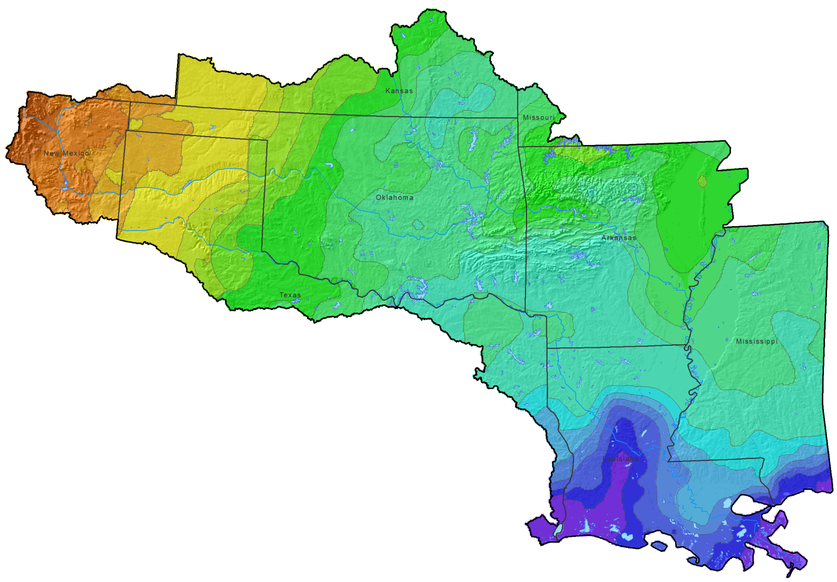
Regional Probable Maximum Precipitation Study

For Oklahoma, Arkansas, Louisiana, and Mississippi

Final Report

Prepared for:

Arkansas Dept. of Natural Resources
Louisiana Dept. of Transportation & Development
Mississippi Dept. of Environmental Quality
Oklahoma Water Resources Board



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Notice

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Executive Summary

This study produced gridded PMP values for the project domain which included the states of Oklahoma, Arkansas, Louisiana, and Mississippi and hydrologically important regions that immediately surround these States at a spatial resolution of 90 arc-seconds, or approximately 2.5-square miles. Variations in topography, climate and storm types across the region were explicitly taken into account. A large set of storm data were analyzed for use in developing the PMP values. These values replace those provided in Hydrometeorological Reports (HMRs) 51, 52, and 55A. Results of this analysis reflects the most current practices used for defining PMP, including comprehensive storm analyses procedures, extensive use of geographical information systems (GIS), explicit quantification of orographic effects, updated maximum dew point and sea surface temperatures climatologies for storm adjustments, and improved understanding of the weather and climate related to extreme rainfall throughout the region.

The approach used in this study followed the same philosophy used in the numerous site-specific, statewide, and regional PMP studies that AWA has completed. This was a storm-based approach and it follows the same general procedures used by the National Weather Service (NWS) in the development of the HMRs. The World Meteorological Organization (WMO) Manual on Estimation of PMP recommends this same approach. The storm-based approach identified extreme rainfall events that have occurred in regions considered transpositionable to any locations within the overall region. These are storms that had meteorological and topographical characteristics similar to extreme rainfall storms that could occur over any location within the project domain and were deemed to be PMP-type storm events. Detailed storm analyses were completed for the largest of these rainfall events.

Data, assumptions, and analysis techniques used in this study have been reviewed and accepted by the review board and the individual state dam safety offices with significant input provided by other study participants including the Federal Energy Regulatory Commission, the Natural Resource Conservation Service, and various private consultants.

Although this study produced deterministic values, it must be recognized that there is some variability associated with the PMP development procedures. Examples of decisions where meteorological judgment was involved included determining which storms are used for PMP, determination of storm adjustment factors, and storm transposition limits. For areas where uncertainties in data were recognized, conservative assumptions were applied unless sufficient data existed to make a more informed decision. All data and information supporting decisions in the PMP development process have been documented so that results can be reproduced and verified.

Sixty-three rainfall events were identified across the storm search area as having similar characteristics to rainfall that could potentially control PMP values at various locations within the four-state study region. Several storm events had multiple Depth-Area-Duration (DAD) zones that were used in the PMP determination process. These include 16 tropical storm rainfall centers, 17 general storm rainfall centers, and 24 local storm rainfall centers. Note, an additional six storm centers exhibited characteristics of more than one storm type and were therefore evaluated as general or tropical and local storm hybrids in the PMP determination process.

Each storm center was analyzed using the Storm Precipitation Analysis System (SPAS), which produced several standard products including DAD values, storm center mass curves, and total storm isohyetal patterns. National Weather Service Next Generation Weather Radar (NEXRAD) data were used in storm analyses when available (generally for storms which occurred after the mid-1990's).

Standard procedures were applied for in-place maximization adjustments (e.g. HMR 51 Section 2.3). New techniques and new datasets were used in other procedures to increase accuracy and reliability when justified by utilizing advancements in technology and meteorological understanding, while adhering to the basic approach used in the HMRs and in the WMO Manual. Updated precipitation frequency analyses data available from the National Oceanic and Atmospheric Administration (NOAA) Atlas 14 were used for this study. These were used to calculate the Geographic Transposition Factors (GTFs) for each storm. The GTF procedure, through its correlation process, provided quantifiable and reproducible analyses of the effects of terrain and all precipitation processes on rainfall difference between two locations. Results of these factors (in-place maximization and geographic transposition) were applied for each storm at each grid point for each of the area sizes and durations used in this study to define the PMP values.

Maximization factors were computed for each of the analyzed storm events using updated dew point and sea surface temperature (SST) climatologies representing the maximum moisture equivalent to the 100-year recurrence interval for dew points or +2 sigma for SST that were associated with each rainfall event. The dew point climatology included the maximum average 3-, 6-, 12-, and 24-hour 100-year return frequency values, while the SST climatology provided the +2 sigma values. The most appropriate duration consistent with the duration of the storm rainfall was used. HYSPLIT model output, which represent model reanalysis fields of air flow in the atmosphere, and NWS synoptic weather maps were used as guidance in identifying the storm representative moisture source regions.

To store, analyze, and produce results from the large datasets developed in the study, the PMP calculation information was stored and analyzed in individual Excel spreadsheets and a GIS database. This combination of Excel and GIS was used to query, calculate, and derive PMP values for each grid point for each duration for each storm type. The database allowed PMP to be calculated at any area size and/or duration available in the underlying SPAS data.

When compared to previous PMP depths provided in HMR 51 the updated values from this study resulted in a wide range of reductions at most area sizes and durations, with some regions resulting in minor increases. PMP depths are highest near the Gulf Coast and along the ridges of the Ouachita and Ozark Mountains in Arkansas. These regions have exhibited past extreme rainfall accumulations that are the result of both moisture availability and topographic enhancement. Regions along and near the coast are also affected by coastal convergence processes and direct access to low-level moisture which act to enhance lift and provide an additional mechanism for enhanced rainfall production versus other locations in the study domain. Minimum values are seen in the western High Plains region of Oklahoma and the northern locations furthest away from the main moisture source, the Gulf of Mexico. This is expected because of the decrease in sustained moisture availability and reduced orographic effects relative to other regions.

Many watersheds regulated by the state dam safety offices and NRCS in the region are relatively small in area size, less than 10-square miles. Therefore, a significant amount of emphasis was placed on developing PMP and temporal patterns most relevant for smaller area sizes and quick response basins. This included extensive analysis of short duration, high intensity rainfall accumulation patterns (local storms) and development of PMP depths for area sizes and durations that are important for these types of basins. Providing PMP depths down to area sizes at 1/3rd-square miles and temporal accumulation patterns at 5-minute increments was a significant improvement for dam safety evaluations over what was previously available in the HMRs

On average, PMP values for local storms resulted in a 16% reduction at 6-hour 10-square miles and a 14% reduction at 12-hour 10-square miles. In general, the largest reductions were over western Oklahoma, with smaller reductions and in some areas small increases over the higher elevations of eastern Oklahoma and Arkansas as well as portions of northern Louisiana. For the longer durations, larger area sizes, statewide reductions were 12% at 24-hours, 14% at 72-hours for 200-square miles, 22% at 24-hours, and 14% at 72-hours for 1,000-square miles. Tables E.1-E.6 provide the average percent difference (negative is a reduction) from HMR 51 across each of the transposition regions analyzed.

Table E.1: Percent difference from HMR 51 PMP at 10-square miles. PMP depths are averaged over each state and represent the largest of all storm types.

Mean Statewide 10 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 6hr	LS/GS/TS PMP 6hr	% Change 6hr	HMR 51 12hr	LS/GS/TS PMP 12hr	% Change 12hr	HMR 51 24hr	LS/GS/TS PMP 24hr	% Change 24hr
Arkansas	29.9"	24.2"	-18.9%	35.8"	30.8"	-13.8%	40.2"	34.8"	-13.3%
Oklahoma	28.4"	24.5"	-13.6%	34.1"	30.4"	-10.9%	37.5"	33.7"	-10.2%
Louisiana	31.9"	29.0"	-9.0%	38.6"	37.3"	-3.1%	46.4"	44.2"	-4.8%
Mississippi	31.1"	26.0"	-16.5%	37.4"	33.5"	-10.4%	43.9"	38.4"	-12.7%

Table E.2: Percent difference from HMR 51 PMP at 200-square miles. PMP depths are averaged over each state and represent the largest of all storm types.

Mean Statewide 200 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 6hr	LS/GS/TS PMP 6hr	% Change 6hr	HMR 51 12hr	LS/GS/TS PMP 12hr	% Change 12hr	HMR 51 24hr	LS/GS/TS PMP 24hr	% Change 24hr
Arkansas	22.1"	17.3"	-21.9%	26.9"	24.5"	-8.8%	30.9"	28.7"	-7.1%
Oklahoma	20.9"	18.4"	-11.9%	25.2"	23.9"	-5.3%	28.3"	27.7"	-2.1%
Louisiana	24.4"	24.3"	-0.2%	30.6"	29.4"	-3.9%	38.4"	35.8"	-6.7%
Mississippi	23.4"	19.3"	-17.4%	28.8"	26.6"	-7.9%	35.4"	31.4"	-11.3%

Table E.3: Percent difference from HMR 51 PMP at 1,000-square miles. PMP depths are averaged over each state and represent the largest of all storm types.

Mean Statewide 1,000 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 24hr	GS/TS PMP 24hr	% Change 24hr	HMR 51 48hr	GS/TS PMP 48hr	% Change 48hr	HMR 51 72hr	GS/TS PMP 72hr	% Change 72hr
Arkansas	25.1"	19.0"	-24.3%	28.8"	24.2"	-15.8%	30.8"	27.8"	-9.6%
Oklahoma	22.4"	18.2"	-18.8%	25.9"	23.3"	-9.9%	27.9"	26.6"	-4.8%
Louisiana	32.2"	28.7"	-11.0%	36.7"	32.5"	-11.6%	40.0"	36.9"	-7.7%
Mississippi	29.1"	22.2"	-23.7%	33.6"	26.8"	-20.1%	36.2"	30.7"	-15.2%

Table E.4: Percent difference from HMR 51 PMP at 5,000-square miles. PMP depths are averaged over each state and represent the largest of all storm types.

Mean Statewide 5,000 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 24hr	GS/TS PMP 24hr	% Change 24hr	HMR 51 48hr	GS/TS PMP 48hr	% Change 48hr	HMR 51 72hr	GS/TS PMP 72hr	% Change 72hr
Arkansas	17.1"	14.9"	-12.7%	21.3"	19.8"	-6.8%	23.8"	20.7"	-13.1%
Oklahoma	15.3"	14.2"	-7.1%	19.3"	18.9"	-2.0%	21.1"	19.8"	-6.4%
Louisiana	21.3"	18.5"	-13.0%	25.9"	24.6"	-5.0%	29.8"	26.4"	-11.4%
Mississippi	19.4"	16.4"	-15.2%	23.8"	21.8"	-8.5%	27.3"	22.7"	-16.9%

Table E.5: Percent difference from HMR 51 PMP at 10,000-square miles. PMP depths are averaged over each state and represent the largest of all storm types.

Mean Statewide 10,000 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 24hr	GS/TS PMP 24hr	% Change 24hr	HMR 51 48hr	GS/TS PMP 48hr	% Change 48hr	HMR 51 72hr	GS/TS PMP 72hr	% Change 72hr
Arkansas	13.9"	13.1"	-5.8%	17.8"	17.3"	-2.5%	20.4"	17.5"	-14.5%
Oklahoma	12.4"	12.5"	0.5%	16.1"	16.6"	2.8%	18.0"	16.7"	-7.1%
Louisiana	17.2"	16.2"	-5.6%	21.9"	21.4"	-2.3%	25.9"	22.3"	-13.7%
Mississippi	15.8"	14.4"	-8.7%	20.2"	19.1"	-5.5%	23.7"	19.3"	-18.8%

Table E.6: Percent difference from HMR 51 PMP at 20,000-square miles. PMP depths are averaged over each state and represent the largest of all storm types.

Mean Statewide 20,000 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 24hr	GS/TS PMP 24hr	% Change 24hr	HMR 51 48hr	GS/TS PMP 48hr	% Change 48hr	HMR 51 72hr	GS/TS PMP 72hr	% Change 72hr
Arkansas	11.4"	11.1"	-2.4%	14.6"	14.7"	0.4%	17.0"	14.8"	-12.7%
Oklahoma	10.0"	10.6"	6.0%	13.2"	14.1"	6.3%	15.1"	14.2"	-6.4%
Louisiana	13.4"	13.8"	2.9%	17.7"	18.6"	5.6%	21.5"	19.3"	-10.2%
Mississippi	12.6"	12.3"	-2.8%	16.5"	16.2"	-1.6%	19.7"	16.4"	-16.6%

Glossary

Adiabat: Curve of thermodynamic change taking place without addition or subtraction of heat. On an adiabatic chart or pseudo-adiabatic diagram, a line showing pressure and temperature changes undergone by air rising or condensation of its water vapor; a line, thus, of constant potential temperature.

Adiabatic: Referring to the process described by adiabat.

Advection: The process of transfer (of an air mass property) by virtue of motion. In particular cases, advection may be confined to either the horizontal or vertical components of the motion. However, the term is often used to signify horizontal transfer only.

Air mass: Extensive body of air approximating horizontal homogeneity, identified as to source region and subsequent modifications.

Barrier: A mountain range that partially blocks the flow of warm humid air from a source of moisture to the basin under study.

Basin centroid: The point at the exact center of the drainage basin as determined through geographical information systems calculations using the basin outline.

Basin shape: The physical outline of the basin as determined from topographic maps, field survey, or GIS.

Cold front: Front where relatively colder air displaces warmer air.

Convective rain: Rainfall caused by the vertical motion of an ascending mass of air that is warmer than the environment and typically forms a cumulonimbus cloud. The horizontal dimension of such a mass of air is generally of the order of 12 miles or less. Convective rain is typically of greater intensity than either of the other two main classes of rainfall (cyclonic and orographic) and is often accompanied by thunder. The term is more particularly used for those cases in which the precipitation covers a large area as a result of the agglomeration of cumulonimbus masses.

Convergence: Horizontal shrinking and vertical stretching of a volume of air, accompanied by net inflow horizontally and internal upward motion.

Cooperative station: A weather observation site where an unpaid observer maintains a climatological station for the National Weather Service.

Correlation Coefficient: The average change in the dependent variable, the orographically transposed rainfall (P_o), for a 1-unit change in the independent variable, the in-place rainfall (P_i).

Cyclone: A distribution of atmospheric pressure in which there is a low central pressure relative to the surroundings. On large-scale weather charts, cyclones are characterized by a system of closed constant pressure lines (isobars), generally approximately circular or oval in form, enclosing a central low-pressure area. Cyclonic circulation is counterclockwise in the northern hemisphere and clockwise in the southern. (That is, the sense of rotation about the local vertical is the same as that of the earth's rotation).

Depth-Area curve: Curve showing, for a given duration, the relation of maximum average depth to size of area within a storm or storms.

Depth-Area-Duration: The precipitation values derived from Depth-Area and Depth-Duration curves at each time and area size increment analyzed for a PMP evaluation.

Depth-Area-Duration Curve: A curve showing the relation between an averaged areal rainfall depth and the area over which it occurs, for a specified time interval, during a specific rainfall event.

Depth-Area-Duration values: The combination of depth-area and duration-depth relations. Also called depth-duration-area.

Depth-Duration curve: Curve showing, for a given area size, the relation of maximum average depth of precipitation to duration periods within a storm or storms.

Dew point: The temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content for saturation to occur.

Envelopment: A process for selecting the largest value from any set of data. In estimating PMP, the maximum and transposed rainfall data are plotted on graph paper, and a smooth curve is drawn through the largest values.

Explicit transposition: The movement of the rainfall amounts associated with a storm within boundaries of a region throughout which a storm may be transposed with only relatively minor modifications of the observed storm rainfall amounts. The area within the transposition limits has similar, but not identical, climatic and topographic characteristics throughout.

First-order NWS station: A weather station that is either automated or staffed by employees of the National Weather Service and records observations on a continuous basis.

Front: The interface or transition zone between two air masses of different parameters. The parameters describing the air masses are temperature and dew point.

General storm: A storm event that produces precipitation over areas in excess of 500-square miles, has a duration longer than 6 hours, and is associated with a major synoptic weather feature.

Geographic Transposition Factor (GTF): A factor representing the comparison of precipitation frequency relationships between two locations which is used to quantify how rainfall is affected by physical processes related to location and terrain. It is assumed the precipitation frequency data are a combination of what rainfall would have accumulated without topographic affects and what accumulated because of the topography, both at the location and upwind of the location being analyzed.

Hydrologic Unit: A hydrologic unit is a drainage area delineated to nest in a multi-level, hierarchical drainage system. Its boundaries are defined by hydrographic and topographic criteria that delineate an area of land upstream from a specific point on a river, stream or similar surface waters. A hydrologic unit can accept surface water directly from upstream drainage areas, and indirectly from associated surface areas such as remnant, non-contributing, and diversions to form a drainage area with single or multiple outlet points. Hydrologic units are only synonymous with classic watersheds when their boundaries include all the source area contributing surface water to a single defined outlet point

HYSPLIT: Hybrid Single-Particle Lagrangian Integrated Trajectory. A complete system for computing parcel trajectories to complex dispersion and deposition simulations using either puff or particle approaches. Gridded meteorological data, on one of three conformal (Polar, Lambert, or Mercator latitude-longitude grid) map projections, are required at regular time intervals. Calculations may be performed sequentially or concurrently on multiple meteorological grids, usually specified from fine to coarse resolution.

Implicit transpositioning: The process of applying regional, areal, or durational smoothing to eliminate discontinuities resulting from the application of explicit transposition limits for various storms.

Isohyets: Lines of equal value of precipitation for a given time interval.

Isohyetal pattern: The pattern formed by the isohyets of an individual storm.

Isohyetal orientation: The term used to define the orientation of precipitation patterns of major storms when approximated by elliptical patterns of best fit. It is also the orientation (direction from north) of the major axis through the elliptical PMP storm pattern.

Jet Stream: A strong, narrow current concentrated along a quasi-horizontal axis (with respect to the earth's surface) in the upper troposphere or in the lower stratosphere, characterized by strong vertical and lateral wind shears. Along this axis it features at least one velocity maximum (jet streak). Typical jet streams are thousands of kilometers long, hundreds of kilometers wide, and several kilometers deep. Vertical wind shears are on the order of 10 to 20 mph per kilometer of altitude and lateral winds shears are on the order of 10 mph per 100 kilometers of horizontal distance.

Local storm: A storm event that occurs over a small area in a short time period. Precipitation rarely exceeds 6 hours in duration and the area covered by precipitation is less than 500 square miles. Frequently, local storms will last only 1 or 2 hours and precipitation will occur over areas of up to 200 square miles. Precipitation from local storms will be isolated from general-storm rainfall. Often these storms are thunderstorms.

Low Level Jet stream: A band of strong winds at an atmospheric level well below the high troposphere as contrasted with the jet streams of the upper troposphere.

Mass curve: Curve of cumulative values of precipitation through time.

Mesoscale Convective Complex: For the purposes of this study, a heavy rain-producing storm with horizontal scales of 10 to 1000 kilometers (6 to 625 miles) which includes significant, heavy convective precipitation over short periods of time (hours) during some part of its lifetime.

Mesoscale Convective System: A complex of thunderstorms which becomes organized on a scale larger than the individual thunderstorms, and normally persists for several hours or more. MCSs may be round or linear in shape, and include systems such as tropical cyclones, squall lines, and MCCs (among others). MCS often is used to describe a cluster of thunderstorms that does not satisfy the size, shape, or duration criteria of an MCC.

Mid-latitude frontal system: An assemblage of fronts as they appear on a synoptic chart north of the tropics and south of the polar latitudes. This term is used for a continuous front and its characteristics along its entire extent, its variations of intensity, and any frontal cyclones along it.

Moisture maximization: The process of adjusting observed precipitation amounts upward based upon the hypothesis of increased moisture inflow to the storm.

Observational day: The 24-hour time period between daily observation times for two consecutive days at cooperative stations, e.g., 6:00PM to 6:00PM.

One-hundred year rainfall event: The point rainfall amount that has a one-percent probability of occurrence in any year. Also referred to as the rainfall amount that has a 1 percent chance of occurring in any single year.

Precipitable water: The total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels in the atmosphere; commonly expressed in terms of the height to which the liquid water would stand if the vapor were completely condensed and collected in a vessel of the same unit cross-section. The total precipitable water in the atmosphere at a location is that contained in a column or unit cross-section extending from the earth's surface all the way to the "top" of the atmosphere. The 30,000 foot level (approximately 300mb) is considered the top of the atmosphere in this study.

Persisting dew point: The dew point value at a station that has been equaled or exceeded throughout a period. Commonly durations of 12 or 24 hours are used, though other durations may be used at times.

Probable Maximum Flood: The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area.

Probable Maximum Precipitation: Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a certain time of the year.

Pseudo-adiabat: Line on thermodynamic diagram showing the pressure and temperature changes undergone by saturated air rising in the atmosphere, without ice-crystal formation and without exchange of heat with its environment, other than that involved in removal of any liquid water formed by condensation.

Saturation: Upper limit of water-vapor content in a given space; solely a function of temperature.

Shortwave: Also referred to as a shortwave trough, is an embedded kink in the trough / ridge pattern. This is the opposite of longwaves, which are responsible for synoptic scale systems, although shortwaves may be contained within or found ahead of longwaves and range from the mesoscale to the synoptic scale.

Spatial distribution: The geographic distribution of precipitation over a drainage according to an idealized storm pattern of the PMP for the storm area.

Storm transposition: The hypothetical transfer, or relocation of storms, from the location where they occurred to other areas where they could occur. The transfer and the mathematical adjustment of storm rainfall amounts from the storm site to another location is termed "explicit transposition." The areal, durational, and regional smoothing done to obtain comprehensive individual drainage estimates and generalized PMP studies is termed "implicit transposition" (WMO, 1986).

Synoptic: Showing the distribution of meteorological elements over an area at a given time, e.g., a synoptic chart. Use in this report also means a weather system that is large enough to be a major feature on large-scale maps (e.g., of the continental U.S.).

Temporal distribution: The time order in which incremental PMP amounts are arranged within a PMP storm.

Tropical Storm: A cyclone of tropical origin that derives its energy from the ocean surface.

Total storm area and total storm duration: The largest area size and longest duration for which depth-area-duration data are available in the records of a major storm rainfall.

Transposition limits: The outer boundaries of the region surrounding an actual storm location that has similar, but not identical, climatic and topographic characteristics throughout. The storm can be transpositioned within the transposition limits with only relatively minor modifications to the observed storm rainfall amounts.

List of Acronyms

AMS: Annual maximum series

AWA: Applied Weather Associates

DA: Depth-Area

DAD: Depth-Area-Duration

dd: decimal degrees

DND: Drop number distribution

DSD: Drop size distribution

EPRI: *Electric Power Research Institute*

F: Fahrenheit

FERC: Federal Energy Regulatory Commission

GCS: Geographical coordinate system

GIS: Geographic Information System

GRASS: Geographic Resource Analysis Support System

GTF: Geographic Transposition Factor

HMR: Hydrometeorological Report

HRRR: High-Resolution Rapid Refresh Model

HYSPLIT: Hybrid Single Particle Lagrangian Integrated Trajectory Model

IDW: Inverse distance weighting

IPMF: In-place Maximization Factor

LLJ: Low-level Jet

MADIS: NCEP Meteorological Assimilation Data Ingest System

mb: millibar

MCC: Mesoscale Convective Complex

MCS: Mesoscale Convective System

MTF: Moisture Transposition Factor

NCAR: National Center for Atmospheric Research

NCDC: National Climatic Data Center

NCEI: National Centers for Environmental Information

NCEP: National Centers for Environmental Prediction

NEXRAD: Next Generation Radar

NOAA: National Oceanic and Atmospheric Administration

NRC: Nuclear Regulatory Commission

NRCS: Natural Resources Conservation Service

NWS: National Weather Service

PMF: Probable Maximum Flood

PMP: Probable Maximum Precipitation

PRISM: Parameter-elevation Relationships on Independent Slopes

PW: Precipitable Water

SMC: Spatially Based Mass Curve

SPAS: Storm Precipitation and Analysis System

SPP: Significant Precipitation Period

SSM: Storm Separation Method

SST: Sea Surface Temperatures

TAF: Total Adjustment Factor

TAR: Total Adjusted Rainfall

USACE: US Army Corps of Engineers

USBR: Bureau of Reclamation

USGS: United States Geological Survey

WMO: World Meteorological Organization

1. PMP Development Background

This study provides Probable Maximum Precipitation (PMP) depths for all drainage basins within the four state region of Oklahoma-Arkansas-Louisiana-Mississippi (the Region), including areas immediately adjacent to the Region that also provide runoff into drainage basins that each of the state dam safety offices are responsible for regulating (Figure 1.1). The PMP depths are used in the computation of the Probable Maximum Flood (PMF), generally for the design of high-hazard structures. PMP depths developed in the study were focused on area sizes ranging from 1-square mile through 20,000-square miles that would be applied to a single basin and its sub basins. Therefore, basins larger than 20,000-square miles and with origins outside of the study domain may require separate site-specific PMP studies. Examples would include the overall Red River, Arkansas, and Mississippi River basins. PMP values provided in this study supersede the current HMR PMP depths from Hydrometeorological Reports (HMRs) HMR 51 (Schreiner and Riedel, 1978) and HMR 52 (Hansen et al., 1982).

PMP is a deterministic estimate of the theoretical maximum depth of precipitation that can occur over a specified area, at a given time of the year. Parameters to estimate PMP were developed using the storm based, deterministic approach as discussed in the HMRs and subsequently refined in the numerous site-specific, statewide, and regional PMP studies completed since the early 1990's.

Methods used to derive PMP values for this study included consideration of numerous extreme rainfall events that have been appropriately adjusted to each grid point and representing each PMP storm type in the Region; local, general, and tropical. Hundreds of storms were considered, with 63 events used for final PMP estimation. The large number of storm events provided enough data from which to derive the PMP depths within an acceptable amount of uncertainty. The process of combining maximized storm events by storm type into a hypothetical PMP design storm resulted in a reliable PMP estimation by combining the worst-case combination of metrological factors in a physically possible manner.

During this calculation process, air masses that provide moisture to both the historic observed storm and the possible PMP storm were assumed to be saturated through the entire depth of the atmosphere and contain the maximum moisture possible based on the surface dew point or sea surface temperatures (SST). This saturation process used moist pseudo-adiabatic temperature profiles for both the historic storm and the PMP storm. The method assumed that a sufficient period of record was available for rainfall observations over a large region and that at least a few storms which have been observed, attained or came close to attaining the maximum storm efficiency possible for converting atmospheric moisture to rainfall for regions with similar climates and topography. The PMP development process assumes that if surplus atmospheric moisture had been available, an individual extreme storm would have maintained the same efficiency for converting atmospheric moisture to rainfall. Therefore, the ratio of the maximized rainfall amounts to the actual rainfall amounts would be the same as the ratio of the precipitable water observed versus the climatological maximum in the atmosphere associated with each storm.

Current understanding of meteorology does not support an explicit evaluation of storm efficiency for use in PMP evaluation. To compensate for this, the period of record was extended to include the entire historic record of rainfall data (nearly 150 years for this study), along with an extended geographic region from which to choose storms. Using the long period of record and the large geographic region, there assumed to have been at least one storm with dynamics (storm efficiency) that approached the maximum efficiency for rainfall production used in the PMP development. In essence, the process is trading time for space to capture PMP processes.

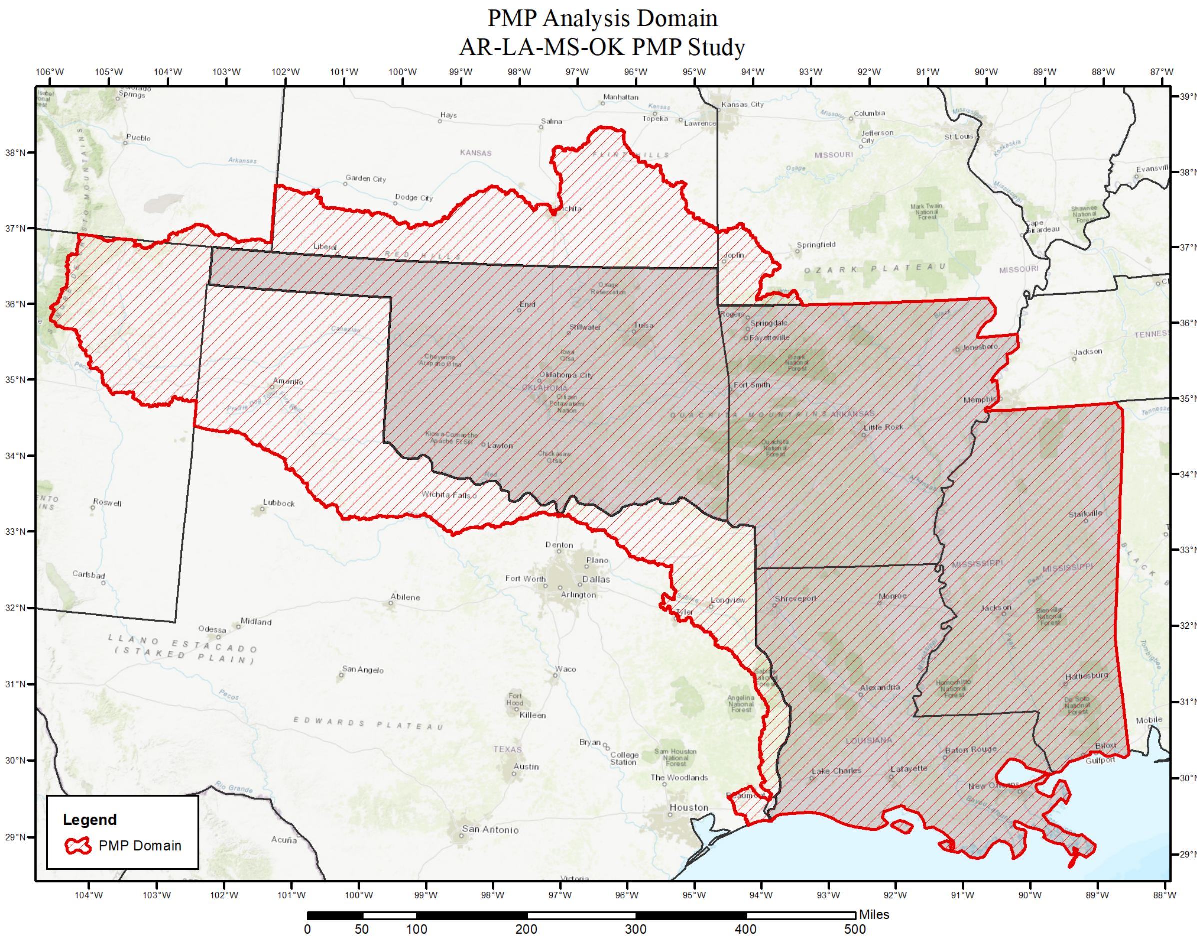

Figure 1.1: Probable Maximum Precipitation study domain

1.1 Background

Definitions of PMP are found in most of the HMRs issued by the National Weather Service (NWS). The definition used in the most recently published HMR is "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" (HMR 59, p. 5) (Corrigan et al., 1999). Since the early 1940s, several government agencies have developed methods to calculate PMP for various regions of the United States. The NWS (formerly the U.S. Weather Bureau), the U.S. Army Corps of Engineers (USACE), and the U.S. Bureau of Reclamation (USBR) have been the primary Federal agencies involved in this activity. PMP values presented in their reports are used to calculate the PMF, which in turn, is often used for the design of significant hydraulic structures. It is important to remember that the methods used to derive PMP and the hydrological procedures that use the PMP values need to adhere to the requirement of being "physically possible." In other words, various levels of conservatism and/or extreme aspects of storms that could not physically occur in a PMP storm environment should not be used to produce combinations of storm characteristics that are not physically consistent in determining PMP values or for the hydrologic applications of those values.

The generalized PMP studies currently in use in the contiguous United States include HMRs 49 (1977) and 50 (1981) for the Colorado River and Great Basin drainage; HMRs 51 (1978), 52 (1982), and 53 (1980) for the U.S. east of the 105th meridian; HMR 55A (1988) for the area between the Continental Divide and the 103rd meridian; HMR 57 (1994) for the Columbia River Drainage; and HMRs 58 (1998) and 59 (1999) for California (Figure 1.2). In addition to these HMRs, numerous Technical Papers and Reports deal with specific subjects concerning precipitation (e.g. Technical Paper 1, 1946; Technical Paper 16, 1952; NOAA Tech. Report NWS 25, 1980; and NOAA Tech. Memorandum NWS HYDRO 40, 1984). Topics in these papers include maximum observed rainfall amounts for various return periods and specific storm studies. Climatological atlases (e.g. Technical Paper No. 40, 1961; NOAA Atlas 2, 1973; and NOAA Atlas 14, 2004-2015) are available for use in determining precipitation return periods. A number of site-specific, statewide, and regional studies (e.g. Tomlinson et al., 2002-2013; Kappel et al., 2012-2019) augment generalized PMP reports for specific regions included in the large areas addressed by the HMRs. Recent site-specific PMP projects completed within the domain have updated the storm database and many of the procedures used to estimate PMP depths in the HMRs. This study continued that process by applying the most current understanding of meteorology related to extreme rainfall events and updating the storm database through June of 2019. PMP results from this study provide values that replace those derived from HMRs 51 and 52.

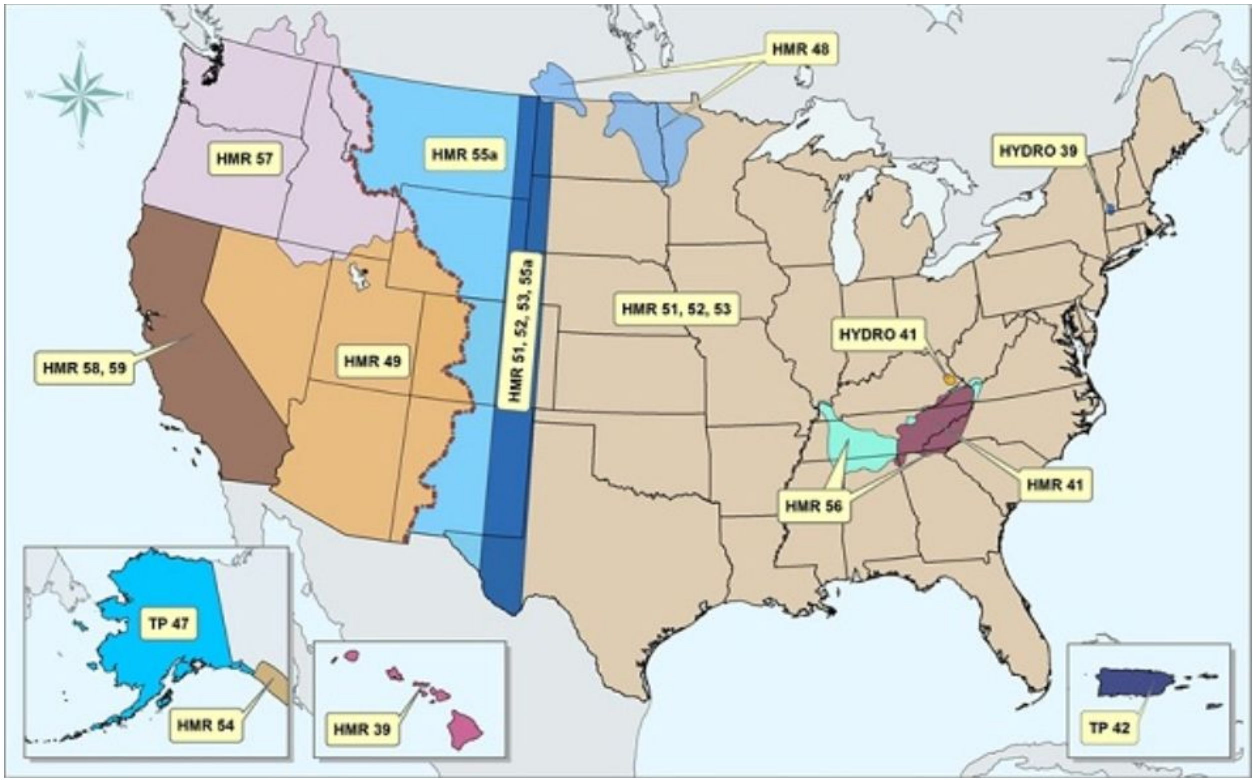

Figure 1.2: Hydrometeorological Report coverages across the United States

The Region is included within the domain covered by HMR 51, HMR 52, and HMR 55A. HMR 51 is the most relevant HMR for this study, covering almost the entire region (Figure 1.3). HMR 55A was developed for orographic regions covering the foothills of the Rocky Mountains through the Continental Divide and is relevant for a very small portion of the far western edge of this study (the headwaters of the Arkansas River). HMR 52 provided background information and hydrologic implementation guidelines for the storm data developed in HMR 51. These HMRs cover diverse meteorological and topographical regions. Although it provides generalized estimates of PMP values for a large, climatologically-diverse area, HMR 51 recognizes that studies addressing PMP over specific regions can incorporate more site-specific considerations and provide improved PMP estimates. Additionally, by periodically reviewing storm data and advances in meteorological concepts, PMP analysts can identify relevant new data and approaches for use in making improved PMP estimates.

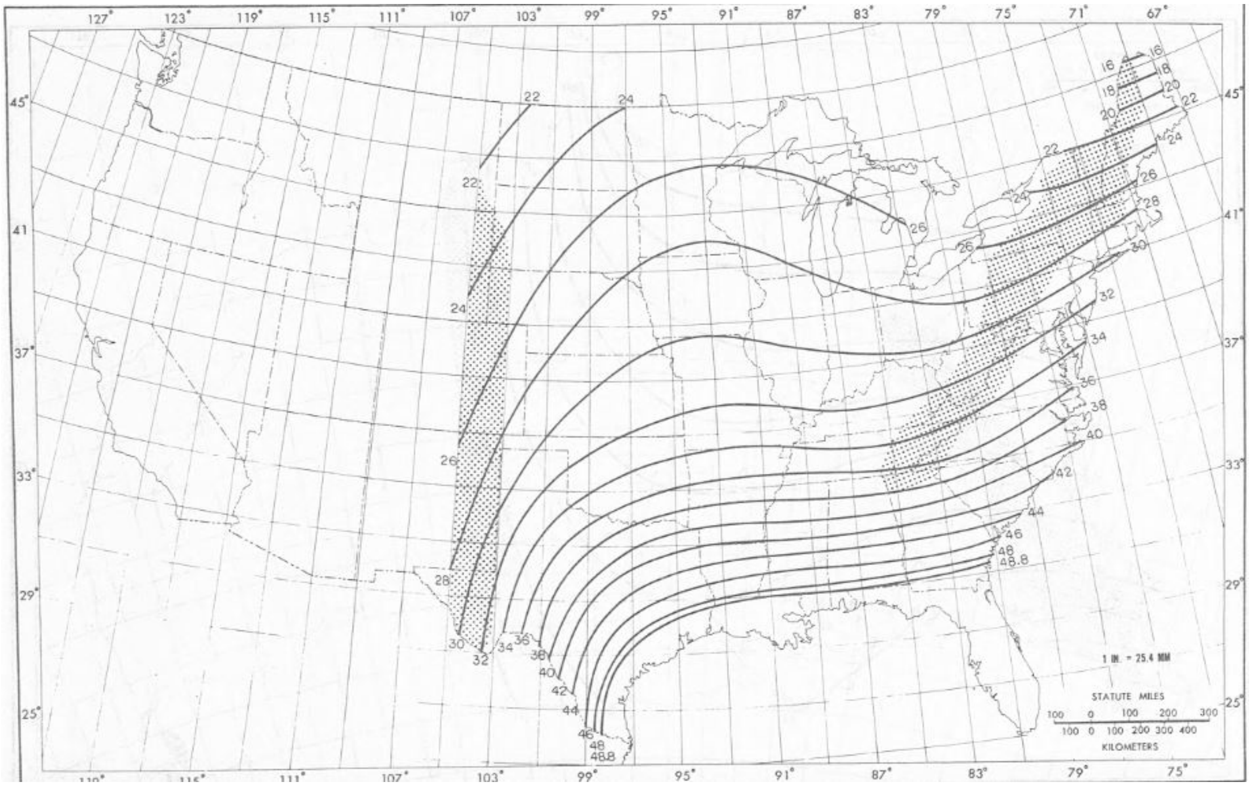

Figure 1.3: Example of HMR 51 72-hour 200-square mile PMP map (from Schreiner and Riedel, 1978).

