)

3.4 Precipitation Frequency Estimates

Precipitation frequency estimates are used as a basis for comparing point PMP estimates, and as a critical data set for estimating PMP in orographic regions (HMR 55A, 57 and 59). HMR 51 used 24-hour precipitation frequency estimates from Technical Paper No. 40 (TP-40) (Hershfield, 1961), with maximum one-day rainfall estimates updated through 1971 (Schreiner and Riedel, 1978). Generalized HMRs for the western U.S. (HMR 55A, 57 and 59) used NOAA Atlas 2 (Miller et al., 1973) for 2-year, 24-hour and 100-year, 24-hour precipitation frequency estimates. These atlases are being revised in stages by NWS-HDSC, and are published in NOAA Atlas 14, Precipitation Frequency Atlas of the United States. A current status map of NOAA Atlas 14 (NWS, 2011) is shown in Figure 3-3. Existing published volumes are shown with horizontal hatched areas. Updates have been completed for a large portion of the eastern U.S. with Volume 2 for the Ohio River basin (Bonnin et al., 2006). The southeastern states volume is currently in progress (NWS, 2011). These data sets and information sources are a valuable, updated source for quality-controlled point precipitation data and frequency information.

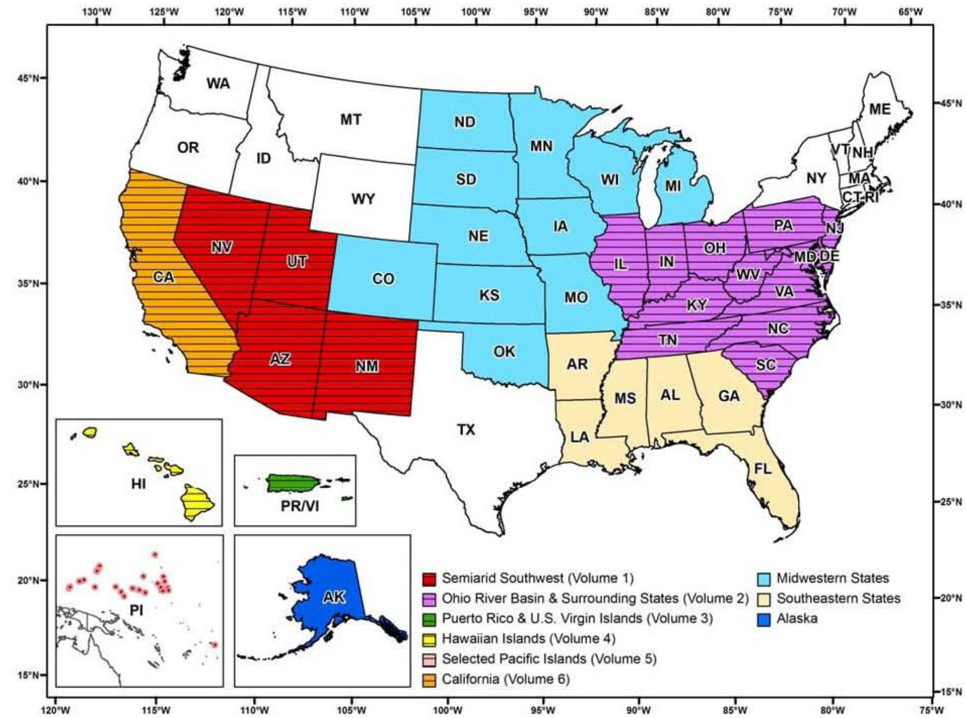


Figure 3-3 NOAA Atlas 14 Precipitation Frequency Atlas of the United States status map (NWS, 2011)

3.5 Current Status of Storm DAD Data

As noted above, the USACE Storm Catalog does not include data from any storms that occurred after 1972. This particular data base has not been updated in nearly 40 years, and most of the data input into the PMP calculations have not been continually revised and updated. Some storm DAD updates have occurred periodically as part of HMR revisions (Table 3-1), but the last one was completed with data from 1986. The data in Table 3-1 indicate that there is a definite need for storm data collection and synthesis into a new catalog. There is also a lack of major storm DAD data within an existing HMR; less than 50 storms have been utilized for these large regions (Table 3-1). Other than the storms used in the HMRs (Table 3-1) little to no new storm data have been collected and analyzed by Federal agencies for regional or generalized PMP estimates. The bucket surveys, once managed by federal agencies, are no longer part of the government curriculum, and dewpoint climatologies, necessary for moisture maximization calculations, have not been revised in recent years to include the latest data. Thus, the data input into the modern PMP calculations is outdated. The USACE has organized some recent storm data collection efforts through their Omaha District to start addressing this situation.

Some limited extreme storm data have been collected and summarized for some states, such as Colorado (McKee and Doesken, 1997) and Texas (Lanning-Rush et al., 1998) and by some consultants for site-specific or statewide PMP work (e.g., AWA, 2008a). These data sets have not yet been analyzed for use in a larger region or for application to multiple structures. These studies concerning more modern storms, in addition to those unlisted, do not constitute a comprehensive dataset of all recent notable storms. Moreover, even though storms have been studied, the reports are scattered throughout several scientific journals and in inconsistent formats consisting of varying amounts of data. These studies are incorporating and using much newer basic data and analysis tools, including radar data sets and reanalysis data. Some of these data sets and methods are described in Caldwell et al. (2011a), with some results synthesized in Caldwell et al. (2011b).

4 EXISTING PMP HYDROMETEOROLOGICAL REPORTS

Generalized Probable Maximum Precipitation estimates are presented in a series of Hydrometeorological Reports. Each report is specific to a region of the United States, where the divisions are delineated so that topographical and meteorological aspects are similar within the region boundaries. A map depicting these regions, and their associated current HMR, may be found in Figure 1-1. Several different methodologies were employed to estimate PMP for various regions of the contiguous United States. Current HMRs that use the generalized methods for mid-latitude regions (WMO, 1986) are: (1) HMR 51 – U.S. East of the 105th meridian; (2) HMR 55A – Continental Divide to the 103rd meridian; (3) HMRs 57 – Pacific Northwest; and (4) HMR 59 - California (Figure 1-1). Each of these reports uses storm DAD data, and the western HMRs use storm separation methods based on HMR 55A (Hansen et al., 1988) for orographic regions. The following sections present an in depth description of those HMRs pertinent to the PMP estimates and potential revisions for the vicinity of North Carolina and South Carolina. Generalized PMP reports prepared prior to HMR 51 for this region, including HMRs 23 and 33, are also reviewed. Pertinent storm DAD data for the Southeast region, from HMRs 23, 33, 51, and USACE (1973) are presented in Appendix A.

4.1 HMR 23 and HMR 33

The first generalized PMP estimates for the eastern United States were published in HMR 23 (USWB, 1947). Estimates covered 10, 200 and 500 mi^2 for 6-, 12-, and 24-hour durations. Basic data included DAD information from an early version of Storm Rainfall (USACE, 1973); preliminary Part I data were also extensively considered. Eighteen storms were considered "controlling" in HMR 23 (USWB, 1947 p. 33); 15 events with the largest magnitudes are listed in Table 4-1.

Table 4-1 Controlling storms in HMR 23 with the largest magnitudes (15 events)

Storm Center Location	Storm Assign. No.	Date	24 hour, 10 mi^2 Precip. (in)
Trenton, FL	SA 5-6	17-22 Oct. 1941	**30.0**
Altapass, NC	SA 2-9	13-17 Jul. 1916	**22.2**
Thrall, TX	GM 4-12	8-10 Sept. 1921	**36.5**
Ewan, NJ	NA 2-4	31 Aug. – 1 Sept. 1940	**22.7 (12-hr)**
Hearne, TX	GM 3-4	27 Jun. – 1 Jul. 1899	**24.1**
Manahawken, NJ	NA 2-3	19 Aug. 1939	**17.8 at 18 hours**
Kerville, TX	GM 5-1	30 Jun. – 2 Jul. 1932	**31.7**
Cherry Creek, CO	MR 3-28A	30-31 May 1935	**22.2**
Stanton, NE	MR 6-15	10-13 Jun. 1944	**15.3**
Springbrook, MT	MR 4-21	17-21 Jun. 1921	**13.3**
Cheyenne, OK	SW 2-11	3-4 Apr. 1934	**21.3 at 18 hours**
Hallett, OK	SW 2-18	2-6 Sept. 1940	**23.6**
Smethport, PA	OR 9-23	17-18 July 1942	**29.2**
Elba, AL	LMV 2-20	11-16 Mar. 1929	**20.0**
Miller Island, LA	LMV 4-24	6-9 Aug. 1940	**22.1**

Hydrometeorological Report No. 33 (Riedel et al., 1956) was published to build upon the results of HMR 23 and to establish seasonal PMP estimates for the domain east of the 105th meridian from the generalized estimates of PMP given in HMR 23. Seasonal estimates were desirable to circumstances that require snowmelt calculations and to assessments of multi-purpose structures (Riedel et al., 1956). An updated HMR for this area was necessitated by revisions to the database of 12-hour persisting dewpoint temperatures resulting from a study conducted after the publication of HMR 23 (USWB, 1949).

Presentation of PMP in HMR 33 included an all-season PMP map of the eastern half of the United States for an area size of 200 mi^2 for the 24-hour duration. Additionally, corresponding depth-area-duration graphs (8 total graphs) are given in which to calculate the PMP for any area ranging from 10 to 1000 mi^2 at the discrete durations of 6, 12, 24, and 48 hours. The logic behind providing eight depth-area-duration graphs as opposed to one single graph is that the domain east of the 105th meridian is rather large. To ease data handling, PMP computation, and presentation of results, the domain was partitioned into 9 zones (Figure 4-1). For transposition, all storms were limited to areas of similar topography, where topography was defined by the slope and elevation of the land. Transposition of each storm was related to the zone where the storm was observed (Riedel et al, 1956 Appendix B). Zones 6, 7, 8, and 9 are relevant to the North Carolina-South Carolina region. In HMR 33, the 8th and 9th zones were combined, as the 9th zone lacked a great deal of storm data (resulting in 8 depth-area-duration graphs per PMP map). The all-season PMP map and graphs were followed by the presentation of the PMP seasonal maps (one per month), similar to the all-season map and its associated graphs.

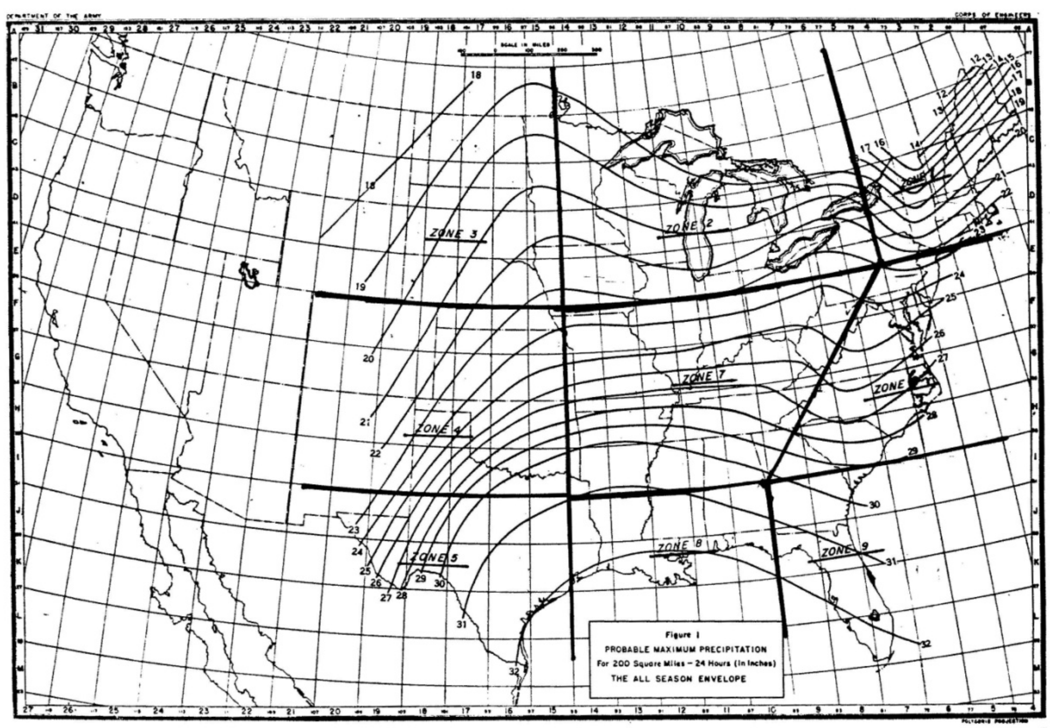


Figure 4-1 HMR 33 PMP map showing nine transposition zones (Riedel et al., 1956)

The storm database for HMR 33, the subset of storms within the USACE Storm Catalog that occurred in the domain east of the 105th meridian, was divided into two categories: processed and controlling storms. Processed storms are those storms that were taken in consideration to calculate PMP, and controlling storms are the storms that heavily influenced the PMP result. The 32 controlling storms used in HMR 33 are listed in Table 4-2. Though additional storms were considered when computing PMP for HMR 33 than for HMR 23, the fact that the storms were distributed seasonally essentially reduced the number of storms available for each PMP analysis. Thus, in the areas with sparse storm data, the highest weekly precipitation values from a 30-year period as determined from Weather Bureau stations and the 24-hour maximum precipitation value over a 10-year period from the same stations were considered. The updated 12-hour maximum persisting dewpoint temperatures were employed (USWB, 1949), thus resulting in revised moisture maximization adjustment values for the controlling storms in comparison to those values used in HMR 23.

The longer duration storms tended to dominate the extreme precipitation values for the longer periods of time (i.e., 24 or 48 hours) in HMR 33, but these longer-duration storms usually did not surpass or match the extreme values at shorter periods (i.e. 6 or 12 hours). The shorter timescales were controlled mostly by thunderstorms. Upon comparison of the seasonal graphs to one another, it is discernable that a correlation between season and precipitation exists as an increase in thunderstorm-type rainfall during the summer season in contrast to the other seasons (Riedel et al., 1956).

Table 4-2 Controlling storms considered in HMR 33 (32 events)

Storm Center Location	Storm Assign. No.	Date	24 hour, 10 mi^2 Precip. (in)
Ironton, MO	MR 2-13	26-31 Jan. 1916	**6.8**
Pinkham Notch, NH	NA 1-29A	9-13 Mar. 1936	
Pinkham Notch, NH	NA 1-29B	16-22 Mar. 1936	
Elba, AL	LMV 2-20	11-16 Mar. 1929	**20.0**
Beloit, WI	GL 4-14	21-27 Mar. 1916	**4.3**
Bellefontaine, OH	OR 1-15	23-27 Mar. 1913	**7.3**
Cheyenne, OK	SW 2-11	3-4 Apr. 1934	**21.3 at 18 hours**
Warner, OK	SW 2-20	6-12 May 1943	**17.2**
Wellsboro, PA	SA 1-1	30 May – 1 Jun. 1889	**9.2**
Warrick, MT	MR 5-13	6-8 Jun. 1906	**10.2**
Springbrook, MT	MR 4-21	17-21 Jun. 1921	**13.3**
Savageton, WY	MR 4-23	27 Sept. - 1 Oct. 1923	**9.5**
Bonaparte, IO	UMV 2-5	9-10 Jun. 1905	**12.0 at 12 hours**
Stanton, NE	MR 6-15	10-13 Jun. 1944	**15.3**
Boyden, IO	MR 4-24	17-19 Sept. 1926	**21.7**
Georgetown, SC		24-27 Jun. 1945	
Hearne, TX	GM 3-4	27 Jun. – 1 Jul. 1899	**24.1**
Kerville, TX	GM 5-1	30 Jun. – 2 Jul. 1932	**31.7**
Altapass, NC	SA 2-9	13-17 Jul. 1916	**22.2**
Smethport, PA	OR 9-23	17-18 July 1942	**29.2**
Miller Island, LA	LMV 4-24	6-9 Aug. 1940	**22.1**
Collinsville, IL	MR 7-2B	12-16 Aug. 1946	**12.1**

Manahawken, NJ	NA 2-3	19 Aug. 1939	**17.8 at 18 hours**
Hallett, OK	SW 2-18	2-6 Sept. 1940	**23.6**
Thrall, TX	GM 4-12	8-10 Sept. 1921	**36.5**
Patterson, NJ	GL 4-9	7-11 Oct. 1903	**13.7**
Kinsman Notch, NH	NA 1-17	2-4 Nov. 1927	**12.0**
Trenton, FL	SA 5-6	17-22 Oct. 1941	**30.0**
Meeker, OK	SW 1-11	19-24 Oct. 1908	**11.4**
Satsuma, TX	GM 5-4	5-8 Dec. 1935	**18.6**
Phillipsburg, MO	MR 1-1	16-20 Dec. 1895	**7.6**
Berlin, NY	**NA 2-18**	**29 Dec. 1948 – 1 Jan. 1949**	

4.2 HMR 51

Hydrometeorological Report No. 51 (Schreiner and Riedel, 1978) was produced to supersede PMP estimates in HMR 33. The goal of this report was two-fold: to revise PMP values for drainages smaller than 1,000 mi^2 and to provide PMP values for drainages up to 20,000 mi^2, both for the domain east of the 105th meridian. Seasonal PMP values for drainages ranging in size from 10 to 1,000 mi^2 were given in HMR 33 (discussed above); however, all data for significant storms were not available at the time of its publication. The DAD study for the Yankeetown, Florida, storm (3-7 Sept. 1950) had not yet been completed. The HMR 51 revision was also completed to address other issues, including: HMR 33 PMP values did not envelope all historic storms in place (1942 Smethport, PA; 1940 Hallett, OK); and the need to address discontinuities at HMR 33 zonal boundaries (e.g. Figure 4-1). As for the larger drainages, PMP values had yet to be computed for drainage basins of this size, and anticipated projects were expected to exploit such drainages. Thus, HMR 51 presents all-season PMP values for basins that range from 10 to 20,000 mi^2 for durations of 6 to 72 hours east of the 105th meridian.