The Region analyzed in this study in climate variations that extend from direct hurricane landfall effects to western High Plains low-level jet (LLJ) interactions to area effected by slow-moving large-scale frontal systems (Figure 1.4). Because of the distinctive climate regions and variance in topography, the development of PMP depths must account for the complexity of the meteorology and terrain throughout the Region. Although the HMRs provided relevant data at the time they were published, the understanding of meteorology and effects of terrain on rainfall (orographic effects) have advanced significantly in the subsequent years. Limitations that can now be addressed include a limited number of analyzed storm events, no inclusion of storms that have occurred since the early 1970's, no process used to address orographic effects, inconsistent data and procedures used among the HMRs, improved documentation allowing for reproducibility, and the outdated procedures used to derive PMP. This project incorporated the latest methods, technology, and data to address these complexities. Each of these were addressed and updated where data and current understanding of meteorology allowed.

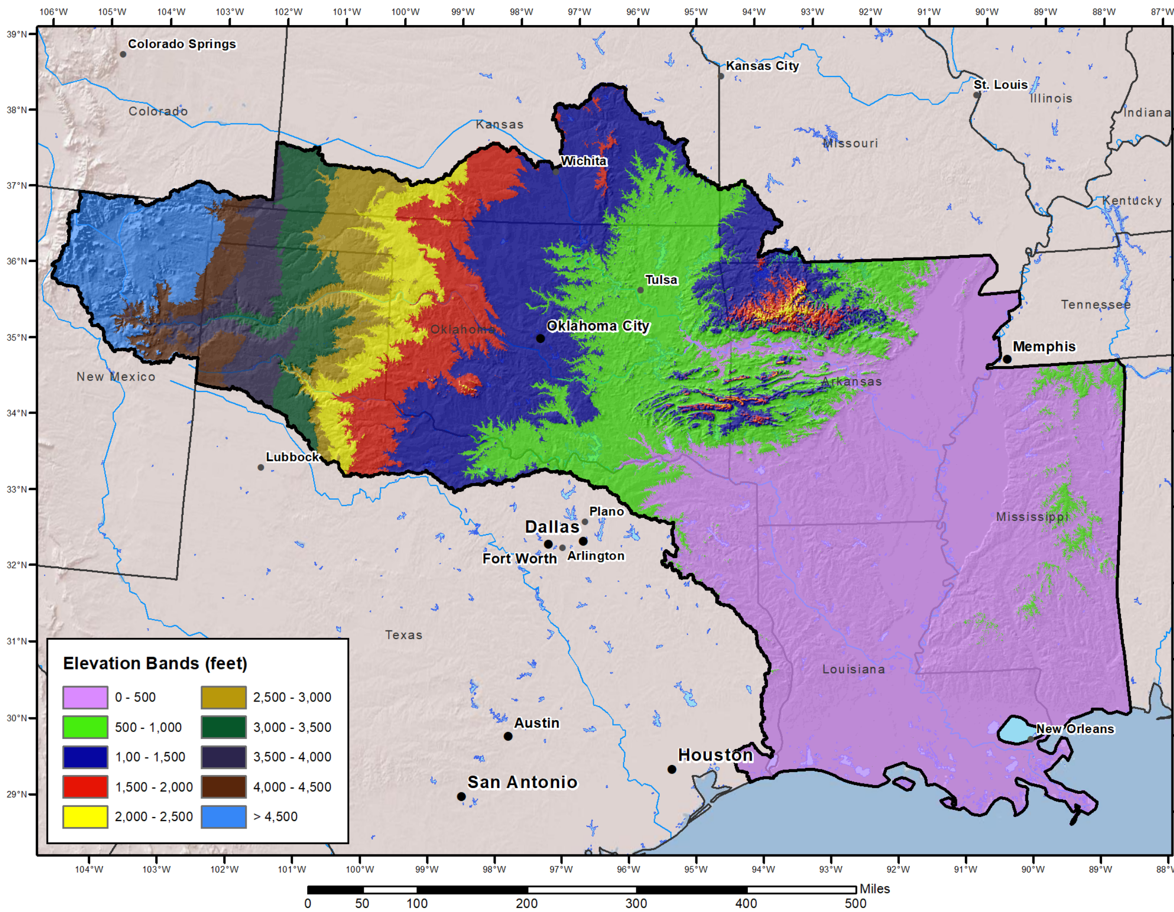

Figure 1.4: Elevations contours over the study Region at 500-foot intervals.

Previous site-specific, statewide, and regional PMP projects completed by AWA provide examples of PMP studies that explicitly consider the unique topography of the area being studied and characteristics of historic extreme storms over meteorologically and topographically similar regions surrounding the area. The procedures incorporate the most up-to-date sets, techniques, and applications to derive PMP. All AWA PMP studies have received extensive review and the results have been used in computing the PMF for the watersheds. This study follows similar procedures employed in those studies while making improvements where advancements in computer-aided tools and transposition procedures have become available.

Several PMP studies have been completed by AWA within the region covered by HMR 51, which are directly relevant to the Region (Figure 1.5). Each of these studies provided PMP depths which updated those from HMR 51. These are examples of PMP studies that explicitly consider the meteorology and topography of the study location along with characteristics of historic extreme storms over climatically similar regions. Information, experience, and data from these PMP studies were utilized in this study. These included use of previously analyzed storm events using the SPAS program, previously derived storm lists, previously derived in-place storm maximization factors, climatologies, and explicit understanding of the meteorology of the region. In addition, comparisons to these previous studies provided sensitivity and context with results of this study. These regional, statewide, and site-specific PMP studies received extensive review and were accepted by the appropriate regulatory agencies including state dam safety regulators, the Federal Energy Regulatory Commission (FERC), the4 Nuclear Regulatory Commission (NRC), and the Natural Resources Conservation Service (NRCS). Results have been used in computing the PMF for individual watersheds. This study followed the same procedures used in those studies to determine PMP values. These procedures, together with the Storm Precipitation Analysis System (SPAS) rainfall analyses (Parzybok and Tomlinson, 2006), were used to compute PMP values following standard procedures outlined in HMR 51

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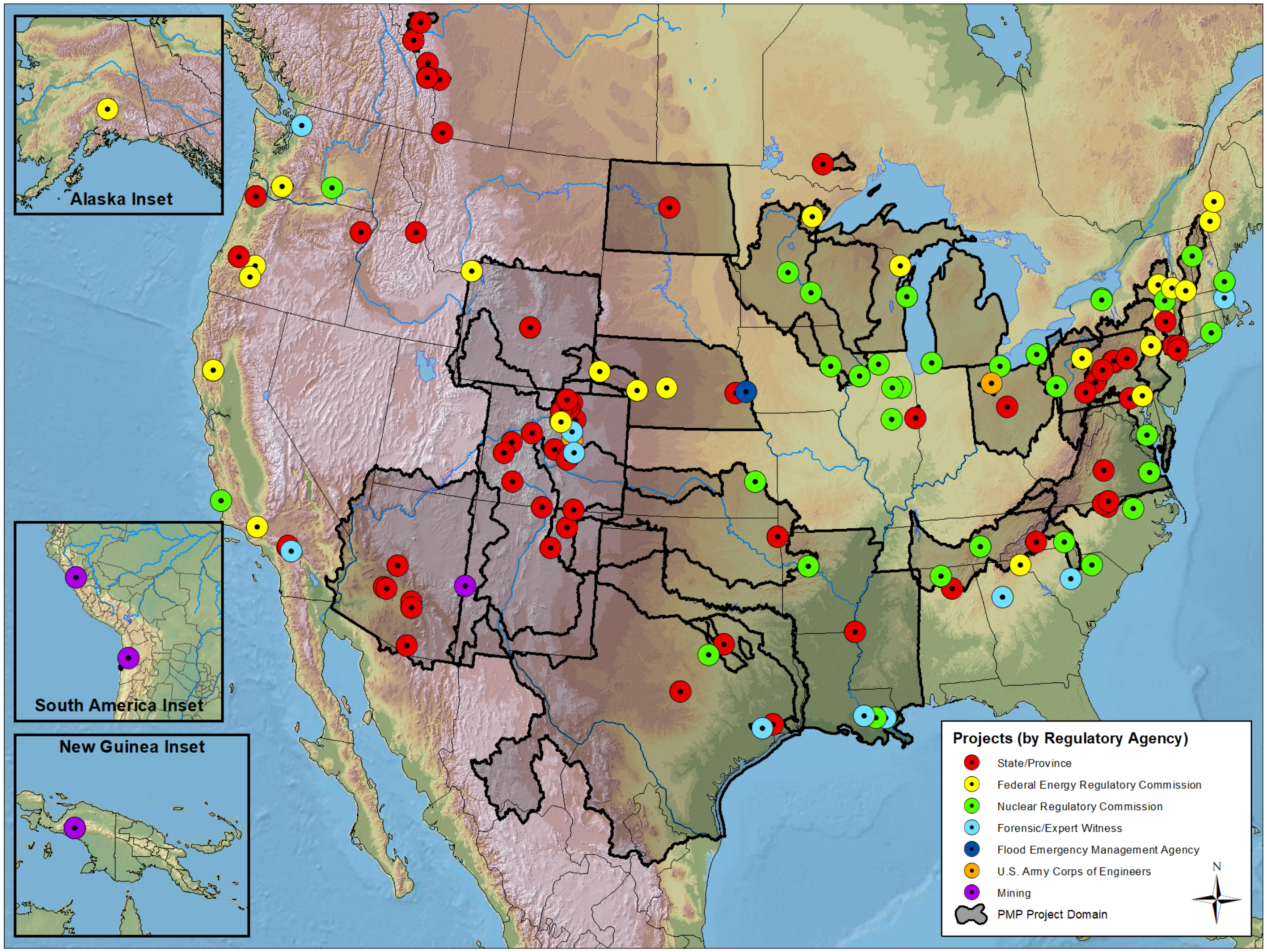

Figure 1.5: Locations of AWA PMP studies as of June 2019

1.2 Objective

This study determines reproducible estimates of PMP depths for use in computing the PMF for various watersheds in each state and within the overall project domain. The most reliable methods and data available were used and updates to methods and data used in HMRs were applied where appropriate.

1.3 PMP Analysis Domain

The project domain was defined to cover all of watersheds that extended beyond state boundaries for which each state dam safety office has responsibility for regulation. This study allows for gridded PMP depths to be determined for each grid cell within the project domain. The full PMP analysis domain is shown in Figure 1.1. Discussions with Oklahoma-Arkansas-Louisiana-Mississippi Dam Safety, FERC, NRCS, review board members, and private consultants involved in the study helped refine the analysis region beyond state boundaries to fully incorporate all potential aspects that may affect any portion of the Region.

1.4 PMP Analysis Grid Setup

A uniform grid covering the PMP project domain provides a spatial framework for the analysis. The PMP grid resolution for this study was 0.025 x 0.025 decimal degrees (dd), or 90 arc-seconds, using the Geographic Coordinate System (GCS) spatial reference with the World Geodetic System of 1984 (WGS 84) datum. This resulted in 129,851 grid cells with centroids within the domain. Each grid cell represents an approximate area of 2.5-square miles. The grid network placement is essentially arbitrary. However, the placement was oriented in such a way that the grid cell centroids are centered over whole number coordinate pairs and then spaced evenly every 0.025 dd. For example, there is a grid cell centered over 30.0° N and 90.0° W with the adjacent grid point to the west at 30.025° N and 90.025° W. As an example, the PMP analysis grid over the Eucha Dam drainage basin is shown in Figure 1.6.

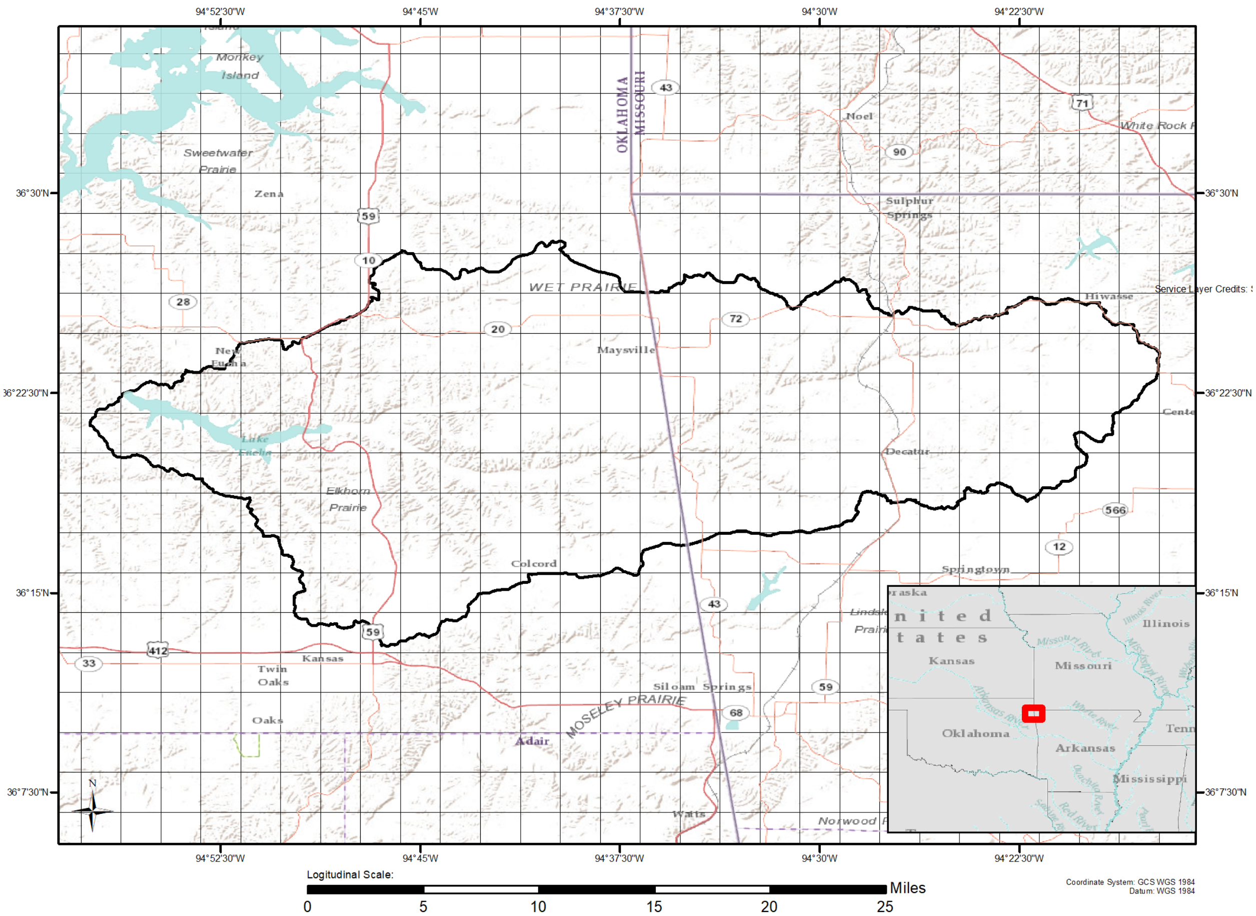

Figure 1.6: PMP analysis grid placement over the Eucha Dam basin

2. Methodology

The storm-based approach used in this study is consistent with many of the procedures that were used in the development of the HMRs and as described in the World Meteorological Organization PMP documents (WMO, 2009), with updated procedures implemented where appropriate. Methodologies reflecting the current standard of practice were applied in this study considering the unique meteorological and topographical interactions within the region as well as the updated scientific data and procedures available. Updated procedures are described in detail later in this report. Figure 2.1 provides the general steps used in deterministic PMP development utilizing the storm-based approach. Terrain characteristics are addressed as they specifically affect rainfall patterns spatially, temporally, and in magnitude.

This study identified major storms that occurred within the Region and areas where those storms were considered transpositionable within the study region. Each of the PMP storm types capable of producing PMP-level rainfall were identified and investigated. The PMP storm types included local storms, general storms, and tropical storms. The "short list" of storms was extensively reviewed, quality controlled, and accepted as representative of all storms that could potentially effect PMP depths at any location or area size within the overall study domain. This short list of storms was utilized to derive the PMP depths for all locations.

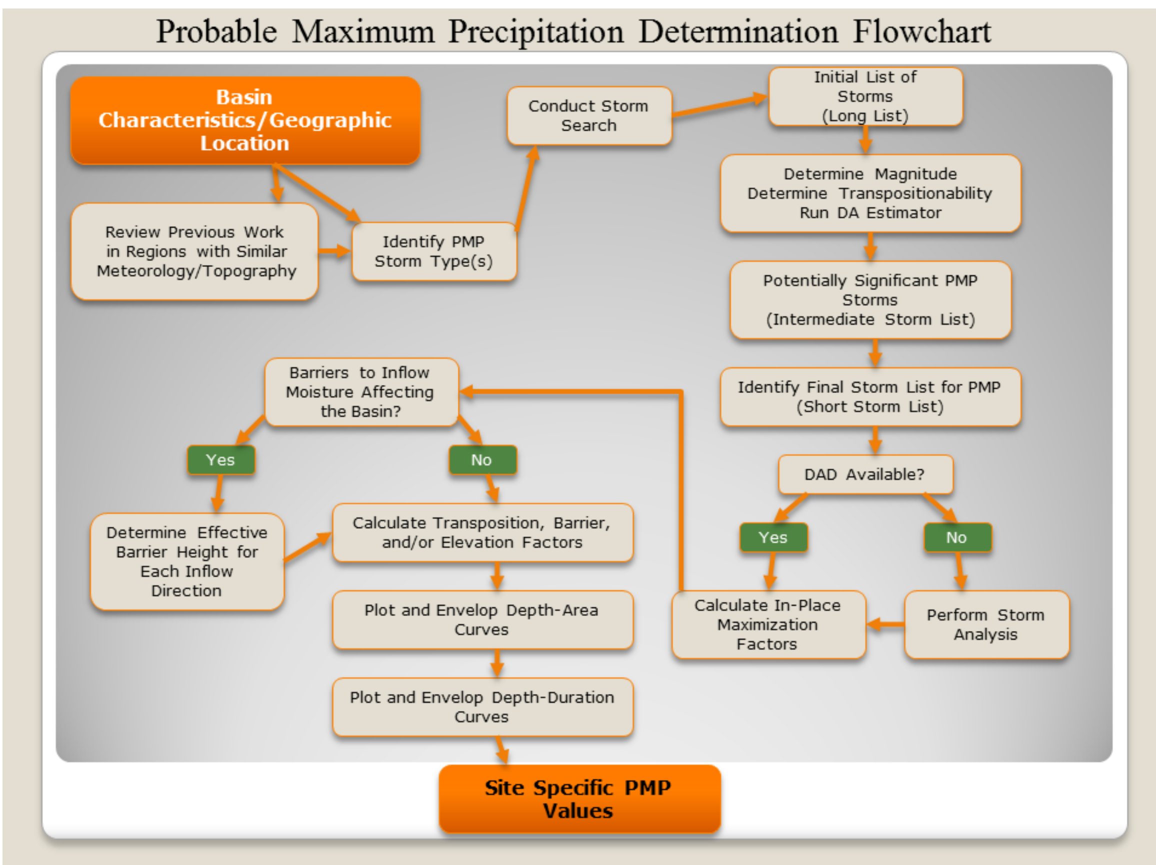

Figure 2.1: Probable Maximum Precipitation calculation steps

The moisture content of each of the short list storms was maximized to provide worst-case rainfall accumulation for each storm at the location where it occurred (in-place storm location). Storms were then transpositioned to locations with similar meteorological and topographical characteristics. Locations where each storm was transpositioned were determined using meteorological judgment, comparison of adjustment factors, comparisons of PMP depths, comparison against previous transposition limits from HMRs and AWA, discussions with the review board/study participants, and comparisons against precipitation frequency climatologies. Adjustments were applied to each storm as it was transpositioned to each grid point to calculate the amount of rainfall each storm would have produced at each grid point versus what it produced at the original location. These adjustments were combined to produce the total adjustment factor (TAF) for each storm for each grid point. The TAF is applied to the observed precipitation depths at the area size of interest to each storm.

Storm Precipitation Analysis System (SPAS) is utilized to analyze the rainfall associated with each storm used for PMP development. SPAS has been used to analyze more than 700 extreme rainfall events since 2002. SPAS analyses are used in PMP development as well as other meteorological applications. SPAS has been extensively peer reviewed and accepted as appropriate for use in analyzing precipitation accumulation by numerous independent review boards and as part of the Nuclear Regulatory Commission (NRC) software certification process. Appendix E provides a detailed description of the SPAS program. The TAF is a product of the In-Place Maximization Factor (IPMF) and the Geographic Transposition Factor (GTF). For this study, extensive discussion took place regarding the use of the MTF and whether it was already accounted for with the GTF process. This included evaluating the results of sensitivity that demonstrated the MTF is sufficiently accounted for in the GTF process (see Section 9.5). Therefore, it was as agreed that the MTF would be set to 1.00 in all calculations and have no effect on PMP.

The governing equation used for computation of the Total Adjusted Rainfall (TAR), for each storm for each grid cell for each duration, is given in Equation 1.

$$TAR_{xhr} = P_{xhr} \times IPMF \times GTF \qquad \text{(Equation 1)}$$

where:

TAR_{xhr} is the Total Adjusted Rainfall value at the x-hour (x-hr) duration for the specific grid cell at each duration at the target location;

P_{xhr} is the x-hour precipitation observed at the historic in-place storm location (source location) for the basin-area size;

In-Place Maximization Factor (*IPMF)* is the adjustment factor representing the maximum amount of atmospheric moisture that could have been available to the storm for rainfall production;

Geographic Transposition Factor (GTF) is the adjustment factor accounting for precipitation frequency relationships between two locations. This is used to quantify the all processes that effect rainfall, including terrain, location, and seasonality.

Note, the largest of these values at each duration becomes PMP at each grid point. The data and calculations are run at the area size and duration(s) specified through user input. The PMP output depths are then provided for durations required for Probable Maximum Flood (PMF) analysis at a given location by storm type and provided as a basin average. These data have a spatial pattern and temporal pattern associated with them for hydrologic modeling implementation. The spatial and temporal patterns are based on climatological patterns (spatial) and a synthesis of historic storm accumulation patterns (temporal) used in this study. Alternative spatial and temporal patterns are also possible at a given location. The user should consult with each state's dam safety offices for guidance regarding the use of alternative spatial and/or temporal patterns beyond what is provided in the tool developed during this study.

3. Weather and Climate of the Region

The region is influenced by several factors that can potentially contribute to extreme rainfall. First is the proximity of the region to the Gulf of Mexico. This allows high amounts of moisture to move directly into the region (Figure 3.1). The lift required to convert these high levels of moisture into rainfall on the ground is provided in several ways to the project domain.

Numerous large-scale weather systems with their associated fronts traverse the region, especially from fall through spring. These are most common in regions further to the north and east of approximately 100°W. The fronts (boundaries between two different air masses) can be a focusing mechanism providing upward motion in the atmosphere. These are often locations where heavy rainfall is produced. A front typically will move through with enough speed that no given area receives excessive amounts of rainfall. However, some of these fronts will stall or move very slowly across the region, allowing heavy amounts of rainfall to continue for several days in the same general area, which can lead to extreme widespread flooding.

Another mechanism, which creates lift in the region, is heating of the surface and lower atmosphere by the sun. This creates warmer air below cold air resulting in atmospheric instability and leads to rising motions. This will often form ordinary afternoon and evening thunderstorms. However, in unique circumstances, the instability and moisture levels in the atmosphere can reach very high levels and stay over the same region for an extended period of time. This can lead to intense thunderstorms and very heavy rainfall. If these storms are focused over the same area for a long period, flooding rains can be produced. This type of storm produces some of the largest point rainfall recorded, but often does not affect larger areas with extreme rainfall amounts.

Several of the most extreme rainfall events associated with the general storm type are enhanced by high levels of moisture streaming in from the south with origins around near the equator. In this region of the United States, these are termed "Maya Express" events because of their origins near Central America (Dirmeyer and Kinter, 2009 and Moore et al., 2011). Similar phenomena occur over many locations around the world, with the most well-known being the Atmospheric River events along the West Coasts of North and South America.

Direct tropical system makes landfall relatively frequently along the Gulf Coast including both Louisiana and Mississippi (Keim et al., 2007 and Keim and Muller, 2009). These storm result in some of the heaviest rainfalls recording the in United States for durations longer than 24-hours. In addition, as they continue to move inland, remnant tropical moisture and circulations associated with decaying tropical systems are another mechanism than can produce heavy rainfall in the region. This often leads to very heavy rainfall production and, when the storm becomes cut off from the main flow, these storms may stay over the same region for an extended period of time, producing devastating rainfall and flooding.

Figure 3.1: Synoptic weather features associated with moisture from the Gulf of Mexico into the Region

3.1 Regional Climatological Characteristics Affecting PMP Storm Types

Weather patterns in the region are characterized by three main types:

1. Areas of low pressure moving through the region from the west through the southwest or redeveloping along the lee slopes of the Rocky Mountains or over the warm water of the Gulf of Mexico (general storms);
2. Direct tropical system or remnant tropical moisture either from the Gulf of Mexico or Tropical easterly waves (tropical storms); and
3. Isolated thunderstorms/Mesoscale Convective Systems (local storms).

General storms which produce PMP-type rainfall are most frequent in the fall through spring. Tropical systems occur from June through October. Local storms which can produce PMP-type rainfall are most active from mid spring through early fall.

3.2 Storm Types

The PMP storm types investigated during the study were local thunderstorms/Mesoscale Convective Systems (MCS) where the main rainfall occurs over short durations and small area sizes, general storms where main rainfall occurs over large areas sizes and longer durations, and tropical systems which occur less frequently and have accumulation characteristics similar to the general storm type. The unique temporal patterns associated with each of these storms types was explicitly investigated. The development of these temporal patterns is described in Section 12.

The classification of storm types, and hence PMP development by storm type used in this study, is similar to descriptions provided in several HMRs (e.g. HMR 55A Section 1.5). Storms were classified by rainfall accumulation characteristics, while trying to adhere to previously used classifications. Several discussions took place with the review board and other study participants to ensure acceptance of the storm classifications. In addition, the storm classifications were cross-referenced with the storm typing completed as part of several other AWA PMP studies in the region (e.g. Kappel et al., 2011; Kappel et al., 2015; Kappel et al., 2018) to ensure consistency between how storms were used in adjacent studies.

Local storms were defined using the following guidance:

- The main rainfall accumulation period occurred over a 6-hour period or less
- Was previously classified as a local storm by the USACE or in the HMRs
- Was not associated with overall synoptic patterns leading to rainfall across a large region
- Exhibited high intensity accumulations
- Occurred during the appropriate season, April through October

General storms were defined using the following guidance:

- The main rainfall accumulation period lasted for 24 hours or longer
- Occurred with a synoptic environment associated with a low-pressure system, frontal interaction, and/or regional precipitation coverage
- Was previously classified as a general storm by the USACE or in the HMRs
- Exhibited lower rainfall accumulation intensities compared to local storms

Tropical storms were defined using the following guidance:

- The rainfall was a direct result of a tropical system, either landfalling or directly offshore
- Was previously classified as a tropical storm by the USACE or in the HMRs
- Occurred during the appropriate season, June through October

It should be noted that some of the storms exhibit characteristics of more than one storm type and therefore have been included for PMP development as more than one type. These are classified as hybrid storms.

3.2.1 Local Storms

Localized thunderstorms and MCSs are capable of producing extreme amounts of precipitation for short durations and over small area sizes, generally 6 hours or less over area sizes of 500 square miles or less. During any given hour, the heaviest rainfall only covers very small areas, generally less than 100 square miles.

Many of the storms previously analyzed by the USACE and NWS Hydrometeorological Branch, in support of pre-1979 PMP research, have features that indicate they were most likely Mesoscale Convective Complexes (MCCs) or MCSs. However, this nomenclature had not yet been introduced into the scientific literature, nor were the events fully understood. It is important to note that an MCC is a subset of the broader MCS category of mesoscale atmospheric phenomena. Another example of an MCS is the derecho, an organized line of thunderstorms that are notable for strong winds and resultant significant wind damage.

A mesoscale convective complex (MCC) is a mesoscale convective system that satisfies all of the following criteria (from Penn State's e-education institute: https://courseware.e-education.psu.edu/courses/meteo361/www.e-education.psu.edu/meteo361/l5_p10.html):

- The spatial extent of the cloud shield with cloud-top temperatures less than or equal to -32 degrees Celsius (-26 degrees Fahrenheit) must be at least 100,000 square kilometers, roughly two-thirds of the state of Iowa;
- The spatial extent of the coldest cloud tops with temperatures less than or equal to -52 degrees Celsius (-62 degrees Fahrenheit) must be at least 50,000 square kilometers;
- These size criteria must persist for at least six hours;
- Around the time of maximum extent, the cloud shield must be roughly circular in shape...refers to the cloud shield of cold cloud tops (temperatures less than or equal to -32 degrees Celsius) reaches its maximum size.

A typical MCC begins as an area of thunderstorms over the western High Plains or Front Range of the Rocky Mountains. As these storms begin to form early in the day, the predominantly westerly winds aloft move them in a generally eastward direction. As the day progresses, the rain-cooled air below and around the storm begins to form a mesoscale high-pressure area. This mesoscale high moves along with the area of thunderstorms. During nighttime hours, the MCC undergoes rapid development as it encounters increasingly warm and humid air from the Gulf of Mexico, usually associated with the low-level jet (LLJ) 3,000-5,000 feet above the ground. In the most extreme cases, this can be associated with the "Maya Express" pattern, where the moisture advecting into the region is enhanced significantly. This feed of moisture at a similar level at the LLJ over the Great Plains, can result in extreme rainfall accumulations when it is focused on the same areas for several days (Dirmeyer and Kitner, 2007).

The area of thunderstorms will often form a ring around the leading edge of the mesoscale high and continue to intensify, producing heavy rain, damaging winds, hail, and/or tornadoes. An MCC will often remain at a constant strength as long as the LLJ continues to provide an adequate supply of moisture. Once the mesoscale environment begins to change, the storms weaken, usually around sunrise, but may persist into the early daylight hours (Maddox, 1980).

Separate from MCC and MCS storm types, individual thunderstorms can be isolated from the overall general synoptic weather patterns and fueled by localized moisture sources. The local storm type in the region has a distinct seasonality, occurring during the warm season when the combination of moisture and atmospheric instability is at its greatest. This is the time of the year when convective characteristics and moisture within the atmosphere are adequate to produce lift and instability needed for thunderstorm development and heavy rainfall.

3.2.2 General Storms

General storms occur in association with frontal systems and along boundaries between sharply contrasting air masses. Precipitation associated with frontal systems is enhanced when the movement of weather patterns slow or stagnates, allowing moisture and instability to affect the same general region for several days. In addition, when there is a larger than normal thermal contrast between air masses in combination with higher than normal moisture, PMP-level precipitation can occur. The processes can be enhanced by the effects of topography, with heavier precipitation occurring along and immediately upwind of upslope regions. Intense regions of heavy rain can also occur along a front as a smaller scale disturbance moving along the frontal boundary, called a shortwave, creating a region of enhanced lift and instability. These shortwaves are not strong enough to move the overall large-scale pattern, but instead add to the storm dynamics and energy available for producing precipitation.

This type of storm will usually not produce the highest rainfall rates over short durations, but instead cause widespread flooding as moderate rain continues to fall over the same region for an extended period of time. Although they can occur at almost any time of the year, they are most likely to produce flooding rainfall from fall through spring. Strong frontal systems do affect many parts of the region in winter.

3.2.3 Tropical Storms

Tropical systems directly impact the coastal regions on a relatively frequent basis. However, by the time they reach inland portions, they have lost most of their closed circulation and pure tropical characteristics due to distance from their energy source in the Gulf of Mexico. In addition, the low-level circulations have been altered by interaction with land and topography in the region. However, the remnant air mass from a tropical system can add high levels of moisture and potential convective energy to the atmosphere, while circulations associated with the original tropical system continue to persist at diminished levels within the atmosphere. When these systems move slowly over the area, large amounts of rainfall can be produced both in convective bursts and over longer durations.

These types of storms require warm water and proper atmospheric conditions to be prevalent over the Gulf of Mexico and therefore only form from June through October, with August and September being the most common period (Keim and Muller, 2009).

Heavy rainfall associated with tropical storms is also associated with tropical easterly waves. These are disturbances which move through the region from east to west, generally south of 30°N latitude and provide lift in the atmosphere. Tropical easterly waves are often the seed for tropical systems as they move east to west across the Atlantic and Caribbean. These can enhance thunderstorm activity and increase rain rates significantly (Leppert et al., 2013). An excellent example of this type of storm in the region was the August 2016 rainfall event over southern Louisiana.

4. Topographic Effects on Precipitation

Terrain plays a significant role in precipitation development and accumulation patterns in magnitude, time and space. Terrain within the region both enhances and depresses precipitation depending on whether the terrain is forcing the air to rise (upslope effect) or descend (downslope). This occurs as air masses are forced to rise as they move inland an encounter higher terrain in norther Mississippi, Arkansas, and Oklahoma. In addition, the difference in frictional forces encountered as air moves from the Gulf of Mexico onto land results in enhanced rising motions.

To account for the effect of precipitation by terrain features (called orographic effects), explicit evaluations were performed using precipitation frequency climatologies and investigations into past storm spatial and accumulation patterns across the region. The NOAA Atlas 14 precipitation frequency climatologies (Bonnin et al., 2006; Bonnin et al., 2011; Perica et al., 2013; Perica et al., 2013; Perica et al., 2018), were used in this analysis. These climatologies were used to derive the GTF and the spatial distribution of the PMP. This approach is similar to the use of the NOAA Atlas 2 100-year 24-hour precipitation frequency climatologies used in HMR 55A (Section 6.3 and 6.4, Hansen et al., 1988), HMR 57 (Section 8.1, Hansen et al., 1994), and HMR 59 (Section 6.61. and 6.6.2, Corrigan et al., 1999) as part of the Storm Separation Method (SSM) to quantify orographic effects in topographically significant regions.

The terrain within the Region does not exhibit a sharp rise through most of Mississippi and Louisiana, before encountering significant terrain in southern Arkansas and southeastern Oklahoma as part of the Ouachita and Ozark Mountains (Figure 4.1). Elevations vary from sea level along the Gulf Coast to over 2,500 feet along the highest peaks of the Ouachita Mountains. When elevated terrain features are upwind of a drainage basin, depletion of low-level atmospheric moisture available to storms over the basin can occur. Conversely, when incoming air is forced to rise as it encounters elevated terrain, release of conditional instability can occur more effectively and enhance the conversion of moisture in the air to precipitation. These interactions must be taken into account in the PMP determination procedure, explicitly in the storm adjustment process.

The quantification of orographic effects was completed by evaluating rainfall depths at the 100-year recurrence interval using the 6-hour duration for local storms and the 24-hour duration for tropical and general storms at both the source (storm center) and target (grid point) location. This comparison produced a ratio that quantified the differences of precipitation processes, including topography, between the two locations. The assumption is that the precipitation frequency data represent all aspects that have produced precipitation at a given location over time, including the effect of terrain both upwind and in-place. Therefore, if two locations are compared within regions of similar meteorological and topographical characteristics, the resulting difference of the precipitation frequency climatology should reflect the difference of all precipitation producing processes between the two locations, including topography.

This relationship between precipitation frequency climatology and terrain is also recognized in the WMO PMP Manual (WMO, 1986 pg. 54 and by the Australian Bureau of

Meteorology (Section 3.1.2.3 of Minty et al., 1996). Although the orographic effect at a particular location may vary from storm to storm, the overall effect of the topographic influence (or lack thereof) is inherently included in the climatology of precipitation that occurred at that location, assuming that the climatology is based on storms of the same type. In WMO 2009 Section 3.1.4 it is stated "since precipitation-frequency values represent equal probability, they can also be used as an indicator of the effects of topography over limited regions. If storm frequency, moisture availability, and other precipitation-producing factors do not vary, or vary only slightly, over an orographic region, differences in precipitation-frequency values should be directly related to variations in orographic effects." Therefore, by applying appropriate transposition limits, analyzing by storm type, and utilizing duration for storm typing, it is assumed the storms being compared using the precipitation frequency data are of similar moisture availability and other precipitation-producing factors.

This assumption was explicitly evaluated and determined to be acceptable during the course of this study through various sensitivities and discussions with the review board, FERC, NRCS, and others involved in this study. These included testing of the variance of the statistical fits, comparing the difference of using the single grid at the storm center location versus an area size of several grids around the storm center. Recent AWA PMP studies have included additional sensitivities and evaluations to confirm the use of precipitation frequency climatologies calculate difference in precipitation producing processes, including topography between two locations (e.g. Tennessee Valley Authority Regional PMP, 2015; Colorado-New Mexico Regional Extreme Precipitation Study 2018; Pennsylvania statewide PMP, 2019).

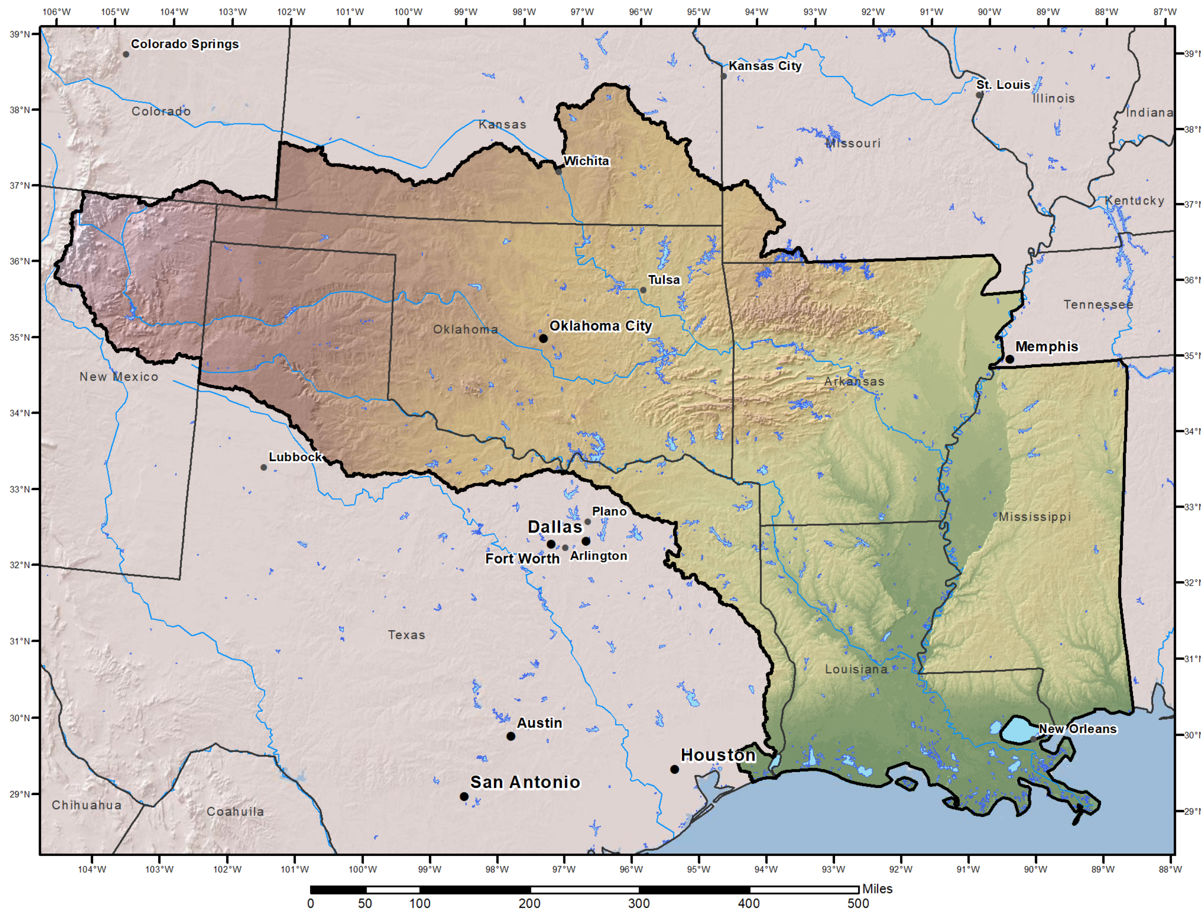

Figure 4.1: Topography variation across the domain analyzed. Reference Figure 1.4 for the elevation ranges across the domain analyzed.

5. Data Description and Sources

An extensive storm search was conducted as part of this study to derive the list of storms to use for PMP development. This included investigating the storm lists from previous relevant studies in the region (e.g. statewide studies in Nebraska, Colorado, New Mexico and Texas, regional PMP study for the Tennessee Valley Authority, and several site-specific studies within the Region). The storm list and the updated storm search completed to augment those previous storm lists utilized data from the sources below:

1. Hydrometeorological Reports 1, 33, 51, 52, 55A each of which can be downloaded from the Hydrometeorological Design Studies Center website at http://www.nws.noaa.gov/oh/hdsc/studies/pmp.html
2. Cooperative Summary of the Day / TD3200 through 2018. These data are published by the National Center for Environmental Information (NCEI), previously the National Climatic Data Center (NCDC). These are stored on AWA's database server and can be obtained directly from the NCEI.
3. Hourly Weather Observations published by NCEI, U.S. Environmental Protection Agency, and Forecast Systems Laboratory (now National Severe Storms Laboratory). These are stored on AWA's database server and can be obtained directly from the NCEI.
4. NCEI Recovery Disk. These are stored on AWA's database server and can be obtained directly from the NCEI.
5. U.S. Corps of Engineers Storm Studies (USACE, 1973).
6. United States Geological Society (USGS) Flood Reports (e.g., Dalrymple et al., 1937; Dalrymple et al., 1939; Paulsen and Wells, 1952; Asquith and Slade, 1995; Asquith, 1998; Asquith, 1999; Juracek, 2001; Al-Asaadi, 2002; Asquith et al., 2004; Williams-Sether et al., 2004; and Costa and Jarrett, 2008).
7. Other data published by NWS offices. These can be accessed from the National Weather Service homepage at http://www.weather.gov/.
8. Data from supplemental sources, such as Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS), Weather Underground, Forecast Systems Laboratories, RAWS, and various Google searches.
9. Previous and ongoing PMP and storm analysis work (Tomlinson, 1993; Tomlinson et al., 2008-2013; Kappel et al., 2013-2019).
10. Peer reviewed journals (e.g., McAuliffe, 1921; Jennings, 1950; Carr, 1951; Lott, 1952; Lott, 1953; Lott, 1954; Schoner and Molansky, 1956; Bosart, 1984; Moore and Riley, 1993; Keim and Faiers, 1999; Smith et al., 2000; Rogash et al., 2006; Furl et al., 2015; Clayton et al., 2015).

5.1 Use of Dew Point Temperatures

HMR and WMO procedures for storm maximization use a representative storm dew point as the parameter to represent available moisture to a given storm. Prior to the mid-1980s, maps of maximum 12-hour persisting dew point values from the *Climatic Atlas of the United States* (EDS, 1968) were the source for maximum dew point values. This study used the 100-year return frequency dew point climatology, which is continuously updated by AWA. Storm precipitation amounts were maximized using the ratio of precipitable water for the maximum dew point to precipitable water for the storm representative dew point, assuming a vertically saturated atmosphere through 30,000 feet. The precipitable water values associated with each storm representative value were taken from the WMO Manual for PMP Annex 1 (1986).

Use of the 100-year recurrence interval dew point climatology in the maximization process is appropriate because it provides a sufficiently rare occurrence of moisture level when combined with the maximum storm efficiency to produce a combination of rainfall producing mechanism that could physically occur. Recent research has shown that the assumption of combining the maximum storm efficiency with the maximum dew point value results in the most conservative combination of storm parameters and hence the most conservative PMP depths when considering all the possibilities of PMP development (Alaya et al., 2018).

An envelope of maximum dew point values is no longer used because in many cases the maximum observed dew point values do not represent a meteorological environment that would produce rainfall, but instead often represents a local extreme moisture value that can be the result of local evapotranspiration and other factors not associated with a storm environment and fully saturated atmosphere. Also, the data available has changed significantly since the publication of the maximum dew point climatologies used in HMR 51. Hourly dew point observations became standard at all first order NWS weather stations starting in 1948. This has allowed for a sufficient period of record of hourly data to exist from which to develop the climatologies out to the 100-year recurrence interval. These data were not available in sufficient quantity and period of record during the development of HMR 51.

Maximum dew point climatologies are used to determine the maximum atmospheric moisture that could have been available. Prior to the mid-1980s, maps of maximum dew point values from the *Climatic Atlas of the United States* (EDS, 1968) were the source for maximum dew point values. For the region covered by HMR 49, HMR 50 (Hansen and Schwartz, 1981) provided updated dew point climatologies. HMR 55A contained updated maximum dew point values for a portion of United States from the Continental Divide eastward into the Central Plains. HMR 57 updated the 12-hour persisting dew points values and added a 3-hour persisting dew point climatology. The regional PMP study for Michigan and Wisconsin produced dew point frequency maps representing the 50-year recurrence interval. The choice to use a recurrence interval and average duration was first determined to be the best representation of the intent of the process during the EPRI Michigan/Wisconsin region PMP study (Section 2-1 and 7, Tomlinson, 1993). That study included original authors of HMR 51 on the review board.

The EPRI study was conducted using an at-site method of analysis with L-moment statistics. The Review Committee for that study included representatives from NWS, FERC, Bureau of Reclamation, and others. They agreed that the 50-year recurrence interval values were appropriate for use in PMP calculations. For the Nebraska statewide study (Tomlinson et al., 2008), the Review Committee and FERC Board of Consultants agreed that the 100-year recurrence interval dew point climatology maps were appropriate because their use added a layer of conservatism over the 50-year return period. This has subsequently been utilized in all PMP studies completed by AWA. This study is again using the 100-year recurrence interval climatology constructed using dew point data updated through 2018 (Figure 5.1).

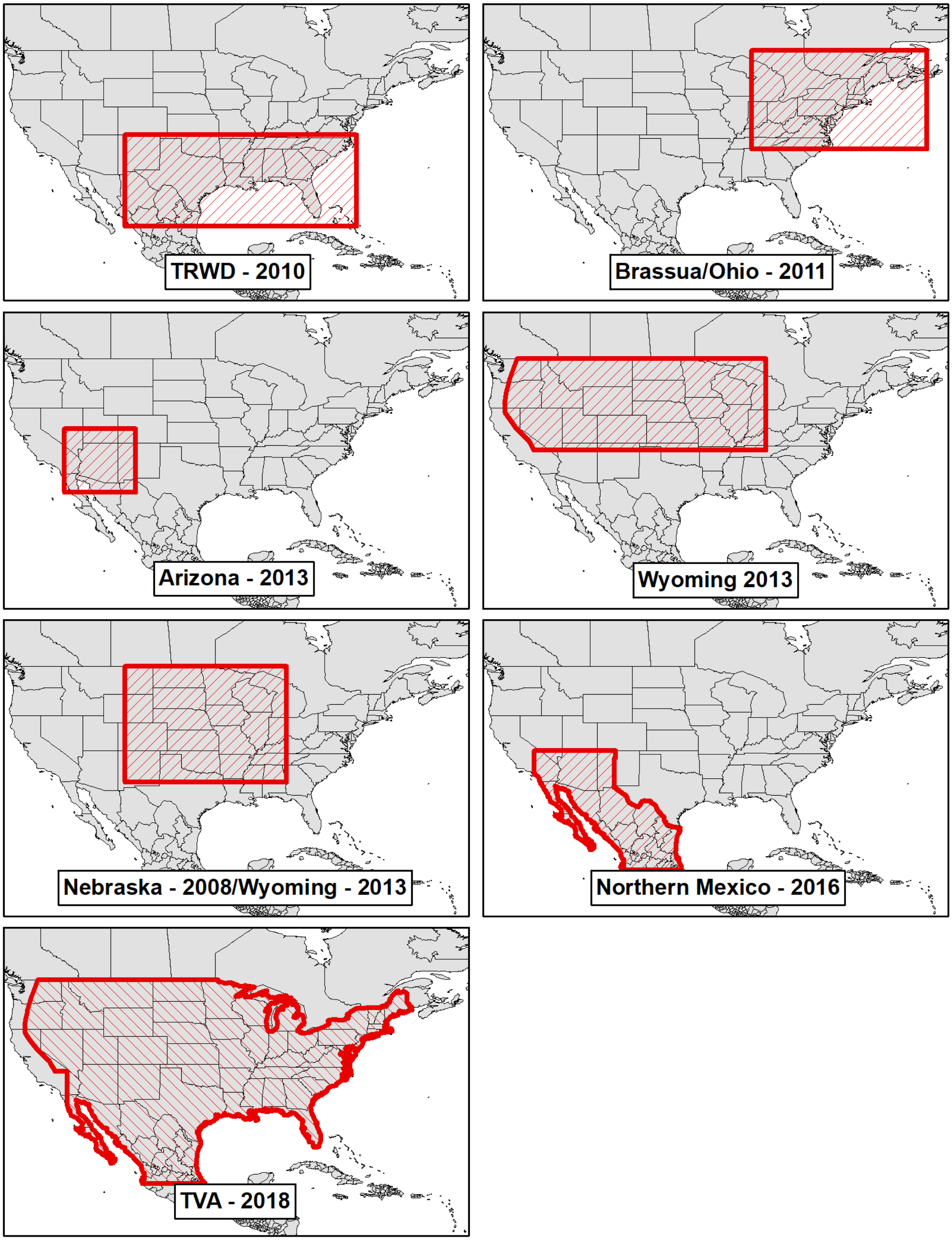

Figure 5.1: Maximum dew point climatology development regions and dates

5.2 Use of Sea Surface Temperatures

Dew point observations are not generally available over ocean regions. When the source region of atmospheric moisture resulting in a rainfall event originates from over the ocean, a substitute for dew points observations is required. The NWS adopted a procedure for using SSTs as surrogates for dew point data (U.S. Navy Marine Climate Atlas, 1981). The value used as the maximum SST in the PMP calculations is determined using the SSTs two standard deviations warmer (+2-sigma) than the mean SST (Worley et al., 2005; Kent et al., 2007; and Reynolds et al., 2007). This provides a value for the maximum SST that has a probability of occurrence of about 0.025 (i.e. about the 40-year recurrence interval value).

HYSPLIT model output provides detailed analyses for determining the upwind trajectories of atmospheric moisture that was advected into the storm systems. Using these trajectories as general guidance, the moisture source locations can be investigated. This is especially helpful over ocean regions where surface data are lacking to help with guidance in determining the moisture source region for a given storm. The procedures followed are similar to the approach used in HMR 59. However, by utilizing the HYSPLIT model trajectories, much of the subjectivity is eliminated. Further, details of each evaluation can be explicitly provided, and the results are reproducible. These trajectories extend over cooler coastal ocean currents to the warmer regions of the ocean that provide the atmospheric moisture that is later converted to rainfall by the storm system. SSTs for in-place maximization and storm transpositioning follow a similar procedure to that used with land-based surface dew points. Use of the HYSPLIT model provides a significant improvement in determining the inflow wind vectors compared to older methods of extrapolating coastal wind observations and estimating moisture advection from synoptic features over the ocean. This more objective procedure is especially useful for situations where a long distance is involved to reach warmer ocean regions.

Timing is not as critical for inflow wind vectors extending over the oceans since SSTs change very slowly with time compared to dew point values over land. What is important is the changing wind direction, especially for situations where there is curvature in the wind fields. Any changes in wind curvature and variations in timing are inherently captured in the HYSPLIT model re-analysis fields, thereby eliminating another subjective parameter. Timing of rainfall is determined using the rainfall mass curves from the region of maximum rainfall associated with a given storm event. The location of the storm representative SST was determined by identifying the location where the SSTs are generally changing less than 1°F in an approximate 1° x 1° latitude and/or longitude distance following the inflow vector upwind. This is used to identify the homogeneous (or near homogeneous) region of SSTs associated with the atmospheric moisture source for the storm being analyzed. The value from the SST daily analysis for that location is used for the storm representative SST. The storm representative SST becomes a surrogate for the storm representative dew point in the maximization procedure.

The value for the maximum SST was determined using the mean +2-sigma (two standard deviations warmer than the mean) SST for that location. SSTs were substituted for dew points in this study for several storms where the inflow vector originated over the Atlantic Ocean. The data presented in Appendix F shows the moisture source region for each storm and whether dew points or SSTs were used in the maximization calculations. For storm maximization, the value for the maximum SST is determined using the mean +2-sigma SST for that location for a date two weeks before or after the storm date (which ever represents the climatologically warmer SST period). Storm representative SSTs and the mean +2-sigma SSTs are used in the same manner as storm representative dew points and maximum dew point climatology values in the maximization and transpositioning procedure. Storm representative SSTs and the mean +2 sigma SSTs are used in the same manner as storm representative dew points and maximum dew point climatology in the maximization and transpositioning procedure.

6. Data Quality Control and Quality Assurance

During the development of the deterministic PMP values, quality control (QC) and quality assurance (QA) measures were in-place to ensure data used were free from errors and process followed acceptable scientific procedures. QC/QA procedures were in-place internally from Applied Weather Associates and externally from the review board and other study participants.

The built in QA/QC checks that are part of the SPAS algorithms were utilized. These include gauge quality control, gauge mass curve checks, statistical checks, gauge location checks, co-located gauge checks, rainfall intensity checks, observed versus modeled rainfall checks, ZR relationship checks (if radar data are available). These data QA/QC measures help ensure accurate precipitation reports, ensure proper data analysis and compilation of values by duration and area size, and consistent output of SPAS results. For additional information on SPAS, the data inputs, modeled outputs, and QA/QC measures, see Appendix E. For the storm adjustment process, internal QA/QC included validation that all IPMF were 1.00 or greater, that the MTF was set to 1.00, that upper (1.50) and lower (0.50) limits of the GTF were applied, and that any unique GTF limits were appropriate.

Maps of gridded GTF values were produced to cover the PMP analysis domain (Appendix B). These maps serve as a tool to spatially visualize and evaluate adjustment factors. Spot checks were performed at various positions across the domain and hand calculations were done to verify adjustment factor calculations are consistent. Internal consistency checks were applied to compare the storm data used for PMP development against previous PMP studies completed by AWA, against HMR 51 PMP depths and other data such as NOAA Atlas 14 precipitation depths, and world record rainfall depths.

Maps of each version (see Appendix I for the Version Log notes) of PMP depths were plotted at standard area sizes and durations to ensure proper spatial continuity of PMP depths. Updates were applied to ensure reasonable gradients and depths based on overall meteorological and topographical interactions. Comparisons were completed against previous PMP values from the appropriate HMRs, from the bordering PMP studies, and against various precipitation frequency climatologies. The PMP tool employs very few calculations, however the script utilizes Python's 'try' and 'except' statements to address input that may be unsuitable or incorrect.

The review board and other study participants completed external QA/QC on several important aspects of the PMP development. Storms used for PMP development were evaluated, the transposition limits of important storms were discussed in detail, the storm representative values for each storm were reviewed, and the PMP depths across the region reviewed and discussed. In addition, the review board and study participants provided extensive review and comment on the temporal accumulation pattern development, the GIS tool output, and report documentation.

7. Storm Selection

7.1 Storm Search Process

The initial search began with identifying storms that had been used in other PMP studies in the region covered by the storm search domain (Figure 7.1). These storm lists were combined to produce a long list of storms for this study. As mentioned in Section 5, previous lists analyzed included the Nebraska statewide PMP study (2008), the Ohio statewide PMP study (2013), the Tennessee Valley Authority regional PMP study (2015), the Texas statewide PMP study (2016), the Colorado-New Mexico Regional PMP (2018), and the numerous site-specific PMP studies in the Region. These previous storms lists were updated with data through the course of this study and from other reference sources such as HMRs, USGS, USACE, USBR, state climate center reports, and NWS reports. In addition, discussions with the review board and other study participants were reviewed to identify dates with large rainfall amounts for locations within the storm search domain. Several new storms were identified for further investigation such as Necaise, LA May 1995 (SPAS 1719); northern Louisiana/eastern Arkansas March 2016; southern Missouri April-May 2017; and central Oklahoma September 2018.

Storms from each of these sources were evaluated to see if they occurred within the overall region considered to be transpositionable to any locations within the Region and were previously important for PMP development. Next, each storm was analyzed to determine whether it was included on the short list for any of the previous studies, whether it was used in the relevant HMRs, and/or whether it produced an extreme flood event. Storms included on the initial storm list all exceeded the 100-year return frequency value for specified durations at the station location. Each storm was then classified by storm type (e.g. local, general, tropical) based on their accumulating characteristics and seasonality as discussed in Section 2. Storm types were discussed with the review board to ensure concurrence and cross-referenced with previous storm typing to ensure consistency. The storms were then grouped by storm type, storm location, and duration for further analysis to define the final short list of storms used for PMP development. These storms were plotted and mapped using GIS to better evaluate the spatial coverage of the events throughout the region by storm type to ensure adequate coverage for PMP development.

The recommended storm list was presented to the review board and other study participants for discussion and evaluation. The recommended short list of storms was based on the above evaluations and experience with past studies and relevance for this project. The recommended short storm list was reviewed by the review board and discussed in detail during review meetings and subsequently through the end of the project as various iterations of the PMP were developed. A few storms were removed from final consideration because of transposition limits and others were classified as hybrid events when they exhibit rainfall accumulation characteristics of more than one storm type. Iterations of how each storm was used can be found in the PMP Version log provided in Appendix I.

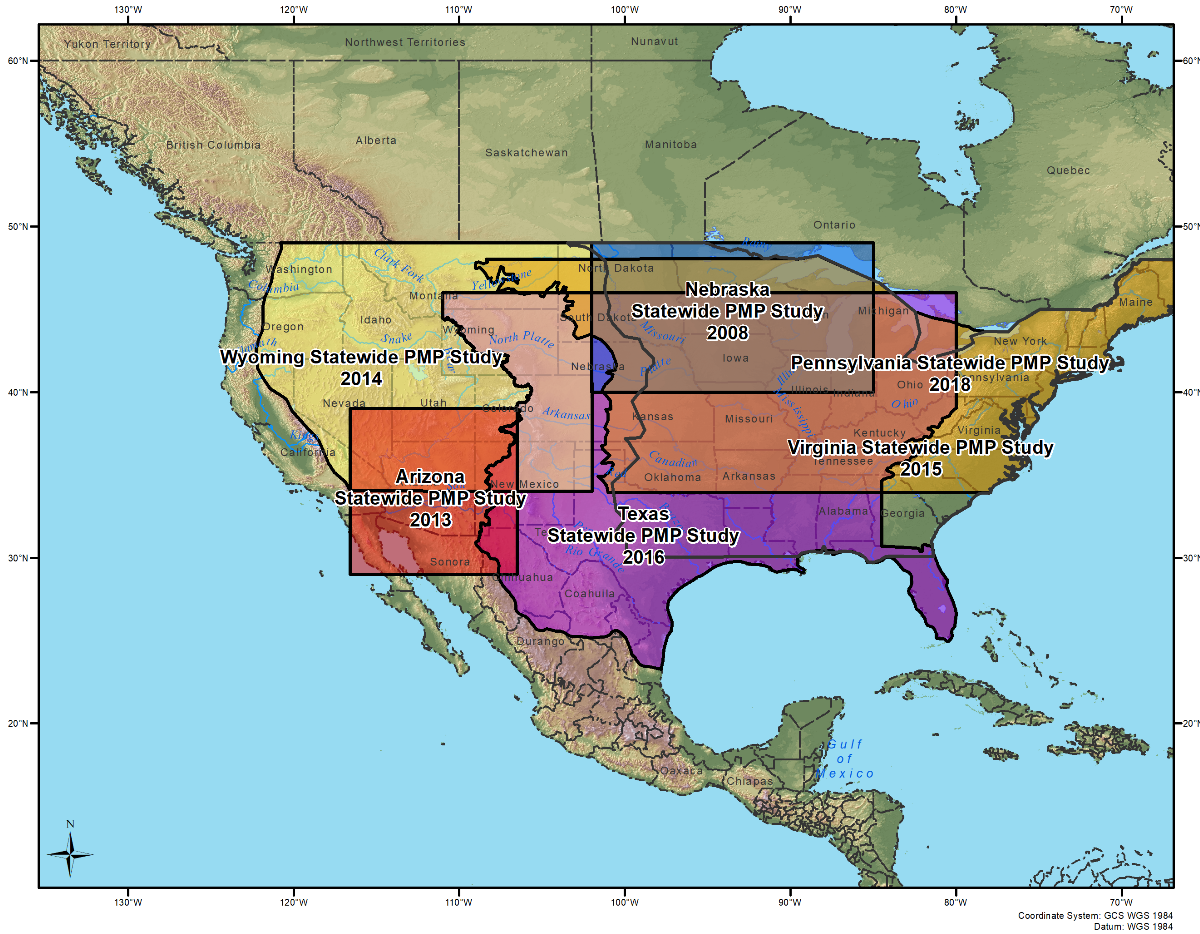

Figure 7.1: Previous AWA PMP studies storm search domains

7.2 Short Storm List Development

From the initial storm list, the storms to be used for PMP development were identified and moved to the recommended short storm list. Each storm was investigated using both published and unpublished references described above and AWA PMP studies to determine its significance in the rainfall and flood history of surrounding regions. Detailed discussions about each important storm took place with the review board and other study participants. These included evaluations and comparisons of the storms, discussions of each storm's effects in the location of occurrence, discussion of storms in regions that were underrepresented, discussion of storms importance for PMF development in previous design analyses, and other meteorological and hydrological relevant topics.

Consideration was given to each storm's transpositionability within the overall domain and each storm's relative magnitude compared to other similar storms on the list and whether another storm of similar storm type was significantly larger. In this case, what is considered is whether after all adjustments are applied a given storm would still be smaller than other storms used. To determine this, several evaluations were completed. These included use of the storm in previous PMP studies, comparison of the precipitation values at area sizes relevant to the basin, and comparison of precipitation values after applying a 50% maximum increase to the observed values.

7.3 Big Rapids, MI September 1986 Storm Removal Discussion

Extensive discussion took place regarding use of the Big Rapids, MI September 1986 (SPAS 1206) storm in this study and specifically whether it is transpositionable to any location within the region. Additional attention was given to the storm because it was controlling of PMP depths and often produced PMP depths significantly greater than HMR 51. Numerous sensitivities were completed to evaluate the effect of the storm and whether various adjustments to adjustment factors could be applied to bring this storm to a more reasonable level compared to other storms in the Region.

However, applying the numerous adjustments still produced significant discontinuities and gradients that were not meteorologically supported. Therefore, given that the storm was already being moved a significant distance, especially for a September storm event, it became obvious that the storm should not be utilized in this study and the storm was removed from final consideration as part of the final PMP development. Appendix J provides the memo provided justifying this decision.

7.4 Final PMP Storm List Development

The final short storm list used to derive PMP depths for this study considered each of the discussions in the previous sections in detail. Each storm on the final short storm list exhibited characteristics that were determined to be possible over some portion of the overall study domain. The storms that made it through these final evaluations were placed on the short storm list (Table 7.1 and Figure 7.2). Figure 7.3, Figure 7.4, and Figure 7.5 provide the short list storms by storm type with a callout providing the storm name and date that can be cross-referenced with the information provided in Table 7.1. Each of these storms were fully analyzed in previous PMP studies or as part of this study using the SPAS process (Appendix E).

Ultimately, only a subset of the storms on the short list control PMP values at a given location for a given duration, with most providing support for the PMP values.

The short storm list contains 63 unique SPAS storm DAD zones, far more storms than were ultimately controlling of the PMP depths. This is one of the steps that helps to ensure no storms were omitted which could have affected PMP depths after all adjustment factors were applied. The conservative development of the short storm list is completed because the final magnitude of the rainfall accumulation associated with a given storm is not known until all of the total adjustment factors have been calculated and applied. In other words, a storm with large point rainfall values may have a relatively small total adjustment factor, while a storm with a relatively smaller but significant rainfall value may end up with a large total adjustment factor. The combination of these calculations may provide a total adjusted rainfall value for the smaller rainfall event that is greater than the larger rainfall event after all adjustments are applied.

Table 7.1: Short storm list

SPAS Number	Storm Name	State	Latitude	Longitude	Year	Month	Day	Maximum total Rainfall (in)	Storm Rep Analysis Duration	PMP Storm Type	Storm Rep Dew Point/SST	Maximum Dew Point/SST	In Place Max Factor	Storm Adjustment Date	Storm Representative Latitude	Storm Representative Longitude	Moisture Inflow Vector	In Place Max Factor
SPAS_1614_2	LAKE MORAINE	CO	38.804	-104.946	1894	5	30	8.91	24	GENERAL	66.0	77.0	1.50	15-Jun	36.45	-101.05	270SE	1.50
SPAS_1591_1	HEARNE	TX	30.840	-96.570	1899	6	27	34.50	SST	TROPICAL	83.5	86.0	1.11	10-Jul	26.50	-90.00	500SE	1.11
SPAS_1426_1	COOPER	MI	42.376	-85.610	1914	8	31	12.60	6	LOCAL	75.0	80.5	1.30	15-Aug	40.25	-89.50	250SW	1.30
SPAS_1294_1	PENROSE	CO	38.464	-105.070	1921	6	2	12.20	6	HYBRID (G/L)	74.0	79.5	1.35	20-Jun	34.25	-100.10	400SE	1.35
SPAS_1294_2	ADELAIDE	CO	38.564	-105.071	1921	6	2	10.14	6	HYBRID (G/L)	74.0	79.5	1.38	20-Jun	34.25	-100.10	400SE	1.38
SPAS_1592_1	THRALL	TX	30.629	-97.388	1921	9	9	39.90	12	HYBRID (T/L)	79.0	80.5	1.07	24-Aug	27.00	-97.39	250SW	1.07
SPAS_1427_1	BOYDEN	IA	43.190	-96.010	1926	9	17	24.00	12	LOCAL	77.0	78.0	1.05	3-Sep	40.85	-94.75	175SSE	1.05
SPAS_1305_1	ELBA	AL	31.363	-86.121	1929	3	12	29.73	24	GENERAL	69.0	73.5	1.13	30-Mar	30.30	-86.12	75S	1.13
SPAS_1494_1	MOUNTAIN HOME	TX	30.171	-99.379	1932	6	30	35.56	12	LOCAL	77.0	80.0	1.15	15-Jul	27.50	-99.15	175S	1.15
SPAS_1495_1	CHEYENNE	OK	35.621	-99.679	1934	4	3	23.01	12	LOCAL	68.0	74.0	1.36	20-Apr	32.25	-98.20	250SE	1.36
SPAS_1295_1	ELBERT CHERRY CREEK	CO	39.238	-104.488	1935	5	30	24.00	6	LOCAL	76.5	78.0	1.09	30-May	33.05	-99.80	500SSE	1.09
SPAS_1295_2	GENOA	CO	39.329	-103.538	1935	5	30	12.65	6	LOCAL	76.5	78.0	1.09	30-May	33.05	-99.80	475SSE	1.09
SPAS_1295_3	HALE	CO	39.613	-102.263	1935	5	30	18.00	6	LOCAL	76.5	78.0	1.08	30-May	33.05	-99.80	475SSE	1.08
SPAS_1496_1	WOODWARD RANCH	TX	29.479	-99.388	1935	5	31	21.93	6	LOCAL	77.0	80.5	1.18	15-Jun	27.77	-97.50	165SE	1.18
SPAS_1582_1	BROOME	TX	31.788	-100.854	1936	9	13	30.34	SST	TROPICAL	84.0	86.0	1.09	1-Sep	27.50	-95.00	460SE	1.09
SPAS_1429_2	HALLETT	OK	36.246	-96.613	1940	9	2	24.00	12	LOCAL	77.5	80.0	1.12	17-Aug	32.90	-93.15	300SE	1.12
SPAS_1596_1	MILLER ISLAND	LA	29.854	-92.246	1940	8	6	37.85	SST	TROPICAL	85.5	87.0	1.06	19-Aug	27.50	-91.00	180SSE	1.06
SPAS_1486_1	MCCOLLEUM RANCH	NM	32.146	-104.746	1941	9	20	21.81	24	GENERAL	74.0	78.0	1.25	10-Sep	29.50	-98.40	420ESE	1.25
SPAS_1587_1	PRAIRIEVIEW	NM	33.138	-103.079	1941	5	20	11.08	24	GENERAL	71.0	78.5	1.48	9-Jun	29.46	-98.43	375SE	1.48
SPAS_1431_1	WARNER	OK	35.479	-95.329	1943	5	6	25.24	24	GENERAL	71.5	77.5	1.34	24-May	31.61	-97.23	290SSW	1.34
SPAS_1432_1	MOUNDS	OK	35.846	-96.071	1943	5	16	19.27	6	LOCAL	73.0	79.0	1.33	1-Jun	33.84	-96.98	150SSW	1.33

Table 7.1: Short storm list (continued)

SPAS Number	Storm Name	State	Latitude	Longitude	Year	Month	Day	Maximum total Rainfall (in)	Storm Rep Analysis Duration	PMP Storm Type	Storm Rep Dew Point/SST	Maximum Dew Point/SST	In Place Max Factor	Storm Adjustment Date	Storm Representative Latitude	Storm Representative Longitude	Moisture Inflow Vector	In Place Max Factor
SPAS_1433_1	COLLINSVILLE	IL	38.672	-89.980	1946	8	12	18.70	24	GENERAL	76.0	80.5	1.23	1-Aug	32.55	-93.00	455SSW	1.23
SPAS_1434_1	HOLT	MO	39.453	-94.342	1947	6	18	17.60	6	LOCAL	79.0	81.5	1.12	5-Jul	36.18	-95.25	230SSW	1.12
SPAS_1613_1	GOLDEN	CO	39.788	-105.288	1948	6	7	6.00	6	LOCAL	74.0	79.5	1.37	21-Jun	35.77	-100.73	370SE	1.37
SPAS_1519_1	YANKEETOWN	FL	29.029	-82.721	1950	9	3	45.18	SST	TROPICAL	84.0	86.5	1.11	20-Aug	25.00	-85.00	310SSW	1.11
SPAS_1560_1	CONWAY	TX	35.221	-101.396	1951	5	13	15.21	24	HYBRID (G/L)	71.5	78.0	1.41	1-Jun	30.51	-97.74	390SE	1.41
SPAS_1583_1	COUNCIL GROVE	KS	38.646	-96.621	1951	7	9	18.56	24	GENERAL	75.0	80.5	1.30	15-Jul	36.05	-93.32	250SE	1.30
SPAS_1602_1	VIC PIERCE	TX	30.404	-101.438	1954	6	23	35.79	24	LOCAL	76.5	80.0	1.16	15-Jun	27.77	-97.51	300SE	1.16
SPAS_1251_1	LAKE MALOYA	NM	37.009	-104.341	1955	5	19	14.82	24	GENERAL	70.5	78.0	1.50	5-Jun	31.50	-98.10	520SE	1.50
SPAS_1030_1	DAVID CITY	NE	41.213	-97.071	1963	6	24	15.98	6	LOCAL	73.5	81.5	1.47	9-Jul	39.41	-94.83	175SE	1.47
SPAS_1226_1	COLLEGE HILL	OH	40.085	-81.648	1963	6	3	19.39	12	LOCAL	68.5	76.5	1.48	15-Jun	39.20	-83.00	95SW	1.48
SPAS_1183_1	EDGERTON	MO	40.413	-95.513	1965	7	18	20.76	24	GENERAL	76.0	80.5	1.24	15-Jul	39.22	-96.58	100SW	1.24
SPAS_1293_1	HOLLY	CO	37.713	-102.404	1965	6	16	19.18	6	LOCAL	77.0	80.5	1.20	1-Jul	33.50	-100.00	320SSE	1.20
SPAS_1293_3	ELBERT	CO	39.188	-104.296	1965	6	16	16.28	6	HYBRID (G/L)	77.0	80.5	1.20	1-Jul	33.50	-100.00	460SE	1.20
SPAS_1568_1	CARLSBAD	NM	32.254	-104.613	1966	8	22	17.35	24	HYBRID (G/L)	74.0	79.0	1.30	7-Aug	31.95	-102.18	145E	1.30
SPAS_1601_1	SOMBRERETILLO	MX	26.279	-99.921	1967	9	19	35.87	SST	TROPICAL	82.0	86.0	1.18	5-Sep	26.45	-94.08	360E	1.18
SPAS_1601_2	DINERO	MX	28.254	-97.904	1967	9	19	35.01	SST	TROPICAL	82.0	86.0	1.18	5-Sep	26.45	-94.08	265E	1.18
SPAS_1253_1	BIG ELK MEADOW	CO	40.267	-105.417	1969	5	4	20.01	24	GENERAL	65.0	74.5	1.50	20-May	38.00	-99.00	375ESE	1.50
SPAS_1034_1	ENID	OK	36.381	-97.868	1973	10	10	19.45	12	LOCAL	75.0	77.0	1.11	25-Sep	33.35	-96.55	225SSE	1.11
SPAS_1179_1	ALBANY	TX	32.726	-99.350	1978	8	3	32.50	12	TROPICAL	78.0	80.0	1.10	15-Jul	29.30	-97.50	260SSE	1.10
SPAS_1463_1	ALVIN	TX	29.429	-95.271	1979	7	25	45.49	SST	TROPICAL	85.0	86.0	1.04	10-Aug	22.60	-95.26	470S	1.04
SPAS_1184_1	CLYDE	TX	32.479	-99.479	1981	10	10	23.23	24	TROPICAL	76.0	77.5	1.08	25-Sep	29.50	-97.00	250SE	1.08

Table 7.1: Short storm list (continued)

SPAS Number	Storm Name	State	Latitude	Longitude	Year	Month	Day	Maximum total Rainfall (in)	Storm Rep Analysis Duration	PMP Storm Type	Storm Rep Dew Point/SST	Maximum Dew Point/SST	In Place Max Factor	Storm Adjustment Date	Storm Representative Latitude	Storm Representative Longitude	Moisture Inflow Vector	In Place Max Factor
SPAS_1247_1	FRIJOLE CREEK	CO	37.096	-104.379	1981	7	3	16.33	6	LOCAL	77.0	78.5	1.09	25-Aug	35.40	-104.45	120S	1.09
SPAS_1219_1	BIG FORK	AR	35.871	-92.121	1982	12	1	15.92	24	GENERAL	72.0	73.0	1.05	15-Nov	30.00	-93.68	415SSW	1.05
SPAS_1185_1	CORRIGAN	TX	30.260	-94.890	1994	10	16	23.31	SST	LOCAL	82.0	84.0	1.09	30-Sep	26.90	-86.25	575ESE	1.09
SPAS_1317_1	AMERICUS	GA	32.096	-84.229	1994	7	4	28.09	24	TROPICAL	76.0	80.0	1.21	15-Jul	30.40	-89.35	325WSW	1.21
SPAS_1719_1	NECAISE	LA	30.565	-89.495	1995	5	8	28.51	24	GENERAL	79.5	82.5	1.15	23-May	26.00	-88.00	330SSE	1.15
SPAS_1286_1	AURORA COLLEGE	IL	41.458	-88.070	1996	7	16	18.13	24	GENERAL	74.0	80.5	1.35	15-Jul	38.63	-92.24	300SW	1.35
SPAS_1036_1	PAWNEE CREEK	CO	40.775	-103.625	1997	7	29	13.58	6	LOCAL	75.5	81.0	1.34	15-Jul	39.20	-100.15	215SE	1.34
SPAS_1569_1	DAUPHIN ISLAND	AL	30.315	-88.035	1997	7	19	45.27	SST	TROPICAL	85.5	87.0	1.06	4-Aug	28.75	-86.25	150SE	1.06
SPAS_1593_1	MUNSON	FL	30.855	-87.725	1998	9	24	24.92	SST	TROPICAL	82.5	86.0	1.16	15-Sep	25.90	-86.00	360SSE	1.16
SPAS_1662_1	SAGUACHE	CO	38.215	-106.295	1999	7	25	6.68	3	LOCAL	76.0	79.0	1.21	15-Jul	36.95	-107.99	130SW	1.21
SPAS_1464_1	HOUSTON	TX	29.755	-95.275	2001	6	5	40.97	SST	TROPICAL	82.5	84.5	1.09	20-Jun	24.00	-95.00	400S	1.09
SPAS_1242_1	ALLEY SPRING	MO	37.160	-91.450	2008	3	17	15.10	24	GENERAL	66.0	71.0	1.28	1-Apr	31.30	-86.40	500SE	1.28
SPAS_1218_1	DOUGLASVILLE	GA	33.870	-84.760	2009	9	19	25.37	24	GENERAL	76.0	77.5	1.08	5-Sep	30.66	-85.42	225SSW	1.08
SPAS_1208_1	WARNER PARK	TN	36.061	-86.906	2010	5	1	19.71	12	GENERAL	75.0	76.5	1.08	15-May	31.50	-90.00	360SSW	1.08
SPAS_1220_1	DUBUQUE	IA	42.440	-90.750	2011	7	27	15.14	12	LOCAL	79.0	81.0	1.09	15-Jul	40.95	-90.27	105SSE	1.09
SPAS_1530_1	GUADALUPE PASS	TX	32.035	-104.555	2013	9	10	18.34	24	GENERAL	74.0	79.0	1.30	25-Aug	29.50	-98.50	400ESE	1.30
SPAS_1590_1	DAWSON	TX	31.895	-96.645	2015	10	23	32.92	12	LOCAL	76.0	77.5	1.05	8-Oct	30.40	-96.40	105SSE	1.05
SPAS_1631_1	WATSON	LA	30.555	-90.965	2016	8	10	34.65	SST	TROPICAL	86.5	87.5	1.04	15-Aug	28.00	-93.50	235SW	1.04
SPAS_1631_1	LAFAYETTE	LA	30.145	-92.085	2016	8	10	28.74	SST	TROPICAL	86.5	87.5	1.04	15-Aug	28.00	-93.50	170SW	1.04
SPAS_1667_1	HARVEY	TX	29.965	-93.915	2017	8	28	61.11	6	TROPICAL	86.0	87.0	1.04	15-Aug	27.00	-93.00	215SSE	1.04