The PMP methodology, that is described in Section 2, was utilized in developing HMR 51. The DAD data employed was from two main sources: the USACE Storm Catalog (USACE, 1973), and storm DAD estimates developed by the Hydrometeorological Branch of the National Weather Service (Shipe and Riedel, 1976). The storms of consideration for HMR 51 occurred between 1878 and 1972. Figure 4-2 depicts the locations of those storms, the ‘important storms’ (55 total), that were most influential in setting PMP for at least one combination of area and duration. Note the generally small number of storms in the southeastern region of the United States (Table 4-3), thus making the technique of transposition significant.

Table 4-3 Important storms from HMR 51 in southeastern United States (12 events)

Storm Center Location	State	HMR 51 Storm No.	Storm Assign. No.	Date	24 hour, 10 mi^2 Precip. (in)
Wellsboro	PA	2	SA 1-1	05/30-06/01/1889	9.2
Jewell	MD	6	NA 1-7B	07/26-29/1897	14.7
Eutaw	AL	8	LMV 2-5	04/15-18/1900	12.6
Paterson	NJ	11	GL 4-9	10/07-11/1903	13.7
Altapass	NC	31	SA 2-9	07/13-17/1916	22.2
Elba	AL	47	LMV 2-20	03/11-16/1929	20.0
Ewan	NJ	68	NA 2-4	09/01/1940	

Smethport	PA	74	OR 9-23	07/17-18/1942	29.2
Big Meadows	VA	76	SA 1-28A	10/11-17/1942	13.4
Yankeetown	FL	85	SA 5-8	09/03-07/1950	38.7
Tyro	VA	99	NA 2-23	08/19-20/1969	25.4
Zerbe	PA	100	NA 2-24A	06/19-23/1972	14.3

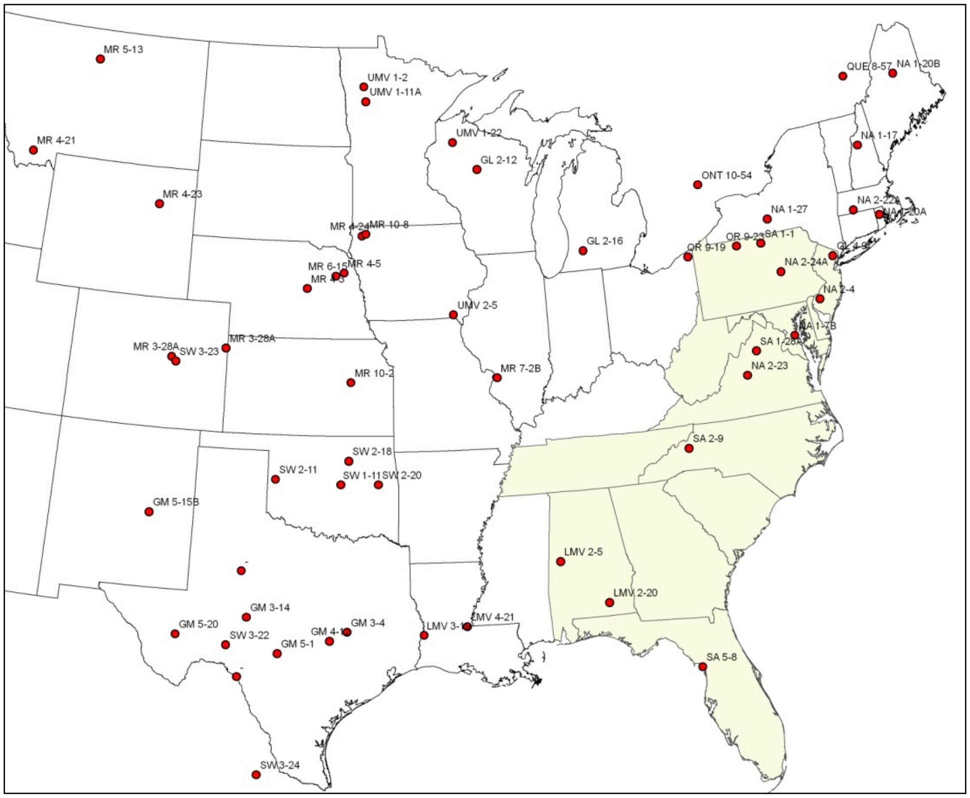


Figure 4-2 Locations of important storms used in HMR 51 (Schreiner and Riedel, 1978), with USACE storm assignment numbers. Southeast study focus area is shaded.

The guidelines on limits of transposition that were used in HMR 51 are as follows (Schreiner and Riedel, 1978 p. 10).

- Transposition was not permitted across the generalized Appalachian Mountain ridge.
- Tropical storm rainfall centers were not transposed farther away from nor closer to the coast without an additional adjustment.
- In regions of large elevation differences, transpositions were restricted to a narrow elevation band (usually within 1000 ft (305 m) of the elevation of the storm center).
- Eastward limits to transposition of storms located in Central United States were the first major western upslopes of the Appalachians.
- Westward transposition limits of storms located in Central United States were related to elevation. This varied from storm-to-storm but in most cases the 3000- or 4000-ft (915- or 1220-m) contour.
- Southern limits to transposition were generally not defined since other storms located farther south usually provided higher rainfall values.
- Northward limits were not defined if they extended beyond the Canadian border (the limits of the study region).

It is evident that areas of complex topography were avoided in HMR 51. HMR 51 did not directly consider orographic influences when computing PMP, consequently resulting in two regions on the PMP maps that purposefully lack detailed estimates. These areas correspond to regions of complex terrain and are represented by a stippled pattern (Figure). The first area consists of the Appalachian Mountains, an area extending from Georgia to Maine. The second region is a strip of land between the 103rd and 105th meridians, just east of the Continental Divide.

The HMR 51 PMP results reflect transposition and envelopment, notably in the Southeast over North and South Carolina (Figure 4-2).Some hand-drawn maps that indicate transposition limits for individual storms (e.g.,Figure 2-4) were available from NWS files. However, there is insufficient information to assess the degree to which transposition calculations affect PMP at individual locations, or to quantitatively assess PMP sensitivities or uncertainties. Envelopment was used to smooth the storm and transposed storm rainfall values into regionally consistent maps and eliminated any anomalies. Furthermore, during smoothing, moisture sources were considered and extreme gradients were reassessed. The results of these computations, are a total of 30 all-season PMP maps for durations of 6 to 72 hours at areal extents of 10 to 20,000 square miles (Figures 18 through 47 in HMR 51). In order to assess potential changes to HMR 51 PMP values, these 30 maps were digitized and converted to various electronic formats, including shapefiles and grids (Appendix A). It should be noted that the DAD value for 10 square miles found in the data tables mentioned above are point values, yet the PMP values for 10 square miles were determined from an average of multiple measurements and not single station precipitation amounts. Therefore, it is possible for areas smaller than 10 square miles to have greater PMP values.

4.3 HMR 52

NOAA Hydrometeorological Report No. 52 (HMR 52), 'Application of Probable Maximum Precipitation Estimates – United States East of the 105th Meridian,' (Hansen et al., 1982) was created as a supplement to HMR 51. The report establishes procedures to apply PMP estimates found in HMR 51 to watersheds. As a supplement, the same dataset employed in HMR 51 (i.e. the subset of 55 storms from the USACE Storm Catalog) is utilized in HMR 52. Additionally, the same areal extent is focused upon: the domain east of the 105th meridian excluding areas of highly complex terrain and orographic regions within HMR 51 (stippled areas shown in Figure 2-6). A description of the methodology to compute PMP is given, including an in depth discussion of the storms' shape and isohyetal pattern. The following summarizes this methodology.

Since all storms are markedly unique, from duration to areal extent, the first step was to create some semblance by dividing the data for each storm into 6-hour increments. Furthermore, to broaden the dataset and have statistically significant results, an additional 183 storms (listed in the appendix of HMR 52) were included in the analysis. The shape of the storms' isohyets was examined first. From the expanded dataset, it was concluded that: (1) approximately 60% of the sample had ellipse shape ratios between 2 and 3; (2) no strong regional variation of shape ratios was apparent, although some meteorologically reasonable trends could be obtained from the data; and (3) no strong relation was found between shape ratio and total-storm area size, but there was some evidence that lower shape ratios occur with the smaller area sizes. Therefore, HMR 52 recommends that an ellipse, with a 2.5 to 1 major to minor axis ratio, be used to represent the spatial distribution of PMP for all basins.

HMR 52 discourages users in applying actual storm spatial distributions to drainages, regardless if they occurred over the basin or within a homogeneous area. Though the spatial pattern of an actual storm may be more similar in shape to a drainage basin than the suggested ellipse, this pattern may result in precipitation values greater than the PMP for areas within the basin. Furthermore, the storm that establishes the PMP for one area size does not necessarily result in the PMP for all area sizes.

Exploiting a single elliptical shape and shape ratio for the entire HMR 51 domain not only simplifies this step of the PMP methodology for users and promotes consistency among basins, but allows for the formation of a generalized procedure to establish DAD tables and placement of isohyetal patterns for all drainages in question. It is recommended that the isohyetal pattern be oriented in such a way as to closely align that of the basin. This orientation is assumed to create the greatest amount of rainfall possible within the drainage, and hence the greatest peak flow. However, it is warned that the meteorological conditions, such as atmospheric circulation patterns, and topographic obstructions be considered and accounted for as well. The isohyetal pattern and orientation is to remain fixed in time; all 6-hour increments of the storm have the same center location even though a storm could potentially move across the entire basin within the 6-hour timeframe.

The elliptical isohyetal pattern will not align precisely with the basin outline. For those areas of the drainage basin beyond the reaches of the ellipse, the concept of residual precipitation is applied to obtain precipitation values for these areas. Residual precipitation is an idea in the computation of PMP that is presented in HMR 52 (Hansen et al., 1982 p. 24). The assumption behind this concept is that rain will fall in these locations, but the amounts will be less than the PMP. Furthermore, in addition to residual precipitation, a 'fit factor' or 'basin shape' adjustment is employed to compensate for the differences between the boundary of the basin and the elliptical isohyetal pattern. This 'basin shape' adjustment is a multiplication factor placed upon the average PMP of the basin. The reduction is not constant over all 6-hour storm increments, but rather decreases with time.

HMR 52 suggests that an isohyetal pattern with a single center be utilized to determine PMP for a basin. However, from the storm dataset, it is apparent that larger storms have a tendency to produce multiple rainfall centers. This concern is addressed in the text with the conclusion that the peak discharge of a drainage basin will actually decrease with the introduction of multiple storm centers when all other parameters are held constant. If multiple centers must be considered, it is recommended that the number of centers be limited to two (Hansen et al., 1982 p. 72). Lastly, HMR 52 gives a procedure for calculating PMP values for periods less than 6 hours. A computer program called "HMR52", that implements most of the procedures in HMR 52, was developed by the USACE Hydrologic Engineering Center (USACE, 1984).

4.4 HMR 53

Hydrometeorological Report No. 53, 'Seasonal Variation of 10-Square-Mile Probable Maximum Precipitation Estimates, United States East of the 105th Meridian,' (Ho and Riedel, 1980), supersedes the seasonal PMP values presented in HMR 33 (Section 4.1). It is not surprising that the monthly PMP values in HMR 33 would require revision given that the all-season PMP values of HMR 33 were updated and presented in HMR 51 (see section 4.2). With HMR 51 as the framework, HMR 53 details the procedure of this seasonal update and presents the results as PMP maps for the durations of 6, 24, and 72 hours for all 12 months, at mid-month, for 10 mi^2 areas.

Again, HMR 51 lays the foundation for HMR 53: the same region, including the removal of the topographic (i.e. stippled) regions, is analyzed; the datasets used in HMR 51 are utilized here; and the methodology for computing the HMR 53 monthly PMP values is similar to that used within HMR 51. The data is supplied by the USACE Storm Catalog (USACE, 1973) and from the Hydrometeorological Branch of the National Weather Service (Shipe and Riedel, 1976) as in HMR 51, yet the dataset is augmented by the maximum values obtained by those NOAA first-order and COOP weather stations that have collected 20+ years of data. This is an attempt to compensate for the lack of storm data during the 'off' seasons (i.e. those seasons that do not normally experience the most intense rainfalls). It was noted that moisture profiles provided by radiosondes would be best, but due to the low density of the radiosonde network, narrow swaths of moisture which may influence record storms could go undetected. Additionally, numerous record storms occurred prior to the institution of the radiosonde network. Thus, the moisture maximization methodology of HMR 51, the process utilizing dew points, is applied in HMR 53. Furthermore, the transposition limits listed in HMR 53 are identical to those limits presented previously in HMR 51.

An added feature in HMR 53 is the use of a set of 20 grid points dispersed sporadically throughout the domain. As opposed to setting bounding regions for the transposition of critical storms, storms were transposed to these 20 grid points (if the grid point was within the transposition limits). Transposing storms to each of these grid points establishes the lowest PMP value possible for that point. Combined with envelopment, this transposition technique not only broadens the region of influence for a single storm but also distributes the data among the 12 months. Great care was taken when enveloping these values to be sure that continuity existed spatially and temporally (Ho and Riedel, 1980).

The process of envelopment was highly stressed in HMR 53 in comparison to the other hydrometeorological reports. This may be the result of having to spread the limited storm data over a 12 month period. The objectives for envelopment were listed as follows (Ho and Riedel, 1980):

- smooth patterns and gradients of PMP for each month and each duration;
- smooth progression or increasing depths with duration;
- smooth progression of PMP depths month to month; and
- envelopment of moisture maximized and transposed storm rainfalls.

Additionally, the authors included an 'unwritten objective' to avoid undue indirect maximization and envelopment in making the PMP estimates (Ho and Riedel, 1980). In other words, as the data becomes increasingly smoothed, the ensuing product could result in an improbable PMP value. If the rainfall of a storm increased during transposition and envelopment to a value greater than 50% of its original rainfall value, the storm was re-evaluated. If the new, computed value closely matched surrounding values, the increased adjustment was allowable, but if the enveloped value was an anomaly, the value was reduced to 150% of the original rainfall depth regardless of the computed value.

Another concern in this domain is the effect of tropical storms on PMP. Tropical storms are most powerful near the shoreline as they are closest to their energy source, the warm ocean water. As these storms move inland, they decrease in intensity. A study by Schwarz (1965) suggests that there will be no decrease in rainfall associated with the storm up to 50 nautical miles from the gulf coast, a linear decrease to 80% strength at 205 nautical miles, then a drop to 55% strength at 400 nautical miles. Similar to HMR 51, this approach was applied in HMR 53 when transposing tropical storms nearer and farther to the coast such that rainfall amounts increase/decrease upon transposition toward/away from the energy source.

The final seasonal PMP values in HMR 53 are displayed as maps for 6, 24, and 72 hours at mid-month for 10 mi^2 areas. If other hourly measurements or another day of the month needs to be investigated, a depth-duration chart can be created. Using duration as the abscissa and depth as the ordinate, the 3 given values can be connected with the origin (0,0). This interpolation scheme gives a rainfall mass curve for a particular location over a 3-day period. A similar scheme can be used to focus on another day of the month (Ho and Riedel, 1980 p. 48).

From the seasonal analysis, the maps for July and August and those for January and February are identical. July and August not only are mirrors of one another but they meet the all-season PMP values and thus match the all-season maps shown in HMR 51. As for general patterns, there is a seasonal variation with higher values in the warm season in comparison to the cool season. Additionally, there are higher values for the 6 hour rainfalls than for the 72 hour rainfalls in the summer season due to the greater occurrence of short-duration thunderstorms. Lastly, it must be noted that the maps are given for 10 mi^2 areas, so it is possible for areas less than 10 mi^2, especially in the summer season, to receive a greater amount of rainfall than HMR 53 PMP values, as PMP was not estimated for areas less than 10 mi^2 in HMR 53 (Ho and Riedel, 1980 p. 1).

4.5 Recent HMRs in the Western United States

Within the United States, advancements in generalized PMP estimation have usually occurred during development of HMRs for individual regions, or updates to previous HMRs (Stallings et al., 1986; Hansen, 1987). We summarize study methods and results for HMRs 55A, 57 and 59 (Figure 1-1), because these reports provide information on the current status of PMP estimation in the United States and other parts of the world. As mentioned in Section 3.2, rather than maintaining and expanding the USACE (1973) DAD data base, the DAD data within each region is summarized in the appendices of HMRs 55A, 57 and 59. Hansen et al. (1988) made a key contribution in HMR 55A by refining the processing of precipitation in orographic regions, using the ‘storm separation’ concept (Hansen, 1987). This concept was then later used, with some minor adjustments, in HMR 56 (Zurndorfer et al., 1986), in HMR 57 (Hansen et al., 1994) and in HMR 59 (Corrigan et al., 1999). For mid latitude orographic regions, the ‘orographic separation’ method developed as part of HMR 55A is still recommended for use in PMP manuals (WMO, 1986; WMO, 2009). Some modest changes to PMP methods were made in HMRs 57 and 59, and are also described.

4.5.1 HMR 55A Overview

The HMRs for the eastern U.S. (51, 52 and 53) stipple out the region between the 103rd and 105th meridians, as well as the Appalachians (Figure 2-6) due to terrain influences. Most reports suggest that this area be investigated on an ‘as needed’ basis. PMP updates were needed in highly orographic areas, including near the 105th meridian. The National Weather Service, the Army Corps of Engineers, and the Bureau of Reclamation collaborated (Stallings et al., 1986) to develop HMR 55A (Hansen et al., 1988) to meet this need. HMR 55A presents all-season, general-storm PMP estimates for durations between 1 and 72 hours for the area between the 103rd meridian and the Continental Divide (CD-103). Estimates are given for area sizes from 10 to 20,000 mi^2, except for the highly orographic area where estimates are only available for area sizes from 10 to 5,000 mi^2. Additionally, local-storm PMP estimates are given for durations between 15 minutes and 6 hours for area sizes from 1 to 500 mi^2.

The CD-103 region has areas of highly complex terrain, with steep mountains and narrow canyons, in addition to areas of open plains. Thus, it is not unexpected that the meteorology of the region is also multifaceted. For example, tropical storms have affected the southern portion of the region, storms originating from upslope flow dominate mountainous areas, and extratropical cyclones influence the northern reaches. For all areas, small convective cells within larger extratropical storms are significant.

With such a highly-varied storm data base, a storm classification scheme was developed. A single storm type was assigned to each of the 82 critical storms within the data base by examining synoptic weather maps, mass curves of rainfall, isohyetal patterns, effective storm durations, and total storm areas (Hansen et al., 1988). From these five criteria, the storm was first determined to be of the general cyclonic or convective type. General cyclonic storms result from synoptic scale weather phenomena such as fronts and pressure systems whereas convective storms are normally isolated events in space and time. Each category is further broken down, and storms with strong orographic influence are grouped separately.

The combination of diverse topography and a diverse storm database presented an interesting challenge for the development of the PMP analysis in this region. For consistency (and simplicity), one single PMP analysis compatible with all terrain was desirable. To accomplish this, the mechanisms that produced rainfall were divided into two categories, convergence and orographic components (Hansen et al., 1988). All rainfall events are, at least partly, the result of some convergence, so this factor was applicable region-wide. Thus, the rainfall resulting from convergence can be moisture maximized and transposed throughout the entire region. From these values, a map of convergence PMP for the whole domain was created. An orographic separation line was defined as the ‘line separating regions where there are different orographic effects on precipitation, where the precipitation results from a combination of atmospheric forces and lifting of air by terrain on one side, and the other side, the non-orographic region, the precipitation is only affected by atmospheric forces’ (Hansen et al., 1988). In the areas on the topographically-complex side of the orographic separation line, the rainfall triggered by orography was added to the convergence rainfall for a total PMP. However, the complication is that the orographically-produced rainfall is not consistent throughout the entire storm, so a storm intensification factor was applied. The storm intensification factor reduces the orographic component in areas outside of the core of the storm and during the most intense 6 hours of a 24-hour storm. Finally, the orographic PMP, with storm intensification factor, is combined with the convergence PMP to provide total PMP.

Besides the addition of an orographic component to the PMP equation, HMR 55A also introduces a local-storm PMP. A local storm is ‘an intense, small-area, short-duration isolated event,’ unrelated to synoptic scale disturbances (Hansen et al., 1988). It is identified for areas from 1 to 500 mi^2 and for durations ranging from 15 minutes to 6 hours. Typically, a watershed is analyzed for both general storm and local-storm PMP events, as well as seasonal PMP events (Cudworth, 1989). PMP estimates in HMR 55A were recommended to supersede those in HMR 51 for overlapping areas.

It should be noted that in HMRs 51-53, it was believed that the PMP for all durations and areas is sufficiently controlled by the general-type storms, with all small convective cells assumed to be embedded within the larger storms. Thus, it was presumed that there was no need to establish a local-storm PMP for areas east of the 103rd meridian. As such, it is thought that somewhere within the domain of HMR 55A (CD-103), the significance of the local storm becomes important, rather than relying on local events embedded in general storms (Hansen et al., 1988).

4.5.2 Orographic Factors used in PMP Computations

In HMR 55A, as in prior HMRs covering the Western U.S. (HMR 36, 43, and 49), the concept of separating the convergence and orographic components of PMP was pursued, but never completely captured. The rationale for using this technique is the assumption that convergence, or non-orographic, precipitation can be readily transposed, whereas precipitation caused by terrain forcing cannot. That is, orographic precipitation is a site-specific phenomenon that cannot be easily separated from the topography in the vicinity of its occurrence.

Convergence PMP was determined by estimating the convergence portion of the 10 mi^2, 24-hr rainfall in the severe storms determined to be the controlling events in the HMR 55A region. The convergence rainfall was then moisture maximized and transposed throughout each storm's area of transposability to provide region-wide estimates of convergence PMP. The results were given the term Free Atmospheric Forced Precipitation (FAFP) (Hansen et al., 1988).

The effect of terrain on precipitation was evaluated using maps of precipitation-frequency, specifically the 100-year, 24-hour rainfall map from NOAA Atlas 2 (Miller et al., 1973). This orographic influence, termed *T/C*, was defined as the ratio of total 100-year rainfall, *T*, to the convergence–only 100-year rainfall, *C*. The total 100-yr rainfall was obtained from the map values for all locations. Convergence-only rainfall was estimated in areas where it was determined that terrain influences would be minimal (e.g., high plains regions, open mountain parks with the least complex terrain, etc). Then a region-encompassing analysis of *C* was created using the assumption that *C* varies gradually and relatively uniformly throughout the study area. By ratioing the 100-yr rainfall map to the *C* map, a geographic pattern of *T/C*, as defined, was produced.

Additional considerations were needed to explain the atmospheric dynamics found in rainstorms in the HMR 55A region. The convective nature of rainfall that frequently occurs in severe storms was approximated by defining a storm intensity factor, *M*, as the ratio of the maximum 6-hr to the maximum 24-hr precipitation in the major storms of record. Regional maps of the *M* factor were created from historical storm data, also using as guidance the premise that *M* is greater in storms that have a lesser degree of orographic influence and smaller in rainstorms with stronger orographic forcing.

Details of the PMP computation methods are in Hansen et al. (1988, pp. 141-142), and are summarized here. A conceptual equation states that PMP is equal to convergence PMP times an orographic influence factor:

$$PMP = (FAFP)K \quad (4)$$

where *FAFP* = convergence-only 10 mi^2, 24-hr PMP and *K* = orographic influence factor, *T/C*, a computational equation for the total 10 mi^2, 24-hr PMP was developed. As defined in HMR 55A, *FAFP* is the acronym for free atmospheric-forced precipitation and is the storm precipitation not produced by orographic forcing and equivalent to convergence-only PMP. Inclusion of the *M* factor concept in the equation was accomplished by defining *FAFP* as

$$FAFP = A(6) + B(18) \quad (5)$$

where *A(6)* is the precipitation during the most intense portion of the 24-hr duration and *B(18)* is precipitation during the remaining 18 hours, or

$$A(6) = (FAFP)(M) \quad (6)$$

and

$$B(18) = (FAFP)(1 - M) \quad (7)$$

From the above discussion, it has been assumed that the orographic influence is different (weaker) for the intense 6-hr period than it is for the remaining 18-hr period; therefore, *K* is broken into two orographic factors, K_1 and K_2, so that the conceptual PMP equation (4) can be written as

$$PMP = (FAFP)(M)(K_1) + (FAFP)(1 - M)(K_2) \quad (8)$$

where K_2 was considered equivalent to *T/C*. K_1 was defined as

$$K_1 = 1 + P\left[\left(\frac{T}{C}\right) - 1\right] \quad (9)$$

where *P* was approximated by

$$P \sim 1 - M \quad (10)$$

Substitution and simplification resulted in the final computational equation for PMP used in HMR 55A:

$$PMP = (FAFP)\left[M^2\left(1 - \frac{T}{C}\right) + \frac{T}{C}\right] \quad (11)$$

It can be seen that the portion of the equation in brackets represents the orographic influence factor, *K*.

4.5.3 PMP Method Changes in HMR 57 and HMR 59

Some changes to DAD computations, individual storm moisture sources, and orographic precipitation procedures were made in HMR 57 and HMR 59, and are relevant to potential HMR 51 PMP updates. Based on initial efforts completed during finalization of HMR 55A, a series of computer programs called ‘Ministorm’ were developed for DAD automation (Stodt, 1995), following USWB (1946) procedures. Most programs were written in Fortran, and were run on Reclamation’s mainframe computer. Heavy utilization was made of gridding and contouring software packages that are no longer available. The Ministorm programs were used to process 30 storms in a near-automated fashion for HMR 57. Storm DAD processing in HMR 59 for 31 storms was completed using Grass GIS routines (Corrigan et al., 1999), with the exception of seven storms that were directly utilized from HMR 57. Both the Ministorm and Grass GIS DAD computer codes were not maintained or updated by Reclamation or NWS.

Sea surface temperatures (SSTs) were used as indexes for individual storm moisture sources, for storms located along the coasts of California, Oregon and Washington in HMRs 57 and 59. Details of the approaches are in Hansen et al. (1994, pp. 41-43) and Corrigan et al. (1999, pp. 41-47), using storm trajectory concepts. The use of SSTs and trajectories is a significant departure from the land-based dewpoints used in HMR 51. Notably, HMRs 57 and 59 used maximum 12-hour persisting dewpoints from climatology (similar to HMR 51), rather than average maximum or frequency-based dewpoints suggested by EPRI (1993a). Some investigators (EPRI, 1993a; AWA, 2008a) suggest that the use of 12-hour maximum persisting dewpoints in PMP estimation needs to be reviewed and the criterion revised (see Section 6).

In HMRs developed for the western states following HMR 55A (HMR 57 and HMR 58/59), the same convergence and orographic precipitation separation procedures were employed with a few modifications. Rather than determine *FAFP* at the elevation of each storm, convergence-only precipitation was adjusted to the 1000 mb standard pressure level. This served to standardize the precipitation amounts so they could readily be compared and analyzed. In developing maps of *T/C*, the convergence-only 100-yr, 24-hr rainfall values were also adjusted to the 1000 mb pressure level, smoothed and analyzed, and then adjusted for the barrier elevation at which the numerator, *T*, is observed.

In both HMR 57 and HMR 58/59 the calculation of *M*, the storm intensity factor, was not limited to using only the 6-hr period as the duration of the most intense rainfall. The “core duration” of intense rainfall in a storm could be of any length. This was primarily because new storm depth-area-duration analyses were available down to the one-hour duration. The importance of *M* was also not as great as in HMR 55A due to differing storm types. For example, the *M* factor in HMR 55A storms was generally between 0.4 and 0.9, whereas in HMR 58/59 storms, *M* varied from 0.0 to 0.55, and in HMR 57 most storms had *M* less than 0.5 and many had an *M* = 0.0. These distinctions and the addition of some minor definition changes cover the extent of differences between HMR 55A and HMR 57 and 58/59 in procedures for determining the orographic influence factor that is applied to the convergence component of PMP

5 HMR COMPARISONS IN THE SOUTHEAST AND ISSUES

The present study focuses on the southeastern United States, with a case study region of the states of North and South Carolina (Figure 4-2). Comparisons of HMR 51 PMP estimates to previous estimates, and DAD data in the Southeast are discussed. Existing PMP comparisons to observed storm data are described. Existing recommendations from the HMRs and some related issues are mentioned.

5.1 HMR 23-33-51 Comparisons

Preliminary comparisons of the changes between HMRs 23, 33 and 51 have been completed informally by the authors of HMR 51 and NWS Hydrometeorological Branch. There were hand-drawn maps of the ratios of 24-hr, 200 mi^2 PMP from HMRs 23, 33 and 51 available; these are shown in Figure 5-1, Figure 5-2, and Figure 5-3. The results for HMR 51/33 were presented in NRC (1985, pp. 47-48); we show results for all three comparisons.