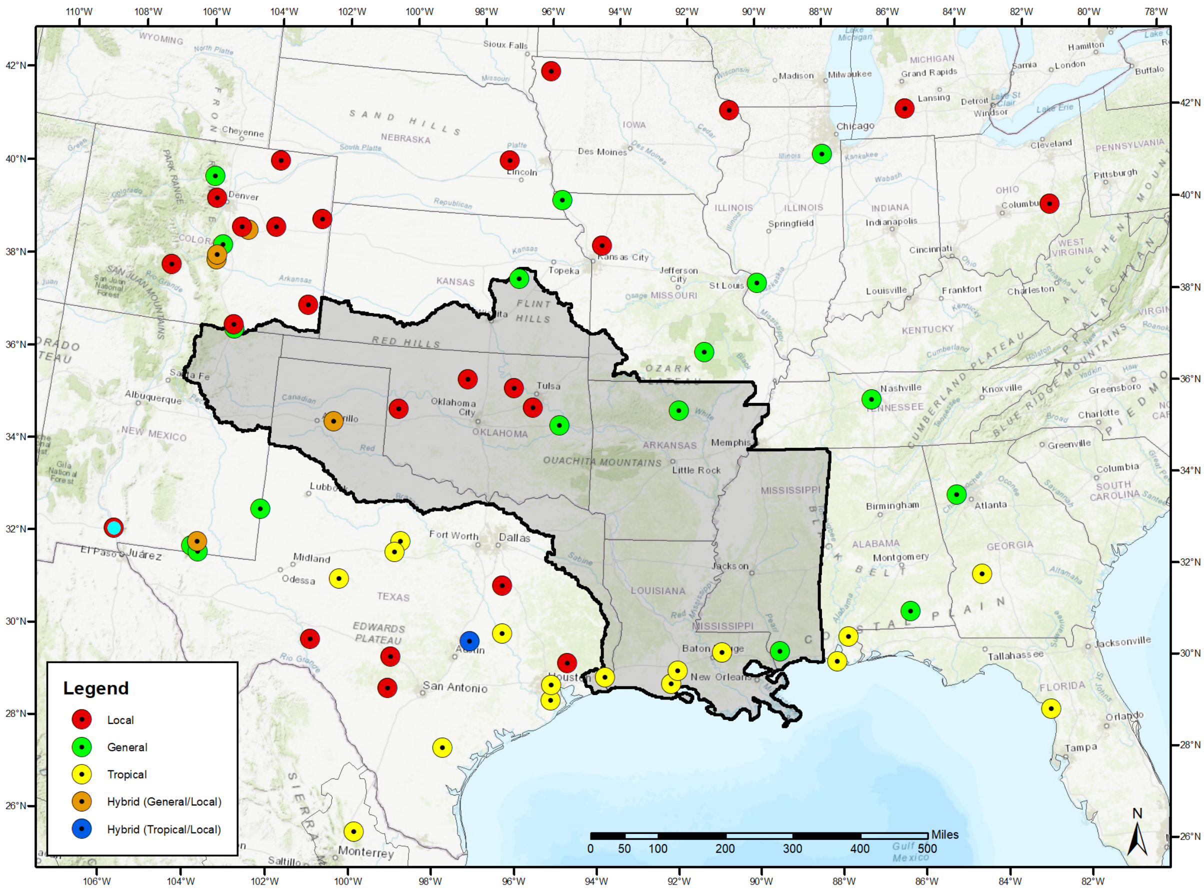

Figure 7.2: Short storm list locations, all storms

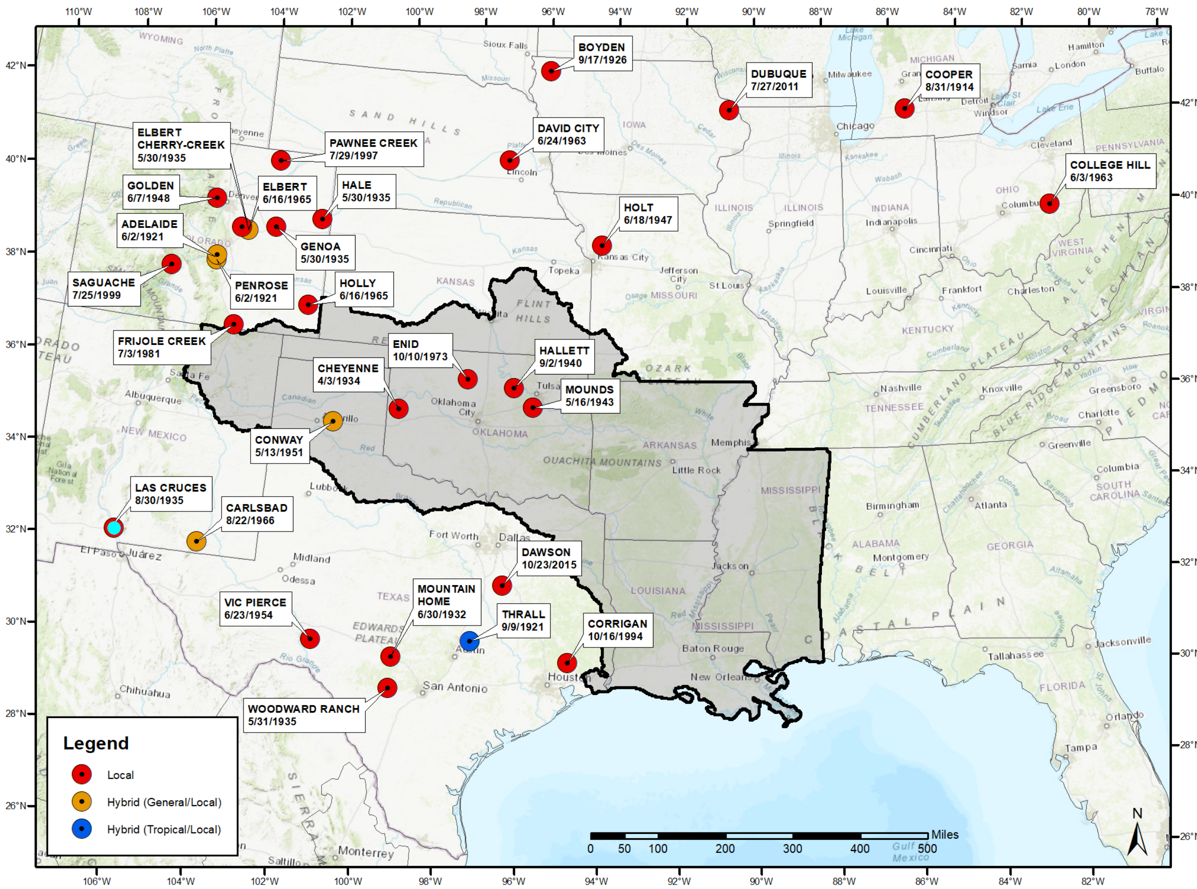

Figure 7.3: Location of local storms on the short list

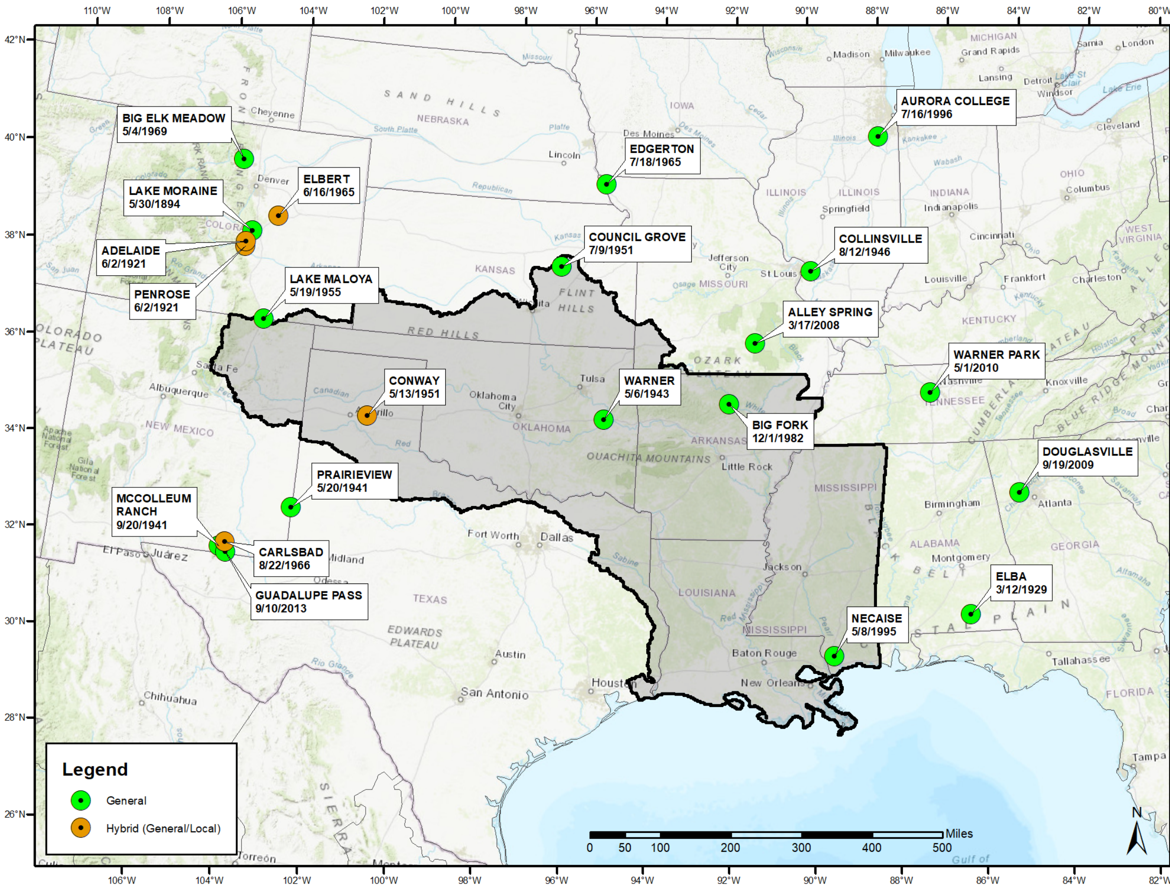

Figure 7.4: Location of general storms on the short list

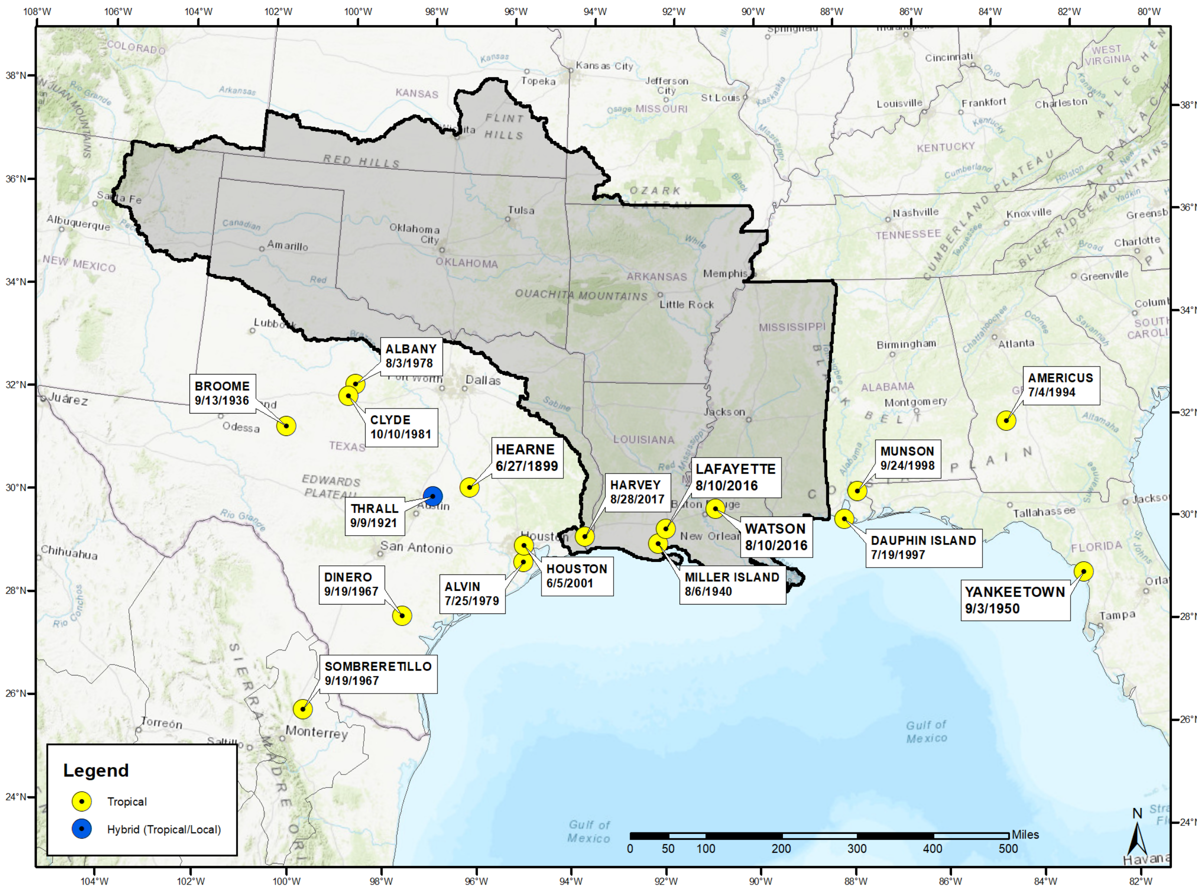

Figure 7.5: Location of tropical storms on the short list

8. SPAS Analysis Results

For all storms identified as part of this study, Depth-Area-Duration (DAD) data needed to be computed. Further, hourly gridded rainfall information was required for all storms for the GTF calculations to be completed and to calculate PMP depths. SPAS was used to compute DADs for all of the storms used in this study. Results of all SPAS analyses used in the study are provided in Appendix F. This Appendix includes the standard output files associates with each SPAS analysis, including the following:

- SPAS analysis notes and description
- Total storm isohyetal
- DAD table and graph
- Storm center mass curve (hourly and incremental accumulation)

There are two main steps in the SPAS DAD analysis: 1) The creation of high-resolution hourly rainfall grids and 2) the computation of Depth-Area (DA) rainfall amounts for various durations, i.e. how the depth of the analyzed rainfall varies with area sizes being analyzed. The reliability of the results from step 2) depends on the accuracy of step 1). Historically the process has been very labor intensive. SPAS utilizes GIS concepts to create spatially-oriented and accurate results in an efficient manner (step 1). Furthermore, the availability of NEXRAD (NEXt generation RADar) data allows SPAS to better account for the spatial and temporal variability of storm precipitation for events occurring since the early 1990s. Prior to NEXRAD, the NWS developed and used a method based on Weather Bureau Technical Paper No. 1 (1946). Because this process has been the standard for many years and holds merit, the DAD analysis process developed for this study attempts to follow the NWS procedure as much as possible. By adopting this approach, some level of consistency between the newly analyzed storms and the hundreds of storms already analyzed by the USACE, USBR, and/or NWS can be achieved. Appendix E provides a detailed description of the SPAS program with the following sections providing a high-level overview of the main SPAS processes.

8.1 SPAS Data Collection

The areal extent of a storm's rainfall is evaluated using existing maps and documents along with plots of total storm rainfall. Based on the storm's spatial domain (longitude-latitude box), hourly and daily rain gauge data are extracted from the database for the specified area, dates, and times. To account for the temporal variability in observation times at daily stations, the extracted hourly data must capture the entire observational period of all extracted daily stations. For example, if a station takes daily observations at 8:00 AM local time, then the hourly data needs to be complete from 8:00 AM local time the day prior. As long as the hourly data are sufficient to capture all of the daily station observations, the hourly variability in the daily observations can be properly addressed.

The daily database is comprised of data from NCDC TD-3206 (pre-1948) and TD-3200 (generally 1948 through present). The hourly database is comprised of data from NCDC TD-3240 and NOAA's Meteorological Assimilation Data Ingest System (MADIS). The daily supplemental database is largely comprised of data from "bucket surveys," local rain gauge networks (e.g., USGS, CoCoRaHS, etc.) and daily gauges with accumulated data.

8.2 SPAS Mass Curve Development

The most complete rainfall observational dataset available is compiled for each storm. To obtain temporal resolution to the nearest hour in the final DAD results, it is necessary to distribute the daily precipitation observations (at daily stations) into hourly bins. In the past, the NWS had accomplished this process by anchoring each of the daily stations to a single hourly station for timing. However, this may introduce biases and may not correctly represent hourly precipitation at locations between hourly observation stations. A preferred approach is to anchor the daily station to some set of nearest hourly stations. This is accomplished using a spatially based approach called the spatially based mass curve (SMC) process (see Appendix E).

8.3 Hourly and Sub-Hourly Precipitation Maps

At this point, SPAS can either operate in its standard mode or in NEXRAD-mode to create high resolution hourly or sub-hourly (for NEXRAD storms) grids. In practice, both modes are run when NEXRAD data are available so that a comparison can be made between the methods. Regardless of the mode, the resulting grids serve as the basis for the DAD computations.

8.4 Standard SPAS Mode Using a Basemap Only

The standard SPAS mode requires a full listing of all the observed hourly rainfall values, as well as the newly created estimated hourly data from daily and daily supplemental stations. This is done by creating an hourly file that contains the newly created hourly mass curve precipitation data (from the daily and supplemental stations) and the "true" hourly mass curve precipitation. If not using a base map, the individual hourly precipitation values are simply plotted and interpolated to a raster with an inverse distance weighting (IDW) interpolation routine in a GIS.

8.5 SPAS-NEXRAD Mode

Radar has been in use by meteorologists since the 1960s to estimate rainfall depth. In general, most current radar-derived rainfall techniques rely on an assumed relationship between radar reflectivity and rainfall rate. This relationship is described by the Equation 2 below:

$$Z = aR^b \qquad \text{Equation 2}$$

where Z is the radar reflectivity, measured in units of dBZ, R is the rainfall rate, a is the "multiplicative coefficient" and b is the "power coefficient". Both a and b are related to the drop size distribution (DSD) and the drop number distribution (DND) within a cloud (Martner et al., 2005).

The NWS uses this relationship to estimate rainfall through the use of their network of Doppler radars (NEXRAD) located across the United States. A standard default Z-R algorithm of $Z = 300R^{1.4}$ has been the primary algorithm used throughout the country and has proven to produce highly variable results. The variability in the results of Z vs. R is a direct result of differing DSD and DND, and differing air mass characteristics across the United States

(Dickens, 2003). The DSD and DND are determined by a complex interaction of microphysical processes in a cloud. They fluctuate hourly, daily, seasonally, regionally, and even within the same cloud (see Appendix E for a more detailed description).

Using the technique described above, also discussed in Appendix E, NEXRAD rainfall depth and temporal distribution estimates are determined for the area in question.

8.6 Depth-Area-Duration Program

The DAD extension of SPAS runs from within a Geographic Resource Analysis Support System (GRASS) GIS environment and utilizes many of the built-in functions for calculation of area sizes and average rainfall depths. The following is the general outline of the procedure:

1. Given a duration (e.g. x-hours) and cumulative precipitation, sum up the appropriate hourly or sub-hourly precipitation grids to obtain an x-hour total precipitation grid starting with the first x-hour moving window.
2. Determine x-hour precipitation total and its associated areal coverage. Store these values. Repeat for various lower rainfall thresholds. Store the average rainfall depths and area sizes.
3. The result is a table of depth of precipitation and associated area sizes for each x-hour window location. Summarize the results by moving through each of the area sizes and choosing the maximum precipitation amount. A log-linear plot of these values provides the depth-area curve for the x-hour duration.
4. Based on the log-linear plot of the rainfall depth-area curve for the x-hour duration, determine rainfall amounts for the standard area sizes for the final DAD table. Store these values as the rainfall amounts for the standard sizes for the x-duration period. Determine if the x-hour duration period is the longest duration period being analyzed. If it is not, analyze the next longest duration period and return to step 1.
5. Construct the final DAD table with the stored rainfall values for each standard area for each duration period.

8.7 Comparison of SPAS DAD Output Versus Previous DAD Results

The SPAS process and algorithms have been thoroughly reviewed as part of many AWA PMP studies. The SPAS program was reviewed as part of the NRC software verification and validation program to ensure that its use in developing data for use in NRC regulated studies was acceptable. The result of the NRC review showed that the SPAS program performed exactly as described and produced expected results.

As part of this study, comparisons were made of the SPAS DAD tables and previously published DAD tables developed by the USACE and/or NWS. AWA discussed these comparisons for important storms where previous DADs were available that covered the same domain as the SPAS analysis. As expected, the differences between SPAS DAD depths and previously published depths varied by area size and duration. The differences were a result of one or more of the following:

- SPAS utilizes a more accurate basemap to spatially distribute rainfall between known observation locations. The use of a climatological basemap reflects how rainfall has occurred over a given region at a given time of the year and therefore how an individual storm pattern would be expected to look over the location being analyzed. Previous DAD analyses completed by the NWS and USACE often utilized simple IDW or Thiessen polygon methods that did not reflect climatological characteristics as accurately. In some cases, the NWS and USACE utilized precipitation frequency climatologies to inform spatial patterns. However, these relied on NOAA Atlas 2 (Miller et al., 1973) patterns and data that are not as accurate as current data from PRISM (Daly et al., 1994 and Daly et al., 1997) and NOAA Atlas 14.

- In some cases, updated sources of data uncovered during the data mining process were incorporated into SPAS that were not utilized in the original analysis.
  SPAS utilizes sophisticated algorithms to temporally and spatially distribute rainfall. In contrast, the isohyetal maps developed previously were hand drawn. Therefore, they reflected the best guess of the analyst of each storm, which could vary between each analyst's interpretations. Also, only a select few stations were used for timing, which limited the variation of temporal accumulation patterns throughout the overall domain being analyzed. SPAS uses the power of all the rainfall observations that have passed QA/QC measures to inform patterns over the entire domain. These temporal and spatial fits are evaluated and updated on an hourly basis for the entire duration.

9. Storm Adjustments

9.1 In-Place Maximization Process

Maximization was accomplished by increasing surface dew points (or SST when the storm representative location is over the ocean) to a climatological maximum and calculating the enhanced rainfall amounts that could potentially be produced if the climatological maximum moisture had been available during the observed storm period. Additionally, the climatological maximum dew point for a date two weeks towards the warm season is selected with higher amounts of moisture from the date that the storm actually occurred. This procedure assumes that the storm could have occurred with the same storm dynamics two weeks towards the time in the year when maximum dew points occur. This assumption follows HMR guidance and is consistent with procedures used to develop PMP values in all the current HMR documents (e.g., HMR 51 Section 2.3), the WMO Manual for PMP (WMO, 2009), as well as in all prior AWA PMP studies. The storm data Appendix F provides the individual analysis maps used for each storm adjustment process including the HYSPLIT model output, the surface dew point observations or sea surface temperature (SST) observations, the storm center location, the storm representative location, and the IMPF for each storm.

Each storm used for PMP development was thoroughly reviewed by the review board to confirm the reasonableness of the storm representative value and location used. As part of this process, AWA provided and discussed all the information used to derive the storm representative value for review, including the following:

- Hourly surface dew point observations
- Daily SST observations
- HYSPLIT model output
- Storm adjustment spreadsheets
- Storm adjustments maps with data plotted

These data allowed for an independent review of each storm. Results of this analysis demonstrated that the values AWA utilized to adjust each storm was reasonable for PMP development.

For storm maximization, average dew point or daily SST values for the appropriate duration that are most representative of the actual rainfall accumulation period for an individual storm (e.g., 6-, 12-, or 24-hour) are used to determine the storm representative value. This value (either dew point or SST) is then maximized using the appropriate climatological value representing the 100-year return interval or +2 sigma SST at the same location moved two weeks towards the season of higher climatological maximum values.

The HYSPLIT model (Draxler and Rolph, 2013; Stein et al., 2015; and Rolph et al., 2017) provides detailed and reproducible analyses for assisting in the determination of the upwind trajectories of atmospheric moisture that was advected into the storm systems. Using these model trajectories, along with an analysis of the general synoptic weather patterns and available surface dew point temperature data/daily SST data, the moisture source region for candidate storms is determined. The procedure is followed to determine the storm representative location and is similar to the approach used in the HMRs. However, by utilizing the HYSPLIT model, much of the subjectivity found in the HMR analysis process was corrected. Further, details of each evaluation can be explicitly provided, and the HYSPLIT trajectory results based on the input parameters defined are reproducible. Available HYSPLIT model results are provided as part of Appendix F.

The process results in a ratio of observed moisture versus climatological maximum moisture. Therefore, this value is always 1 or greater. In addition, the intent of the process is producing a hypothetical storm event that represents the upper limit of rainfall that a given storm could have produced with the perfect combination of moisture and maximum storm efficiency (atmospheric processes that convert moisture to precipitation) associated with that storm. This assumes that the storm efficiency processes remain constant as more moisture is added to the storm environment. Therefore, an upper limit of 1.50 (50%) is applied to the IPMF with the assumption that increases beyond this amount would change the storm efficiency processes and the storm would no longer be the same storm as observed from an efficiency perspective.

This upper limit is a standard application applied in the HMRs (e.g. HMR 51 Section 3.2.2). Note, this upper limit was investigated further during the Colorado-New Mexico REPS study using the Dynamical Modeling Task and the HRRR model interface (Alexander et al., 2015). This explicitly demonstrated that storm efficiency changes as more moisture is added, well before the 50% moisture increase level for the storms investigated (Mahoney, 2016). Therefore, the use of 1.50 as an upper limit is a conservative application. During this study the 1.50 upper limit was applied against three storms:

- Lake Moraine, CO May 1894 (SPAS 1614)
- Lake Maloya, NM May 1955 (SPAS 1251)
- Big Elk Meadow, CO May 1969 (SPAS 1253)

9.2 Storm Representative Dew Point Determination Process

For storm maximization, average dew point values for the duration most consistent with the actual rainfall accumulation period for an individual storm (i.e. 3-, 6-, 12-, or 24-hour) were used to determine the storm representative dew point. To determine which time frame was most appropriate, the total rainfall amount was analyzed. The duration closest to when approximately 90% of the rainfall had accumulated was used to determine the duration used, i.e. 3-hour, 6-hour, 12-hour, or 24-hour.

The storm representative dew point was investigated for each of the storm events analyzed during this study. Once the general upwind location was determined, the hourly surface observations were analyzed for all available stations within the vicinity of the inflow vector. From these data, the appropriate durational dew point value was averaged for each station (3-, 6-, 12-, or 24-hour depending on the storm's rainfall accumulation). These values were then adjusted to 1,000mb (approximately sea level) and the appropriate storm representative dew point and location were derived. The line connecting this point with the storm center location (point of maximum rainfall accumulation) is termed the moisture inflow vector. The information used and values derived for each storm's moisture inflow vector are included in Appendix F.

HYSPLIT was used during the analysis of each of the rainfall events included on the short storm list when available (1948-present). Use of a trajectory model provides increased confidence in determining moisture inflow vectors and storm representative dew points. The HYSPLIT trajectories have been used to analyze moisture inflow vectors in other PMP studies completed by AWA over the past several years. During these analyses, the model trajectory results were verified, and the utility explicitly evaluated (e.g. Tomlinson et al., 2006-2012; Kappel et al., 2013-2019).

In determining the moisture inflow trajectories, the HYSPLIT was used to compute the trajectory of the atmospheric moisture inflow associated with the storm's rainfall production, both location and altitude, for various levels in the atmosphere. The HYSPLIT model was run for trajectories at several levels of the lower atmosphere to capture the moisture source for each storm event. These included 700mb (approximately 10,000 feet), 850mb (approximately 5,000 feet), and storm center location surface elevation. For the majority of the analyses, a combination of all three levels was determined to be most appropriate for use in evaluation of the upwind moisture source location. It is important to note that the resulting HYSPLIT trajectories are only used as a general guide to evaluate the moisture source for storms in both space and time. The final determination of the storm representative dew point and its location was determined following the standard procedures used by AWA in previous PMP studies (e.g. Tomlinson, 1993; Tomlinson et al., 2006-2012; Kappel et al., 2012-2019) and as outlined in the HMRs (e.g. HMR 51 Section 2.3) and WMO Manual for PMP (Section 2.2).

The process involves deriving the average dew point (or SST) values at all stations with dew point (or SST) data in a large region along the HYSPLIT inflow vectors. Values representing the average 3-, 6-, 12-, and 24-hour dew points or daily SST are analyzed in Excel spreadsheets. The appropriate duration representing the storm being analyzed is determined and data are plotted for evaluation of the storm representative dew point (or SST). This evaluation includes an analysis of the timing of the observed dew point (or SST) values to ensure they occurred in a source region where they would be advected into the storm environment at the time of the rainfall period. Several locations are investigated to find values that are of generally similar magnitude (within a degree or two Fahrenheit). Once these representative locations are identified, an average of the values to the nearest half degree is determined and a location in the center of the stations is identified. This becomes the storm representative dew point (or SST) value and the location provides the inflow vector (direction and distance) connecting that location to the storm center location. This follows the approach used in HMR 51 Section 2, HMR 55A Section 5, and HMR 57 Section 4, with improvements provided by the use of HYSPLIT and updated maximum dew point and SST climatologies. Appendix F of this report contains each of the HYSPLIT trajectories analyzed as part of this study for each storm (when used).

9.2.1 Storm Representative Dew Point Determination Example

As an example, Figure 9.1 shows the HYSPLIT trajectory model results used to analyze the inflow vector for the Madisonville, KY March 1964 (SPAS 1278) storm. HYSPLIT trajectories showed a general inflow from the Gulf of Mexico flowing north, then northeast into the storm and along the frontal boundary. The turning of the moisture in a clockwise direction was around the western edge of the general high pressure located to the east of the Atlantic (the Bermuda High). This is a common scenario for heavy rains over the region, where moisture is drawn up around the western edge of high pressure from the Gulf of Mexico and forced to lift over a frontal system stalled over the region and then further enhanced by topography of the Appalachian Mountains. In this case, surface dew point values were analyzed for a region starting at the storm center and extending southward to the Gulf of Mexico and from Texas eastward to Georgia/Florida/South Carolina. All the HYSPLIT inflow vectors showed a south to southeast inflow direction from the storm center over Kentucky (the most common direction for general storms west of the Appalachians). The air mass source region supplying the atmospheric moisture for this storm was located over southern Texas/Louisiana/Mississippi/Alabama 24-36 hours prior to the rainfall occurring over Tennessee and Kentucky. Surface dew points were analyzed over this source region, ensuring that the dew point observations were located outside of the area of rainfall to avoid contamination of the dew points by evaporating rainfall. Figure 9.2 displays the stations analyzed and their representative 24-hour average dew point values. The region encircled in red is considered the moisture source region for this storm.

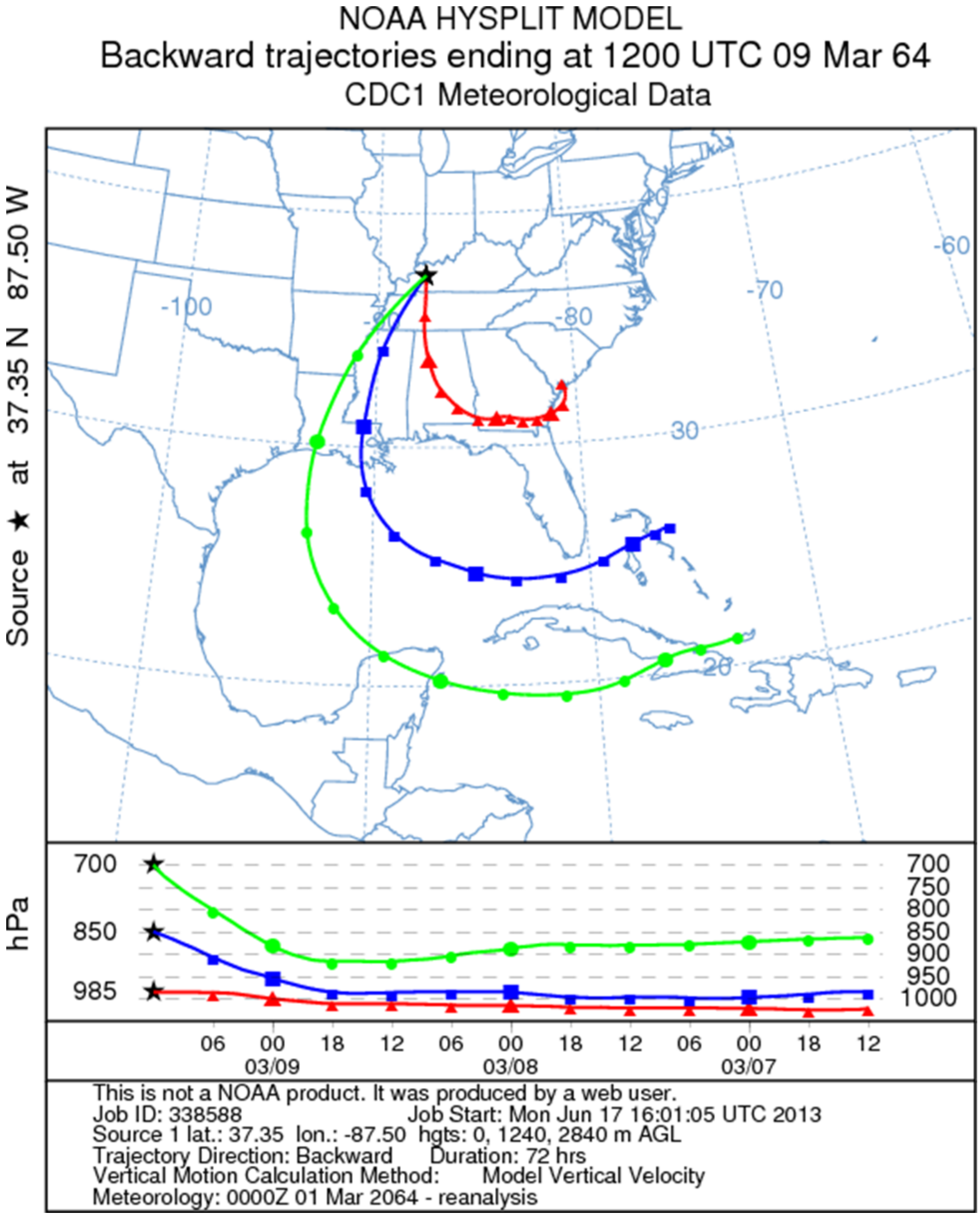

Figure 9.1: HYSPLIT trajectory model results for the Madisonville, KY March 1964 (SPAS 1278) storm

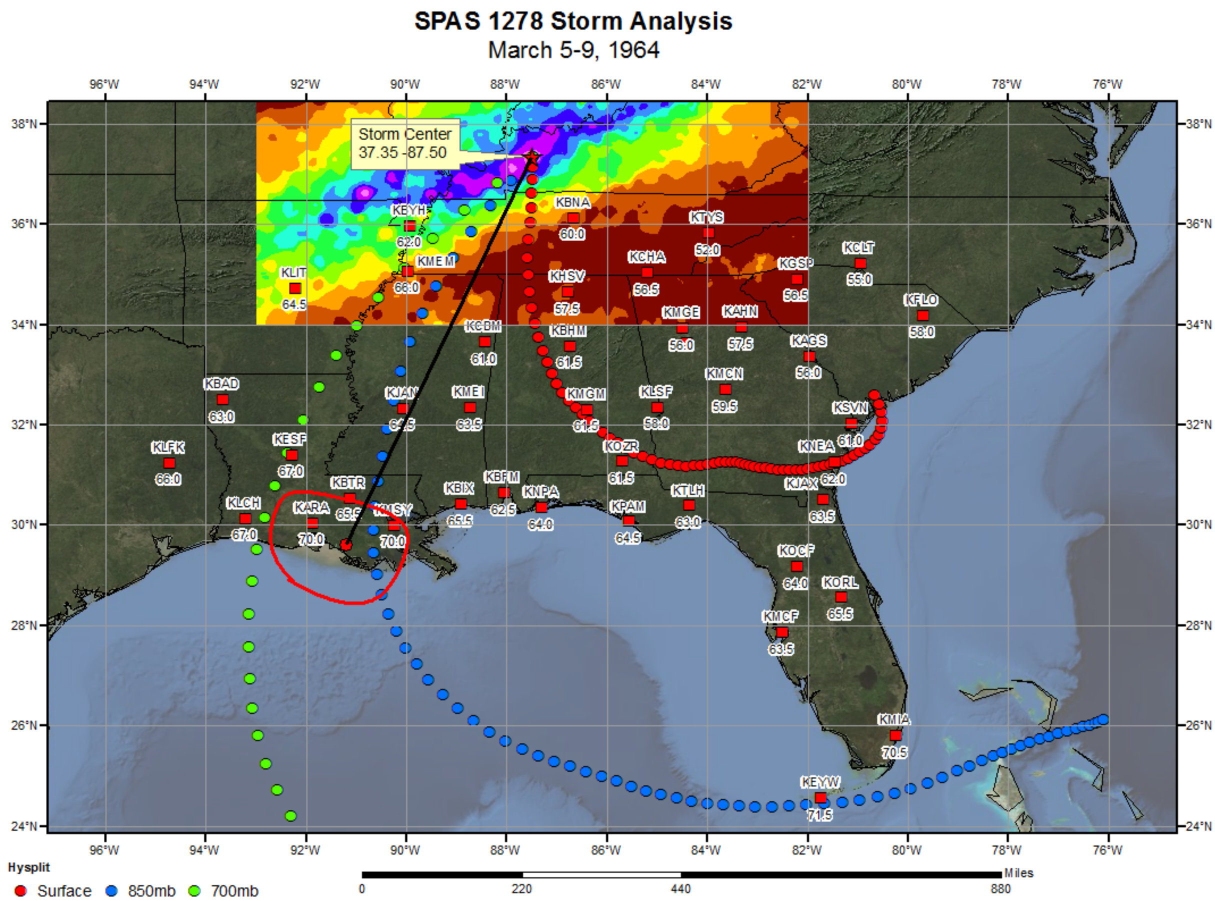

Figure 9.2: Surface stations, 24-hour average dew points, and moisture source region, along with HYSPLIT trajectory model results for the Madisonville, KY March 1964 (SPAS 1278) storm.

Most storms have maximization factors that are significantly greater than 1.00, with a general average of around 1.20 (e.g. the average of all storms in this study was 1.18, see Table 7.1). Exceptions occur when a storm is as close to PMP as can reasonably be expected. An example is Hurricane Harvey August 2017. In this case, the amount of atmospheric moisture available to each storm was near its maximum when combined with the extreme storm efficiency. Therefore, when maximizing these storms, the resulting maximization factors are close to 1.00. The IPMF for Harvey is 1.04. The values reflect observed dew point/SST values in the moisture source region which were near the climatological maximum that could be expected to occur along with maximum storm efficiency. Note that every degree change of the storm representative dew point values results in approximately 4-5% change in the maximization factor. For example, for the Harvey storm, a 1.04 IPMF shows that the observed storm representative value was only a 1°F from the 100-year value. This is not surprising given the magnitude of the rainfall this storm produced. To produce this much rainfall, the atmospheric environment must have contained an optimum combination of moisture and storm dynamics.

9.2.2 Storm Representative Sea Surface Temperatures Calculation Example

The value for the maximum SST was determined using the mean +2-sigma (two standard deviations warmer than the mean) SST for that location. SSTs were substituted for dew points in this study for many storms where the inflow vector originated over the Atlantic Ocean. Data presented in Appendix F show the moisture source region for each storm and whether dew points or SSTs were used in the maximization calculations. For storm maximization, the value for the maximum SST was determined using the mean +2-sigma SST for that location for a date two weeks before or after the storm date (which ever represents the climatologically warmer SST period). Storm representative SSTs and the mean +2-sigma SSTs were used in the same manner as storm representative dew points and maximum dew point climatology representing the 15th of the month values in the maximization and transpositioning procedure. Figures 9.3 and 9.4 are examples of a daily SST maps used to determine the storm representative SST for the Harvey August 2017 storm (SPAS 1667.

In this example, the first decision was whether surface dew points were available to derive the storm representative dew point. However, this was not possible for this storm because there was rainfall to the coast, thereby making the dew point readings along the inflow pathway not useable for storm representative analysis. Next, SSTs were investigated to determine regions of homogenous temperatures in a region that was appropriate in time and space according to the HYSPLIT trajectories. Several regions were possibilities in this case. Next, the track of the Hurricane and its relation to moisture advection into the storm center was considered. This better matched the surface (red dots) HYSPLIT trajectory. Finally, sensitivity calculations were performed using several couplets of storm representative SST values versus the +2-sigma climatological maximum values to ensure the range of maximizations was within a reasonable range (i.e. greater than 1.00). After the investigations were completed, the storm representative location of 27.0°N and 93.0°W was chosen. This was an average of several of the SST values within the red circled area of Figures 9.3 and 9.4 on August 28 and August 29, 2017.

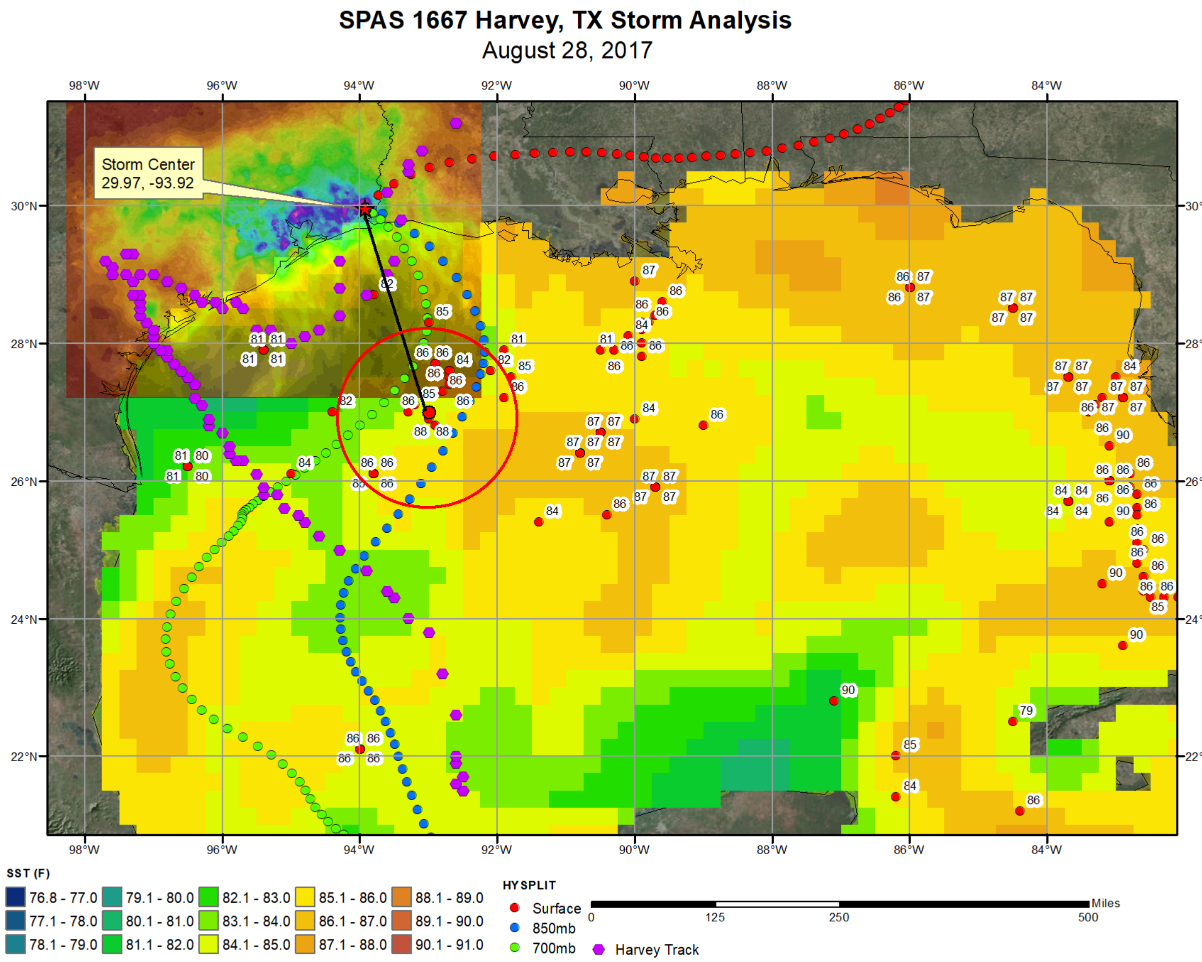

Figure 9.3: Daily SST observations from August 28, 2017 used to determine the storm representative SST value for the Harvey August 2017 SPAS 1667 storm

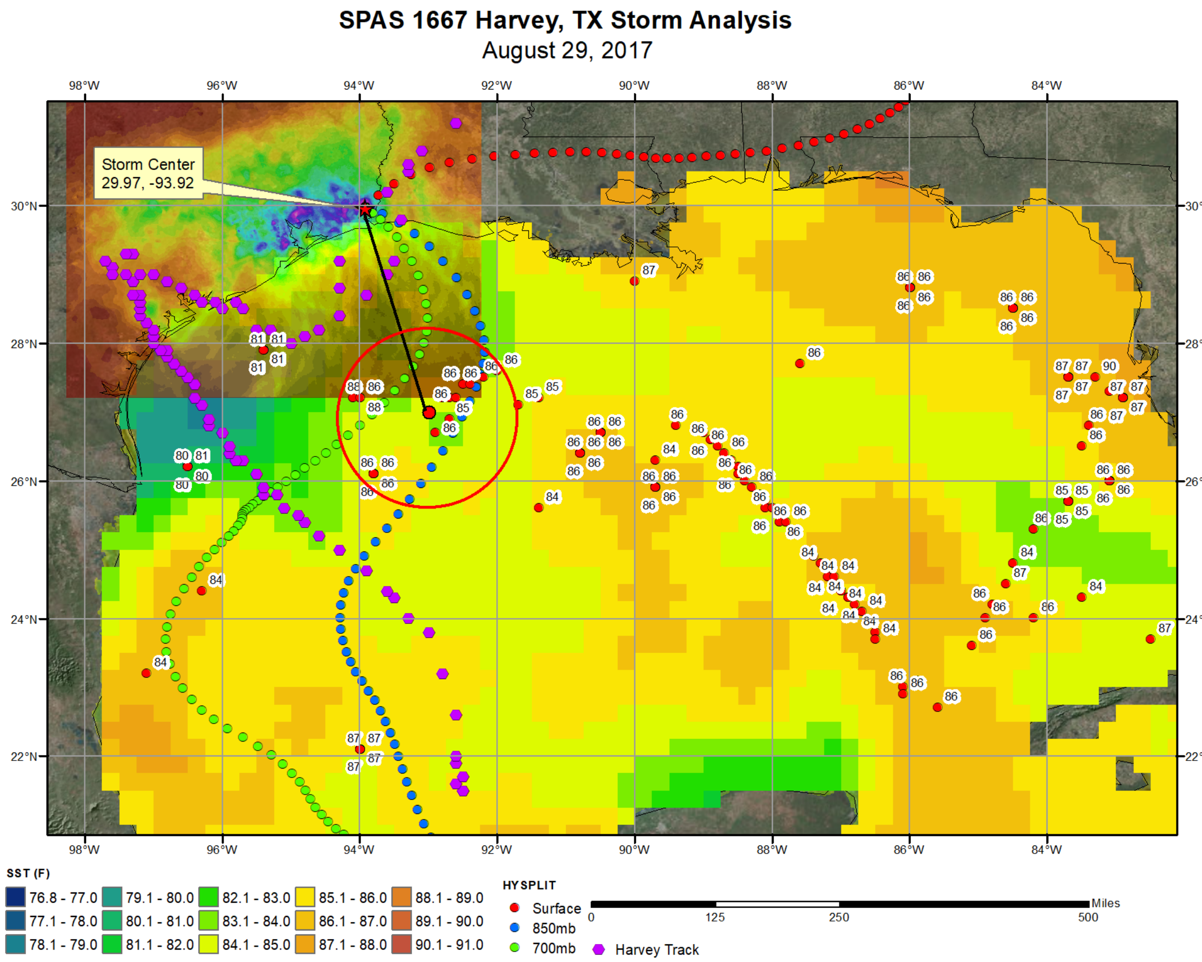

Figure 9.4: Daily SST observations from August 29, 2017 used to determine the storm representative SST value for the Harvey August 2017 SPAS 1667 storm

9.3 In-Place Maximization Factor (IPMF) Calculation

Storm maximization is quantified by the IPMF using Equation 3.

$$IPMF = \frac{W_{p,max}}{W_{p,rep}} \qquad \text{Equation 3}$$

where,

$W_{p,max}$ = precipitable water for maximum dew point (in.)

$W_{p,rep}$ = precipitable water for representative dew point (in.)

The available precipitable water, Wp, is calculated by determining the precipitable water depth present in the atmospheric column (from sea level to 30,000 feet) and subtracting the precipitable water depth that would not be present in the atmospheric column between sea-level and the surface elevation at the storm location using Equation 4.

$$W_p = W_{p,30,000'} - W_{p,elev} \qquad \text{Equation 4}$$

where,

W_p	=	precipitable water above the storm location (in.)
$W_{p,30,000'}$	=	precipitable water, sea level to 30,000′ elevation (in.)
$W_{p,elev}$	=	precipitable water, sea level to storm surface elevation (in.)

9.4 Transposition Zones

PMP-type storm events in regions of similar meteorological and topographic settings surrounding a location are a very important part of the historical evidence on which a PMP estimate is based. Since most locations have a limited period of record for rainfall data, the number of extreme storms that have been observed over a location is limited. Historic storms that have been observed within similar meteorological and topographic regions are analyzed and adjusted to provide information describing the storm rainfall as if that storm had occurred over the location being studied.

Transfer of a storm from where it occurred to a location that is meteorologically and topographically similar is called transposition. The underlying assumption is that storms transposed to the location could have occurred under similar meteorological and topographical conditions. To properly relocate such storms, it is necessary to address issues of similarity as they relate to meteorological conditions, moisture availability, and topography. In this study, adjustment factors used in transpositioning of a storm are quantified by using the Geographic Transposition Factor (GTF).

The regional transposition zones developed for this study were largely imported from the previous overlapping studies of Colorado-New Mexico and Texas and were based on the variable meteorological and topographical characteristics across the domain along with considerations of moisture source region characteristics. National Centers for Environmental Information (formally the National Climatic Data Center) climate regions, USGS physiographic regions, NOAA Atlas 14 precipitation frequency climatologies, discussions with the review board/study participants, and transposition regions used in adjacent/overlapping PMP studies.

Figure 9.5 shows the transposition zones utilized in this study. Note, that the zones were used as a general guidance and for initial evaluations and to provide consistency with previous studies. Many storms were ultimately allowed to move between zones and/or were restricted within a given zone for final PMP development. In addition, for transposition zones that were continued from adjacent studies, the same zone numbers were used. Therefore, numbers 4, 7, and 10 are not used in this study as the numbers used in this study the zone number from the Colorado, New Mexico, and Texas PMP studies for consistency.

Transposition zones 1, 2, 3, and 6 represent regions that were identified during the Colorado-New Mexico Regional PMP study and were kept consistent with that study. The represent the far western regions of the overall study domain where topography plays a significant role in precipitation processes. Transposition zone 5 represents the coastal region where there is direct access to the Gulf of Mexico allows direct Tropical System effects to occur and no significant topography exists. Transposition zones 8 and 9 represent the transition from the direct Gulf of Mexico to the southern Great Plains. Transposition zones 11 and 12 represent that areas that area transitioning away from the more direct Gulf of Mexico influence and southern Great Plains to the western High Plains. In these zones, moisture is generally more limited, but rising terrain can help overcome and enhance small area rainfall amounts. Storm characteristics were considered in relation to the general meteorological, topographic, and seasonality characteristics of each of these zones when assigning transposition limits.

Storm Transposition Zones
AR-LA-MS-OK PMP Study

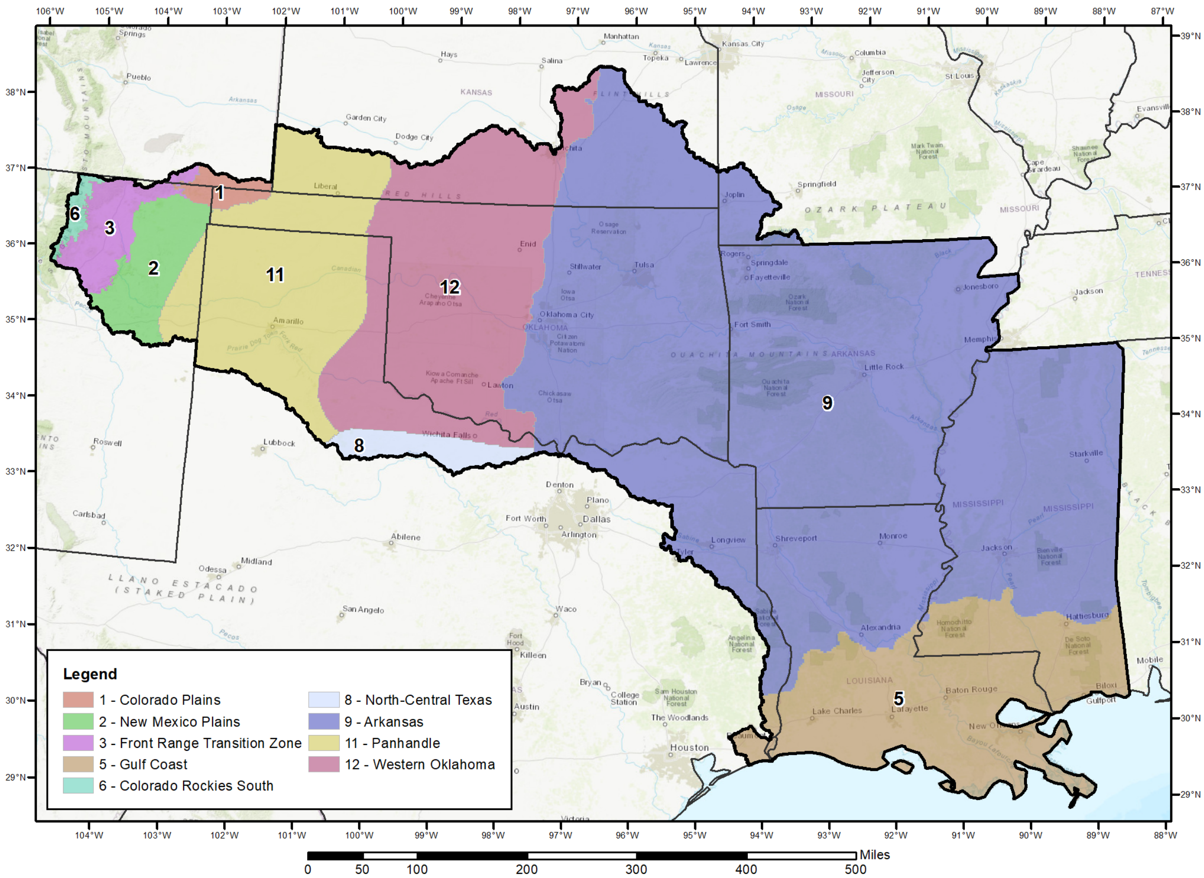

Figure 9.5: Transposition zones utilized

The transposition process is one of the most important aspects of PMP development. This step also contains significant subjectivity as the processes utilized to define transposition limits are difficult to quantify. General guidelines are provided in the HMRs (e.g. HMR 51 Section 2.4.1 and HMR 55A Section 8.2). AWA utilized these guidelines as well as updated procedures and data sets developed during the many PMP studies completed in the region since the HMRs were published. General AWA guidelines included:

- Investigation of previous NWS transposition limit maps
- Experience and understanding of extreme rainfall processes in the study region and how those factors vary by location, storm type, and season
- Understanding of topographical interactions and how those effect storms by location, storm type, and season

- Previously applied transposition limits from adjacent statewide PMP studies
- Use of GTF values as sensitivity
- Spatial continuity of PMP depths
- Comparisons against NOAA Atlas 14 precipitation frequency climatology
- Discussions with the review board and others involved in the study

An important aspect of this study was the involvement of the review board and other study participants in evaluating and reviewing individual storm transposition limits of controlling storms. AWA received input in helping to define the overall transposition zones used in the study shown in Figure 9.5. Once initial transposition limits were applied to each storm, the resulting GTF values were reviewed during the in-person review meetings and during various teleconferences. These were most focused on the controlling storms. The PMP Version Log provided in Appendix I provides the numerous iterations of PMP development and the various transposition limit adjustments that were applied to storms during the PMP development process. In some cases, storms originally considered for a given location were removed after evaluation and in other cases transposition limits were adjusted within a given transposition zone. The red hatch area on the GTF maps contained in Appendix B indicate the final transposition limits applied to each storm.

Initial transposition limits were assigned with the understanding that additional refinements would take place as the data were run through the PMP evaluation process. Numerous sensitivity runs were performed using the PMP database to investigate the results based on the initial transposition limits. Several storms were re-evaluated based on the results that showed inconsistencies and/or unreasonable values either too high or too low. Examples of inconsistencies and unreasonable values include areas where gradients of PMP depths between adjacent grid points that were significantly different and not specifically related to a similar meteorological or topographical change. When these occur because of excessive GTF values or because a storm was likely moved beyond reasonable transposition limits, adjustments are applied. Conversely, transposition limits were relaxed for several storm to allow for smoother gradients between PMP depths.

A significant amount of time was spent on the storms which were most important for controlling PMP depths. These included storms such as Thrall, TX September 1921 (SPAS 1592), Cheyenne, OK April 1943 (SPAS 1495), Vic Pierce, TX June 1954 (SPAS 1602), Big Rapids, MI September 1986 (SPAS 1206), and Warner Park, TN May 2010 (SPAS 1208). In addition, adjustments were applied to the inland limit of the tropical systems to allow them to be transpositioned inland approximately 3° from the coastline. This is a slightly more conservative application than was applied in previous studies (e.g. Texas statewide PMP) but produced a smooth gradient in PMP depths from south to north.

Although somewhat subjective, decisions to adjust the transposition limits for a storm were based on the understanding of the meteorology which resulted in the storm event, similarity of topography between the two locations, access to moisture source, seasonality of occurrence by storm type, and comparison to other similar storm events. Appendix I provides a description of the iterations and adjustments that were applied during each PMP version to arrive at the final values via the PMP Version Log.

For all storms, the IPMF does not change during this process. The GTF changes as a storm is moved from its original location to a new location. The spatial variations in the GTF were useful in making decisions on transposition limits for many storms. As described previously, values larger than 1.50 for a storm's maximization factor exceed limits that would no longer produce the same storm as the originally observed event. In these situations, changing a storm by this amount is likely also changing the original storm characteristics so that it can no longer be considered the same storm at the new location. The same concept applies to the GTF. GTF values greater than 1.50 indicate that transposition limits have most likely been exceeded. In addition, a lower limit of 0.50 was applied for the same reason, but this inherently affects a much more limited set of storms and regions. Therefore, storms were re-evaluated for transpositionability in regions which results in a GTF greater than 1.50.

9.5 Moisture Transposition Factor

The MTF was developed to represent the difference in available moisture from a 100-year recurrence interval climatological perspective between two locations. This was done assuming that the precipitation frequency climatologies do not fully quantify this difference. Numerous discussions have occurred during previous studies and again during this study with the review board to try and quantify moisture differences. Recent analyses as part of ongoing PMP studies (Scott Dam, CA and Pennsylvania Statewide) has demonstrated that the MTF (i.e. moisture differences at the 100-year recurrence interval level between two locations) was adequately accounted for in the precipitation frequency climatologies. Investigations and sensitivities completed during this study demonstrated that the MTF was likely accounted for as well.

As part of the sensitivity analysis for this study, comparisons were made of the PMP depths resulting from inclusion of the MTF versus not including the MTF. In almost all cases the effect of the MTF was less than +/- 5%, well within the uncertainty bounds of the overall PMP development process. This is partially the result of the fact that most of the controlling storms are summer season events and during this season there is very little spatial variation in dew point climatology from the Gulf of Mexico through most of the Midwest/Great Plains. Figures 9.6-9.8 display the percent change of the PMP depths when utilizing the MTF across the entire domain for the local, general, and tropical storms types respectively.

Therefore, although explicit MTF values were calculated for all grids for each short list storm, the factor was set to 1.00 in all cases for this study. Although the MTF was not ultimately utilized in this study in the TAF calculations, the values were still calculated for use in sensitivity evaluations and to ensure the data set is available if needed in the future. Section 9.6 provides a description of the MTF calculations process for reference.

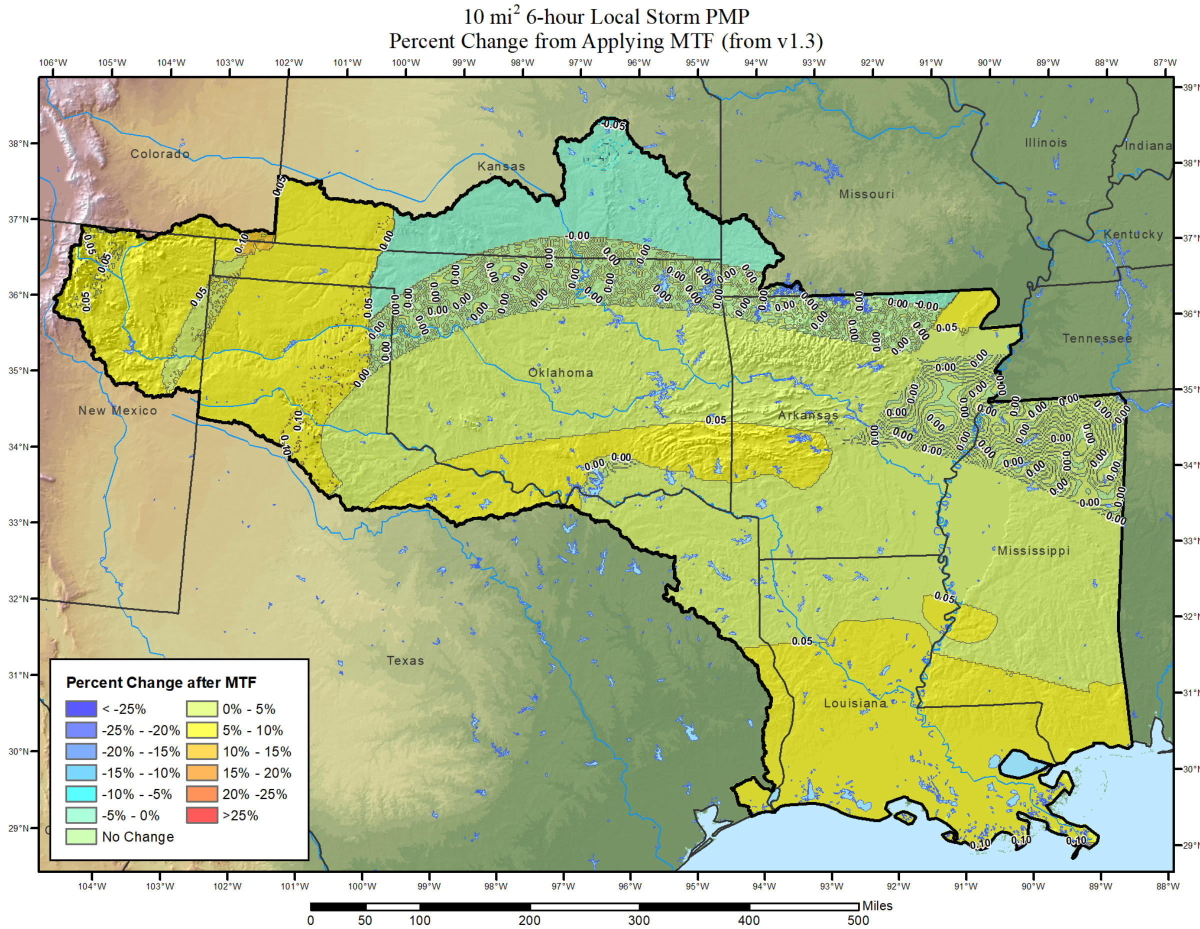

Figure 9.6: Percent change in PMP depths, local storm type at 10-square mile 6-hour with the MTF

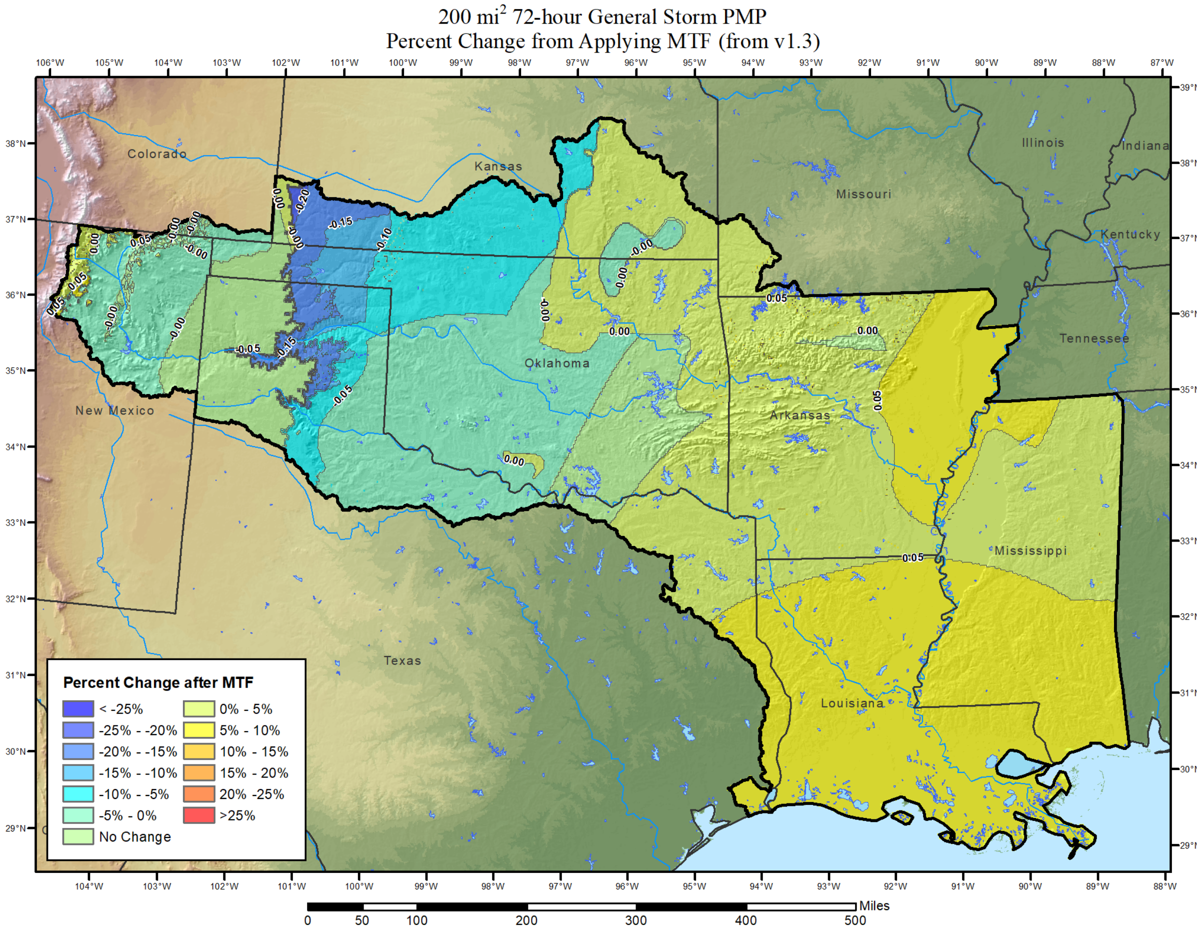

Figure 9.7: Percent change in PMP depths, general storm type at 200-square mile 72-hour with the MTF

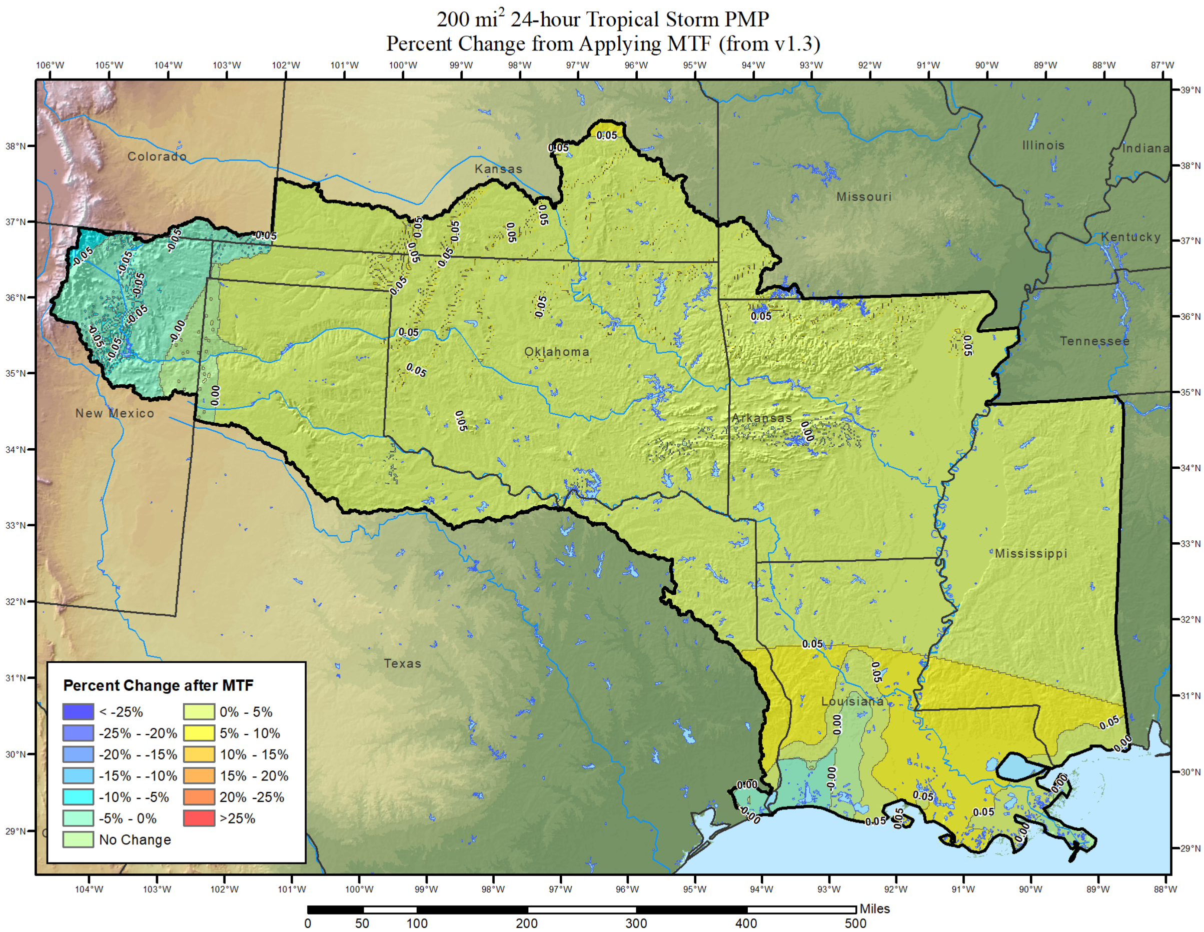

Figure 9.8: Percent change in PMP depths, tropical storm type at 200-square mile 24-hour with the MTF

9.6 Moisture Transposition Factor Calculation Example

The MTF is calculated as the ratio of precipitable water for the maximum dew point at the target location to precipitable water for the storm maximum dew point at the storm center location as described in Equation 5. This MTF represents the change in climatological maximum moisture availability between two locations due to horizontal distance. The change due to vertical displacement is quantified inherently within the GTF, described in the next section. Elevation is not considered in the MTF calculation; therefore, the precipitable water depth is calculated for the entire atmospheric column, from sea level to 30,000 feet[1].

$$MTF = \frac{W_{p,trans}\,(30{,}000')}{W_{p,max}\,(30{,}000')} \qquad \text{Equation 5}$$

where,

[1] The precipitable water values are taken from Annex I. Tables of precipitable water in saturated pseudo-adiabatic atmosphere (WMO, 2009).

$W_{p,trans(30,000')}$ = maximum precipitable water, sea level to 30,000′ elevation, target moisture inflow source location (in.)

$W_{p,max\ (30,000')}$ = maximum precipitable water, sea level to 30,000′ elevation, storm representative moisture source location (in.)

9.7 Geographic Transposition Factor

The GTF process is used to not only capture the difference in terrain effects between two locations but also to capture all processes that result in precipitation reaching the ground at one location versus another location. The GTF is a mathematical representation of the ratio of the precipitation frequency climatology at one location versus another location. The precipitation frequency climatology is derived from actual precipitation events that resulted in the Annual Maximum Series (AMS) at a given station. An upper limit of 1.50 and a lower limit of 0.50 were applied to the GTF as described in Section 9.4. This was done to ensure the storm being adjusted was not adjusted beyond limits, which would change the original storm characteristics in a manner that would violate the PMP process assumptions.

The GTF values were calculated utilizing NOAA Atlas 14 precipitation frequency data at the 100-year recurrence interval. These data sets were used to ensure consistency in the climatological datasets and to ensure required coverage for all storm locations within the overall storm search domain. The storms used in NOAA Atlas 14 represent observed precipitation events that resulted in an AMS accumulation. Therefore, they represent all precipitation producing processes that occurred during a given storm event. In HMR terms, the resulting observed precipitation represents both the convergence-only component and any orographic component. The NOAA Atlas 14 gridded precipitation frequency climatology was produced using gridded mean annual maxima (MAM) grids that were developed with the PRISM (Daly et al., 1994). PRISM utilizes geographic information such as elevation, slope, aspect, distance from coast, and terrain weighting for weighting station data at each grid location. The use of the precipitation frequency climatology grids should be reflective of all precipitation producing processes. Further, the use of the gridded precipitation climatology at the 100-year recurrence interval represents an optimal combination of factors, including representing extreme precipitation events equivalent to the level of rainfall utilized in AWA's storm selection process, and providing the most robust statistics given the period of record used in the development of the precipitation frequency climatologies.

Therefore, the GTF does not just represent the difference in topographic effects between two locations, but instead represents the difference in all precipitation processes between two locations. This is one reason it is very important to apply appropriate transposition limits to each storm during the PMP development process.

There are many orographic processes and interactions related to terrain interactions that are not well understood or quantified. Therefore, observed data (precipitation accumulations represented in the precipitation frequency data) are used as a proxy, where it is assumed that the observed precipitation represents all the precipitation processes associated with a storm event. Again, this follows guidance provided by the WMO 2009, Section 3.1.4 and discussed in Section 4 of this document. Given this, it seems logical that observed precipitation at a given location represents a combination of all factors that produced the precipitation, including what would have occurred without any terrain influence and what actually occurred because of the terrain influence (if any). Significant judgment is inherent when determining transposition regions because the process of determining similar meteorology and topography is highly subjective. As part of the GTF process the following assumptions are applied:

- NOAA Atlas 14 precipitation frequency climatologies represent all precipitation producing factors that have occurred at a location. This is based on the fact that the data are derived from AMS values at individual stations that were the result of an actual storm event. That actual storm event included both the amount of precipitation that would have occurred without topography and the amount of precipitation that occurred because of topography (if any).
- If it is accepted that the precipitation frequency climatology is representative of all precipitation producing processes for a given location, then comparing the precipitation frequency climatology at one point to another will produce a ratio that shows how much more or less efficient the precipitation producing processes are between the two locations. This ratio is called the GTF.
- If there is no orographic influence at either location being compared or between the two locations, then the differences should be a function of (1) storm precipitation producing processes in the absence of topography (thermodynamic and dynamic), (2) how much more or less moisture is available from a climatological perspective, and/or (3) elevation differences at the location.

9.8 Geographic Transposition Factor (GTF) Calculation

The GTF is calculated by taking the ratio of transposed 100-year rainfall to the in-place 100-year rainfall.

$$GTF = \frac{R_t}{R_s} \qquad \text{Equation 6}$$

where,

R_t = climatological 100-year rainfall depth at the target location

R_s = climatological 100-year rainfall depth at the source storm center

The in-place climatological precipitation (R_s) was determined at the grid point located at the SPAS-analyzed total storm maximum rainfall center location. The corresponding transposed climatological precipitation (R_t) was taken at each grid point in the basin. The 100-year precipitation was used for each transposed location and also for the in-place location for storm centers. For this region, the 6-hour precipitation frequency climatologies were used for the local storm type. Conversely, the 24-hour precipitation frequency climatologies are used for the general and tropical storm types. Precipitation frequency data were taken from NOAA Atlas 14 volume 1 (Bonnin et al., 2011), NOAA Atlas 14 volume 2 (Bonnin et al., 2006), NOAA Atlas 14 volume 8 (Perica et al., 2013), NOAA Atlas 14 volume 9 (Perica et al., 2013), and NOAA Atlas 14 volume 11 (Perica et al., 2018).

9.9 Total Adjustment Factor (TAF)

The TAF is a combination of the total moisture and terrain differences on the SPAS analyzed rainfall after being maximized in-place and then transpositioned to the target grid point.

$$TAF_{xhr} = P_{xhr} \times IPMF \times GTF \qquad \text{(from Equation 1)}$$

The TAF, along with the other storm adjustment factors, is exported and stored within the storm's adjustment factor feature class to be accessed by the GIS PMP tool as described in the following section.

10. Development of PMP Values

10.1 PMP Calculation Process

To calculate PMP, the TAF for each storm must be applied to the storm's SPAS analyzed DAD value for the area size and duration of interest to yield a total adjusted rainfall value. The storm's total adjusted rainfall value is then compared with the adjusted rainfall values of every storm in the database transposable to the target grid point. The largest adjusted rainfall depth becomes the PMP for that point at a given duration. This process must be repeated for each of the grid cells intersecting the input drainage basin for each applicable duration and storm type. The gridded PMP is averaged over the drainage basin of interest to derive a basin average and the accumulated PMP depths are temporally distributed.

A GIS-based PMP calculation tool was developed to automate the PMP calculation process. The PMP tool is a Python scripted tool that runs from a Toolbox in the ArcGIS desktop environment. The tool accepts a basin polygon feature or features as input and provides gridded, basin average, and temporally distributed PMP depths as output. These PMP output elements can be used with hydrologic runoff modeling simulations for PMF calculations. Full documentation of the PMP tool usage and structure is found in Appendix H.

The PMP tool can be used to calculate PMP depths for the following durations.

Local Storm PMP Durations:
1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hour

General/Tropical Storm PMP Durations:
1-, 2-, 3-, 4-, 5-, 6-, 12-, 24-, 48-, and 72-hour

The PMP tool provides depths at an areal-average for the drainage basin area size. This area can be overwritten with a specific user-defined area-size within the tool dialogue.

10.1.1 Spatial Application Considerations

It is important to remember that the initial gridded PMP depths are spatially distributed closely following the NOAA Atlas 14 precipitation frequency patterns. This represents one possible spatial scenario and is generally considered a conservative application. However, other spatial patterns are possible that may result in a more severe flood response. For smaller basins, less than 10-square miles, the choice of spatial pattern should make little difference. However, for larger basins, this may have a significant impact. Because the number of possible spatial patterns for all of the basins covered in the study is almost unlimited, it is not feasible to include others int eh GIS tool. Instead it is recommended that other spatial patterns be tested. These could be based on HMR 52 guidance, the successive subtraction method, or previously observed storm patterns over the basin of interest. In all cases, it is important that the spatial pattern adhere to the caveat of producing a "physically possible" representation of the PMP design storm.

10.1.2 Sample Calculations

The following sections provide sample calculations for the storm adjustment factors for the Alley, Spring MO of March, 2008 (SPAS 1242) general storm event when transposed to 35.0°N, 92.0°W (grid point ID #71,392). The target location is about 245 miles south-southwest of the storm location at an elevation of 270 feet within the Arkansas River valley south of the Ozark Plateau (Figure 10.1). Table 10.1 highlights the adjustment factors in the Storm Adjustment Factor feature class table for the storm at this target grid point location.

Table 10.1 - Alley Spring, MO Adjustment Factors for Sample Target Location

ID	STORM	LON	LAT	ELEV	IPMF	GTF	TAF	TRANS
71392	1242_1	-92.00	35.00	269.8	1.34	1.16	1.56	1

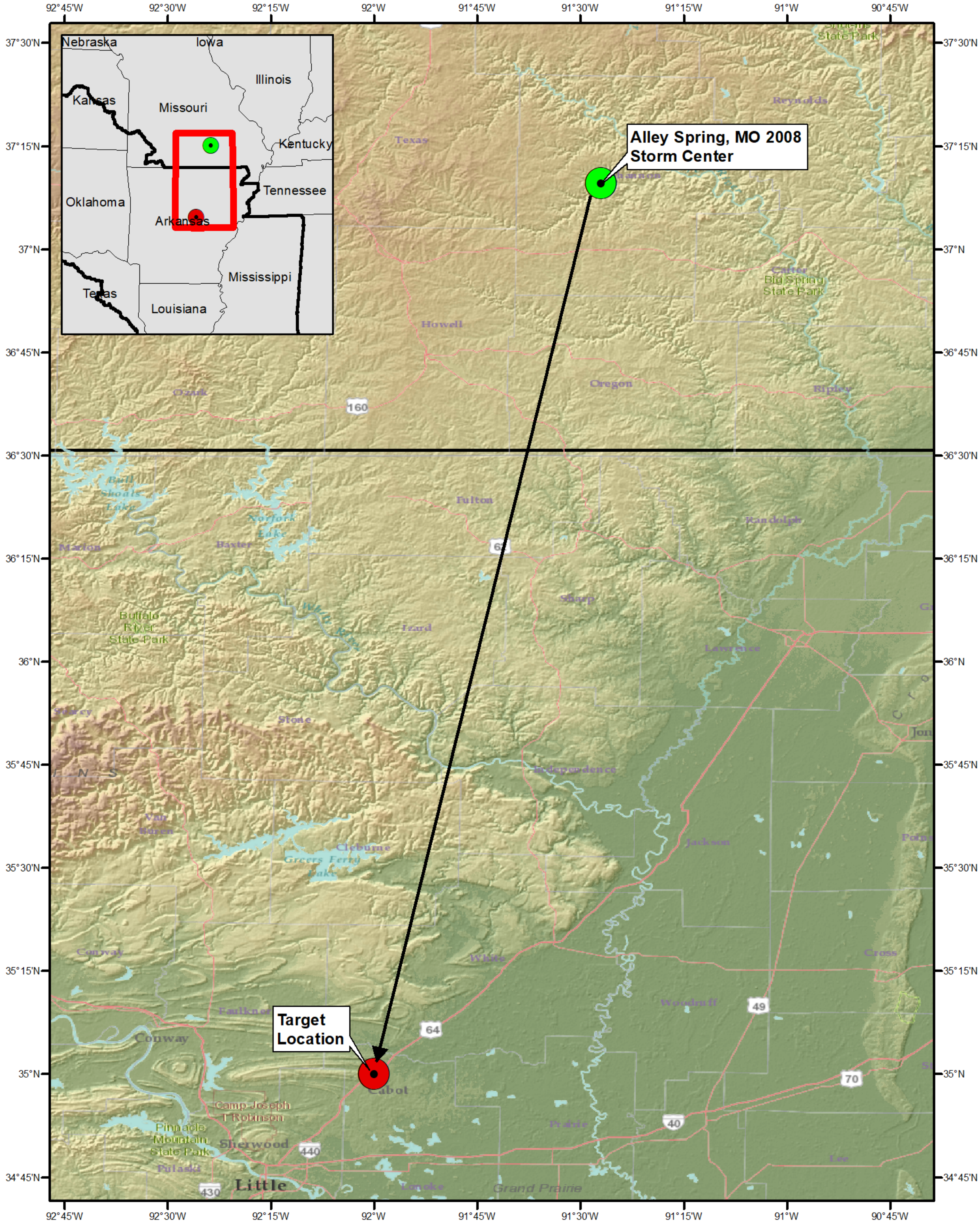

Figure 10.1: Sample transposition of Alley Spring, MO, 2008 (SPAS 1242) to grid point #71,392

10.1.3 Sample Precipitable Water Calculation

Using the storm representative dew point temperature and storm center elevation as input, the precipitable water lookup table returns the depth, in inches, used in Equation 4. The storm representative dew point temperature is 66.0°F at the storm representative dew point location 500 miles southeast of the storm center (see Appendix F for the detailed storm maximization and analysis information). The storm center elevation is approximated at 900 feet at the storm center location of 37.115°N, 91.445°W. The storm representative available moisture ($W_{p,\ rep}$) is calculated using Equation 4:

$$W_{p,rep} = W(@66.0°)_{p,30{,}000'} - W(@66.0°)_{p,900'}$$

or,

$$W_{p,rep} = 1.86" - 0.17"$$

$$W_{p,rep} = 1.69"$$

The mid-March storm was adjusted 15 days toward the warm season to a temporal transposition date of April 1st. A weighted average of the March and April 24-hour climatological maximum dew point temperatures was used for the April 1st temporal transposition date. The March climatological 100-year maximum 24-hour average dew point at the storm representative dew point location is 70.19°F and the April average is 73.18°F. The two monthly temperatures are averaged (weighted toward April 1st) and rounded to the nearest ½ degree to a climatological maximum dew point temperature of 71.79°F. The in-place climatological maximum available moisture ($W_{p,\ max}$) is calculated.

$$W_{p,max} = W(@71.79°)_{p,30{,}000'} - W(@71.79°)_{p,900'}$$

$$W_{p,max} = 2.47" - 0.21"$$

$$W_{p,max} = 2.26"$$

10.1.4 Sample IPMF Calculation

In-place storm maximization is applied for each storm event using the methodology described in Section 7.2. Storm maximization is quantified by the IPMF using Equation 4:

$$IPMF = \frac{W_{p,max}}{W_{p,rep}}$$

$$IPMF = \frac{2.26"}{1.69"}$$

$$IPMF = 1.34$$

10.1.5 Sample GTF Calculation

The ratio of the 100-year 24-hour climatological precipitation depth at the target grid point #71,392 location to the Alley Spring, MO 2008 storm center was evaluated to determine the storm's GTF at the target location. The 24-hour rainfall depth (R_t) of 8.69" was extracted at the grid point #71,392 location from the 100-year 24-hour NOAA Atlas 14 precipitation frequency climatology.

$$R_t = 8.69"$$

Similarly, the 24-hour rainfall depth (R_s) of 7.47" was extracted at the storm center location from the 100-year 24-hour NOAA Atlas 14 precipitation frequency climatology.

$$R_s = 7.47"$$

Equation 6 provides the climatological precipitation ratio to determine the GTF.

$$GTF = \frac{R_t}{R_s}$$

$$GTF = \frac{8.69"}{7.47"}$$

$$GTF = 1.16"$$

The GTF at grid #71,392 is 1.16, or a 16% rainfall increase from the storm center location due to the geographic effects captured within the precipitation climatology. The GTF is then considered to be a temporal constant for the spatial transposition between that specific source/target grid point pair, for that storm only, and can be applied to the other durations for that storm.