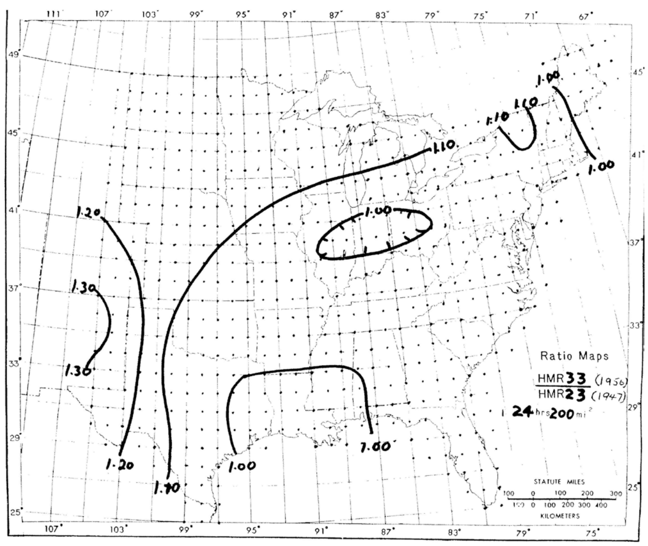


Figure 5-1 Ratio map of HMR 33 to HMR 23 for the 24-hour, 200 mi^2 precipitation depth. Source: NWS and Bureau of Reclamation files

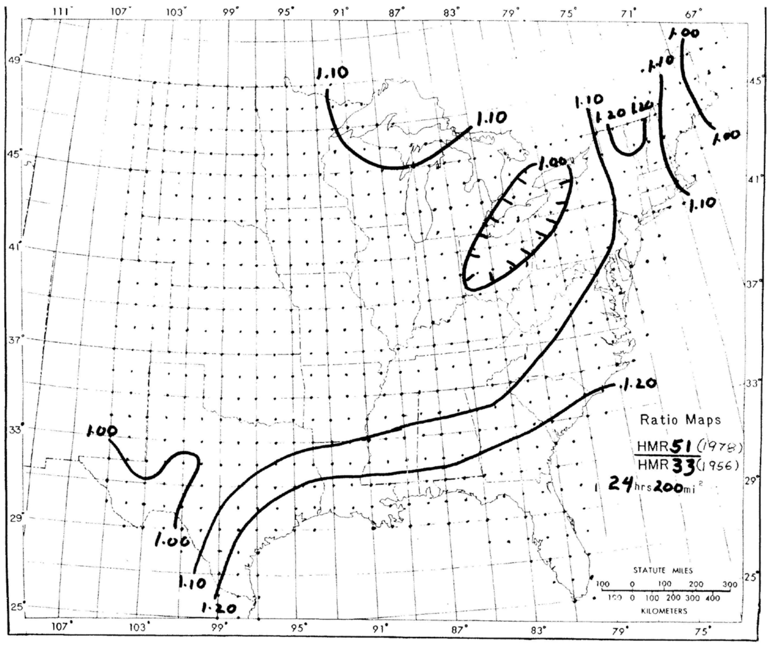


Figure 5-2 Ratio map of HMR 51 to HMR 33 for the 24-hour, 200 mi^2 precipitation depth. Source: NWS and Bureau of Reclamation files

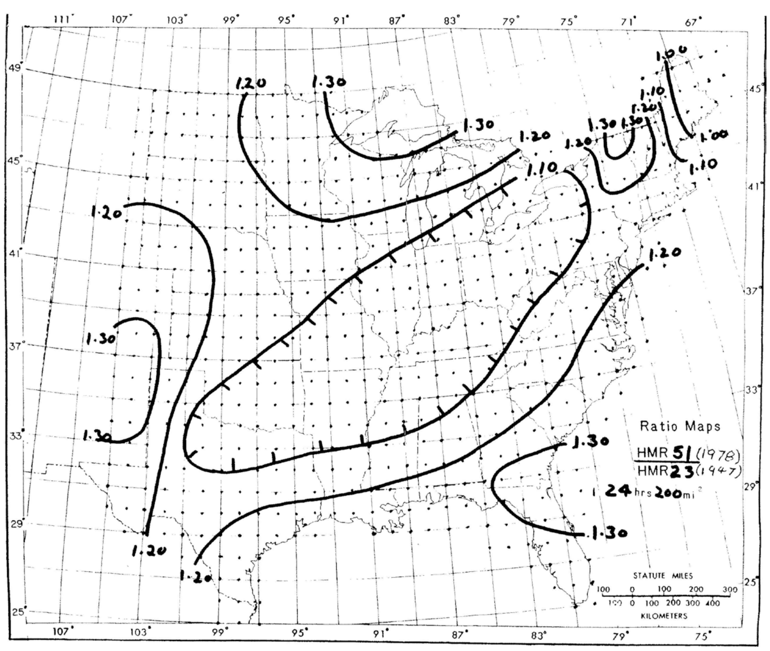


Figure 5-3 Ratio map of HMR 51 to HMR 23 for the 24-hour, 200 mi^2 precipitation depth. Source: NWS and Bureau of Reclamation files

There is little change in the Southeast PMP from HMR 23 to 33 for the 24-hour, 200 mi^2 amount (Figure 5-1), as ratios are about 1.0. For the same duration and area size, there are changes from HMR 33 to 51 (Figure 5-2). For most regions of the Atlantic seaboard and southern U.S., HMR 51 exceeds HMR 33 values by at least 10 percent. Ratios of at least 120% cover the immediate Gulf coastal regions, all of Florida, southern Georgia, and coastal South Carolina.

The most recent storm taken into account in HMR 33 occurred in 1949. However, a greater number of storms overall was included within the analysis for HMR 33. There were a number of overlapping storms between the two HMRs, but HMR 51 eliminated numerous storms that were analyzed in HMR 33 in the Southeast, added storms in the Midwest region, and included more recent storms, including the significant Yankeetown, Florida (Hurricane Easy) storm (Figure 2-1, Figure 2-2, Figure 2-3). The increases seen for HMR 51 are primarily due to the inclusion of DAD data from the Yankeetown, Florida, storm not yet available when HMR 33 was completed. This one storm also explains the 130% increase in PMP over the Southeast between HMRs 51 and 23 (Figure 5-3). Thus, over the approximate 30-year time frame between storm data collection efforts and HMR publication dates, there was a 20- to 30-percent increase in PMP estimates over the Southeast (Figure 5-3). Analysis and synthesis of new storm data (e.g., Caldwell et al., 2011a; Caldwell et al., 2011b) is needed and crucial in determining if PMP estimates would increase over the 30 years since HMR 51 was published.

Since short-duration PMP is also of concern to NRC, we completed a cursory analysis of 6-hr, 200 mi^2 PMP estimates for the Carolinas from HMRs 33 and 51. The ratios of HMR 51 to HMR 33 vary from 95 to 98% across both states (Figure 5-4). Only in extreme western North Carolina do the ratios rise above 100% to approximately 105%. A closer examination shows the reason for this change is the transition from Zone 6 to Zone 7 in HMR 33 (Figure 4-1). The 6 to 24-hour ratio in the HMR 33 DAD relationships drops 10% from Zone 6 (eastern zone) to Zone 7, and even though 24-hr, 200 mi^2 PMP doesn’t effectively change across the state, 6-hr PMP values in western NC do because of the drop from the highest to one of the lowest 6 to 24-hr ratios in the entire HMR 33 study area.

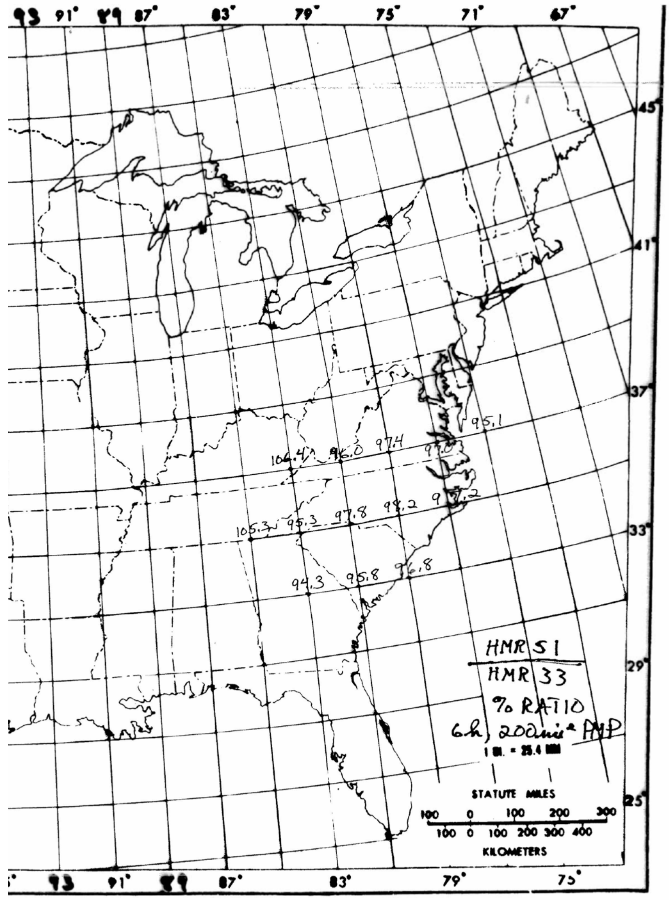


Figure 5-4 Ratio map of HMR 51 to HMR 33 for the 6-hour, 200 mi^2 precipitation depth

Because HMR 33 and 51 used various versions of the USACE (1973) storm DAD catalog, we conducted a detailed search and data collection for past events from this catalog that might have an impact on PMP values in the southeastern U.S. It is important to reiterate (see Section 3.1) that the DAD data from USACE (1973) and data from HMRs 33 and 51 are in paper format; no electronic data are available. As part of this case study project, Reclamation developed various electronic data sets of existing DAD data for the Southeast that are described in Appendix A. Information was gathered for a total of 83 major storms at various levels of detail. The changes between 'controlling' storms from HMR 33 and 'important' (or major) storms used in HMR 51 (Figure 4-2) are shown in Figure 5-5. There are very few observed storms in North and South Carolina in these categories. From HMR 33 and 51, the storms from the DAD catalog that are important to PMP estimates in the Carolinas are Yankeetown (SA-5-8), Elba (LMV 2-20), Altapass (SA 2-9), and Ewan (NA 2-4) (Figure 5-5), and are listed in Table 5-1. These storms are most influential in setting the level of PMP for at least one combination of area size and duration in HMR 51 in the Carolinas.

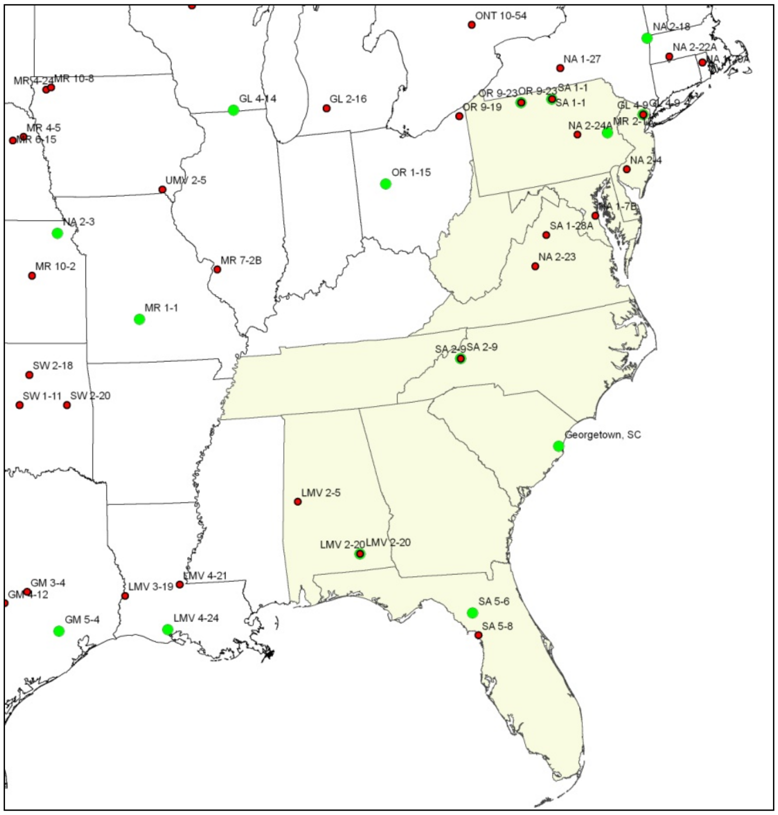


Figure 5-5 Locations of 'controlling' storms from HMR 33 (green) and 'important' storms used in HMR 51 (red), with USACE storm assignment numbers. Southeast study focus area is shaded.

Table 5-1 Controlling and important storms from HMRs 33 and 51 in the Carolinas and Southeast

HMR51 No.	COE Assign	Storm Date	Location	State	24hr, 10mi² depth (in)	Total 10mi² depth (in)	Moisture Adj
85	SA 5-8	09/03-07/1950	Yankeetown	FL	38.7	45.2	110
-	SA 5-6	10/17-22/1941	Trenton	FL	30.0	35.0	113
74	OR 9-23	07/17-18/1942	Smethport	PA	29.2	29.2	110
99	NA 2-23	08/19-20/1969	Tyro	VA	25.4	25.4	105
-	SA 4-20	10/04-11/1924	New Smyrna	FL	23.2	36.5	121
68	NA 2-4	09/01/1940	Ewan	NJ	22.7	22.7	122
31	SA 2-9	07/13-17/1916	Altapass	NC	22.2	23.8	121
-	LMV 4-24	08/06-09/1940	Miller Island	LA	22.1	37.3	110

47	LMV 2-20	03/11-16/1929	Elba	AL	20.0	29.6	134
-	SA 3-11	08/28-31/1911	St. George	GA	19.0	19.1	121
-	GM 5-4	12/05-08/1935	Satsuma	TX	18.6	20.8	152
-	NA 2-3	08/19/1939	Manahawken	NJ	17.8	17.8	122
-	SA 3-20	09/23-28/1929	Glennville	GA	16.0	20.0	121
-	SA 4-15	08/01-03/1915	St. Petersburg	FL	15.5	16.6	116
-	SA 2-9A	07/13-17/1916	Kingstree	SC	15.1	16.8	121
6	NA 1-7B	07/26-29/1897	Jewell	MD	14.7	15.8	141

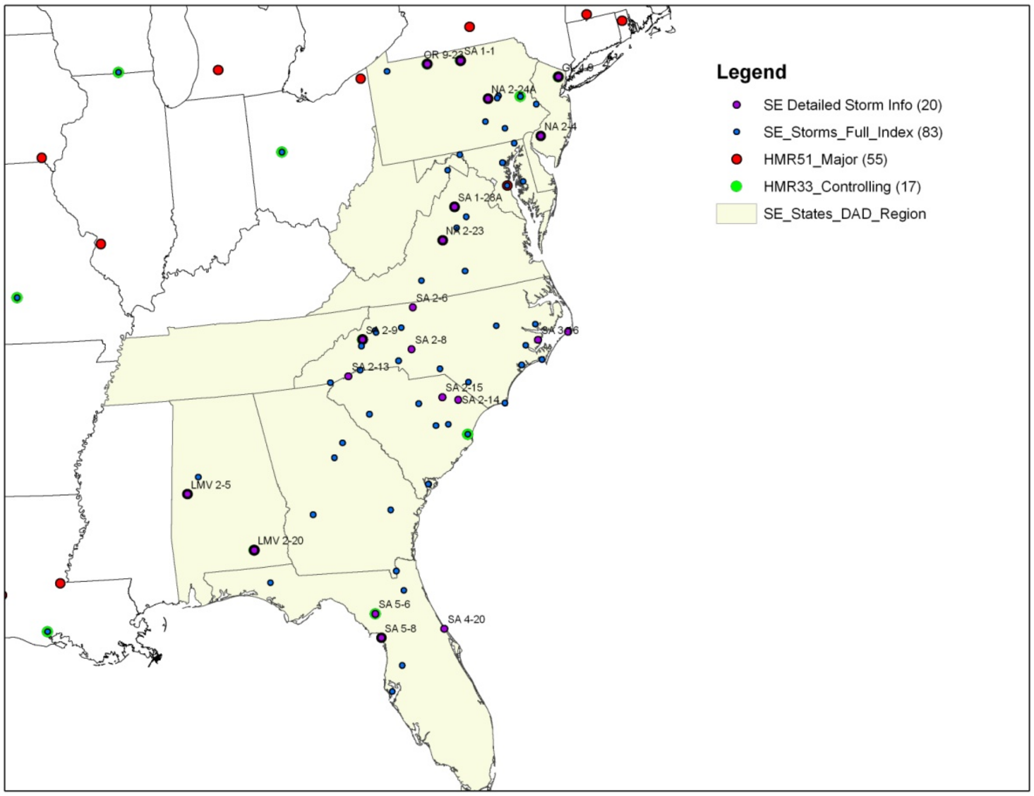


Figure 5-6 Locations of storm DAD data (83 Southeast events) developed into an electronic catalog. Detailed storm information is provided electronically for the 20 events shown with USACE Assignment No. labels. Southeast study focus area is shaded.

There are very few controlling or major storms with centers located within the Carolinas (Figure 5-5). In order to better understand extreme storm rainfall magnitudes, and to eventually understand frequencies, information from USACE (1973) was gathered for all storms with centers within the Carolinas, as well as many storms in the Southeast region. Data gathering and electronic processing were completed for 83 storms; detailed information was gathered for 20 events within and surrounding the Carolinas. There are many storms with storm centers in the Carolinas from USACE (1973); locations are shown in Figure 5-6. Detailed information that was gathered for each of these storms is listed in Appendix A.