10.1.6 Sample TAF Calculation

$$TAF = IPMF \times GTF \qquad \text{(from Equation 1)}$$

$$TAF = 1.34 \times 1.16$$

$$TAF = 1.55$$

The TAF for Alley Spring, MO 2008 when moved to the grid point at 35.0°N, 92.0°W, representing storm maximization and transposition, is 1.55. This is an overall increase of 55% from the original SPAS analyzed in-place rainfall. The TAF can then be applied to the storm's rainfall depth taken from the SPAS depth-area-duration table, at the basin area-size, to calculate the total adjusted rainfall. If the total adjusted rainfall is greater than the depth for all other transposable storms, it becomes the PMP depth at that grid point for that duration.

11. PMP Results

The PMP tool provides basin-specific PMP based on the area-size of the basin. For each storm type analyzed, the tool provides output in ESRI file geodatabase format. The output also includes a basin average PMP table. If the sub-basin average option was checked, the tool provides averages for each sub-basin. The depths are calculated for the area-size of the basin, so no further areal reduction should be applied. The tool also provides a point feature class containing PMP depths and controlling storms listed by SPAS ID and storm name, date, and state, in addition to gridded raster PMP depth files. There are also temporally distributed accumulated rainfall tables for each temporal pattern applied to the basin described in Section 10.7. Finally, a basin average PMP depth-duration chart in the .png image format is also included in the output folder. An example depth-duration chart is shown in Figure 11.1. Detailed output information is included in the PMP tool documentation in Appendix G.

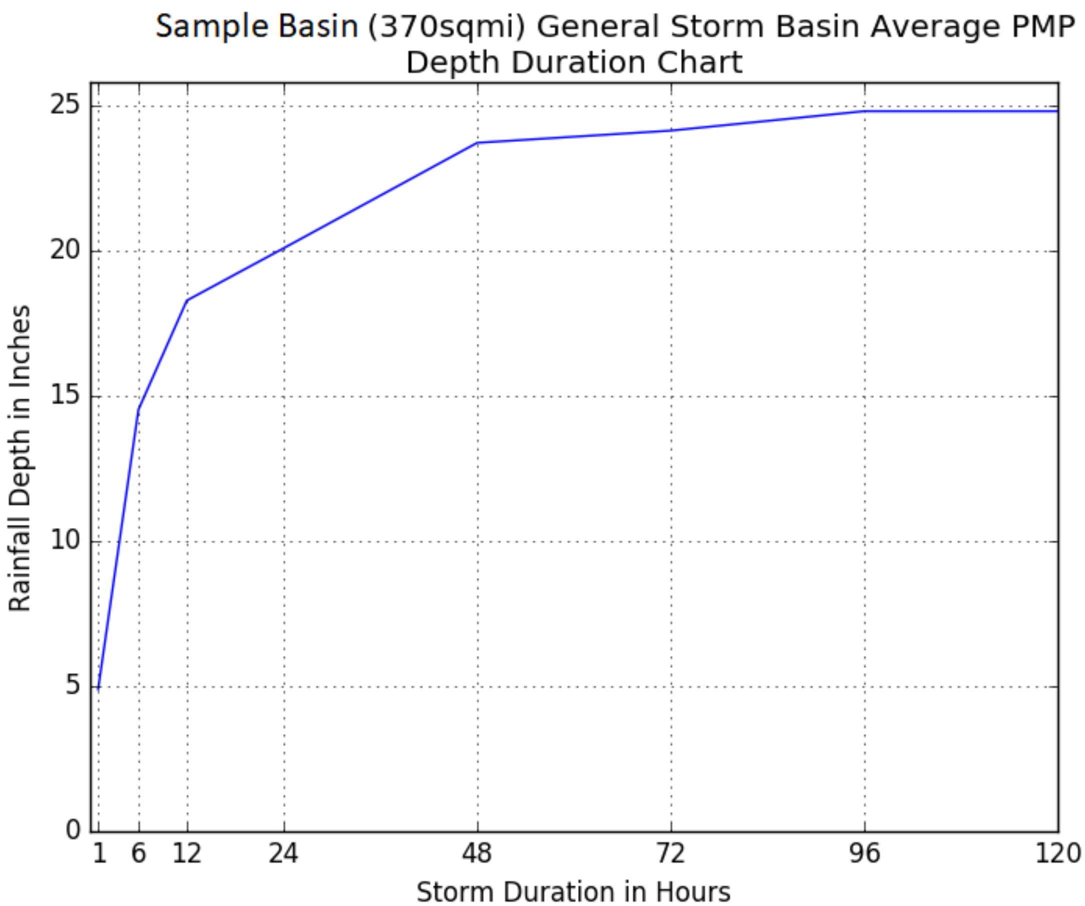

Figure 11.1: Sample PMP depth-area chart image provided in output folder

Gridded PMP depths were calculated for the entire study region at various index area-sizes for several durations as a visualization aid. The maps in Appendix A illustrate the depths for 1-, 10-, and 200-square mile area sizes for local storm PMP at 1-, 3-, 6-, 12-, and 24-hour durations and 10-, 200-, 1,000-, 5,000-, 10,000-, and 20,000-square mile area sizes for general and tropical storm PMP at 6-, 12-, 24-, 72-, 96-, and 120-hour durations.

12. Development of Temporal Distribution for Use in Runoff Modeling

The development of the site-specific temporal patterns was completed following similar processes as those used in the Wyoming PMP temporal study (Kappel et al., 2015), the Virginia PMP temporal study (Kappel et al., 2018), the Colorado-New Mexico Regional PMP study (Kappel et al., 2018), and the Pennsylvania PMP temporal study (Kappel et al., 2019). All short list storms used in this study were used to develop temporal accumulation patterns associated with each storm type and general region. Storms were grouped by geographic location and by storm type: local, general, tropical.

In terms of storm types, local storms are characterized by short duration (6-hours or less) and small area size (less than 500-square miles) high intensity rainfall accumulations. They are often not associated with large scale weather patterns and can be influenced by local moisture sources. General storms produce precipitation over longer durations (greater than 6-hours) and cover larger areas with comparatively lower intensity rainfall accumulations. General storms are produced by large scale synoptic patterns generally associated with areas of low pressure and fronts. These are most common during the fall, winter, and spring seasons. Tropical storms rely on warm water from the Gulf of Mexico with supporting synoptic and upper level weather patterns and occur from June through October. When these storms move slowly over a region, large amounts of rainfall can be produced both in convective bursts and over longer durations. Some storms exhibit characteristics of both the local and general storm or local and tropical rainfall accumulation patterns. These are termed hybrid storms and are evaluated as more than one storm type.

Two methods were used to investigate and derive temporal patterns: i) Synthetic Curves based on SPAS mass curves and ii) Huff Curves (see Section 12.2) based on SPAS mass curves. Investigations were completed by analyzing the rainfall accumulation of each storm and the time over which the main rainfall accumulated. During these analyses, consideration was given to the synoptic meteorological patterns that created each storm type, access to moisture sources, and the general topographic setting. The location of the storm center associated with each SPAS DAD zone was used for the temporal distribution calculations. Hourly gridded rainfall data were used for all SPAS analyzed storms.

HMRs 49, 52, 55A, 57, and 59 utilized similar qualitative investigations of rainfall accumulation patterns. However, very little background information was provided as to how those rainfall data were analyzed to derive the temporal patterns applied in those documents. HMR 49 Section 4.4 provides background on investigations completed in that study to derive depth-duration information. HMR 49 Section 4.7 provides background on the time distribution of incremental PMP for the local storm type. HMR 55A Section 12.5 addresses local storm incremental accumulation but again provides very limited data and analysis background.

12.1 Synthetic Curve Methodology

Hourly gridded rainfall data were used for all SPAS analyzed storms. The maximum rain accumulations were based on rainfall at the storm center. The rainfall mass curve at the storm center were used for the temporal calculations. The steps used to derive the synthetic curves are described below.

12.1.1 Standardized Timing Distribution by Storm Type

The Significant Precipitation Period (SPP) for each storm was selected by excluding relatively small rainfall accumulations at the beginning and end of the rainfall duration. Accumulated rainfall (R) amounts during the SPP were used in the analysis for the hourly storm rainfall. The total rainfall during the SPP was used to normalize the hourly rainfall amounts. The time scale (T_S) was computed to describe the time duration when half of the rainfall accumulated (R). The procedures used to calculate these parameters are listed below.

12.1.2 Parameters

SPP - Significant Precipitation Period when the majority of the rainfall occurred
R - Accumulated rainfall at the storm center during the SPP
R_n - Normalized R
T - Time when R occurred
T_s – Time when 50% accumulation occurs, value is set to zero. Negative time values precede the time to 50% rainfall, and positive values follow
T50 - Time when $R_n = 0.5$

12.1.3 Procedures used to calculate parameters

1. Determine the SPP. Inspect each storm's rainfall data for "inconsequential" rainfall at either the beginning and/or the end of the records. Remove these "tails" from calculations. Generally, AWA used a criterion of less than 0.1 inches/hour intensity to eliminate non-intense periods. No internal rainfall data were deleted.
2. Recalculate the accumulated rainfall records for R. This yields the SPP.
3. Plot the SPAS rainfall and R mass curves and inspect for reasonableness.
4. Normalize the R record by dividing all values by the total R to produce R_n for each hour, R_n ranges from 0.0 to 1.0.
5. Determine T50 using the time when $R_n = 0.5$.
6. Calculate T_s by subtracting T50 from each value of T. Negative time values precede the time to 50% rainfall, and positive values follow.
7. Determine max24hr and max6hr precipitation, convert accumulations into a ratio of the cumulative rainfall to the total accumulated rainfall for that duration.
8. Visually inspect resulting data to determine a best fit of the curves. This includes both the intensity (steepness) of accumulation and whether most of the accumulations are exhibiting a front, middle, or back loaded accumulation.

Graphs were prepared of a) R vs T, b) R_n vs T, c) R_n vs T_s, and d) maximum point precipitation for General (24-hour), Local (6-hour), and Tropical (24-hour) storm events. Evaluations of the resulting rainfall accumulation curves individually and in relation to each other were completed by visually inspecting the data. From these investigations, a rainfall accumulation pattern that represented a significant majority of the patterns with a steep intensity was utilized as the synthetic pattern. This process is highly subjective. The objective of the process is to produce a synthetic pattern that captures the majority of the worst-case runoff scenarios for most basins and represents a physically possible temporal accumulation pattern. However, it is not possible for a single synthetic curve to capture all of the worst-case runoff scenarios for all basins. Therefore, the user should consult with the appropriate dam safety regulator for further guidance on temporal applications beyond what is provided in the GIS PMP tool.

12.1.4 Results of the Analysis

Following the procedures and description from the previous section, results are presented as three graphs. The graphs are a) R vs T, b) R_n vs T, and c) R_n vs T_s for local, general, tropical, and hybrid storm types. Figure 12.1 to Figure 12.12 show these graphs for SPAS storm. AWA created "synthetic" temporal patterns based on these results (See Section 12.7) by applying meteorological judgment to the data. This included determining how the group of curves fit in relation to each other and the shapes of the curves representing intensity of accumulations. Finally, AWA's recommended synthetic curves were presented and discussed with participants in this study. The curves were then texted on numerous test basins throughout the domain to test the resulting runoff characteristics and ensure they were behaving as anticipated.

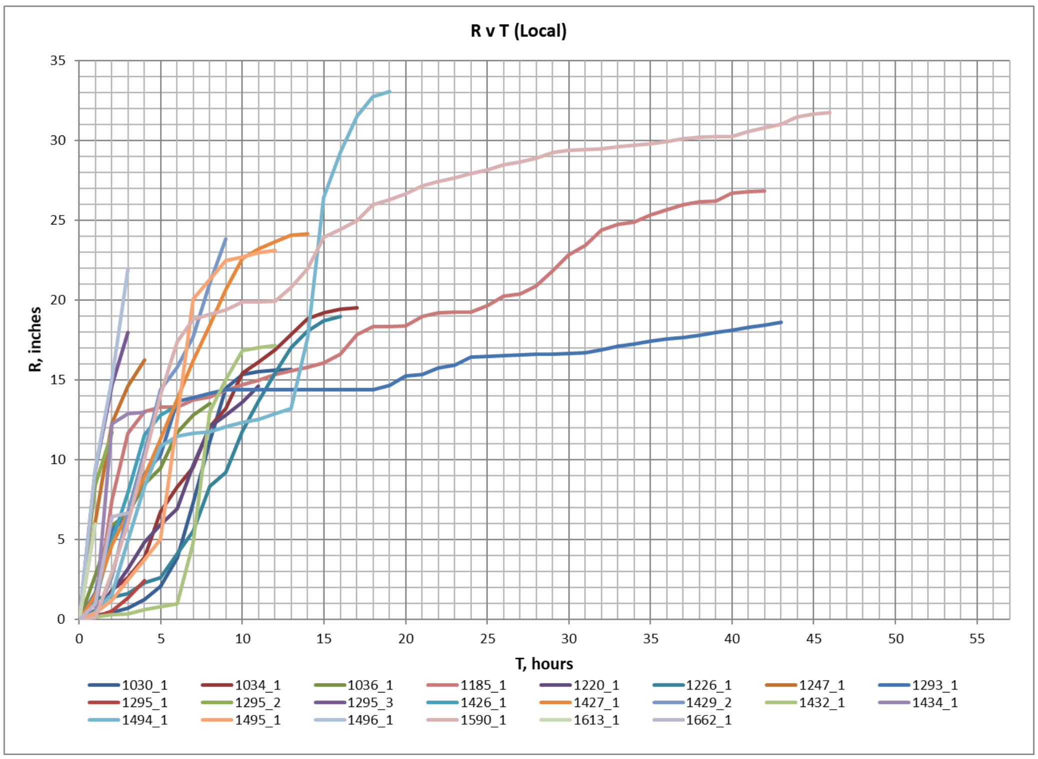

Figure 12.1: SPAS Rainfall (R) versus time (T) for Local Type Storm

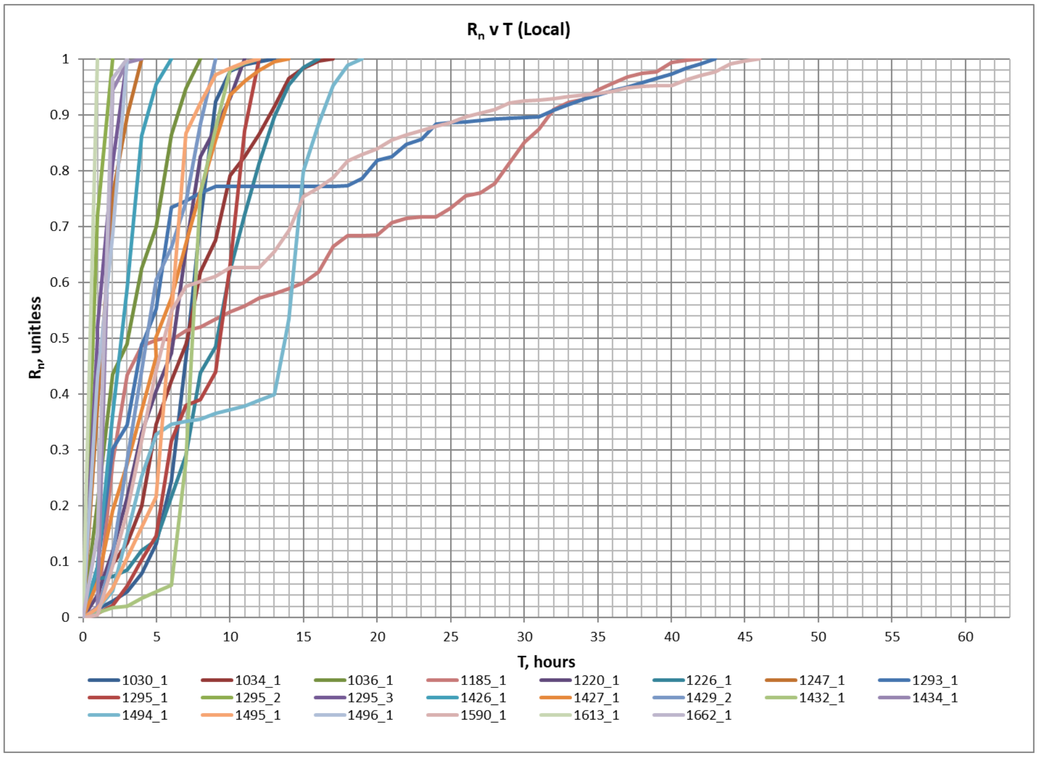

Figure 12.2: Normalized R (Rn) versus time (T) for Local Type Storm

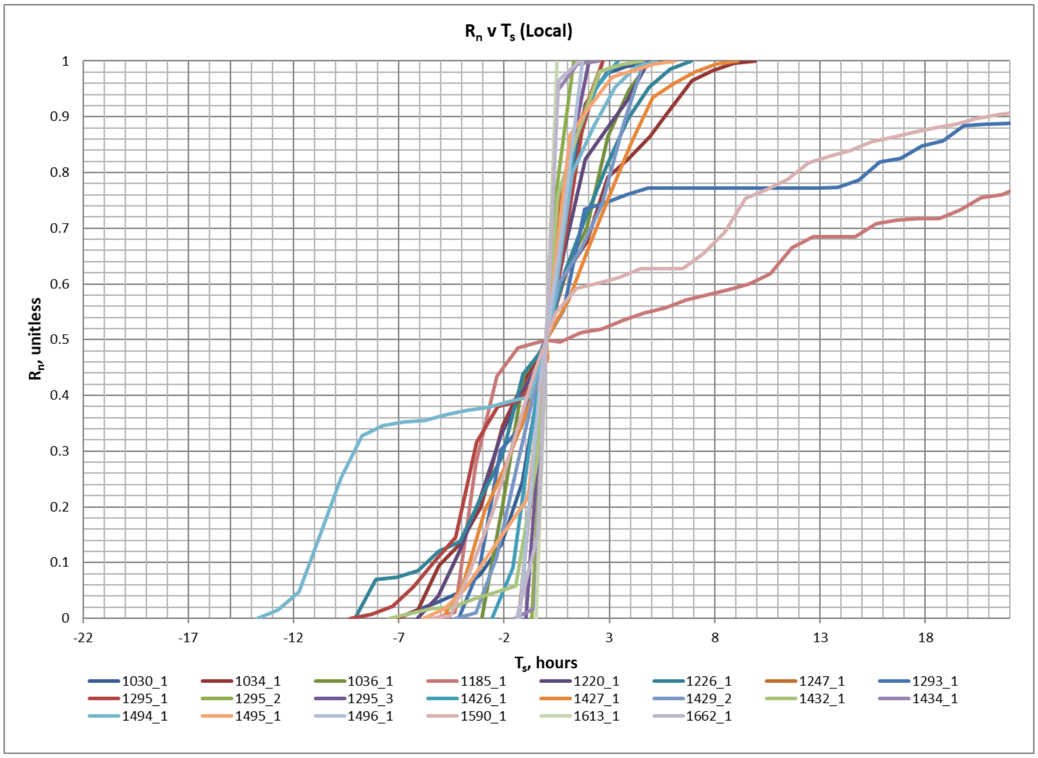

Figure 12.3: Normalized R (Rn) versus shifted time (Ts) for Local Type Storm

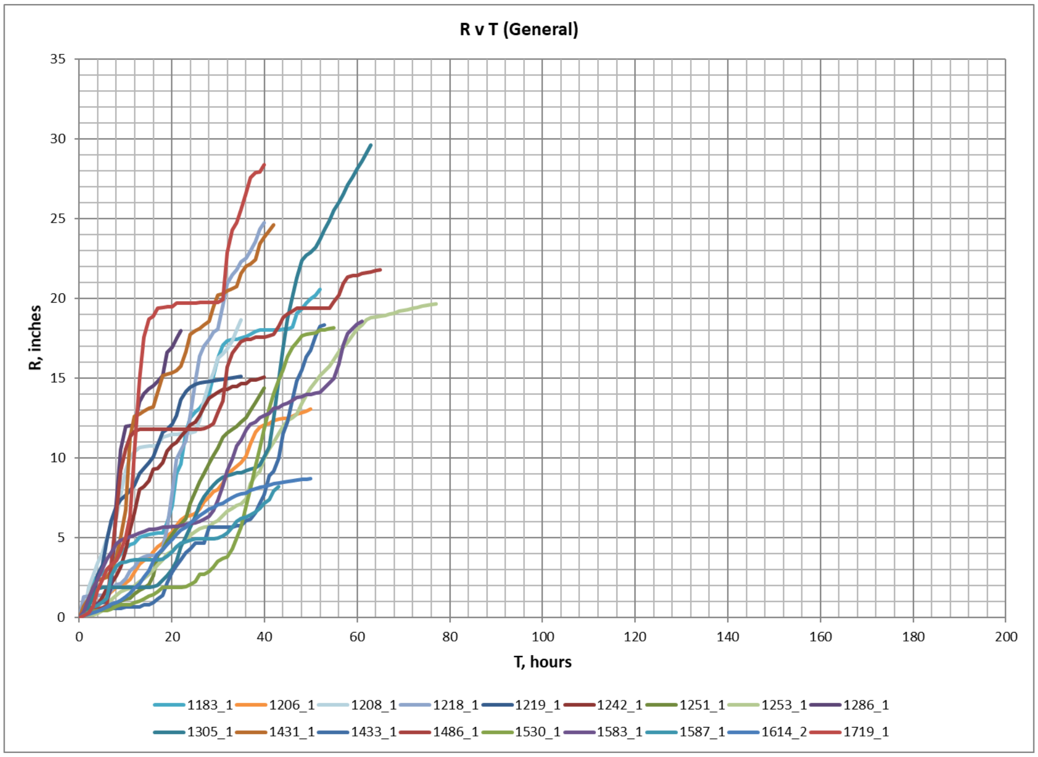

Figure 12.4: SPAS Rainfall (R) versus time (T) for General Type Storm

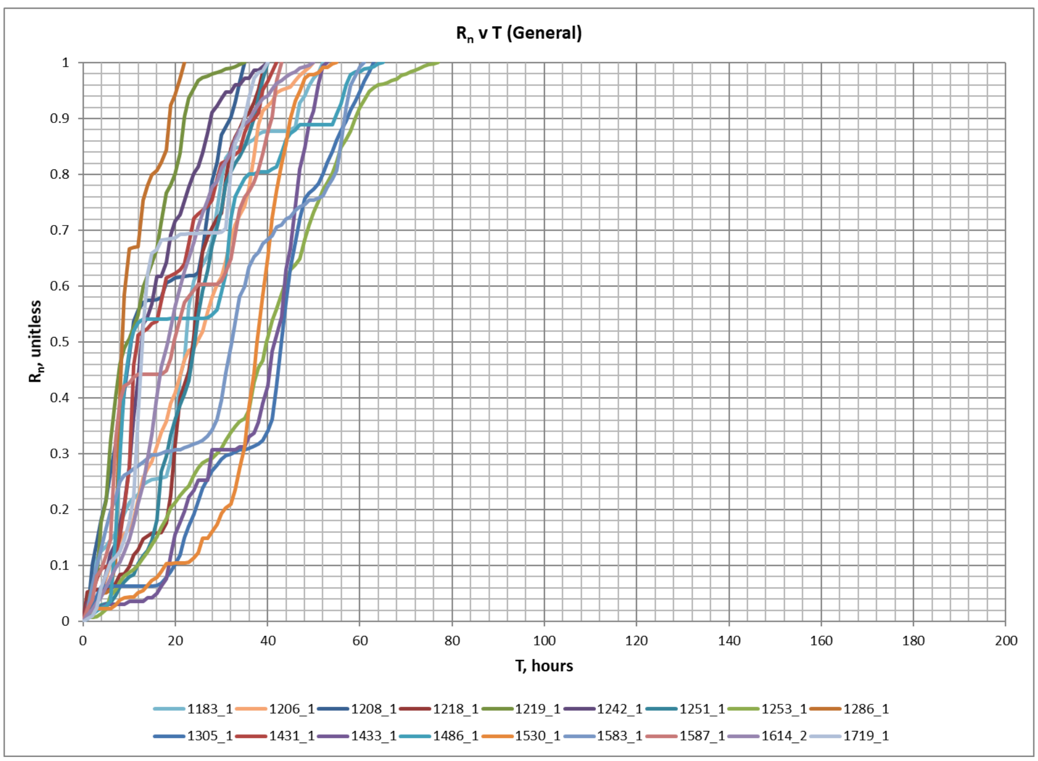

Figure 12.5: Normalized R (Rn) versus time (T) for General Type Storm

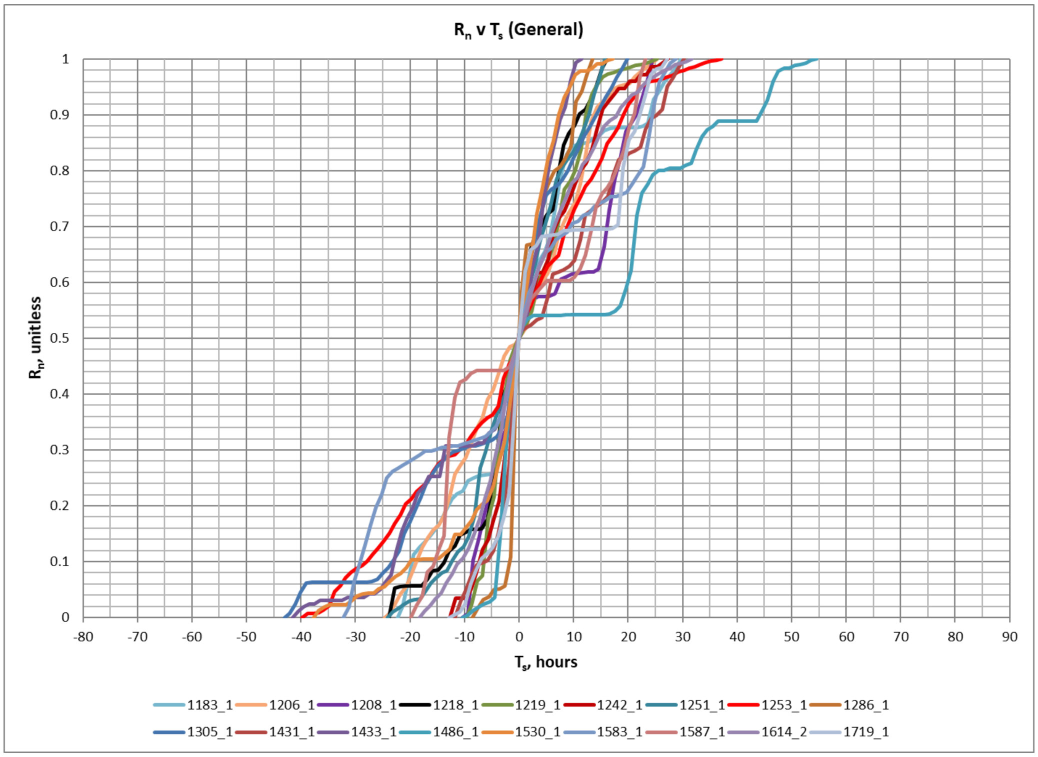

Figure 12.6: Normalized R (Rn) versus shifted time (Ts) for General Type Storm

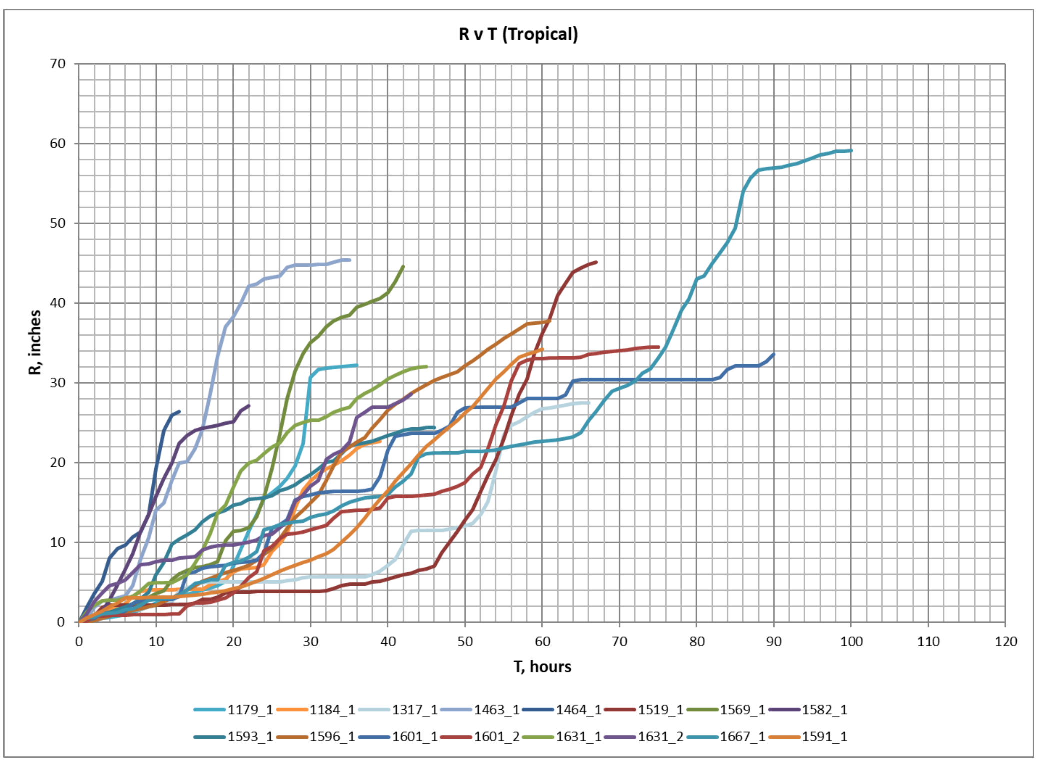

Figure 12.7: SPAS Rainfall (R) versus time (T) for Tropical Type Storm

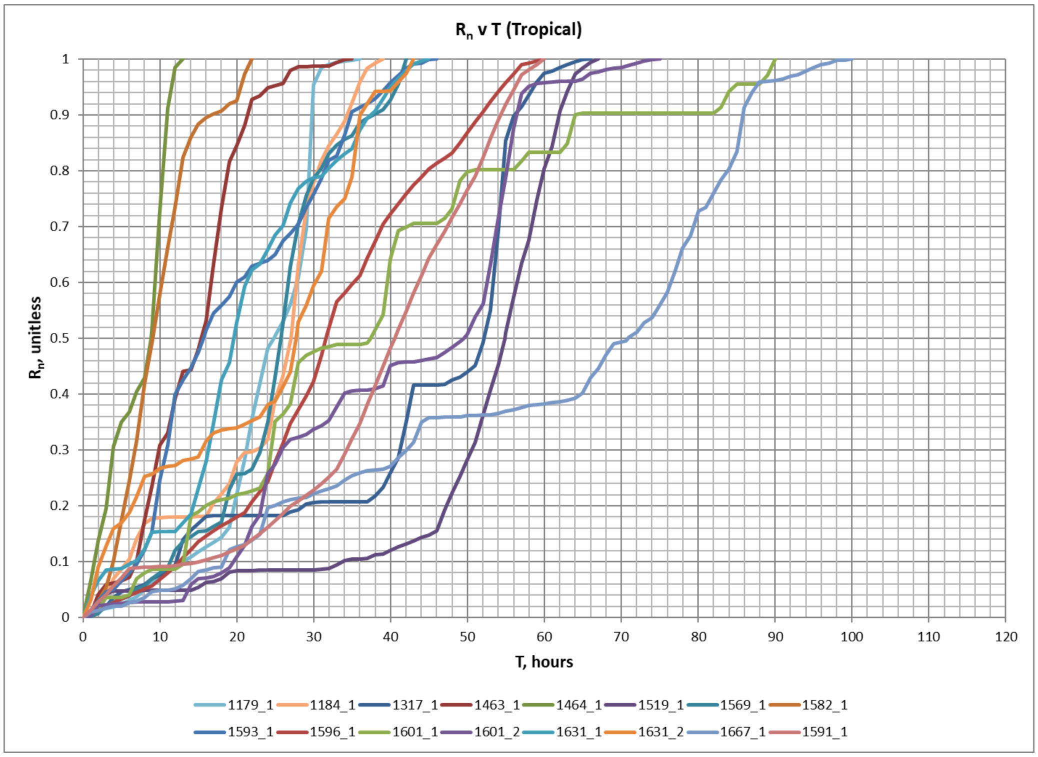

Figure 12.8: Normalized R (Rn) versus time (T) for Tropical Type Storm

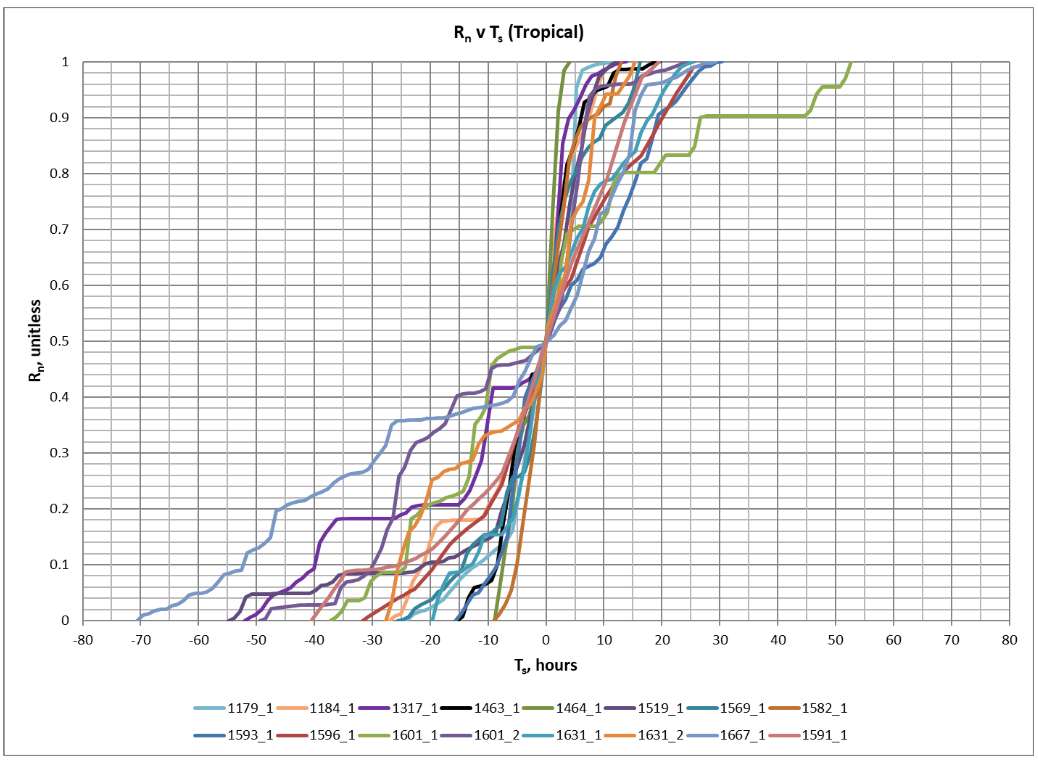

Figure 12.9: Normalized R (Rn) versus shifted time (Ts) for Tropical Type Storm

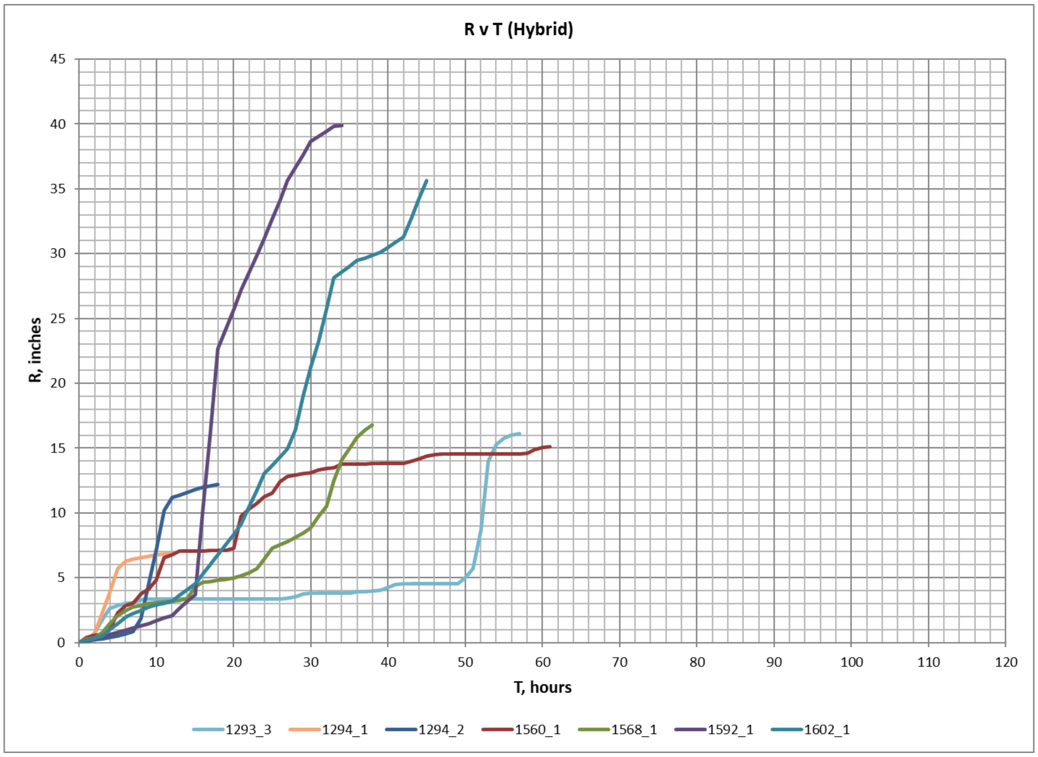

Figure 12.10: SPAS Rainfall (R) versus time (T) for Hybrid Type Storm

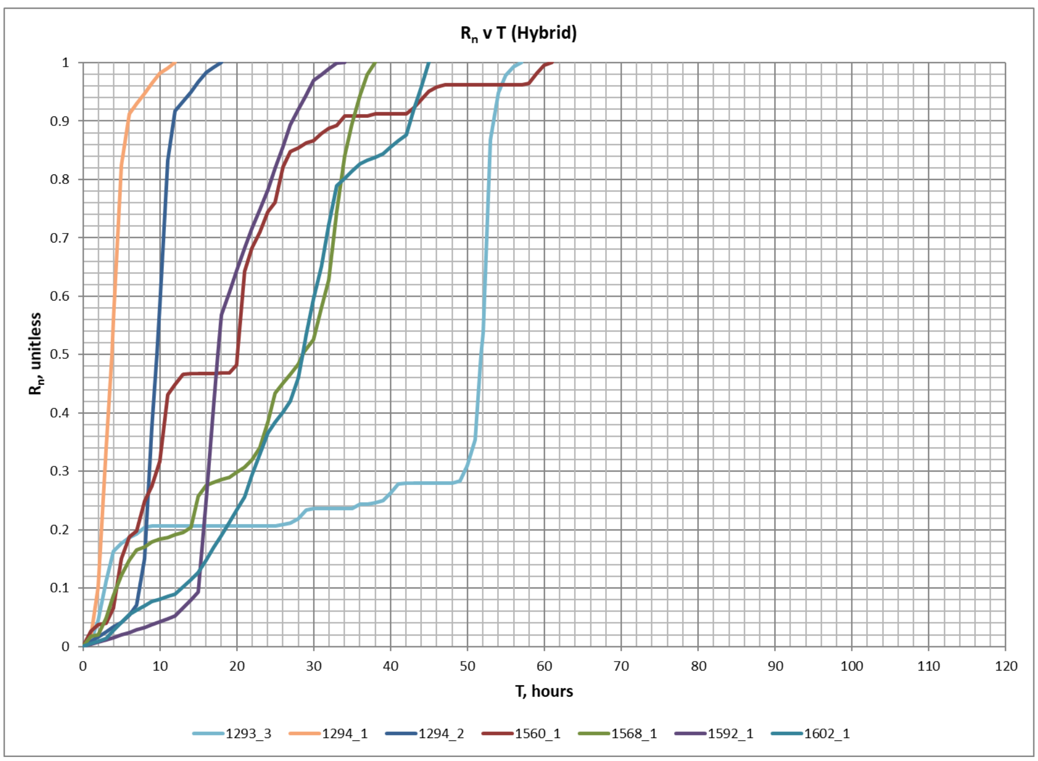

Figure 12.11: Normalized R (Rn) versus time (T) for Hybrid Type Storm

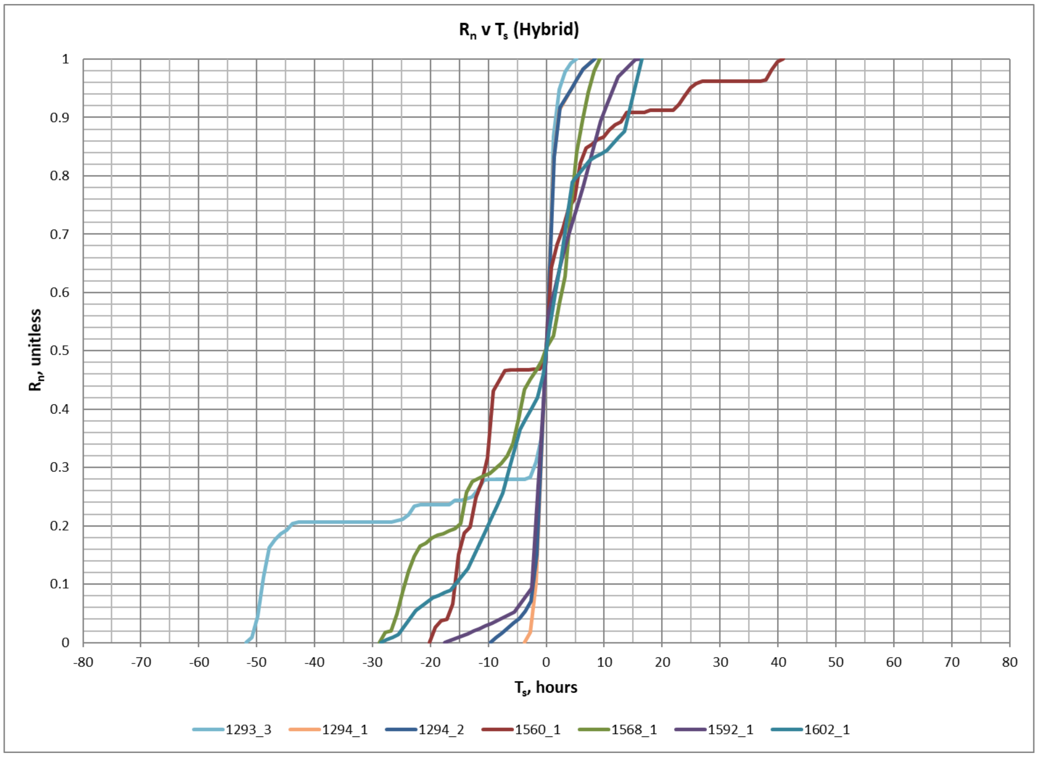

Figure 12.12: Normalized R (Rn) versus shifted time (Ts) for Hybrid Type Storm

12.2 Huff Curve Methodology

Huff curves provide a method of characterizing storm mass curves. They are a probabilistic representation of accumulated storm depths for corresponding accumulated storm durations expressed in dimensionless form. The development of Huff curves is described in detail in Huff (1967) and Bonta (2003) and summary of the steps is listed below.