5.2 PMP and Observed Storm Comparisons

As part of each HMR, some limited comparisons are made between observed storms and PMP estimates, or previous PMP estimates. For example, in HMR 57, comparisons were made to previous PMP estimates from HMR 43 in the Pacific Northwest as well as to observed storm maxima (Hansen et al., 1994 pp. 174-180). Likewise, in HMR 59, comparisons were made between HMR 59 PMP values and previous estimates published in HMR 36 for California, as well as with 24-hour point rainfall amounts (Corrigan et al., 1999 pp. 211-217).

In the case of HMR 51, a subsequent effort was made after HMR 51 to compare observed extreme storm rainfalls and PMP values (Riedel and Schreiner, 1980). The data used in comparison were from USACE (1973), Shipe and Riedel (1976), station point data, and frequency information from TP-40 (Hershfield, 1961). Comparisons were made across the United States for various storm durations and area sizes. Here, the focus is limited to the eastern U.S., covered by HMR 51. There were 59 storms that were greater than 50% PMP east of the 105th meridian (Riedel and Schreiner, 1980 p. 22). Some of the most important largest storms in the southeastern U.S., that exceeded 50% of PMP, are listed in Table 5-1. Comparisons were also made with point rainfall frequency estimates using ratios. One particular interesting example is shown in Figure 5-7, and suggests high ratios (exceeding 5) along the Appalachians in North Carolina and moderate ratios within the Carolina Piedmont. The HMR 51 PMP grids, described in Appendix A, are used for new storm PMP comparisons (Caldwell et al., 2011a) as well as similar ratio comparisons to that shown below (Caldwell et al., 2011b). Instead of relying on TP-40 (Hershfield, 1961), NOAA Atlas 14 frequency information (Bonnin et al., 2006), with much more spatial detail, is used for comparisons.

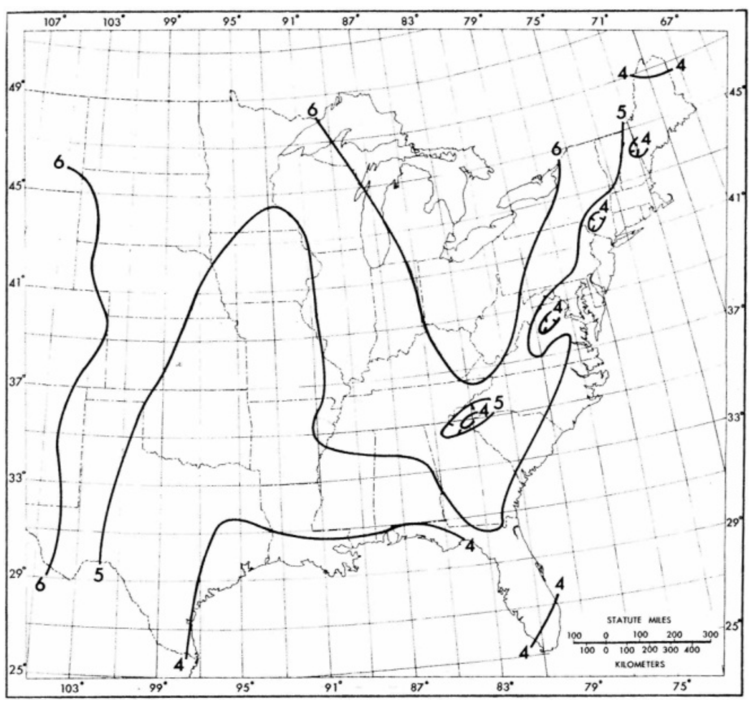


Figure 5-7 Ratios of 10 mi^2 PMP (HMR 51) to 100-year rainfalls (TP-40) for 24 hours (Riedel and Schreiner, 1980 Chart No. 38)

Since Riedel and Schreiner (1980) was published, there have been no comprehensive comparisons of HMR 51 PMP and newer storms that have occurred since that time. Caldwell et al. (2011b) present some comparisons based on ten recent tropical cyclones that have occurred over the Carolinas. Some other comparisons, based on individual events, are listed in Section 6. In order to properly assess PMP magnitudes with observations, uncertainty estimates are needed for both PMP quantities and observations. Unfortunately, the PMP estimates within the HMRs are not supplied with any estimates of uncertainty, such as standard errors or confidence intervals. Some preliminary uncertainty estimates have been made for previous HMRs, notably HMR 43 (superseded by HMR 57) in the Pacific Northwest. In a memorandum to the Army Corps of Engineers regarding HMR 43, Myers (1967b) provided some subjective estimates of uncertainty, expressed in terms of lower and upper "confidence bands". A lower limit of PMP confidence band for areas west of the Cascades was to reduce the orographic portion by 5% and the convergence portion by 10%. For areas east of the Cascades, a 15% reduction for both orographic and convergence components was suggested. General guidance on factors that would apply to an upper limit of PMP confidence band, rather than percent increases, was suggested (Myers, 1967b). As noted in Section 7, PMP probabilities and uncertainty is an area of research.

5.3 Additional HMR Studies and Issues

There are several needed studies and issues related to the HMRs that have been previously recognized. As part of Interagency cooperative PMP studies, Stallings et al. (1986) listed three anticipated future activities, including: (1) revising PMP estimates in California; (2) investigating antecedent rainfall prior to PMP; and (3) revising and expanding areas and durations for PMP estimates in Alaska. The first two of these activities have been initiated. Corrigan et al. (1999) provide PMP updates for California. Chin and Vogel (1995) studied antecedent storms in Kansas, Oklahoma, and eastern Colorado for areas up to about 100 mi^2; similar studies have not been completed for other locations or area sizes. HMRs 55A, 57 and 59 also provided recommendations for future work; these are summarized in Table 5-2. For details, see Hansen et al. (1988, pp. 220-222), Hansen et al. (1994 p. 185) and Corrigan et al. (1999, p. 231). Notably, HMRs 51-53 made no recommendations for future studies. It is clear from Table 5-2 that there are many unmet needs in PMP application and understanding, especially on the spatial and temporal distributions of extreme rainfalls in orographic areas.

Table 5-2 HMR recommendations summary and status

HMR	Topic	Status
55A	Seasonal PMP variation	Incomplete
55A, 57, 59	Temporal distribution of rainfall	Incomplete
55A, 57, 59	Spatial precipitation patterns for individual drainages	Incomplete
55A, 57	Snowpack, temperature and snowmelt criteria	Incomplete
59	Review of temperatures, dewpoints and winds for snowmelt	Incomplete
55A **59**	Antecedent precipitation	Partially Complete (Chin and Vogel, 1995)
57 **59**	Automated DAD capability by NWS More efficient DAD storm processing	Partially Complete

59	Applying radar precipitation data for spatial and temporal patterns	Incomplete
59	Enhance understanding of physical processes assumed in PMP studies with models	Incomplete

One issue that was not mentioned for further work is that related to small-area, short-duration precipitation. Further work is needed on describing relations between point and 10mi^2 areal amounts; they are used to represent the same area in many cases. Jensen (1995) provided some guidance for applications in Utah. Extreme local storms and their effects on PMP estimates, such as the Smethport, PA, 1942 record storm (Table 5-1) also are in need of review. Smith et al. (2011) examine some of these issues

6 PMP-RELATED STUDIES

In addition to NWS PMP reports, other PMP reports, and work on extreme storms have been completed and documented in consultant reports, workshop notes, and journal articles. After the publications of HMR 57 in 1994 and HMR 59 in 1999, most work on PMP-related topics have been conducted by the academic community and consultants, in selected areas. These topics include: regional and site-specific PMP estimates, PMP concepts and numerical modeling, workshops, and radar-based studies. Relevant research related to extreme storms in the southeastern United States in these areas is listed in this section. There is an opportunity to leverage this work to improve PMP methodologies and estimates of extreme storms in space and time. Most of this has not been synthesized for operational use in making revised PMP estimates over large areas.

6.1 Regional and Site-Specific PMP Studies

Pioneering work on PMP regional studies and data sets was led by the Electric Power Research Institute (EPRI) in a series of studies on regional PMP for Michigan and Wisconsin (EPRI, 1993a), radar data (EPRI, 1993b), and satellite data (EPRI, 1993c). Because the Michigan and Wisconsin study was the groundwork for many later studies, we summarize that work. Some published and ongoing regional and site-specific PMP studies are also listed. These studies are important because the Federal Energy Regulatory Commission allows site-specific and regional PMP studies to be considered as part of flood studies and relicensing of hydropower projects (FERC, 2001).

6.1.1 Michigan/Wisconsin PMP Study

The Electric Power Research Institute initiated a regionalized PMP study for the states of Wisconsin and Michigan in 1990. The impetus for the study was the concern that observed historical rainfall amounts in the region were much less than the PMP values provided in HMR 51. It was deemed to be unusual "that none of the observed precipitation was greater than about 55 percent of the PMP," whereas in "most other areas of the eastern U.S., the ratio exceeded 60 percent." The study investigators were required to follow the procedures of HMR 51, unless improvements due to technological changes and database availability could be employed (EPRI, 1993a). Both cold and warm season (all season) PMP estimates were developed.

Due to the request for consistency with HMR 51, the same basic procedures of moisture maximization and transposition of observed severe storms and envelopment of the results both areally and durationally were used. Several apparently important differences in the process were invoked. In PMP studies, the measure of available atmospheric moisture for precipitation production has traditionally centered on the use of dewpoint temperature measurements. In HMR 51 and other HMRs the maximum *persisting* 12-hour dewpoints at the 1000 mb (millibar) pressure level (essentially sea level) have always been used for calculating the moisture maximization and transposition adjustments that are made to individual storms. The EPRI investigators decided that *average* 1000 mb dewpoints for durations of 6, 12, and 24 hours developed with a return period climatology would be more appropriate to use.

Because of the inconsistency caused by using different dewpoint procedures for the older storm data set from HMR 51 versus the more recent storms, an approach was developed to estimate *average* representative dewpoints for the older storms. Maximum persisting and average dewpoints were determined for the seven recent storms not considered in HMR 51 and the average difference between the two dewpoint measures calculated. The differences were stratified by the two storm types believed to occur in the study region, mesoscale convective systems (MCS) and synoptic scale systems. The 12-hour average dewpoint for MCS-type storms averaged five degrees (°F) greater than the maximum persisting 12-hour dewpoint for the same storms, and the 12-hour average dewpoint for synoptic – type storms averaged two degrees greater than the maximum persisting 12-hour dewpoint for the same synoptic storms. By increasing the 12-hour persisting storm dewpoints in the older storms by these amounts, it was felt that a reasonable 12-hour average storm dewpoint was obtained for each storm.

Precipitation data from newer storms of interest, that did not have existing DAD data, were analyzed using computerized automation techniques with customized and commercial software. The new DAD data were included with the DAD data for the HMR 51 storms. A total of 25 warm season storms and 8 cold season storms were used in the study. Seventeen of the warm season storms were also used in HMR 51, with the remaining eight storms being more recent events. Moisture maximization and transposition of the storm data set was then accomplished using the return period dewpoint climatology and the adjusted representative average storm dewpoints. Transposition limits were determined for each storm, and a grid of 2° longitude by 2° latitude points was used as the locations for transposition over the study area. In this way, gridded maps of maximized storm rainfall amounts for various durations and areas were produced. The final contour analyses were created by the standard process of enveloping the largest value at each grid point with the goal of providing smooth curves with spatial continuity in the final results.

It was also surmised that storms occurring within a short distance of the Great Lakes shoreline may experience enhanced low-level convergence and increased vertical motion due to the frictional convergence of onshore-blowing winds. To account for this effect, the recommendation was made that 6- and 12-hour PMP amounts at locations within 30 miles of the lake shorelines be increased by 10 percent and 5 percent for the 100 and 200 mi^2 areas, respectively.

Storm rainfall patterns for the study area were analyzed for storm shape and preferred orientation of occurrence as was done in HMR 52 for the entire country east of the Rockies. Some minor differences from the HMR 52 results were derived based on the limited storm sample for the study area.

The EPRI study resulted in differences in PMP estimates over those provided by HMR 51 for Wisconsin and Michigan. For most areas and durations the EPRI PMP values were less, ranging from 75 to over 90 percent of HMR 51 PMP. Differences were largest at the smaller areas, but at larger areas of 5,000 and 10,000 mi^2 and at longer durations, the EPRI study amounts exceeded HMR 51 PMP by several percent.

6.1.2 Regional, Statewide and Site-Specific PMP Studies

Other than the EPRI (1993c) regional study for Michigan and Wisconsin, there have been no other major, regional PMP studies that have been published in the United States. Instead, there have been several statewide PMP studies and site-specific studies that focus on particular drainages. The statewide and site-specific studies (e.g., AWA, 2008b) have been completed mainly by consultants for use in evaluating projects regulated by the Federal Energy Regulatory Commission. Statewide studies include the Nebraska PMP study (AWA, 2008a), the Extreme Precipitation Analysis Tool (EPAT) for Colorado and New Mexico (developed by HDR, Inc.), and ongoing statewide PMP studies in Arizona, Ohio and Wyoming by Applied Weather Associates. Site-specific PMP studies have also been completed to assess projects by the Army Corps of Engineers, Bureau of Reclamation and Nuclear Regulatory Commission. Notable examples include the Hoover and Glen Canyon Upper Limit Design Storm study (M-K Engineers, 1990) for Reclamation, the Dewey Dam study (Fenn, 1985) for the Army Corps of Engineers, and the Upper Deerfield River study (Miller et al., 1984) for the NRC. Many other, more recent site-specific PMP studies have been performed by consultants (e.g., Applied Weather Associates; HDR, Inc.) for projects throughout the United States. Some of the site-specific PMP issues and techniques are summarized by FEMA (2002), AWA (2008b) and Tomlinson and Kappel (2009).

6.2 PMP-Related Workshops

There have been several extreme storm and PMP-related workshops that have been held over the past 25 years. The objectives of the workshops have varied, but overall goals are to improve estimates of extreme rainfalls and floods. Major workshops and reports include the following. The National Academy of Sciences (NAS) has hosted three main symposia, resulting in several National Research Council (NRC) publications. Methods and techniques to estimate extreme flood probabilities, including extreme storm rainfall data, are described in NRC (1988), a study that was sponsored by the Nuclear Regulatory Commission. This study and report is the basis for much probabilistic work described in Section 7. The Federal Energy Regulatory Commission sponsored an October 1993 workshop on preliminary assessments on probabilities and bounds on extreme precipitation. A workshop summary (NRC, 1994) noted several key recommendations, including: use of WSR-88D radar in storm studies and integrating data into a PMP catalog; increased research efforts for numerical modeling of extreme storms in mountainous regions; and strategies on storm-based analyses of extreme rainfall and extreme probabilities. Recently, an October 2008 NAS workshop on needs in flood hydrology science (Logan and Helsabeck, 2009) highlighted improved assessment of hydrologic data (including reanalysis) is needed, and there are challenges with research to operations in flood hydrology.

Several workshops have been sponsored by Reclamation and FEMA/USACE, focusing on flood-related dam safety aspects. The Bureau of Reclamation hosted a workshop in June 1997 on extreme rainfalls, storms and floods (Reclamation, 1999), focusing on flood risk for dam safety. Analysis of extreme precipitation and data collection were highlighted. A November 2001 workshop held at USACE (FEMA, 2002) includes a comprehensive list and ranking of extreme storm meteorology needs. The following elements were ranked highest: historical database of storms and floods; precipitation analysis; analysis of the last 10 years of storm data; and analysis of older storms. Several other workshops have been held on extreme storms and rainfall at Association of State Dam Safety Officials meetings, and by smaller, local groups such as the State of Colorado, but these typically lack workshop reports. Notably, McKee and Doesken (1997, p. 24) listed a workshop agenda on modeling large convective storms in complex terrain. That workshop led to a study using the RAMS atmospheric model to simulate extreme storms in Colorado (Cotton et al., 2003), that is mentioned below.