For each SPAS storm center mass curve, the core cumulative precipitation amounts (R, noted in above section) were identified, the core cumulative rainfall were non-dimensionalized and converted into percentages of the total precipitation amount at one-hour time steps. The non-dimensionalized duration values were interpolated and extracted at 0.02 increments from 0 to 1. Storms were grouped by geographic location (east versus west of the Appalachian Crest) and by storm type: local, general, tropical, and hybrid. The uniform incremental storm data (by duration and location) were combined and probabilities of occurrence were estimated at each 0.02 increment. Probabilities were estimated as 0.1 increments. The raw recommended curves (90^{th} and 10^{th}) were smoothed using a non-linear regression. Smoothing of the raw curves is performed to account for statistical noise in the analysis (Huff, 1967; Bonta, 2003).

The curves generated in this study can be generically described as:

- 90^{th} curve - the 90th curve indicates that 10% of the corresponding SPAS storms had distributions that fell above and to the left of the 90^{th} curve (front-loaded)
- 50^{th} curve - the 50th curve indicates that 50% of the corresponding SPAS storms had distributions that fell above and below the 50^{th} curve (mid-loaded)

- 10th curve - the 10th curve indicates that 10% of the corresponding SPAS storms had distributions that fell below and to the right of the 10th curve (back-loaded)

The raw data results are presented below (Figures 12.13-12.16), the final curves selected for use were smoothed using non-linear regression and data were provided at 5-minute (local storms) and 15-minute (general, hybrid, tropical) time steps from the non-linear regression equation (data were extracted from the non-linear equation). Some of the Huff curves result in accumulated precipitation at time zero, this is a result of front-loaded storms that generate a significant portion of their precipitation in the first hour, the analysis was performed on hourly data, and the interpolation method for did not force the curve to zero. The final set of Huff curves were set to zero at time zero. The NRCS Type II curve (also known as the SCS curve) is considered a standard temporal pattern for design purposes in many regions of the country; see Section 12.7 for additional description (NRCS, 2005). The Type II curve is added to figures in its native state for comparison (Type II).

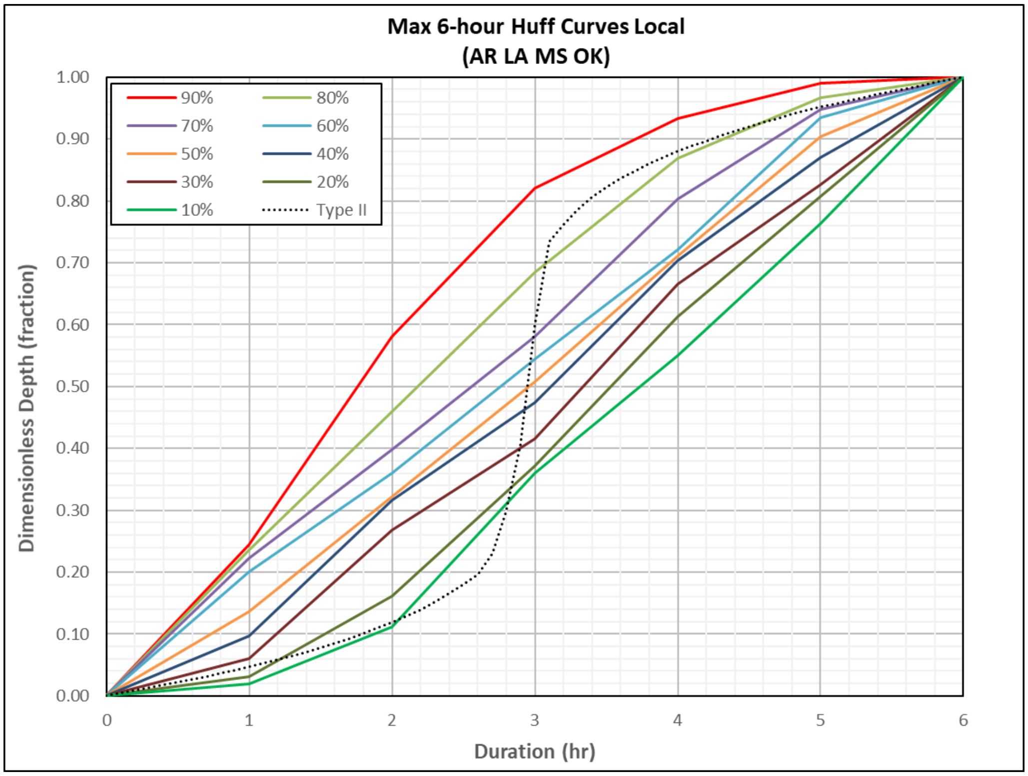

Figure 12.13: Raw Huff temporal curves for 6-hour Local storms

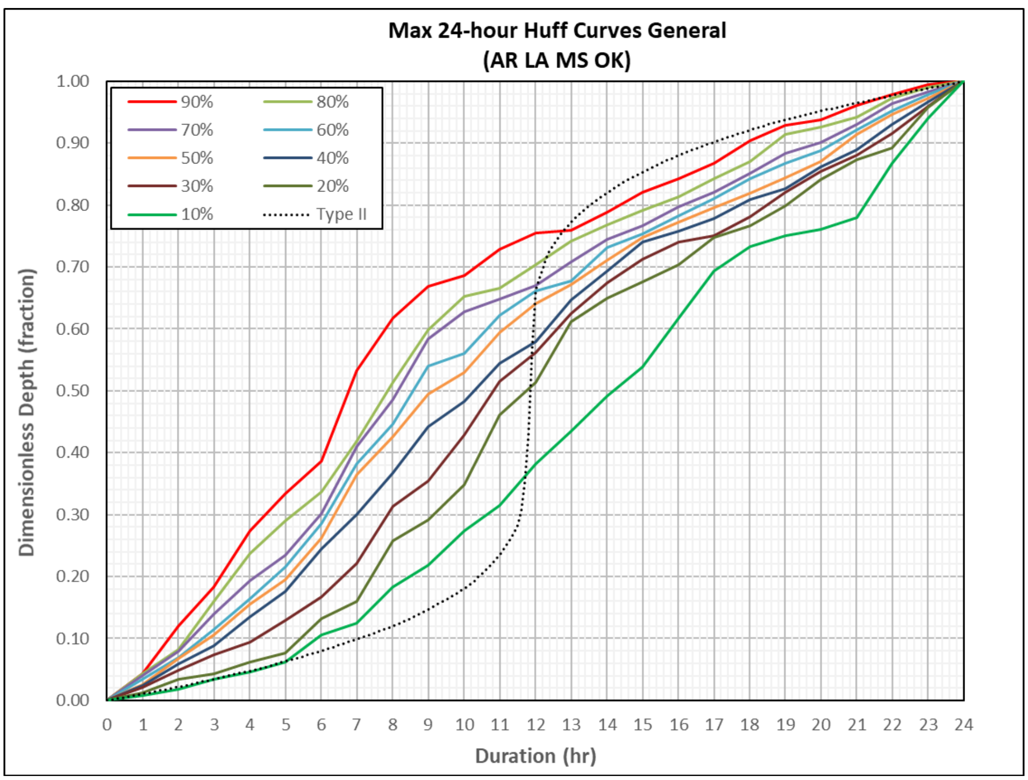

Figure 12.14: Raw Huff temporal curves for 24-hour General storms

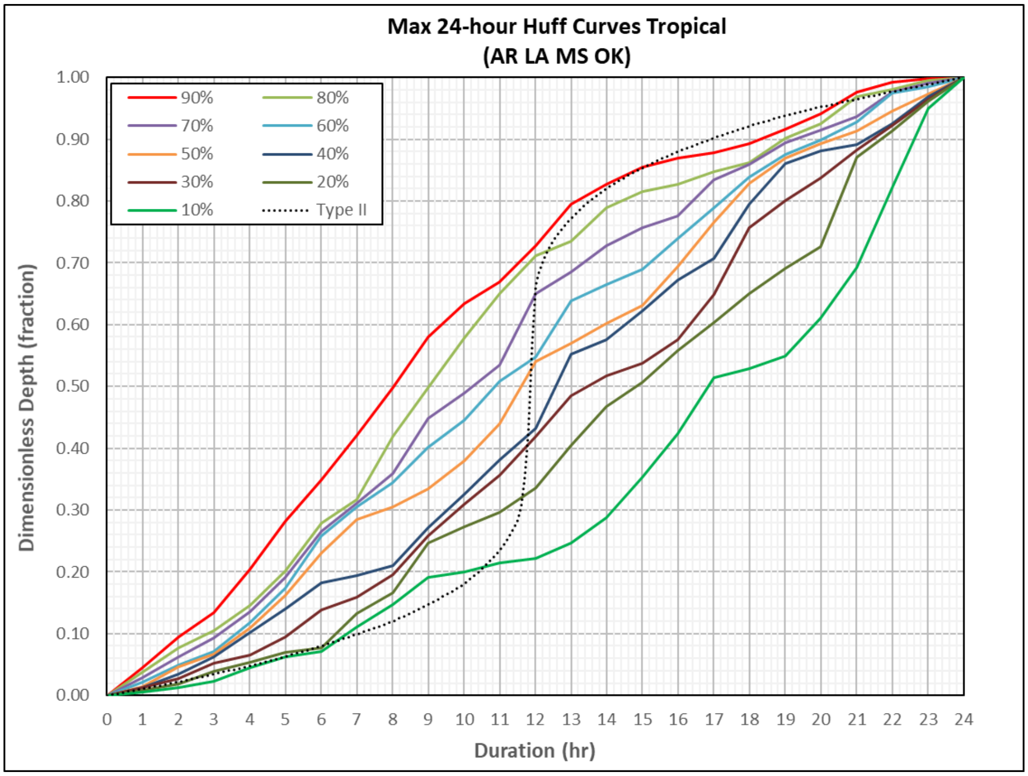

Figure 12.15: Raw Huff temporal curves for 24-hour Tropical storms

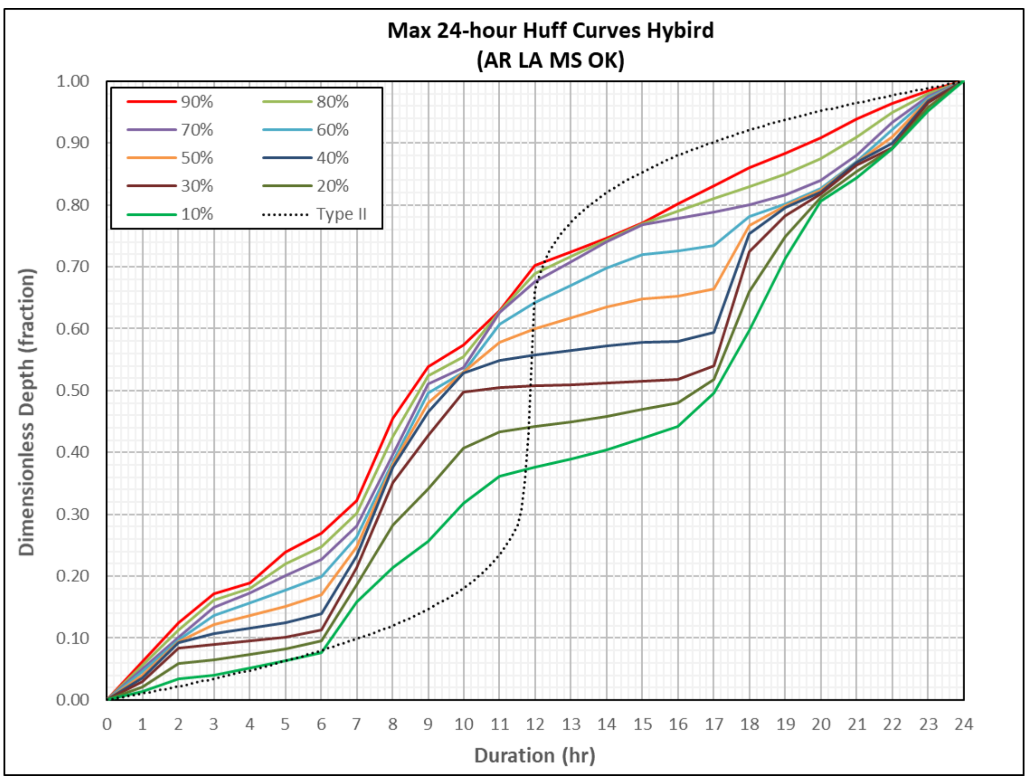

Figure 12.16: Raw Huff temporal curves for 24-hour Hybrid storms

12.3 Alternating Block (Critically Stacked) Pattern

Based on HMR 52 (Hansen et al., 1982) procedures and the USBR Flood Hydrology Manual (Cudworth, 1989) a "critically stacked" temporal distribution was developed to try and develop a synthetic rainfall distribution. The critically stacked temporal pattern yields a significantly different distribution than actual distributions associated with the storms used for PMP development in this study and in similar analysis of adjacent PMP studies (e.g. Ohio and Virginia). The critically stacked pattern imbeds PMP depths by duration within one another, i.e. the one-hour PMP is imbedded within the 3-hour, which is imbedded within the 6-hour, which is in turn imbedded in the 24-hour PMP. Figure 12.17 provides a graphical illustration of a critically stacked pattern. The critically stacked procedure has often been chosen in the past for runoff modeling because it represents a worst-case design scenario and ensures PMP depths are equaled at all durations.

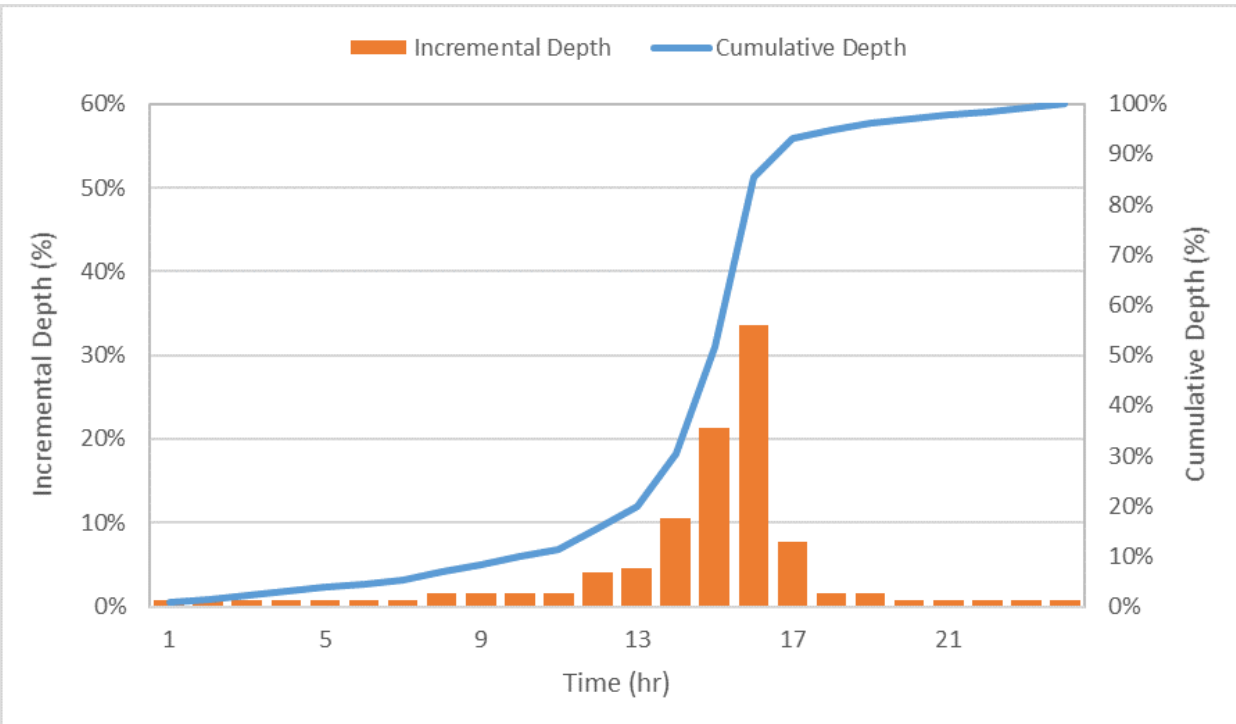

Figure 12.17: Graphical representation of the critically stacked temporal pattern

12.4 Sub-hourly Timing and 2-hour Local Storm Timing

AWA evaluated the 5-minute incremental rainfall accumulations patterns for thirty-six PMP type storms that had been analyzed with SPAS-NEXRAD to identify events that could be used to derive site-specific sub-hourly accumulation guidance. The SPAS-NEXRAD 5-minute data were used to derive ratios of the greatest 5-, 10-, 15-, 20-, 25-, 30-, 35-, 40-, 45-, 50-, and 55-minute accumulations during the greatest 1-hour rainfall accumulation. Data from eighteen of the thirty-six storms events allowed a specific evaluation of the sub-hourly rainfall patterns to be considered for the OK-AR-LA-MS PMP study region.

HMR 55A provided recommended temporal patterns to be applied to the PMP to estimate sub-hourly timing. It is important to note that the 15-minute incremental accumulation ratios derived for the local PMP storm in HMR 55A is based on very limited (almost none) sub-hourly data. HMR 55A made reference to the limited amount of available data and suggested using HMR 49 information instead (HMR 55A Section 12.7).

Table 12.1 displays the results of this analysis. The largest difference between HMR 55A and this study occurs during the greatest 15-minute increment, where HMR 55A provides a value of 68% (see HMR 55A Table 12.4), while the actual storm data have an average of 36% and a maximum of 55%. AWA completed additional sensitivity analysis by comparing the sub-hourly ratio data to similar data developed during the Arizona statewide PMP study (Kappel et al., 2013) and the Colorado-New Mexico statewide study (Kappel et al., 2018) and the Pennsylvania statewide PMP study (Kappel et al, 2019). The results from the Pennsylvania, Arizona and Colorado-New Mexico statewide PMP analyses are provided in Table 12.1 for comparison with the OK-AR-LA-MS results. The 2-hour local storm temporal pattern was developed to account for local storms that are less than 2-hours. The 2-hour local storm temporal pattern utilized the stacked 5-min sub-hourly ratio data for the first hour (centered in 2-hour duration) and the second hour was evenly distributed (30-minutes at beginning and 30-minutres after largest 1-hour). For example, if a storm event had 8-inches in the first hour and an additional 1-inch for a total storm of 9-inches in 2-hours, the accumulation pattern is shown in Figure 12.18.

Table 12.1: Sub-hourly ratio data from HMR 55A and the OK-AR-LA-MS study

Duration (hr)	Duration (min)	HMR 55a	AR-LA-MS- OK	PA	CO/NM	AZ
0.083	5	-	15%	16%	15%	-
0.167	10	-	26%	28%	28%	-
0.25	15	68%	36%	38%	39%	34%
0.50	30	86%	61%	64%	65%	61%
0.75	45	94%	80%	83%	84%	82%
1.00	60	100%	100%	100%	100%	100%

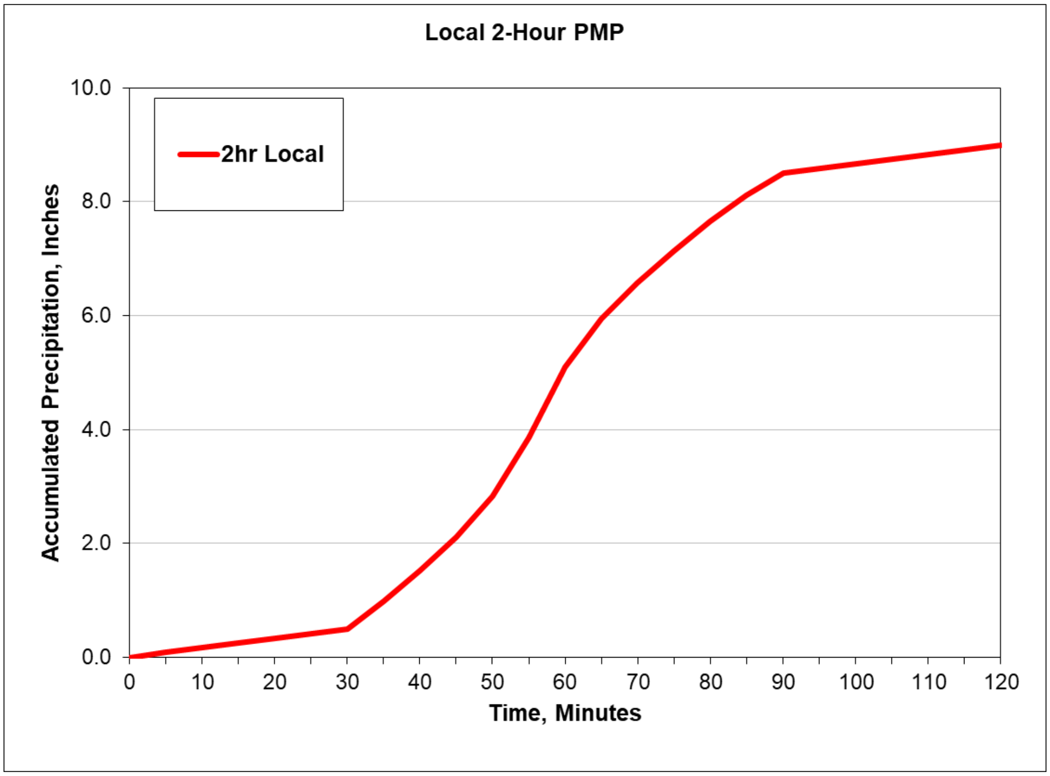

Figure 12.18: Hypothetical 2-hour local storm distribution

12.5 Meteorological Description of Temporal Patterns

Each of the temporal patterns were derived through visual inspection, meteorological analyses, and comparisons with similar work. Analysis was completed after separating each event by storm type (e.g. general, local, tropical, hybrid). The temporal patterns reflect the meteorological conditions that produce each storm type. These represent observed extreme rainfall accumulation characteristics. It is assumed that similar patterns would occur during a PMP event.

12.6 NRCS Type II Distribution Discussion

Each of the temporal patterns analyzed for all sites were significantly different than the NRCS Type II curve. Figure 12.19 displays the NRCS Type II curve. The accumulation pattern shown with this curve is much more intense than the patterns shown as part of this analysis. This same finding was evident in previous statewide and site-specific temporal analyses (e.g. Kappel et al., 2015; Kappel et al., 2016; Kappel et al., 2017; Kappel et al., 2018; and Kappel et al., 2018).

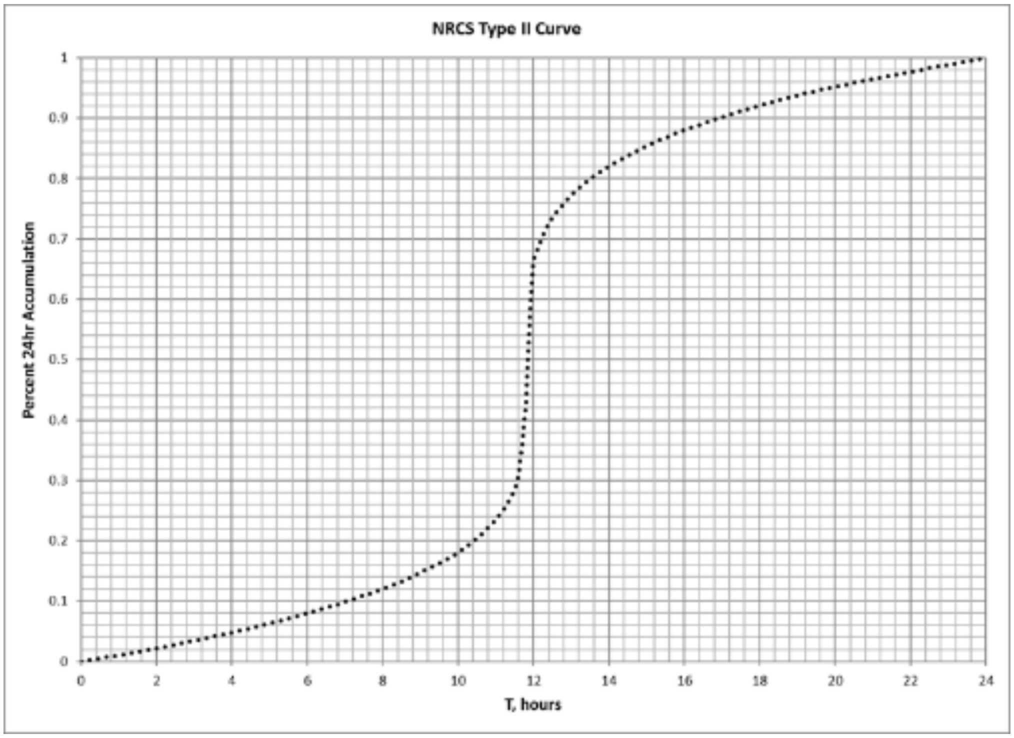

Figure 12.19: Natural Resource Conservation Service (NRCS) Type II curve

12.7 PMP Tool Temporal Distributions

The output PMP depths are distributed to 5-minute accumulations for local storm PMP and 15-minute accumulations for general tropical and Hybrid storm PMP for potential use in runoff modeling for dam safety analysis. The distributions are applied by a function within the PMP tool. The following distributions were developed based on investigation of storm data used in this study. The USACE EM temporal pattern was also added to the PMP Tool for runoff modeling for dam safety analysis.

The total duration for potential use in runoff modeling for the general storm and tropical storm PMP is 72-hours. The first 24-hour period is the second largest 24-hour PMP evenly distributed. The second 24-hour period are distributed according to the five curves listed above. The final 24-hour period is the third largest 24-hour PMP evenly distributed. The user is reminded to consult the appropriate dam safety regulator on the accepted application of these distributions for runoff modeling.

The final seventeen storm patterns recommended and included in the PMP Tool are shown in six Figures 12.20-12.24 as hypothetical PMP. The final local storm, general, tropical, and Hybrid storm patterns are compared to NRCS Type II temporal pattern (Figures 12.25 – 12.28). The storm-base temporal patterns developed for OK-AR-LA-MS resulted in accumulation patterns and intensities that were less extreme than the NRCS Type II temporal patterns.

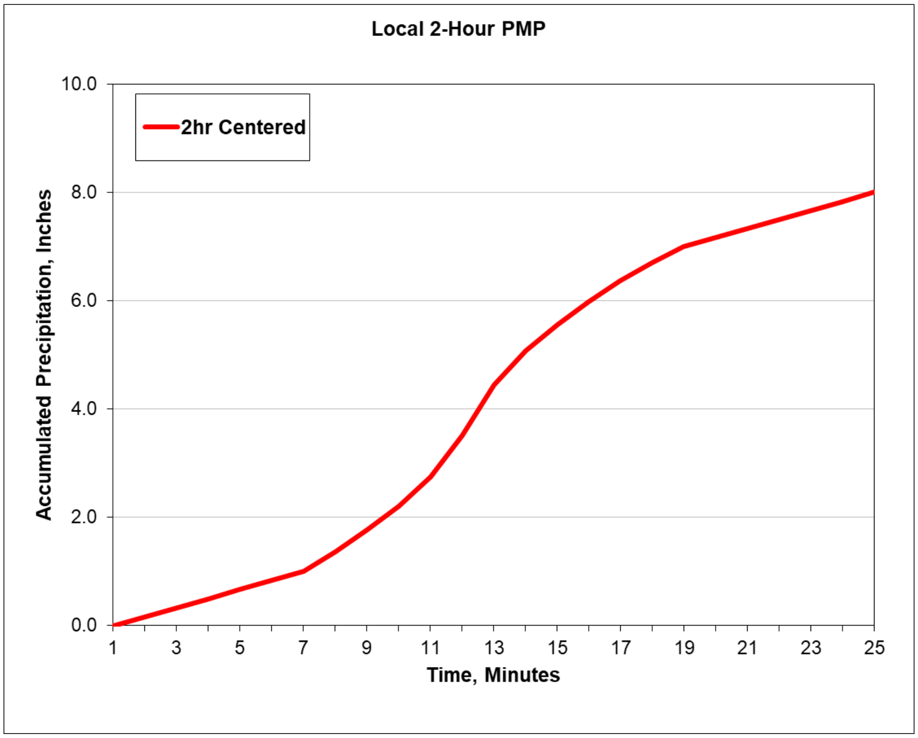

Figure 12.20: Hypothetical 2-hour local storm pattern at 5-minute time step.

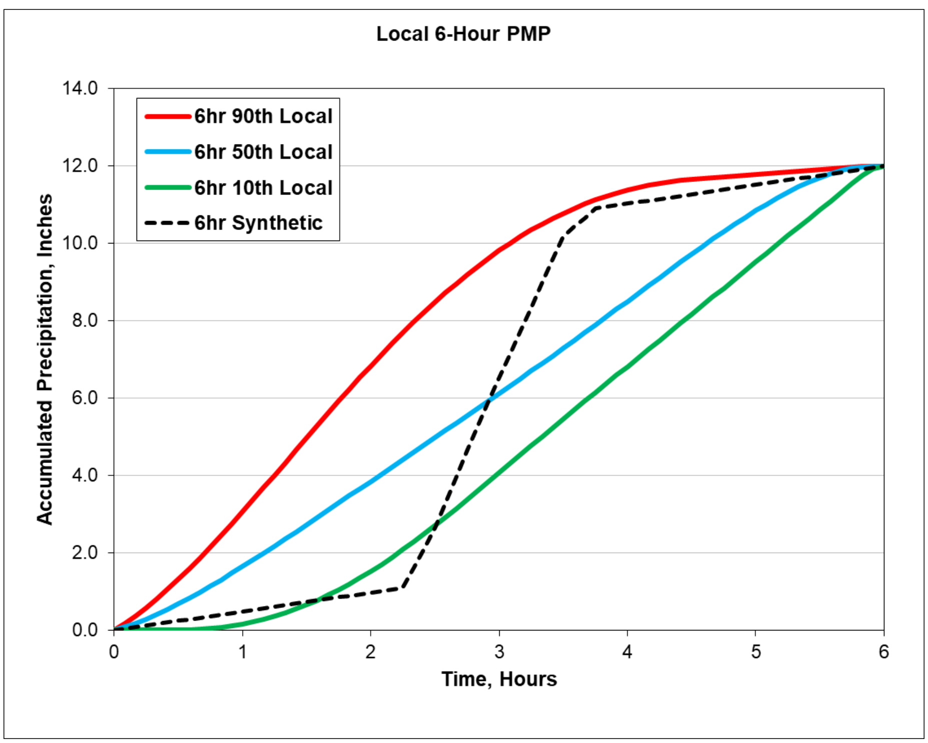

Figure 12.21: Hypothetical 6-hour local storm pattern at 5-minute time step. Red line is the 90th percentile curve, blue line is the 50th percentile curve, green line is the 10th percentile curve, and the black dashed line is the synthetic curve.

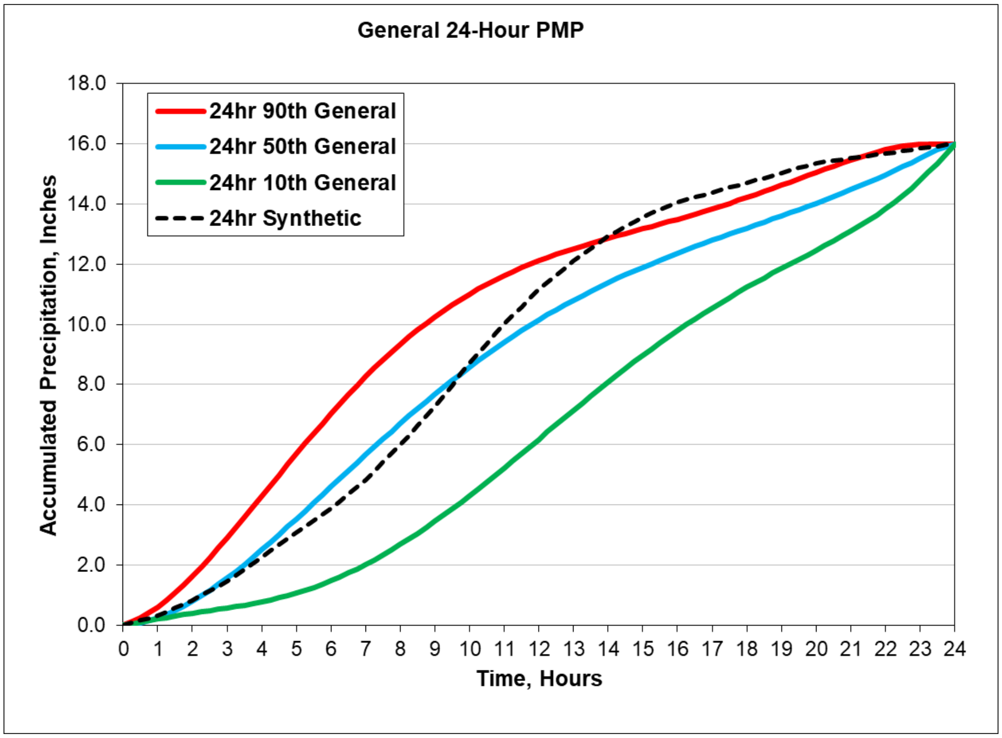

Figure 12.22: Hypothetical 24-hour general storm pattern at 15-minute time step. Red line is the 90th percentile curve, blue line is the 50th percentile curve, green line is the 10th percentile curve, and black dashed line is the synthetic curve.

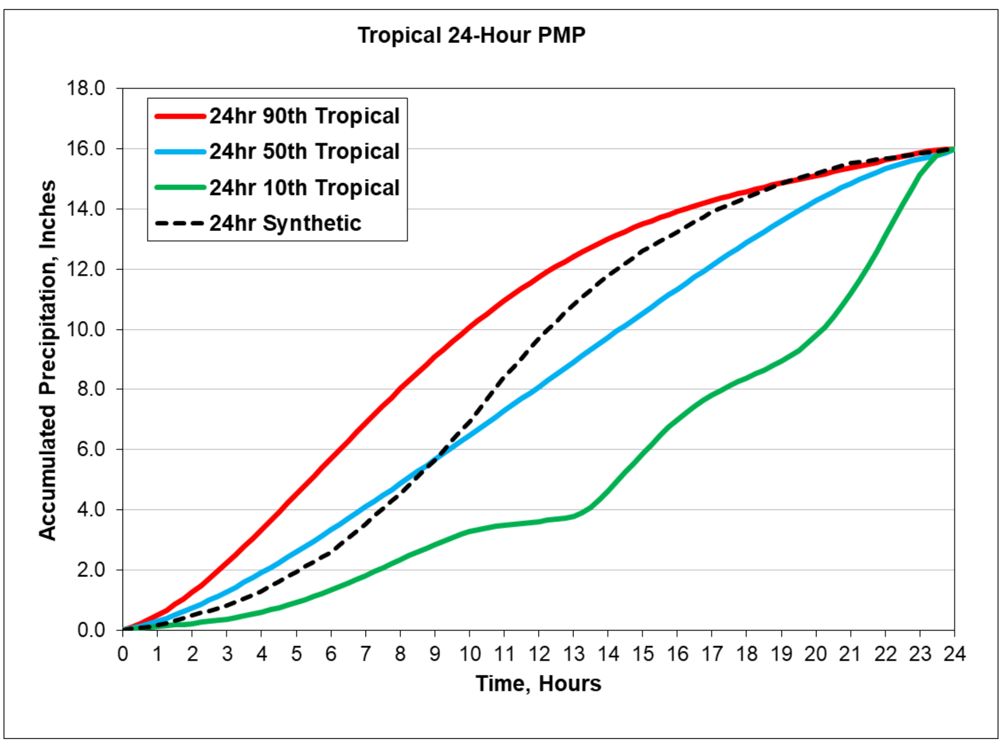

Figure 12.23: Hypothetical 24-hour Tropical storm pattern at 15-minute time step. Red line is the 90th percentile curve, blue line is the 50th percentile curve, green line is the 10th percentile curve, and black dashed line is the synthetic curve.

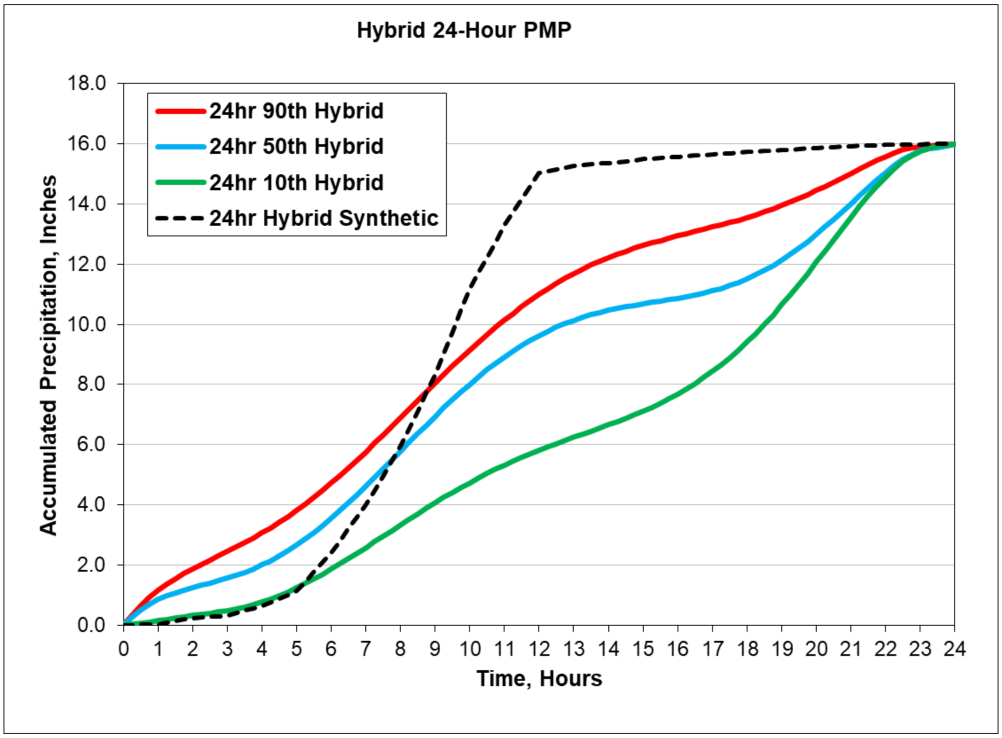

Figure 12.24: Hypothetical 24-hour Hybrid storm pattern at 15-minute time step. Red line is the 90th percentile curve, blue line is the 50th percentile curve, green line is the 10th percentile curve, and the black dashed line is the synthetic curve.