An Extreme Storm Events Work Group, under the Subcommittee on Hydrology is currently coordinating Federal agencies regarding issues on PMP and extreme storms (England et al., 2008; England et al., 2010). Further details on the workgroup are available on the web at http://acwi.gov/hydrology/extreme-storm/index.html.

6.3 PMP-Related Research

A brief survey and listing of recent literature is provided on two major topics related to PMP: (1) PMP methods and numerical modeling studies; and (2) radar-based extreme storm studies. There has been some directly-relevant research on PMP methods, assumptions, estimation and modeling over the past 10 years. We have attempted to summarize the relevant PMP literature on the topic, and have expanded the topics to cover analyses of extreme storms. As such, there may be some research studies that may have been overlooked or missed, or discussed elsewhere. For example, some tropical cyclone literature related to the Southeast is presented in Caldwell et al. (2011b). Most of this research has yet to be assimilated into operational estimates of PMP; thus there are a host of opportunities to make substantial improvements to existing methods and data described in Sections 2-4.

Several investigators have utilized advanced, 3-D atmospheric models, including the Regional Atmospheric Modeling System (RAMS), and the fifth-generation NCAR/Penn State Mesoscale Model (MM5), to replicate observed extreme storms, simulate them, and investigate the precipitation and other ingredients for extreme rainfalls and floods. This research area is one mentioned by NRC (1994); results have not yet made their way into PMP practice. Katzfey (1995a,b) utilized the Division of Atmospheric Research (DAR) hydrostatic model nested within the ECMWF (European Center for Medium-Range Weather Forecasts) to simulate extreme precipitation over New Zealand. Collier and Hardaker (1996) developed a simple model of storm convective systems to simulate PMP over the United Kingdom, focusing on mesoscale convective systems (MCSs). Hardaker (1996) subsequently used this model to estimate PMP for a particular catchment in Greece. Abbs (1997) utilized RAMS to investigate several key PMP assumptions. Two key conclusions she found, based on four case studies, are: storm efficiency does not increase as moisture availability increases; and the spatial distribution of rainfall changes as moisture availability increases. The convergence component (Section 4) of orographic rainfall is changed due to terrain effects (Abbs, 1997). Cole et al. (2000) utilized MM5 to reproduce the 5-9 February 1996 flooding event over the Pacific Northwest, using precipitation gages and radar data for verification, and suggested that improvements to microphysical schemes were needed in order to improve precipitation prediction. Chen and Bradley (2000) utilized MM5 to examine moisture availability for the extreme 17-18 July 1996 Illinois storm. Their study utilized the methods from Zhao et al. (1997) (along with two others), to adjust the moisture availability over a wide range, but within upper limits of the maximum observed precipitable water. Tomlinson and Desereau (2002a,b) utilized MM5 to model five extreme storms in the Pacific Northwest to understand the meteorology, how they were produced, and potentially transpose the storms to a watershed in eastern Oregon for the Bureau of Reclamation. Results of their research were summarized by England (2003), indicating that further work was needed in this area.

Over the past decade, there have been advancements in understanding of extreme storms with several modeling approaches, such as RAMS and the Weather Research and Forecasting (WRF) model. In a pioneering study for the State of Colorado, Cotton et al. (2003) utilized RAMS to examine extreme storms and precipitation mechanisms at high elevations, simulating the 1976 Big Thompson, 1997 Fort Collins, and 1999 Dallas Divide storms (among others), and making preliminary PMP estimates. Numerical modeling of individual storm events is now beginning to be a standard research technique. Some example recent studies using WRF include: examination of the 7 July 2004 storm over Baltimore (Ntelekos et al., 2008); evaluations of extreme precipitation and potential climate change impacts at high elevations over the Colorado Front Range (Mahoney et al., 2010; Mahoney et al., 2011); and investigating complex terrain and storm dynamics of four extreme storms in the Appalachians (Smith et al., 2011).

Alternatives to PMP have been explored by Ohara et al. (2011) using MM5 in a case study of the American River watershed. Evaluation of PMP moisture maximization assumptions by Chen and Bradley (2006) and effects of individual extreme storms on PMP (Chen and Bradley, 2007) suggest that existing PMP method are in need of revision. Physically based numerical models are currently available to provide a test bed for storm duration and intensity analysis. In existing PMP methods an intense storm with multiple rain periods might be assigned an incorrect mean moisture availability index. Also, the estimated precipitable water based on existing PMP assumptions is much greater than that observed with upper-air soundings. Improvements to PMP and extreme storm estimation practice can be made by utilizing results of these investigations and associated methodologies.

Radar-based extreme storm studies are a second research avenue that is complementary to numerical modeling investigations. Observation-based analyses, focusing on radar rainfall estimation (e.g. Krajewski and Smith, 2002; NRC, 2005), has been an active research area to investigate critical factors in storms that produce extreme rainfalls, storm evolution, and spatial and temporal information on individual events. Smith et al. (1996) explored the effects of terrain on the 27 June 1995 extreme storm in Virginia; they suggested this near-record event has a very limited transposition region. Doswell et al. (1996) proposed an ingredients-based methodology for forecasting extreme rainfalls. Their methods have subsequently been used for understanding extreme storms in a variety of settings. Pontrelli et al. (1999) to compare the 27 June 1995 Madison County, Virginia flash flood to the 1976 Big Thompson and 1997 Fort Collins floods. Smith et al. (2000) examined two extreme rainfalls in Texas, describing storm structure, evolution, and motion and their effects on maximum flood peaks. Rainfall from supercell thunderstorms, responsible for major floods in Texas, Florida, Nebraska and Pennsylvania were described by Smith et al. (2001). Sturdevant-Rees et al. (2001) explored the effects of 1996 Hurricane Fran in Virginia, showing relationships between storm evolution, topography, and orographic enhancement. Analysis of a local, orographic thunderstorm by Hicks et al. (2005) helped to document this 9 August 2003 record event in West Virginia. Javier et al. (2007) used radar analyses from a series of storms to illustrate prominent terrain effects in the upper Arkansas River in Colorado, and limits to westward propagation of storm rainfall amounts. Nykanen (2008) used a multiscale statistical framework to analyze effects of orographic forcing, storm movement and terrain and storm classification, based on several radar data sets. Recently, Nelson et al. (2010) developed a relatively long-term, archival data set of gridded precipitation based on radar rainfall estimates merged with precipitation gages, called Multisensor Precipitation Reanalysis (MPR). This radar-based MPR data set is utilized in Caldwell et al. (2011a) for the Southeast case study project. Based on the extensive research using radar rainfall mentioned above, it is clear that radar rainfall estimates need to be used in extreme storm processing and PMP estimation, thereby fulfilling the initial ideas presented in EPRI (1993b).

6.4 PMP and Climate Change

One pertinent question on PMP procedures is the following: “What are the potential impacts of climate variability and change on Depth-Area Duration relationships and PMP procedures, including transposition, moisture maximization and envelopment?” The potential effects of climate variability and change on PMP estimates have not been subject to much previous investigation. We briefly summarize relevant literature in three areas: PMP modeling and climate change; trends in station data; and trends in moisture potential inferred from Global Climate Model (GCM) projections.

Two studies that were conducted by the Bureau of Reclamation in the western United States focused on climate change impacts to PMP. Jensen (1994) conducted a brief literature review and synthesized data on nine extreme rainfall events in Wyoming, Utah and Arizona. An attempt was made to transpose these storms and compare them with results from four climate models. Results were inconclusive because temperature and precipitation fields were only available as seasonal means (Jensen, 1994). In a subsequent study, Eddy (1996) examined potential climate change effects on PMP estimates from HMR 49 in the Southwest and HMR 57 in the Pacific Northwest. A sensitivity/delta method was used, investigating impacts to: dewpoint temperature increases; estimation errors; and average variability for local storms, with standard and site-specific scenarios created. The results suggest that there might be increases in a few percent to PMP values; larger increases might result from increases in maximum dewpoint temperatures (Eddy, 1996).

Many authors have conducted trend analysis of precipitation and streamflow observations, or other factors, to detect potential climate variability. Bonnin et al. (2006) used linear trend analysis to detect trends in precipitation in the southeastern United States. They found some positive and negative trends in the region, but no spatial coherence to the patterns. Smalley et al. (2007) found positive and negative changes in relative storm efficiency and storm depth in Australia. Alfnes and Førland (2006) found positive and negative trends in extreme one-day maximum precipitation in Norway. They infer small increases (up to 5%) in PMP estimates based on this and other work. Research to date on flood and streamflow trends (e.g. Lins and Slack, 1999; Cohn, 2008; Hirsch, 2008) suggests that streamflow may be increasing in some parts of the United States, but that no spatially coherent trends in extreme floods (peaks or annual maximum values) are found.

In contrast to streamflow, investigations into extreme precipitation amounts from station data appear to reveal increased frequencies of heavy precipitation. A series of studies by Kunkel and coauthors, including Kunkel et al. (1999), Kunkel (2003), Kunkel et al. (2007) and Kunkel et al. (2008) suggests that heavy precipitation amounts or exceedances are increasing. DeGaetano (2009) suggested that GEV precipitation frequency model parameters were changing, leading to heavier-tailed distributions and increases in 50-year quantiles. Bonnin et al. (2011) suggest that there are differences in climatological terminology on exceedances and heavy rainfall that cloud the issues, and that magnitudes of increasing precipitation trends may be small for the Ohio River basin and Southwestern U.S. In an investigation of Midwest heavy rainfall, Villarini et al. (2011) examined temporal stationarity and long-term persistence; their results showed (among other things) slight positive trends in annual maximum daily rainfall, but trends were less significant for higher quantiles.

Some researchers have very recently commenced preliminary investigations into the potential impacts of moisture increases from GCM projections. Kunkel et al. (2010), Easterling and Kunkel (2011) and Kunkel and Easterling (2011) are exploring changes to PMP using present and future simulations from global and regional models. It is clear that additional work is needed in order to begin to answer the question on climate variability and change on PMP estimates. Caldwell et al. (2011b) investigate trends in moisture potential in the Southeast using newer gridded data sets, as an initial practical (operational) step toward addressing this question.

7 PROBABILISTIC ALTERNATIVES TO PMP

There are readily-available probabilistic alternatives to PMP for assessments and designs of critical infrastructure. Existing methods that have been applied for high-hazard assessments of major dams consist of: PMP probabilities using Hershfield's approach; regional precipitation frequency with L-Moments; estimating annual exceedance probabilities (AEPs) of the PMP with Australian Rainfall-Runoff; and stochastic storm transposition techniques. We briefly summarize these methods, along with some other recent alternatives. These methods need to be considered as part of any transition away from PMP (maximum) rainfall concepts toward Probabilistic Risk Analysis (PRA). Schaefer (1994) and Koutsoyiannis (1999) highlight some of the philosophical and conceptual issues regarding PMP and risk concepts.

The concepts that are the foundation for probabilistic alternatives to PMP are described in NRC (1988), and include: substitution of space for time (e.g. regional precipitation frequency); introduction of more 'structure' into models; and focus of extremes or 'tails' as opposed to or even to the exclusion of central characteristics. One simple method to estimate PMP probabilities, and full rainfall probability distributions, is Hershfield's approach; this method is described in some detail in WMO (1986) and WMO (2009). This method utilized the Gumbel distribution and a frequency factor based on the rainfall duration and the mean to estimate PMP. Some examples of applications of these probabilistic alternative methods to specific sites are as follows. Koutsoyiannis (1999) conducted a critical appraisal of Hershfield's approach, and suggested some improvements with the Generalized Extreme Value (GEV) distribution and frequency factors based on duration. Cotton et al. (2003) used Hershfield's method to compare PMP estimates in Colorado from RAMS. Papalexiou and Koutsoyiannis (2006) utilized frequency analysis of dewpoints to compare maximized rainfall time series with observations, and the GEV distribution with Hershfield concepts to estimate PMP at four sites in the Netherlands.

Regional precipitation frequency with L-Moments (Stedinger et al., 1993; EPRI, 1994; Hosking and Wallis, 1997) is a key method used for estimating extreme precipitation frequencies and subsequent flood probabilities in various rainfall-runoff models such as the Stochastic Event Flood Model (Swain et al., 2004). Schaefer (1990) conducted a study for extreme precipitation frequency estimates in the State of Washington using L-Moments. This was one of the first published uses of this method. Regional frequency with L-Moments is now the basis for precipitation frequency estimates published in NOAA Atlas 14 (e.g., Bonnin et al., 2006). Schaefer (1994) provides background information and rationale for using this method to assess critical infrastructure. This method has been applied to estimate extreme precipitation probabilities for dam safety at many locations in the Western U.S. by the Bureau of Reclamation (England, 2010; England, 2011), as well as for the Army Corps of Engineers (MGS Engineering, 2005) in a study for Folsom Dam in California.

Australian Rainfall-Runoff (ARR) (Nathan and Weinmann, 2001) provides a method and guidelines to estimate PMP AEP based on drainage area, and a full rainfall probability distribution. Typical estimates of basin-average PMP AEPs range from 10^{-4} to 10^{-7}, with AEP uncertainty estimates typically one or two orders of magnitude. These guidelines were based on a research practice report by Weinmann and Kuczera (1998). Reclamation has utilized the ARR and PMP probability concepts (Swain et al., 2006) to estimate hydrologic hazards for some dam safety assessments (England, 2010).

Stochastic storm transposition is a generalization of the concept of storm transposition (Section 2), by incorporating the probability of occurrence (NRC, 1988; Fontaine and Potter, 1989). It is an alternative to PMP, whereby AEPs of basin-average extreme storm rainfall are estimated. This method has been developed and applied to various watersheds by Yankee Atomic Energy Company (YAEC) (1984), Fontaine and Potter (1989), Foufoula-Georgiou (1989) and Wilson and Foufoula-Georgiou (1990). Stedinger et al. (1993) provide a brief summary of the method. Most of the work on stochastic storm transposition involved using DAD data (e.g., USACE, 1973; Hansen et al., 1988). Statistical evaluations of this catalog in the Midwest provided crucial information on DAD and extreme storm variability, as shown by Foufoula-Georgiou and Wilson (1990). England et al. (2006) utilized stochastic storm transposition to estimate extreme rainfall frequency curves for a large, orographic watershed in Colorado for dam safety, based on data from Hansen et al. (1988) and newer storms.

A recent alternative to PMP estimation using multifractals was proposed by Douglas and Barros (2003), following work by Hubert et al. (1993). Douglas and Barros applied mutifractal concepts to estimate the fractal maximum precipitation (FMP) and the design probable maximum precipitation (DPMP) for some example sites in Pennsylvania. Veneziano et al. (2006) provide a recent review of multifractals and precipitation in hydrology. These most recent techniques have not been directly applied in practice. Nevertheless, there are clear alternatives to PMP that use probabilistic concepts. Several methods, including regional precipitation frequency with L-Moments, ARR concepts, and stochastic storm transposition, have been utilized in probabilistic assessments of major infrastructure

8 SUMMARY

A review of PMP methods and databases was conducted. The main objectives of the review were to: (1) review PMP procedures and databases used to develop HMRs; (2) examine storm databases in the Southeast and document the evolution in PMP methodologies and estimates over time; and (3). summarize extreme storm research and PMP work done since HMR 51 was published, that is germane to PMP estimates in the Southeast. Most of the review was limited to describing existing, generalized PMP reports (HMRs) and existing data related to those reports, including HMRs 51-53. Subsequent HMRs were reviewed for their treatment of PMP in orographic regions, and to summarize changes in methodologies. Comparisons were made between storm data and procedures used in HMR 33 and HMR 51 for the southeastern U.S. case study region. Studies related to PMP and recent research on extreme storm estimation were briefly reviewed and summarized. Based on this review, we provide the following main conclusions.

The PMP DAD storm data base and related data bases are outdated. The USACE (1973) data base, the basis for HMR 51, is no longer maintained. Updates to extreme storm DAD data bases were made over time for individual HMRs (55A, 57 and 59). These data bases are also not being updated. There are relatively poor records and documentation in reports and files on individual extreme storms. Dewpoint climatology information is outdated and data sources for coastal areas have changed from land-based dewpoints (HMR 51) to SST estimates (HMRs 57 and 59). Precipitation frequency estimates, used for PMP comparisons (TP-40) and as base maps in orographic areas (NOAA Atlas 2), are outdated. These information sources are being updated with NOAA Atlas 14, with a much finer spatial resolution and improved methodology. Newer data sets, including radar-based precipitation estimates are available and the authors recommend that they be used in extreme storm processing and PMP estimation, thereby fulfilling the initial ideas presented in EPRI (1993b).

Generalized PMP reports in the eastern US, from HMR 23 to HMR 33 to HMR 51, were continually updated and improved. Updates in this region have since ceased. There was approximately a 30% increase in PMP for certain area sizes and durations in the Southeast over about a 30-year period (HMR 23 to HMR 51). The major change in PMP estimates from HMR 33 to HMR 51 was due to one storm (Yankeetown, 1950) and larger transposition regions. This one storm controls most PMP estimates in the Carolinas. A substantial amount of DAD data was gathered to expand and examine existing storms with centers in the Carolinas.

In terms of PMP methods, little has changed over the past 25 years since WMO (1986), as the recent WMO (2009) report includes the same base methodologies. As HMR 51 did not include orographic factors; limited PMP estimates were provided over the Appalachians and western parts of the region. Orographic methods, including storm separation, were developed in HMR 55A and subsequently documented in WMO (1986). These methods were used in HMR 57 and HMR 59, but the concept of storm separation has not been critically reviewed. There are several limitations noted in the western HMRs on providing space-time estimates of PMP, especially within orographic areas. Unlike the procedures in HMR 52, there are no methods for spatially and temporally distributing PMP over a watershed for locations other than the eastern United States.

Essentially, PMP methods as applied in the HMRs, are static and have not kept pace with the state of practice in meteorological observation and storm modeling. A brief review of recent literature indicated some key areas for improvement. The National Research Council (NRC

1994) recommended major research in several areas, including: incorporation of WSR-88D radar data into a PMP storm catalog; and studies for scientific understanding of extreme rainfalls, storm rainfall studies and extreme rainfall probabilities using numerical weather prediction models. Much research has been completed on these topics. As mentioned earlier, it is clear that radar rainfall estimates need to be used in extreme storm processing and PMP estimation. Several investigators have utilized advanced, 3D atmospheric models, including RAMS, MM5 and WRF, to replicate observed extreme storms, simulate them, and investigate the precipitation and other ingredients for extreme rainfalls and floods. Ready improvements to PMP and extreme storm estimation practice can be made by fully utilizing results of these investigations and associated methodologies. Most of this research has yet to be assimilated into operational estimates of PMP; thus there are a host of opportunities to make substantial improvements to existing PMP methods and data utilized. Key improvements based on numerical modeling, inclusion of uncertainties, finer spatial discretization, incorporation of local climate effects, use of climate variability/change information, and probabilistic estimates should be considered.

There are readily-available probabilistic alternatives to PMP for assessments and designs of critical infrastructure. Several methods, including regional precipitation frequency with L-Moments, ARR concepts, and stochastic storm transposition, have been utilized in probabilistic assessments of major infrastructure. These methods should be considered, along with improvements on extreme storm rainfall estimation, in lieu of or including PMP.

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APPENDIX A
DEPTH-AREA DURATION DATA AND HMR 51 PMP GIS FILES

This appendix summarizes electronic data sets, contents and formats developed based on existing data published in the U.S. Army Corps of Engineers Storm Rainfall catalog (USACE, 1973), and HMR 51 PMP GIS files.

These data sets were developed for the Nuclear Regulatory Commission (NRC) for the southeastern United States. The data sets are provided in support of ongoing studies to examine potential changes to PMP amounts in North and South Carolina (NC-SC), published in HMR 51 (Schreiner and Riedel, 1978). Three levels of detail were used to collect D-A-D data and supporting information for the NRC NC-SC case study study. Some examples of using the data set are listed below. Demonstrations of these examples, as well as other ideas, were presented to the NRC at their November 2009 Technical Advisory Group meeting, and the October 2011 Technology Transfer meeting at NRC.

The electronic data sets are supplied to the Nuclear Regulatory Commission under contract with the Bureau of Reclamation. The data sets are also provided to the National Weather Service, Office of Hydrology, Hydrometeorological Design Studies Center, and the U.S. Army Corps of Engineers, Omaha District, for in-kind support of this work.

Storm Rainfall Data and Report

The basic data set for this effort is USACE (1973). The U.S. Army Corps of Engineers has kindly provided an electronic copy of this report in pdf format. The report consists of two files, named:
US_Storm_Rainfall Data_VOL1.pdf and
US_Storm_Rainfall Data_VOL2.pdf.

The report consists of a listing of storms and pertinent data sheets for Depth-Area Duration (D-A-D) analyses (USWB, 1946). Storm data are organized by U.S. Army Corps of Engineers divisions. The first page of volume 1 is a map of the regions, showing acronyms for each region, such as: North Atlantic Division (NA), Upper Missouri Valley (UMV), and Great Lakes (GL). Volume 1 consists of NA, SA, LMV and UMV Divisions. Volume 2 contains GL, OR, MR, SW, GM and NP Divisions. This ordering follows the table of contents on numbered pages 1-14, shown in the front of each volume.

Additional, existing extreme storm D-A-D data were investigated and gathered from three other reports: HMR 33 (Riedel et al., 1956), HYDRO-33 (Shipe and Riedel, 1976) and HMR 51 (Schreiner and Riedel, 1978).

Regional Coverage

Storm D-A-D data were gathered from two general areas: a broad area of the eastern United States encompassing HMR 51; and a detailed area in the southeastern United States. For the broad HMR 51 area, data collection was limited to existing D-A-D data published within HMR 51. The HMR 51 D-A-D region is shown in Figure A-1, and includes 55 storms.

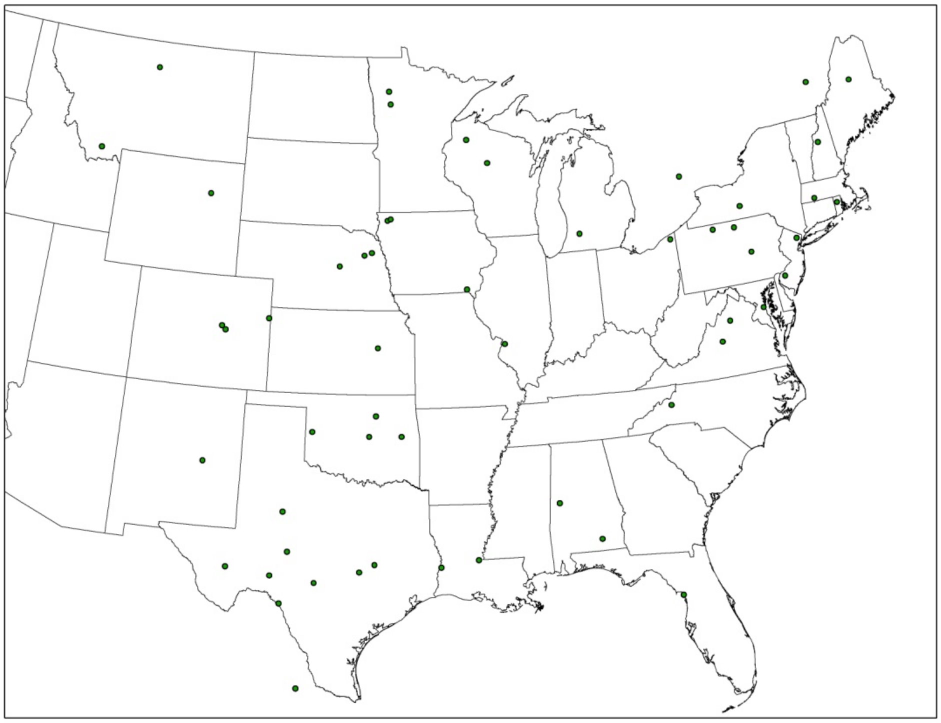

Figure A-1 HMR 51 Storm D-A-D region, with storm centers shown as dots

The detailed area for the Southeast surrounds the states of North and South Carolina. These two states consist of a 'case study' region for the NRC. Storm D-A-D data and detailed supporting information were collected from an area that generally consists of the eastern seaboard from Pennsylvania to Florida, and west to Alabama. The Southeast storms region is shown in Figure A-2. Detailed storm information was obtained for controlling storms, as defined in HMR 33, that have storm centers located within North and South Carolina. Additional information was collected for storms within North and South Carolina, consisting primarily of D-A-D data. There are 74 storms within the region that have some information available.

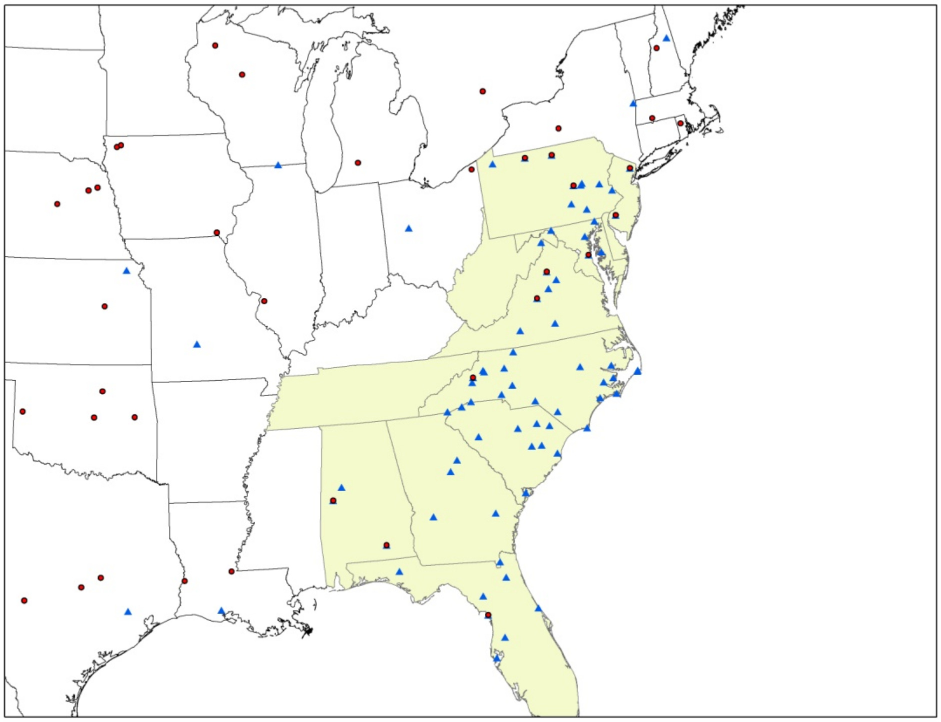

Figure A-2 Southeastern U.S. detailed D-A-D area depicted as color shaded state boundaries. Storms from HMR 51 shown as red dots. Storms from HMR 33 and USACE (1973) that have been gathered first-level (D-A-D) information within the region are shown as blue triangles.

Storm Focus and Detail

Three levels of detail were used to collect D-A-D data and supporting information for the NRC NC-SC case study. The first level of data detail includes listings and summaries of selected storms from USACE (1973), HMR 33 and HMR 51. The second level of detail included electronic D-A-D files for each storm. The third level of detail includes D-A-D files, Part II reports and supplemental information, for important storms within the southeastern region. The typical contents of Part II analyses are summarized in USWB (1946).

Storm listings for the first level of detail included the following: (1) all storms listed in HMR 51; (2) all storms listed in HMR 33; and (3) storms with centers in North and South Carolina listed in USACE (1973). These index listings are in spreadsheets and GIS layers described below. Data collected under the second level of detail includes all the 55 D-A-D tables listed in the HMR 51 Appendix. The tables were converted to electronic format that is described below. Data collected under more detail (third level) was completed for 20 sites that are listed in Table A-1 and shown in Figure A-3. These storms were selected based on their importance in determining PMP for HMRs 51 and 33. The listing includes the major (critical) storms in HMR 51 and the controlling storms in HMR 33 for the Southeast region, as well as supplemental storms that occurred within North and South Carolina. Further details on storm selection criteria for the region will be described in a separate data report to the NRC.

Table A-1 Important Southeast Storms Detailed Site Collection Listing

Storm Number (SE_Index)	COE Assignment No.	Storm Date	Location	State	Directory Name
1	SA 1-1	05/30-06/01/1889	Wellsboro	PA	SA_1-1
2	LMV 2-5	04/15-18/1900	Eutaw	AL	LMV_2-5
3	GL 4-9	10/07-11/1903	Paterson	NJ	GL_4-9
4	SA 2-9	07/13-17/1916	Altapass	NC	SA_2-9
5	LMV 2-20	03/11-16/1929	Elba	AL	LMV_2-20
6	NA 2-4	09/01/1940	Ewan	NJ	NA_2-4
7	OR 9-23	07/17-18/1942	Smethport	PA	OR_9-23
8	SA 1-28A	10/11-17/1942	Big Meadows	VA	SA_1-28A
9	SA 5-8	09/03-07/1950	Yankeetown	FL	SA_5-8
10	NA 2-23	08/19-20/1969	Tyro	VA	NA_2-23
11	NA 2-24A	06/19-23/1972	Zerbe	PA	NA_2-24A
12	SA 2-6	08/23-28/1908	Vade Mecum	NC	SA_2-6
13	SA 2-8	10/13-16/1914	Mt. Mitchell	NC	SA_2-8
14	SA 3-16	09/13-17/1924	Beaufort	NC	SA_3-16
15	SA 4-20	10/04-11/1924	New Smyrna	FL	SA_4-20
16	SA 2-13	08/13-17/1928	Caesars Head	SC	SA_2-13
17	SA 2-14	09/04-07/1928	Marion	SC	SA_2-14
18	SA 2-15	09/16-19/1928	Darlington	SC	SA_2-15
19	SA 5-6	10/17-22/1941	Trenton	FL	SA_5-6
20	SA 1-28B	10/11-17/1942	Hatteras	NC	SA_1-28B

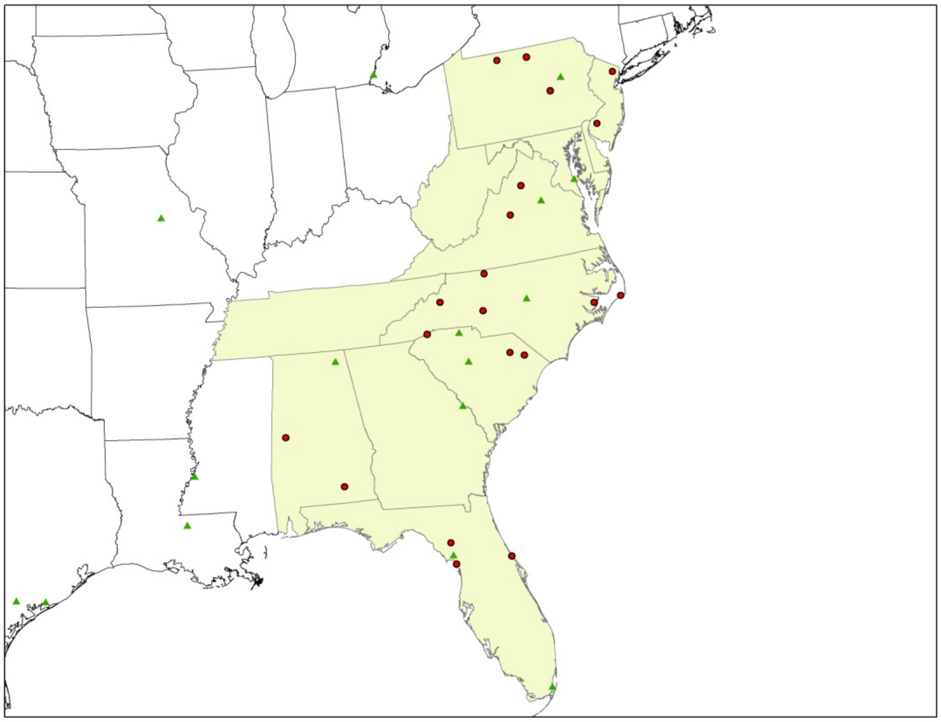

Figure A-3 Locations of 20 storms (shown as red dots) with detailed information that are summarized in Table A-1. Locations of projected new reactors within the southeastern region are shown as green triangles

Directory Structure and Contents

The top-level directory is called “NRC_SE_DAD” and contains this file. Subdirectories are listed in Table A-2. Full descriptions of the directories and file naming conventions are described below.