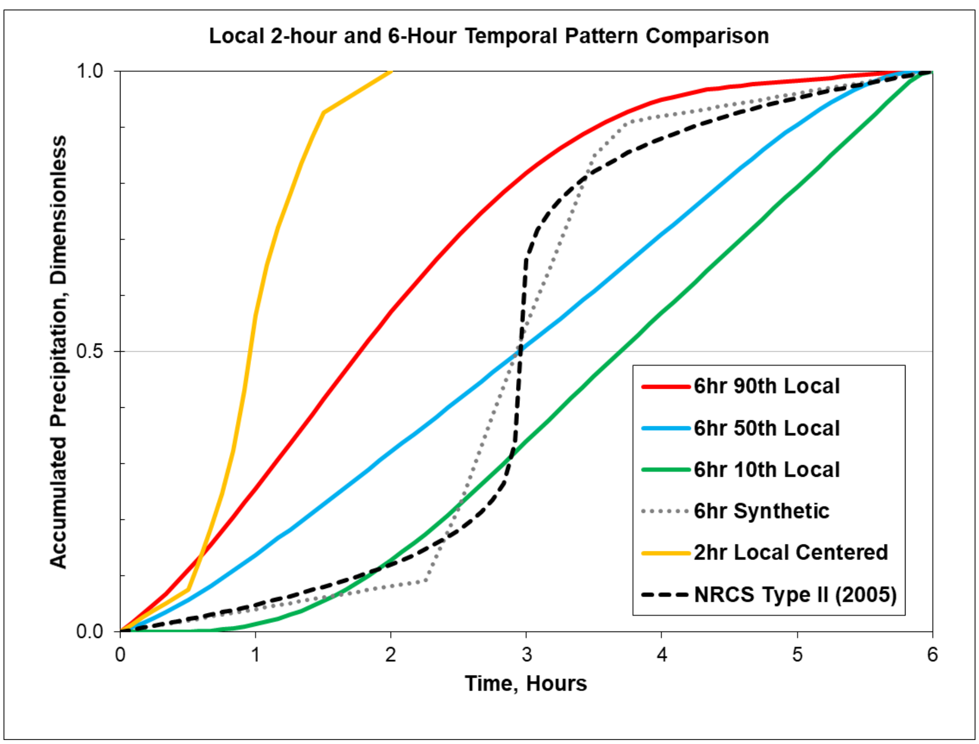

Figure 12.25: Comparison of final Local storm patterns to NRCS Type II temporal pattern.

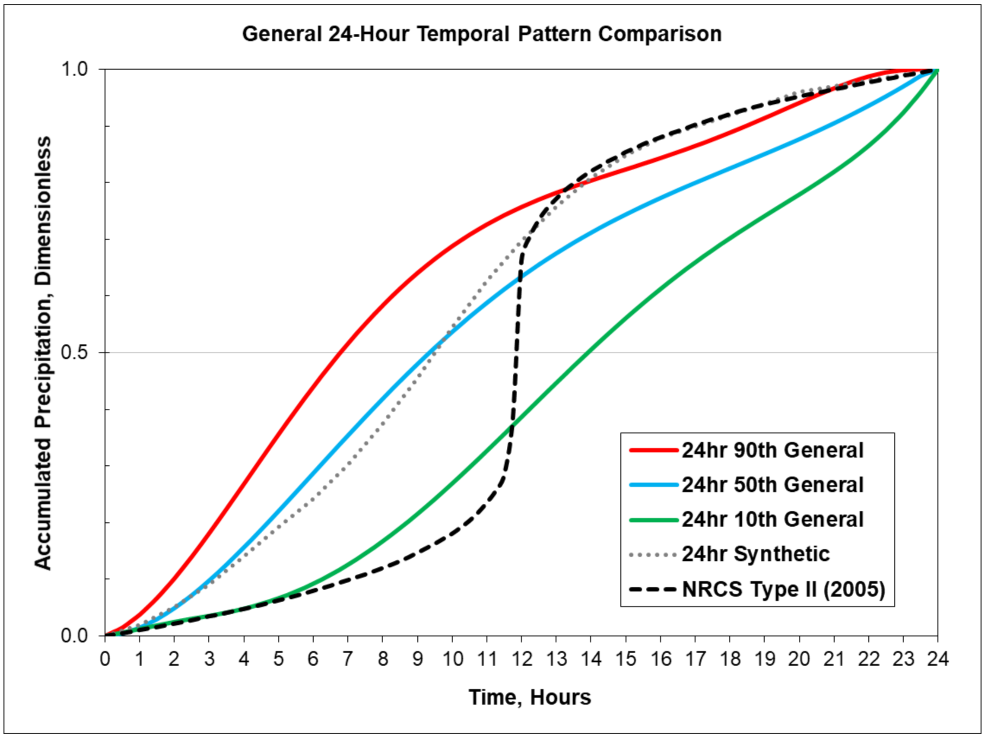

Figure 12.26: Comparison of final General storm patterns to NRCS Type II temporal pattern.

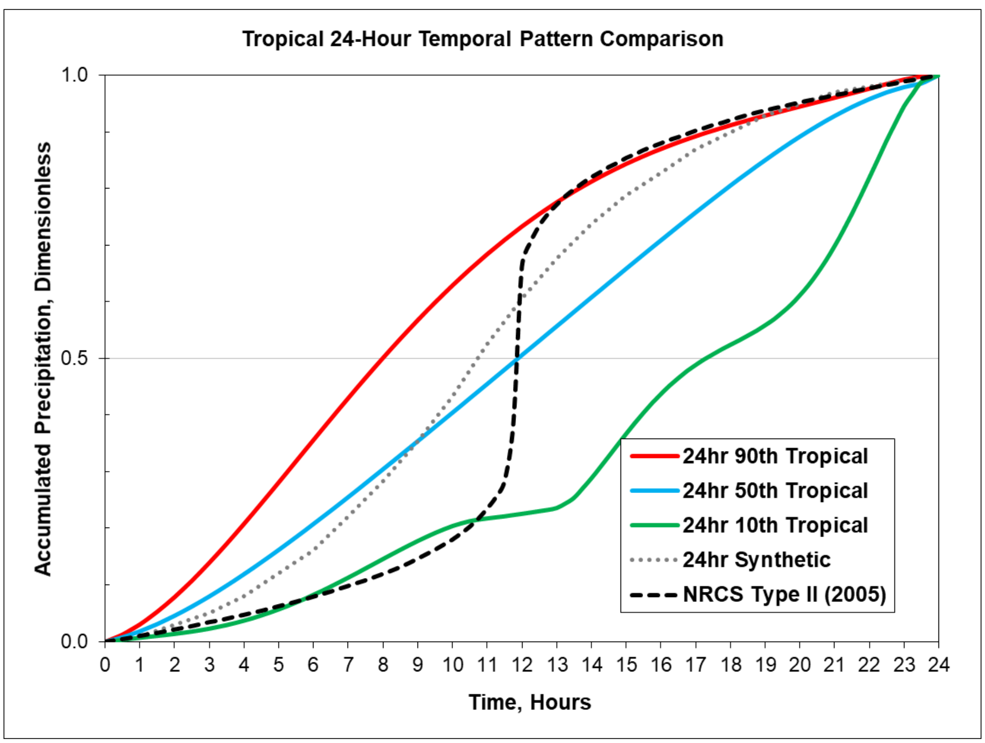

Figure 12.27: Comparison of final Tropical storm patterns to NRCS Type II temporal pattern.

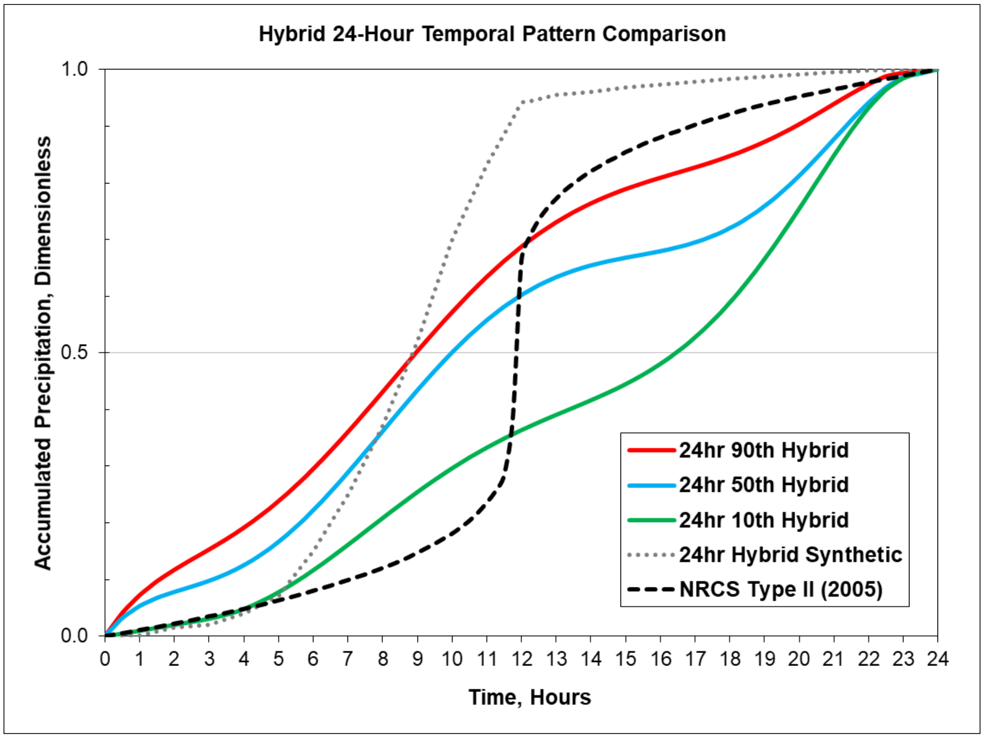

Figure 12.28: Comparison of final Hybrid storm patterns to NRCS Type II temporal pattern.

13. Sensitivities and Comparisons

In the process of deriving PMP values, various assumptions and meteorological judgments were made within the framework of state-of-the-practice processes. These parameters and derived values are standard to the PMP development process; however, it is of interest to assess the sensitivity of PMP values to assumptions that were made and to the variability of input parameter values.

PMP depths and intermediate data produced for this study were rigorously evaluated throughout the process. ArcGIS was used as a visual and numerical evaluation tool to assess gridded values to ensure they fell within acceptable ranges and met test criteria. Several iterations of maps were produced as visual aids to help identify potential issues with calculations, transposition limits, DAD values, or storm adjustment values. The maps also helped to define storm characteristics and transposition limits, as discussed previously. Over the entire PMP analysis domain, different storms control PMP values at different locations for a given duration and area size.

In some instances, a discontinuity of PMP depths between adjacent grid point locations resulted. This occurs as a result of the binary transposition limits applied to the controlling storms, with no allowance for gradients of transpositionability. Therefore, different storms are affecting adjacent grid points and may result in a shift in values over a short distance. In reality, there would be some transition for a given storm, but the process and definition of transpositionability does not allow for this. It is important to note that these discontinuities make little difference in the overall basin average PMP values as applied for hydrologic analysis purposes for most basins. The discontinuities are only seen when analyzing data at the highest resolution (e.g., individual grid points). Any significant discontinuities would potentially have the most significant effect for small basins where there are a small number of grid points representing the drainage. In those instances, each grid point value would have an exaggerated effect on the basin average PMP.

13.1 Comparison of PMP Values to HMR Studies

This study employs a variety of improved methods when compared to previous HMR studies. These methods include:

- A far more robust storm analysis system with a higher temporal and spatial resolution
- Improved dew point/SST and precipitation climatologies that provide an increased ability to maximize and transpose storms
- Gridded PMP calculations which result in higher spatial and temporal resolutions
- A greatly expanded storm record

Unfortunately, working papers and notes from the HMRs are not available in most cases. Therefore, direct PMP comparisons between the HMRs and the values from this study are somewhat limited. Furthermore, due to the generalization of the regionally-based HMR studies, comparisons to the detailed gridded PMP of this study can vary greatly over short distances. However, comparisons were made for sensitivity purposes where data allowed. The PMP values in this study resulted in a wide range of both reductions and increases as compared to the HMRs.

Gridded index PMP depths were available for HMR 51 allowing a direct gridded comparison with the depths produced for this study. A gridded percent change was calculated for the area-sizes and durations common with the HMR index PMP maps. The maximum PMP depth from the general storm, tropical storm, or local storm types were used for the HMR 51 comparisons to account for differences in storm typing between the PMP from this study and HMR studies. Tables 13.1-13.6 provide the average percent difference (negative is a reduction) from HMR 51 across each of the transposition regions analyzed.

Table 13.1: Percent difference from HMR 51 PMP at 10-square miles. PMP depths are averaged over each state and represent the largest of all storm types

Mean Statewide 10 mi^2 PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 6hr	LS/GS/TS PMP 6hr	% Change 6hr	HMR 51 12hr	LS/GS/TS PMP 12hr	% Change 12hr	HMR 51 24hr	LS/GS/TS PMP 24hr	% Change 24hr
Arkansas	29.9"	24.2"	-18.9%	35.8"	30.8"	-13.8%	40.2"	34.8"	-13.3%
Oklahoma	28.4"	24.5"	-13.6%	34.1"	30.4"	-10.9%	37.5"	33.7"	-10.2%
Louisiana	31.9"	29.0"	-9.0%	38.6"	37.3"	-3.1%	46.4"	44.2"	-4.8%
Mississippi	31.1"	26.0"	-16.5%	37.4"	33.5"	-10.4%	43.9"	38.4"	-12.7%

Table 13.2 Percent difference from HMR 51 PMP at 200-square miles. PMP depths are averaged over each state and represent the largest of all storm types

Mean Statewide 200 mi^2 PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 6hr	LS/GS/TS PMP 6hr	% Change 6hr	HMR 51 12hr	LS/GS/TS PMP 12hr	% Change 12hr	HMR 51 24hr	LS/GS/TS PMP 24hr	% Change 24hr
Arkansas	22.1"	17.3"	-21.9%	26.9"	24.5"	-8.8%	30.9"	28.7"	-7.1%
Oklahoma	20.9"	18.4"	-11.9%	25.2"	23.9"	-5.3%	28.3"	27.7"	-2.1%
Louisiana	24.4"	24.3"	-0.2%	30.6"	29.4"	-3.9%	38.4"	35.8"	-6.7%
Mississippi	23.4"	19.3"	-17.4%	28.8"	26.6"	-7.9%	35.4"	31.4"	-11.3%

Table 13.3 Percent difference from HMR 51 PMP at 1,000-square miles. PMP depths are averaged over each state and represent the largest of all storm types

Mean Statewide 1,000 mi^2 PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 24hr	GS/TS PMP 24hr	% Change 24hr	HMR 51 48hr	GS/TS PMP 48hr	% Change 48hr	HMR 51 72hr	GS/TS PMP 72hr	% Change 72hr
Arkansas	25.1"	19.0"	-24.3%	28.8"	24.2"	-15.8%	30.8"	27.8"	-9.6%
Oklahoma	22.4"	18.2"	-18.8%	25.9"	23.3"	-9.9%	27.9"	26.6"	-4.8%
Louisiana	32.2"	28.7"	-11.0%	36.7"	32.5"	-11.6%	40.0"	36.9"	-7.7%
Mississippi	29.1"	22.2"	-23.7%	33.6"	26.8"	-20.1%	36.2"	30.7"	-15.2%

Table 13.4 Percent difference from HMR 51 PMP at 5,000-square miles. PMP depths are averaged over each state and represent the largest of all storm types

Mean Statewide 5,000 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 24hr	GS/TS PMP 24hr	% Change 24hr	HMR 51 48hr	GS/TS PMP 48hr	% Change 48hr	HMR 51 72hr	GS/TS PMP 72hr	% Change 72hr
Arkansas	17.1"	14.9"	-12.7%	21.3"	19.8"	-6.8%	23.8"	20.7"	-13.1%
Oklahoma	15.3"	14.2"	-7.1%	19.3"	18.9"	-2.0%	21.1"	19.8"	-6.4%
Louisiana	21.3"	18.5"	-13.0%	25.9"	24.6"	-5.0%	29.8"	26.4"	-11.4%
Mississippi	19.4"	16.4"	-15.2%	23.8"	21.8"	-8.5%	27.3"	22.7"	-16.9%

Table 13.5 Percent difference from HMR 51 PMP at 10,000-square miles. PMP depths are averaged over each state and represent the largest of all storm types

Mean Statewide 10,000 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 24hr	GS/TS PMP 24hr	% Change 24hr	HMR 51 48hr	GS/TS PMP 48hr	% Change 48hr	HMR 51 72hr	GS/TS PMP 72hr	% Change 72hr
Arkansas	13.9"	13.1"	-5.8%	17.8"	17.3"	-2.5%	20.4"	17.5"	-14.5%
Oklahoma	12.4"	12.5"	0.5%	16.1"	16.6"	2.8%	18.0"	16.7"	-7.1%
Louisiana	17.2"	16.2"	-5.6%	21.9"	21.4"	-2.3%	25.9"	22.3"	-13.7%
Mississippi	15.8"	14.4"	-8.7%	20.2"	19.1"	-5.5%	23.7"	19.3"	-18.8%

Table 13.6 Percent difference from HMR 51 PMP at 20,000-square miles. PMP depths are averaged over each state and represent the largest of all storm types

Mean Statewide 20,000 mi² PMP (max of all types) Percent Change from HMR 51									
State	HMR 51 24hr	GS/TS PMP 24hr	% Change 24hr	HMR 51 48hr	GS/TS PMP 48hr	% Change 48hr	HMR 51 72hr	GS/TS PMP 72hr	% Change 72hr
Arkansas	11.4"	11.1"	-2.4%	14.6"	14.7"	0.4%	17.0"	14.8"	-12.7%
Oklahoma	10.0"	10.6"	6.0%	13.2"	14.1"	6.3%	15.1"	14.2"	-6.4%
Louisiana	13.4"	13.8"	2.9%	17.7"	18.6"	5.6%	21.5"	19.3"	-10.2%
Mississippi	12.6"	12.3"	-2.8%	16.5"	16.2"	-1.6%	19.7"	16.4"	-16.6%

13.2 Comparison of PMP Values with Previous Studies

The gridded PMP calculation process used in this study closely follows the methods applied to the surrounding Texas statewide PMP Study (2016) and Colorado-New Mexico Regional Precipitation Study (2018). In addition, many of the same storms were used in the Nebraska statewide PMP Study (2008), the Arkansas Nuclear One PMP study (2014) and the TVA PMP study (2015). In addition, a site-specific PMP study was completed for the Eucha Dam basin in Oklahoma (2015). However, in all these cases there were updates and differences in storm lists, storm typing, storm analysis methods, maximization methods, source data, transposition methods, and/or transposition limits. In addition, site-specific considerations can contribute to discrepancies from PMP provided in the previous studies in areas of overlap.

Efforts have been made to be consistent with previous work. However, the PMP depths provided in this study should be considered more reliable in cases where differences occur.

Figure 13.1 shows an example of the differences in PMP depths in areas where the OK-AR-LA-MS study overlaps with the Texas study. In this case, the primary source of discrepancy lies in the differences between the NOAA Atlas 14 100-year climatology used for the GTF calculation versus the Texas statewide precipitation frequency estimates used for the Texas PMP study.

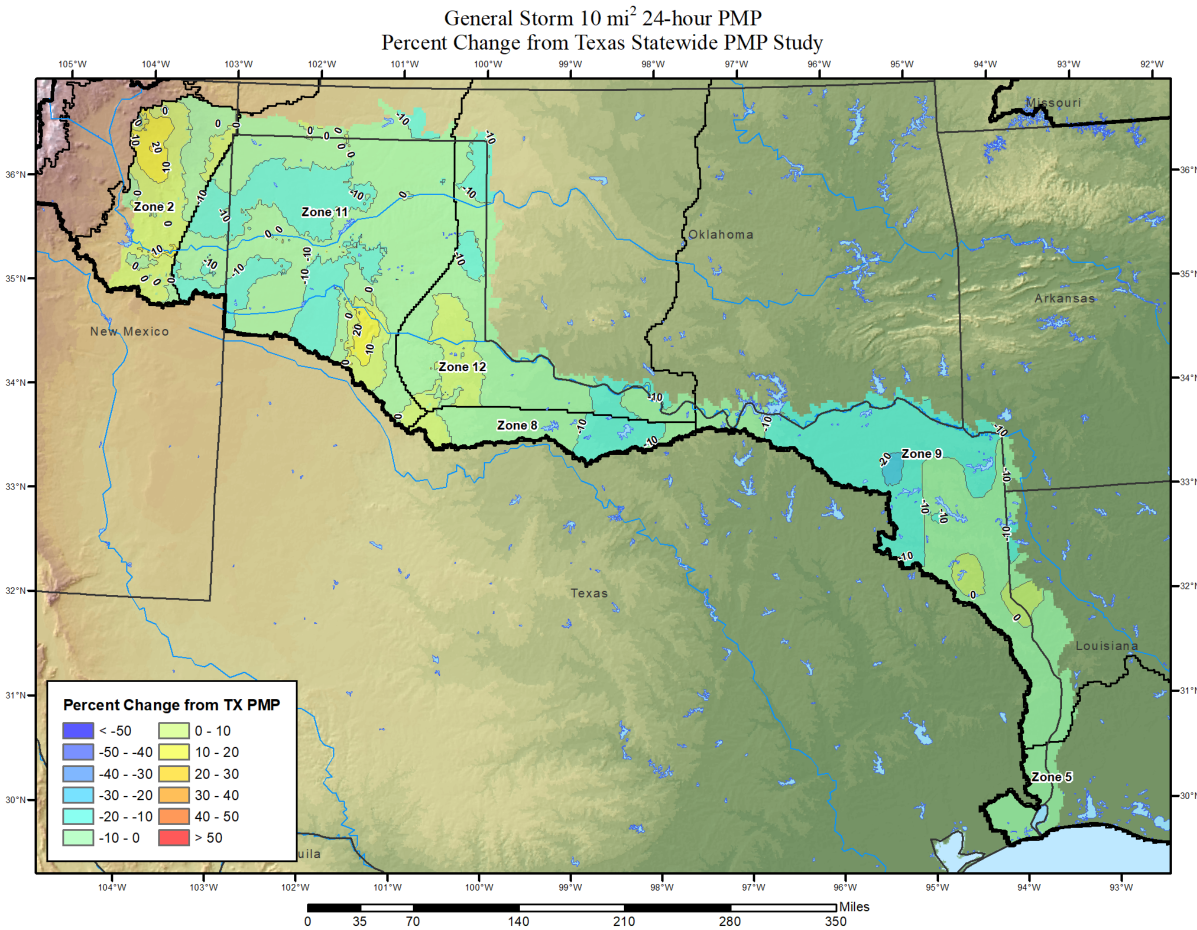

Figure 13.1: Percent change in general storm type 10 square mile 24-hour PMP from Texas Statewide PMP Analysis

13.3 Comparison of PMP Values with Precipitation Frequency

The ratio of the PMP to 100-year return period precipitation amounts is generally expected to range between two and four, with values as low as 1.7 and as high as 5.5 for regions east of 117°W found in HMR 57 and HMR 59 (Hansen et al., 1994; Corrigan et al., 1999). Further, as stated in HMR 59 "*…the comparison indicates that larger ratios are in lower elevations where short-duration, convective precipitation dominates, and smaller ratios in higher elevations where general storm, long duration precipitation is prevalent*" (Corrigan et al., 1999, p. 207).

For this study, the maximum 24-hour 1-square mile PMP was compared directly to the 100-year 24-hour rainfall-only values on a grid-by-grid basis for the entire analysis domain using a GIS. The comparison was presented as a ratio of PMP to 100-year rainfall, and it was determined for each grid point. Figures 13.2-13.4 illustrate the PMP to 100-year rainfall ratios for 6-hour local storm PMP, 24-hour general storm PMP, and 24-hour tropical storm PMP, respectively. The PMP to 100-year return period rainfall ratios vary from 2.12 to 5.14, after combining storm types. The values are in reasonable proportion expected for the study area and demonstrate the PMP values are at appropriately rare levels.

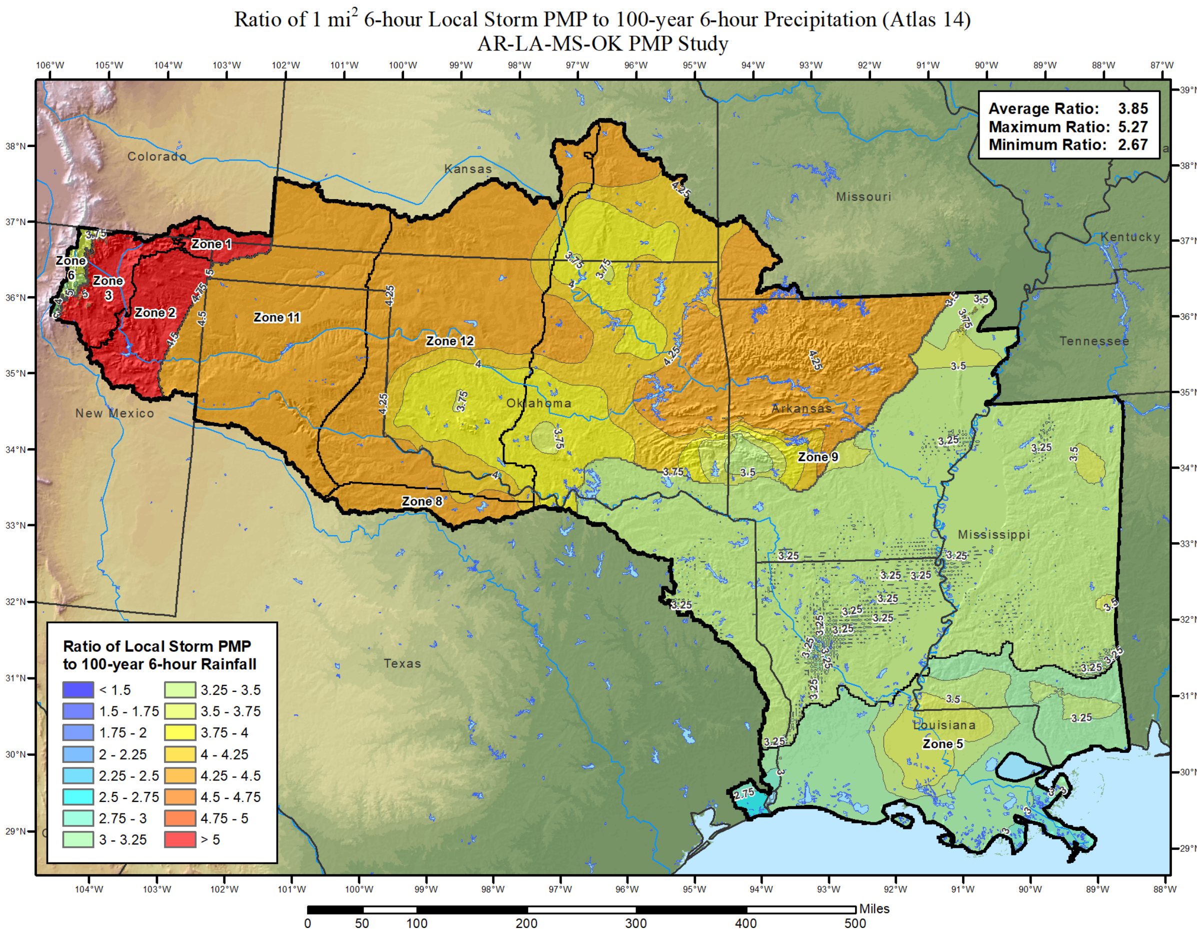

Figure 13.2: Ratio of 6-hour 1-square mile local storm PMP to 100-year precipitation

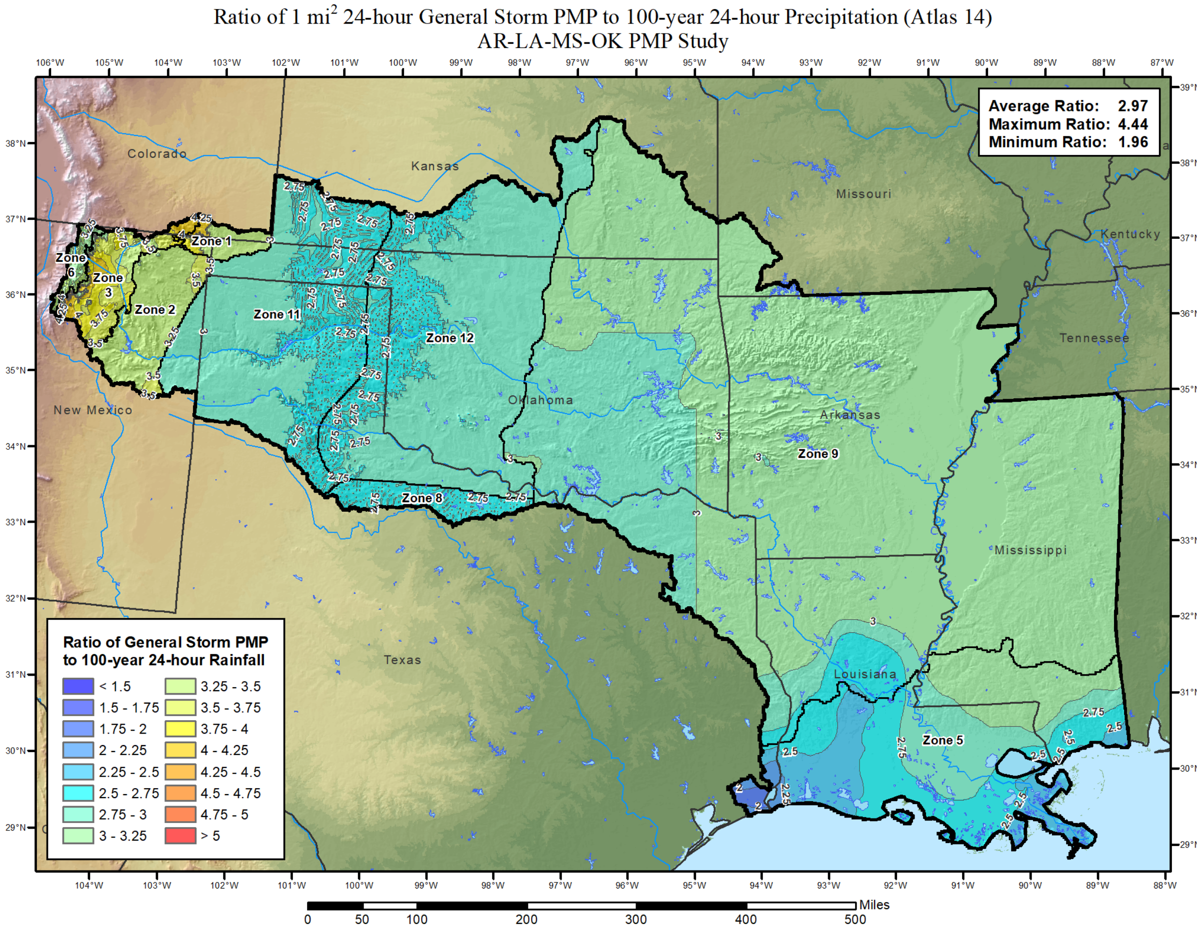

Figure 13.3: Ratio of 24-hour 1-square mile general storm PMP to 100-year precipitation

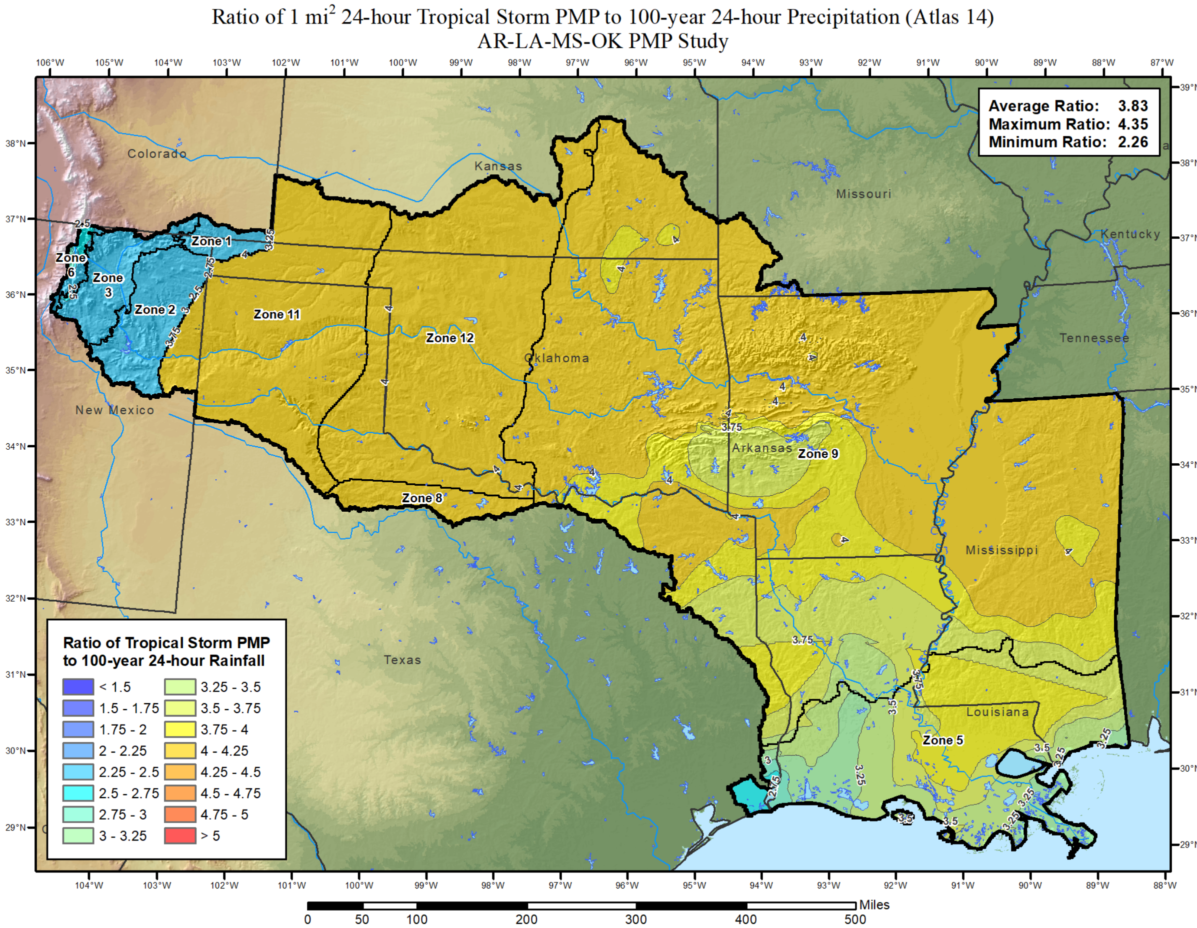

Figure 13.4: Ratio of 24-hour 1-square mile tropical storm PMP to 100-year precipitation

14. Uncertainty and Limitations

14.1 Sensitivity of Parameters

In the process of deriving PMP values, various assumptions and meteorological judgments were made. Additionally, various parameters and derived values were used in the calculations, which are standard to the PMP development process. It is of interest to assess the sensitivity of PMP values to assumptions that were made and to the variability of parameter values.

14.2 Saturated Storm Atmosphere

The PMP development process assumes that the atmosphere is saturated from the ground through the top of the atmosphere (30,000 feet or 300mb) for both the observed storm events and the hypothetical PMP storms. Applying this assumption, a moist pseudo-adiabatic temperature profiles is applied to both the historic storms and the hypothetical PMP storm to quantify the amount of atmospheric moisture available to the observed storm and the maximized (PMP storm). Initial evaluations of this assumption in the EPRI Michigan/Wisconsin PMP study (Tomlinson, 1993) and the Blenheim Gilboa study (Tomlinson et al., 2008) indicated that historic storm atmospheric profiles were generally not entirely saturated and contained somewhat less precipitable water than was assumed in the PMP procedure. This was also shown by Chen and Bradley (2006). More detailed evaluations were completed by Alaya et al., (2018) utilizing an uncertainty analysis and modeling framework. This again demonstrated that the assumption of a fully saturated atmosphere in conjunction with maximum storm efficiency may not be possible. However, recent work on a PMP storm, Hurricane Harvey utilized high resolution atmospheric profiles and showed that the atmosphere was fully saturated (Fernandez-Caban et al., 2019). This demonstrates that this assumption is possible when associated with a PMP-type storm event.

What is used in the storm maximization process during PMP development is the ratio of precipitable water associated with each storm. If the precipitable water values for each storm were both slightly overestimated, the ratio of these values would be essentially unchanged.

For example, consider the case where instead of a historic storm with a storm representative dew point of 70° F degrees having 2.25 inches of precipitable water assuming a saturated atmosphere, it actually had 90% of that value or about 2.02 inches. The PMP procedure assumed the same type of storm with similar atmospheric characteristics for the maximized storm but with a higher dew point, say 76° F degrees. The maximized storm, having similar atmospheric conditions, would have about 2.69 inches of precipitable water instead of the 2.99 inches associated with a saturated atmosphere with a dew point of 76° F degrees. The maximization factor computed using the assumed saturated atmospheric values would be 2.99″/2.25″ = 1.33. If both storms were about 90% saturated instead, the maximization factor would be 2.69″/2.02″ = 1.33. Therefore, potential inaccuracy of assuming saturated atmospheres (whereas the atmospheres may be somewhat less than saturated) should have a minimal impact on storm maximization and subsequent PMP calculations.

14.3 Maximum Storm Efficiency

The assumption is made that if a sufficient period of record is available for rainfall observations, at least a few storms would have been observed that attained or came close to attaining the maximum efficiency possible in nature for converting atmospheric moisture to rainfall for regions with similar climates and topography. The further assumption is made that if additional atmospheric moisture had been available, the storm would have maintained the same efficiency for converting atmospheric moisture to rainfall. The ratio of the maximized rainfall amounts to actual rainfall amounts would be the same as the ratio of precipitable water in the atmosphere associated with each storm.

There are two issues to be considered. First relates to the assumption that a storm has a rainfall efficiency close to the maximum possible. Unfortunately, state-of-the-science in meteorology does not support a theoretical evaluation of storm efficiency. However, if the period of record is considered (generally over 100 years), along with the extended geographic region with transpositionable storms, it is accepted that there should have been at least one storm with dynamics that approached the maximum efficiency for rainfall production.

The other issue pertains to the assumption that storm efficiency does not change if additional atmospheric moisture is available. Storm dynamics could potentially become more efficient or possibly less efficient depending on the interaction of cloud microphysical processes with the storm dynamics. Offsetting effects could indeed lead to the storm efficiency remaining essentially unchanged. For the present, the assumption of no change in storm efficiency seems acceptable.

14.4 Storm Representative Dew Point and Maximum Dew Point

The maximization factor depends on the determination of storm representative dew points, along with maximum historical dew point values. The magnitude of the maximization factor varies depending on the values used for the storm representative dew point and the maximum dew point. Holding all other variables constant, the maximization factor is smaller for higher storm representative dew points as well as for lower maximum dew point values. Likewise, larger maximization factors result from the use of lower storm representative dew points and/or higher maximum dew points. The magnitude of the change in the maximization factor varies depending on the dew point values. For the range of dew point values used in most PMP studies, the maximization factor for a particular storm will change about 5% for every 1°F difference between the storm representative and maximum dew point values. The same sensitivity applies to the transposition factor, with about a 5% change for every 1°F change in either the in-place maximum dew point or the transposition maximum dew point.

14.5 Judgment and Effect on PMP

During the process of PMP development several decisions were based on meteorological judgment. These include the following:

- Storms used for PMP development
- Storm representative dew point/SST value and location
- Storm transposition limits

- Use of precipitation frequency climatologies to represent differences in precipitation processes (including orographic effects) between two locations

Each of these processes were discussed and evaluated during the PMP development process internally within AWA and with the Board of Consultants and others involved in the project. The resulting PMP depths derived as part of the PMP development reflect the most defensible judgments based on the data available and current scientific understanding. The PMP results represent reproducible, reasonable, and appropriately conservative estimates for use in the development of the PMF for high hazard and critical infrastructure.

14.6 Limitation of Applying the PMP Depths

This study focused on the development of PMP depths from 1-hour through 120-hours at areas sizes from 1-square mile through 20,000-square miles that would be applied to a single basin and its sub basins. Therefore, for rivers systems exceeding these bounds a separate site-specific PMP study may require separate site-specific PMP studies. Examples would include the overall Red River, Arkansas, and Mississippi River basins. In addition, no detailed analysis was completed regarding antecedent or subsequent precipitation or hydrologic conditions and these should be investigated separately and on an individual basin level. Finally, PMP depths from this study are to be applied to a single basin or region assuming that PMP occurs in a worst-case, yet meteorologically possible scenario over a given location. Therefore, if concurrent precipitation depths are needed over adjoining or nearby locations, PMP should not be applied concurrently. Instead other methods should be utilized to derive the concurrent rainfall. Examples would include running the PMP tool again at the overall larger area size and subtracting out the PMP volume over the basin of interest, utilizing precipitation frequency climatologies and appropriate areal reduction factors to distribute concurrent rainfall outside of the PMP region, or utilizing observed rainfall patterns to inform the spatial extent of a giving synoptic weather pattern. In all cases, care should be taken so as to not violate the requirement of the PMP design storm being “physically possible”.

14.7 Climate Change and PMP

The effect of climate change on the number and intensity of extreme rainfall events is unknown as of the date of this report. With a warming of the atmosphere, there can potentially be an increase in the available atmospheric moisture for storms to convert to rainfall (e.g. Kunkel et al., 2013). However, storm dynamics play a significant role in that conversion process and the result of a warming climate on storm dynamics is not well understood. A warmer climate may lead to a change in the frequency of storms and/or a change in the intensity of storms, but there is no definitive evidence to indicate the trend or the magnitude of potential changes regarding PMP level rainfall (Herath et al., 2018).

Based on these discussions, it is apparent that the current practice of PMP determination should *not* be modified in an attempt to address potential changes associated with climate change. This study has continued the practice of assuming no climate change, as climate trends are not considered when preparing PMP estimates (WMO 2009, Section 1.1.1).

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