Table A-2 Southeastern U.S. Existing Storms Directory Structure

Directory Name	General Contents
USACE_1973	pdf version of the USACE (1973) Storm Rainfall publication
Base_GIS_Layers	Base GIS data layers for map display, such as states, counties, cities (etc.) described below
HMR51_GIS	HMR 51 storm index in Excel, ESRI shapefile, and D-A-D tables for 55 storms in .xls and .csv format
HMR51_PMP_Maps	two directories: TIFF contains HMR 51 Figures 18-47 in tif images; GEOREF contains the images in ArcGIS img format, georeferenced.
SE_Storms	Directory that contains detailed information on 20 storms. One directory for each storm; directory names listed in Table 1. Contents in each storm directory varies. This top directory contains a SE_Storms_GIS directory with the storm index in Excel and ESRI shapefile. It also contains D-A-D tables for each of the SE storms with less detail.

D-A-D and Detailed Data

The minimum content for D-A-D data and representative file naming conventions for detailed storm collection is as follows. The D-A-D data are summarized in two index files: “HMR51_Storm_Summary.xls”, and “SE_Important_Storms_Index.xls”. Complete D-A-D table (xls, csv format) are available for the 55 storms in HMR 51, and are labeled by USACE Assignment Number. This is a 2 or 3-letter abbreviation for a USACE Division (described above), followed by a number. For example, refer to the directory names in Table A-1. For storm SA 1-1, the D-A-D file name is SA_1-1_DAD.xls

For detailed storms listed in Table A-1, the following information is available, at a minimum:

- Pertinent Data sheets (pdf);
- D-A-D Tables (xls and csv);
- Part II (pdf)
- Isohyetal map (pdf and/or tif); and
- Maximum depth-area curves.

File naming conventions for these files follows the same format as D-A-D tables, using underscores “_” with USACE Storm assignment number. The contents for each detailed directory vary, and depend on the information available in hard copy at various locations, including the NWS Hydrometeorological Design Studies Center in Silver Spring, MD and the Bureau of Reclamation in Denver.

GIS Files

The Geographic Information System (GIS) files are in ESRI shapefile or image file formats. Images and shapefiles generated using ESRI ArcGIS 9.3. Other file formats mentioned above, include: Adobe pdf; tif images; comma-separated – .csv; database – .dbf; and Excel - .xls.

Base Layers

The GIS base layers for the southeastern region are listed in Table A-3. Each layer is in ESRI ArcGIS shapefile format. The spatial reference for each layer is Geographic, Albers Equal Area, North American Datum 1983.

Table A-3 Base GIS Layers Contents

File Name	Content
US_States_Coterminous	U.S. state boundaries (coterminous)
US_Cities_Coterminous	U.S. cities (coterminous)
US_Counties_Coterminous	U.S. county boundaries (coterminous)
US_Climate_Divisions	NOAA climate division boundaries (coterminous)
HUC8_Coterminous	USGS Hydrologic Unit Codes (8 digit), (coterminous)
XYNRO-Locations	Locations of NRC New Licensing applications
US_Rivers_Simple_Coterminous	Simplified U.S. rivers (coterminous)

D-A-D Summary Layer – HMR 51

A summary layer of all storms used to set PMP in HMR 51 was created, and is called "HMR51_Storm_Summary.xls". The spreadsheet is also available in csv and .dbf formats. A GIS layer called "XYHMR51_Storm_Summary " was created. The spreadsheet and GIS layer contain the characteristics that are listed in Table A-4. This table is also included in the spreadsheet as the "Definitions" worksheet.

Table A-4 HMR 51 Storm Index Characteristics

Column Header	Description
HMR51_No	Storm number as listed in HMR 51, Figure 1
COEAssign	Corps of Engineers Storm assignment number as listed in HMR 51, Figure 1; some storms assigned from Canada and in HMR 51
Category	Critical - storms within 10% of PMP; Major - storms of appendix; Supplemental - storms from text; determined from HMR 51 Figure 1
Storm_Date	Duration of storm, given as calendar days
Start_Date	Date of storm initialization
End_Date	Date that storm dissipated
Location	City of storm center, defined as area of max precip, as listed in USACE 1973 or HMR 51 Appendix
State	State of storm center, defined as area of max precip, as listed in USACE 1973 or HMR 51 Appendix
Latitude	position of storm center, defined as area of precipitation maximum, as listed within USACE 1973, latitude from Google Earth
Longitude	position of storm center, defined as area of precipitation maximum, as listed within USACE 1973, longitude from Google Earth
Area_mi2	Greatest area in which precipitation was measured, given in square miles from the USACE 1973 DAD table or HMR 51 Appendix
Duration	duration of storm, in hours, as determined from USACE 1973 DAD tables or HMR 51 Appendix
D24h_10mi2	24-hr depth at 10-mi2 (inches) - from the USACE 1973 DAD table, the amount of precip in inches that accumulated during the maximum 24 hours of the storm at the 10 mi^2 ellipse. Value obtained from HMR 51 or HMR 55-A if NO USACE 1973 table. If storm duration < 24 hrs, value is missing (-9999.0).
DT_10mi2	Total depth at 10-mi2 (inches) - from the USACE 1973 DAD table, the total amount of precip in inches that accumulated over the duration of the storm at the 10 mi^2 ellipse. Value obtained from HMR 51 or HMR 55-A if NO USACE 1973 table. If storm area size not reported, value is missing (-9999.0).
D24h_100mi2	24-hr depth at 100-mi2 (inches) - from the USACE 1973 DAD table, the amount of precip in inches that accumulated during the maximum 24 hours of the storm at the 100 mi^2 ellipse. Value obtained from HMR 51 or HMR 55-A if NO USACE 1973 table. If storm area < 100 mi^2 or area size not reported, value is missing (-9999.0).
Moist_Adj	Moisture adjustment (percent) from HMR 51, listed in Appendix and Table 4; LIMITED moisture adjustment amounts for: No. 8 LMV 2-5; No. 26 LMV 3-19
Orient_Deg	orientation of precipitation ellipse, in degrees from north, in quadrant from 135 to 315, as found in HMR 52 Table 1
DAD_HMR51	'y' (yes) if D-A-D table is in HMR51 Appendix, or 'n' if D-A-D table is not in appendix
HMR33	n' (no) if storm does not appear within HMR 33 Appendix A; 'a' (approved) if it appears and has approved part II data; 'p' if preliminary within HMR 33
SE_Storm	y' (yes) if storm is important to NRC southeastern U.S. study, 'n' (no) if not important to NC and SC case study area

HMR 51 PMP GIS Data Layers

Data Set Directory Contents:

These directories consist of digitized (GIS) versions of Probable Maximum Precipitation (PMP) estimates as given in Figures 18 through 47 from HMR 51 (Schreiner and Riedel, 1978). An example is shown in Figure A-4.

Directory (zip file) contents are as follows.

/HMR_51_Plates/ Contains georeferenced images (.tif) of each Figure (30 images).

/HMR_51_Shapefiles/ contains polyline shapefiles (ESRI shapefile format) of PMP isolines for each Figure (30 images), and a 'stipple' region.

Metadata for each shapefile contains further details on development.

/HMR_51_Grids/ contains gridded versions (ESRI grids) of each shapefile (30 PMP grids; one stipple region).

Data Set Comments:

Users of this data set are responsible for assessing this information and its accuracy for their intended purpose or application.

There is no warranty, expressed or implied, with this data set.

Linear interpolation methods were used to develop PMP grids from the PMP isolines (in the shapefiles).

The grids provide PMP values beyond the edges of the isolines and are not clipped in any way.
These gridded PMP values are NOT recommended for use outside PMP isolines.
It is recommended that users follow guidance in HMR 51 (page 43) for PMP estimates in the Gulf Coast states.

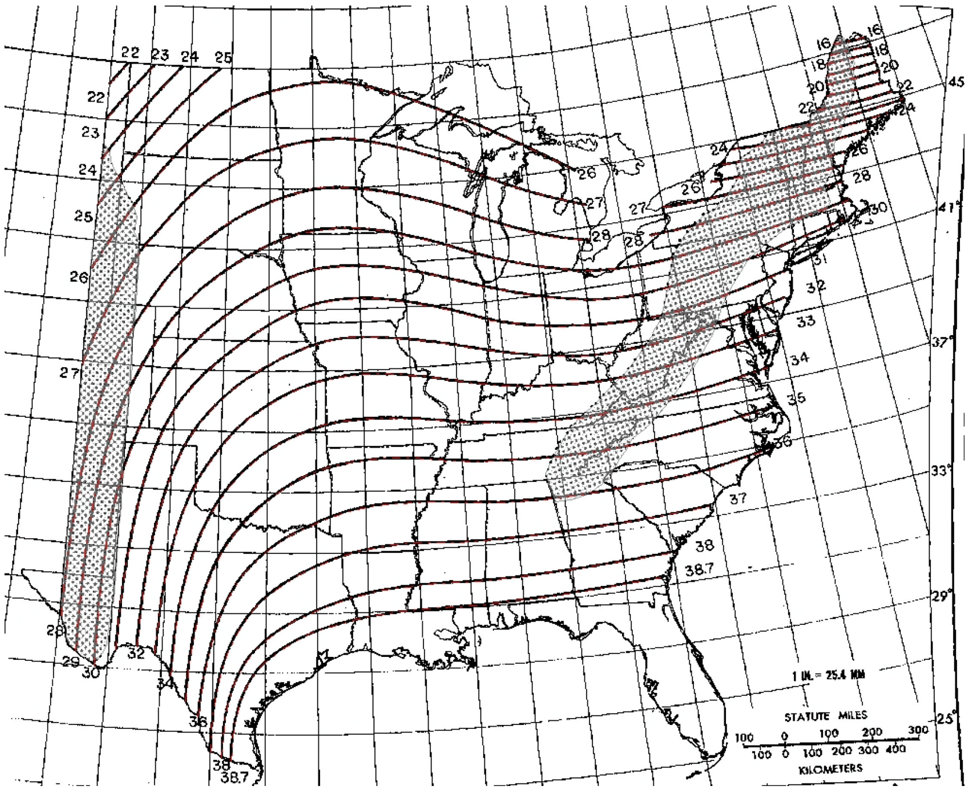

Figure A-4 Example georeferenced 12-hour, 10 mi^2 PMP map from HMR 51 over the southestern region

D-A-D Summary Layer – SE Storms

A summary layer of important storms in the southeastern United States was created. It was based on all storms used to set PMP in HMR 33, and additional D-A-D information from USACE (1973). Because "controlling" storms in HMR 33 were later used in HMR 51, there is some overlap between the two index maps. The summary layer is called "SE_Important_Storms_Index.xls". The spreadsheet is also available in csv and .dbf formats. A GIS layer called "XYSE_Important_Storms_Index" was created. The spreadsheet and GIS layer contain the characteristics that are listed in Table A-5. This table is also included in the spreadsheet as the "Definitions" worksheet.

Electronic D-A-D tables for all storms in the current Southeast database, focusing on SC and NC, are also included in spreadsheet format. The database also includes storm dewpoints, maximum dewpoints, reference locations and elevations for all events in the Southeast database.

Table A-5 Southeast Storm Index Characteristics

Column Header	Description
SE_Index	Simple working index of detailed storms, as of September 2009
Index_Date	Date index, enables sorting by excel by date including pre-1900 events
HMR51_No	Storm number as listed in HMR 51, Figure 1
COEAssign	Corps of Engineers Storm assignment number as listed in HMR 51, Figure 1; some storms assigned from Canada and in HMR 51
Category	Critical - storms within 10% of PMP in HMR 51; Major - storms of appendix in HMR 51; Supplemental - storms from text in HMR 51; Controlling - defined as a controlling storm in HMR 33. Most storms that were 'Controlling' in HMR 33 were defined as Major or Critical in HMR 51.
Storm_Date	Duration of storm, given as calendar days
Start_Date	Date of storm initialization
End_Date	Date that storm dissipated
Location	City of storm center, defined as area of max precip, as listed in USACE 1973 or HMR 51 Appendix
State	State of storm center, defined as area of max precip, as listed in USACE 1973 or HMR 51 Appendix
Latitude	position of storm center, defined as area of precipitation maximum, as listed within USACE 1973, latitude from Google Earth
Longitude	position of storm center, defined as area of precipitation maximum, as listed within USACE 1973, longitude from Google Earth
Area_mi2	Greatest area in which precipitation was measured, given in square miles from the USACE 1973 DAD table or HMR 51 Appendix
Duration	duration of storm, in hours, as determined from USACE 1973 DAD tables or HMR 51 Appendix
D24h_10mi2	24-hr depth at 10-mi2 (inches) - from the USACE 1973 DAD table, the amount of precip in inches that accumulated during the maximum 24 hours of the storm at the 10 mi^2 ellipse. Value obtained from HMR 51 or HMR 55-A if NO USACE 1973 table. If storm duration < 24 hrs, value is missing (-9999.0).
DT_10mi2	Total depth at 10-mi2 (inches) - from the USACE 1973 DAD table, the total amount of precip in inches that accumulated over the duration of the storm at the 10 mi^2 ellipse. Value obtained from HMR 51 or HMR 55-A if NO USACE 1973 table. If storm area size not reported, value is missing (-9999.0).
D24h_100mi2	24-hr depth at 100-mi2 (inches) - from the USACE 1973 DAD table, the amount of precip in inches that accumulated during the maximum 24 hours of the storm at the 100 mi^2 ellipse. Value obtained from HMR 51 or HMR 55-A if NO USACE 1973 table. If storm area < 100 mi^2 or area size not reported, value is missing (-9999.0).
Moist_Adj	In-Place moisture adjustment (percent) from: HMR 51 listed in Appendix and Table 4; or HMR 33 Appendix B; or from handwritten, informal index cards at NWS. LIMITED moisture adjustment amounts for: No. 8 LMV 2-5; No. 26 LMV 3-19
Orient_Deg	orientation of precipitation ellipse, in degrees from north, in quadrant from 135 to 315, as found in HMR 52 Table 1. If not estimated, value is missing (-9999.0).
DAD_1973	y' (yes) if D-A-D table is in USACE (1973) or HMR51 Appendix; or 'n' if D-A-D table is not in these two references
HMR33	n' (no) if storm does not appear within HMR 33 Appendix A; 'a' (approved) if it appears and has approved Part II data; 'p' if preliminary within HMR 33
HMR33Contr	y' (yes) if storm is defined as a 'Controlling' storm from HMR 33 Appendix B.
SE_Storm	y' (yes) if storm is important to NRC southeastern U.S. study, 'n' (no) if not important to NC and SC case study area
Detailed	y' (yes) if detailed information has been collected - principally Part II analysis report in pdf, isohyetal maps, etc. (subject to change). A separate directory is included for each detailed storm, with Part II in pdf, isohyetal map in tif and max depth-area map in pdf. Additional information may vary and depends on the storm.
DAD_xls	y' (yes) if D-A-D table currently available in electronic format (Excel, csv, etc.) (subject to change)

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10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report presents a review of existing Probable Maximum Precipitation (PMP) methodologies, data bases, and estimates within the United States. The major focus is on a review of generalized PMP estimates in the Southeastern United States, in order to subsequently assess the adequacy of existing PMP estimates and the need for potentially updating the PMP estimates in this region. The main objectives of the review were to: (1) review PMP procedures and databases used to develop Hydrometeorological Reports (HMRs); (2) examine storm databases in the Southeast and document the evolution in PMP methodologies and estimates over time; and (3); summarize extreme storm research and PMP work done since HMR 51 was published, that is germane to PMP estimates in the Southeast. Most of the review was limited to describing existing, generalized PMP reports (HMRs) and existing data related to those reports, including HMRs 51-53, and HMR 55A. Subsequent HMRs were reviewed for their treatment of PMP in orographic regions, and to summarize changes in methodologies. Comparisons were made between storm data and procedures used in HMR 33 and HMR 51 for the Southeastern U.S. case study region. Studies related to PMP and recent research on extreme storm estimation were briefly reviewed and summarized.

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